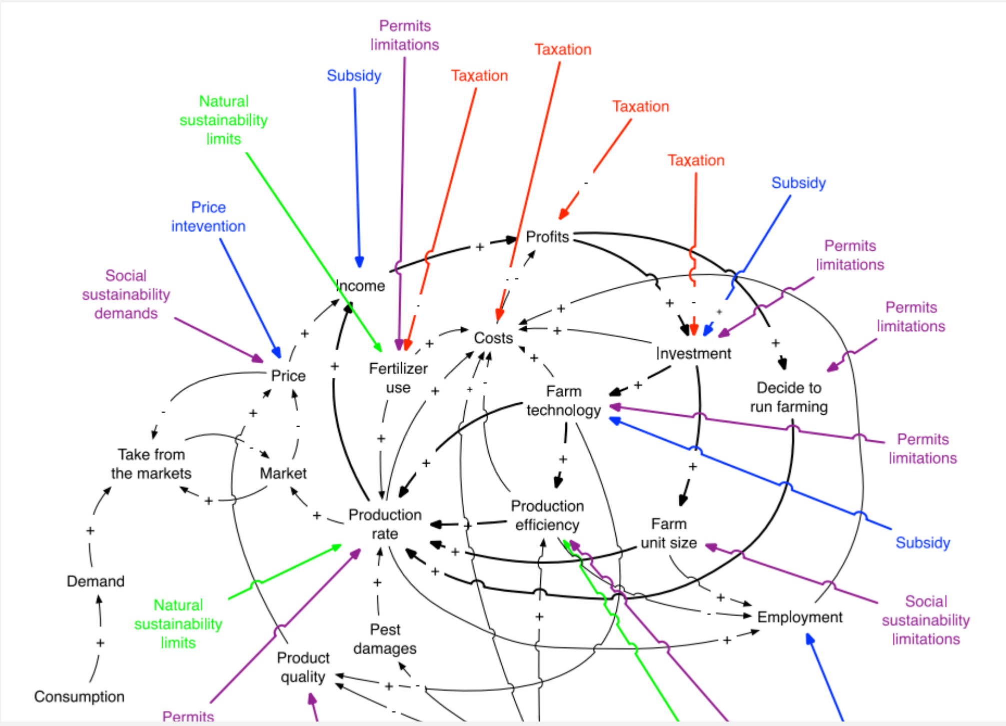
Realizing the EEA Imaginaries: Pathways to a Resilient Food Sector in Europe 2050 through System Dynamics Modelling



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Key Messages

- **Interconnected Systems**
  The food system is deeply intertwined with energy and mobility systems, highlighting the need for integrated policy approaches to address sustainability challenges. The analysis underscores the intricate connections between food production, consumption, mobility, and energy systems, advocating for a weighed policy approach to address these multifaceted challenges.

- **Methodological Approach**
  The project adopted a multi-method systems approach, combining qualitative and quantitative system dynamics modelling. This approach facilitated a multi-faceted understanding of the complex feedback loop interactions and interdependencies within the food system of the Farm 2 Fork and integrating visioning, foresight, system dynamics modelling, and policy analysis in the broader socio-economic and environmental contexts of the food value chain.

- **Synthesizing Farm-to-Fork strategies**
  The report analysed and represented the Farm-2-Fork (F2F) strategic objectives, their connection to broader policy goals, and how these relate to specific policy instruments. It applied qualitative analysis by employing Causal Loop Diagrams (CLDs), which allowed for detailed visualization of the cause-and-effect relationships across the food value chain. By mapping these instruments, it was possible to identify how they support or contradict each other, highlighting the importance of strategic policy mix designs to achieve the desired outcomes.

- **Policy Levers and Imaginaries**
  The report explores policy levers essential for transitioning towards the EEA's four Imaginaries: Ecotopia, The Great Decoupling, Unity in Adversity, and Technocracy for the Common Good. Each imaginary offers a distinct vision for Europe’s future, emphasizing different strategies for sustainability, social cohesion, technological advancement, and environmental protection.

- **Quantitative modelling results and pathways**
  The development of the CRAFT model marks a novel step in applying quantitative, data-rich system dynamics modelling to simulate the EU food sectors complex dynamics. This model facilitated a first step to an in-depth examination of how different policies and practices could influence the different sector, environmental impacts and offering valuable insights into the potential pathways towards each of the EEA's imaginaries and the effectiveness of various policy levers.

- **Recommendations and future directions**
  The report recommends continued investment in system dynamics modelling as a tool for policy analysis and decision support. Further research should explore the interactions between the food systems and other critical sectors, such as energy and transportation, to identify additional synergies and trade-offs. Expanding the model to incorporate more detailed data and scenarios can provide deeper insights into the pathways towards sustainability within the Imaginaries.

Executive Summary

Realizing the EEA Imaginaries for a Sustainable Food Sector in Europe by 2050
This report, prepared by the European Topic Centre on Sustainability Transitions (ETC ST), explores pathways towards realizing the European Environment Agency's (EEA) imaginaries for a resilient food sector in Europe by 2050. The overall goal of the project was to assess the extent to which policy targets related to Farm-2-Fork (F2F) and mobility can be reached using explorative dynamic modelling approaches. Synergies and conflicts between policy targets were analysed. Policies to develop transition pathways towards reaching the four different imaginaries for a sustainable future in Europe in 2050 were developed.

Interconnected Systems
The food system is deeply intertwined with energy and mobility systems, highlighting the need for integrated policy approaches to address sustainability challenges. The analysis underscores the intricate connections between food production, consumption, mobility, and energy systems, advocating for a weighed policy approach to address these multifaceted challenges through the entire food value chain.

Methodological Approach
The project adopted a multi-method systems approach, combining qualitative and quantitative system dynamics modelling. This approach facilitated a multi-faceted understanding of the complex feedback loop interactions and interdependencies within the food system of the Farm 2 Fork and integrating visioning, foresight, system dynamics modelling, and policy analysis in the broader socio-economic and environmental contexts of the food value chain.

From the production and processing side of the food value chain, the analysis provided in this report highlighted some aspects that need to be considered when modelling food systems or thinking about food policy. These are:

- Different systems have different productivities and productivity rates in time and space. Ecological modes of production have lower productivity (product per unit of area) than intensive and super-intensive modes of production. This means that more area would be required from ecological modes of production (if existent and with all the environmental impacts associated with this area increases) to fully be seen as a substitution for intensive and super-intensive modes of production. Sustainable food systems need to tackle food security (satisfying food demand) and the environmental impacts of production at the same time. This may require increasing the productivity of ecological modes of production and niches that are currently not utilised (where research is required) and reducing the environmental impacts of intensive and super-intensive modes of production.
- The efficiency of the entire food system value chain, encompassing both its hierarchical support structures within the EU and its external connections, requires thorough analysis. Throughout the value chain, the diverse objectives pursued by each sector manifest in the maximization of value per unit of production, focusing on outputs rather than optimizing for overall systemic efficiency or consumer benefits. This approach worsens food losses across the value chain and promotes the production of energy-intensive, nutrient-deficient foods, thereby inflating demand and diminishing the system’s resilience against external shocks. Addressing these inherent inefficiencies, driven by conflicting goals, is critical for enhancing system performance.

Synthesizing Farm-to-Fork strategies
The report analysed and represented the F2F strategic objectives, their connection to broader policy goals, and how these relate to specific policy instruments. The report applied qualitative analysis by employing Causal Loop Diagrams (CLDs), which allowed for a detailed visualization of the cause-and-effect relationships across the food value chain. By mapping these instruments, it was possible to identify how

they support or contradict each other, highlighting the importance of strategic policy mix designs to achieve the desired outcomes.

Policy Levers and Imaginaries
The report explores policy levers essential for transitioning towards the EEA's four Imaginaries for sustainable Europe 2050: Ecotopia, The Great Decoupling, Unity in Adversity, and Technocracy for the Common Good. Each Imaginary offers a distinct vision for Europe's future, emphasizing different pathways and transitioning for sustainability, social cohesion, technological advancement, and environmental protection.

Policy and modelling exercises need to tackle the demand side of the food value chain.
The factors that affect consumer choices are manifold. The way these factors influence food choices is also non-linear, forming a web of interactions and resulting in complex dynamic causal-chains. Dealing with the factors that affect consumer choices will inevitably bring many other systems in the near and long-term, namely, the planning of urban-rural systems, the transport and mobility system, labour and social policy, education policy, and public procurement policies. Facilitating the need for anticipatory policy design, which is rooted in the back-casting of principles for future-proofed policies, is essential. Futureproofing for sustainability hinges on the balance between fail-safe and save-fail policies, guided by back-casting from fundamental principles. This iterative approach ensures that policies evolve in alignment with sustainability goals, effectively bridging the gap between current states and desired future outcomes.

Quantitative modelling results and pathways
The development of the CRAFT model marks a novel step in applying quantitative, data-rich system dynamics modelling to simulate the EU food sector's complex dynamics. This model facilitated a first step to an in-depth examination of how different policies and practices could influence the different sector, environmental impacts and offering valuable insights into the potential pathways towards each of the EEA's imaginaries and the effectiveness of various policy levers.

Recommendations and future directions
The report recommends continued investment in system dynamics modelling as a tool for policy analysis and decision support. For the long term, the report advocates for combining CLD with system dynamic modelling to identify incremental policy adjustments and develop a quantitative model for analyzing Farm to Fork (F2F) and EEA-related systems, transitioning towards a data-enriched analysis approach.

Additionally, it calls for greater investigation into policy coherence across sectors, enhanced stakeholder engagement, and the integration of sustainability principles into all aspects of the food value chain. Further research should explore the interactions between the food systems and other critical sectors, such as energy and transportation, to identify additional synergies and trade-offs. Expanding the model to incorporate more detailed data and scenarios can provide deeper insights into the pathways towards sustainability within the Imaginaries.

1 Introduction

The production-consumption systems in Europe place significant strain on the environment. The European Green Deal (EGD) stands as one of the most critical political programs aimed at advancing sustainability in Europe and alleviating the environmental burden. The question of whether the EGD will reach its targets is of great importance. The European Environment Agency (EEA) is responsible for monitoring Europe's environmental status and, if environmental objectives are not met, proposing measures to achieve them, or at least fostering a scientifically informed political discussion on enhancing the effectiveness of these measures. To this end, the EEA needs to analyze how the targets for a sustainable Europe by 2050 can be achieved, determine the optimal approach to transitioning to a sustainable Europe, and assess the extent to which the EGD and 8th Environmental Action Program (8th EAP) can deliver under current and future conditions.

The energy, food, and mobility systems are key interconnected components of our consumption-production processes. Their strong interconnections mean that actions in one area can unexpectedly affect the others, highlighting the importance of understanding the interplay between various policies and goals outlined in the EGD. This includes recognizing potential synergies and trade-offs, as well as identifying effective strategies for achieving these objectives. While certain goals have been established, the future remains inherently uncertain. The outcomes of these policies over time will shape the future that emerges. Furthermore, the success of the EU's policy objectives also hinges on the evolving landscape in Europe over the next few decades.

Different futures can already be *imagined* today. As part of the initiative for creating foresight solution scenarios for a sustainable Europe by 2050, the EEA, in collaboration with EIONET FORESIGHT, has recently developed four visions of sustainable futures. These visions, titled (1) Ecotopia, (2) The Great Decoupling, (3) Unity in Adversity, and (4) Technocracy for Good, describe potential states of Europe in 2050 under different sustainable development scenarios (EEA, 2022). These envisioned futures serve dual purposes. First, they offer reflections on the core objectives established in the EGD and the possible futures these objectives may enable. Second, they provide a framework to (i) explore viable pathways from our current state to each of these envisioned future scenarios, and (ii) identify key levers, enablers, and policies that could enhance policy coherence, guide present actions towards one of these desired futures, and accelerate the transition. The concept of dynamic coherence refers to the approach of addressing the connections, including both synergies and trade-offs, among various policy objectives within the Commission's agenda with a focus on transition. This approach emphasizes the importance of coordinating policies more effectively across different time horizons, ensuring a balance between immediate actions and long-term goals. Dynamic coherence aims to improve how policies are formulated at different scales (both broad and specific) and timelines (short-term and long-term), ensuring that immediate actions align with and support long-term objectives.

1.1 Rationale for analysing the production-consumption systems

The EGD prioritizes food systems and mobility transformations as key avenues towards Europe's sustainability by 2050, given their critical role and complex links to human needs. This effort faces the challenge of enhancing the sustainability of production and consumption through strategies like 'Farm to Fork' (F2F) (European Commission 2020). Evaluating the effectiveness of current initiatives, such as the EGD and the 8th EAP, is essential for guiding this sustainable transition. An in-depth analysis is required to identify the factors, stakeholders, and actions crucial for success across various timeframes while also considering the feasibility of policy targets and the potential for synergies or conflicts between food and mobility systems. Understanding the interconnections and ensuring policy coherence is vital for navigating towards a sustainable future. This task demands a systematic approach to map out driving forces, feedback loops, interconnections, and key stakeholders, alongside assessing the impact of policy strategies, including **both the overarching policy levers, such as financial instruments and tools used to implement those levers.** Achieving a dynamic policy coherence will ensure that strategies across the proposed scenarios remain effective and mutually reinforcing, facilitating a comprehensive assessment of Europe's path to sustainability by 2050.

1.2 Goals and Objectives of the project

The overall goal is to assess the extent to which policy targets related to F2F and mobility can be reached using explorative dynamic modelling approaches. Analyse what type of synergies or conflicts exist between them and explore policies to evaluate transition pathways towards reaching the four different envisioned imaginaries for a sustainable future in Europe in 2050.

The specific objectives of this ETC task involve developing novel systems model outlines and applications that include qualitative systems thinking models (e.g. Causal Loop diagrams) and quantitative data-driven multi-scale system dynamic models to use them to assess cross-systems effects and effectiveness in policy to reach cross-systems goals in view of the State of the Environment Report (SOER2025), and to evaluate the approach for future use.

The specific tasks involve:

1. Assessing on an overall level how different systems interact and the impact of various policies over different timeframes for F2F.
2. Identify policy objectives in F2F and policy instruments that are instrumental for assessing the performance of different pathways towards sustainable Europe 2050 Imaginaries.
3. Evaluate the effectiveness of different modelling approaches for ongoing and future applications and environmental assessments.

The key questions of the study included:

1. What are the potential actors and activities that may impact the success of transitioning food and mobility towards sustainability over time? Are the policy objectives regarding food and mobility systems achievable, and what potential interdependencies or clashes could emerge between them?
2. How can a qualitative and quantitative system dynamics model of the EU agricultural and food system be developed to assess potential policies for a transition to sustainability, including cross-sectoral interactions with the transport and energy sectors?
3. How can a system dynamics model be used to interpret and represent the EEA imaginaries, and how can it include policy levers for transitioning to sustainability for the food sector in the context of the EEA imaginaries?

The key stakeholders for disseminating the project outputs are EU institutions (JRC, ECs), EEA experts across thematic areas, and the EEA SOER 2025 team.

1.3 Results from the project

The project has delivered new research in three areas, i.e. on methods and scenario analysis and assessment of the EEA imaginaries.

Results on qualitative modelling

The project provided a qualitative analysis of the F2F value chain and its connection to mobility systems. It also delivered a qualitative analysis of the framing of policy objectives for F2F and identified areas for developing policy instruments relevant for pathways toward the EEA imaginaries. The findings are presented in models that include qualitative system thinking models, such as Causal Loop Diagrams (CLD), Impact System modelling (Imodeler), and flow diagrams using Stocks and Flow Diagrams (SFD).

Results on methods for data-rich system dynamics
The project delivered results on methods. The project applied system dynamics (SD) analysis to the EU agro-food system including the feedbacks to the transport system. A qualitative system of thinking and analysis, developing causal loop diagrams (CLDs), describes the structure of the agro-food system along the whole value chain of the F2F. This system understanding was then used to develop a system model of the agro-food production system, with connections to the transport system. The modelling used a 'data rich' approach. Data for the EU agriculture system and global imports and exports of agricultural produce was compiled from EU and international sources. This data was used to calibrate a new dynamic simulation model - the CRAFT model. This is the first application of a 'data rich' approach to EU agricultural systems analysis. This approach gives a very detailed description of the historical data. It enables the comparison of key performance indicators (KPIs) across EU countries and aggregation to the EU level. This high level of detail in the data has enabled a comprehensive representation of the EU agricultural system. The dynamic simulation structure applying SD modelling methods and software has been used to develop non-linear projections of system change into the future.

Results on analysis of the EEA imaginaries
This dynamic simulation model (CRAFT) was then used to simulate, for the first time, pathways to the four EEA imaginaries (EEA 2023a). This involved the interpretation of the qualitative imaginaries in terms of possible policy levers to implement sustainability, identification of relevant KPIs for representation in the CRAFT model and variables to represent different combinations of policies.

The project delivered a first pilot version of the simulation model, showing how the policy levers in the model could be adjusted to generate pathways to the four imaginaries of a sustainable agro-food system in 2050. Although the results are preliminary, they indicate possible pathways to achieve a sustainable agro-food system.

1.4 Structure of this report

In the context of the description above, this report focuses on an experimental work using a combination of different conceptual approaches rooted in system thinking methods, linking with a novel data-driven system dynamics approach.

The report covers two main parts: 1) a qualitative analysis employing system thinking and systemic analysis approaches and 2) a quantitative analysis utilizing the system dynamics method. While section 1 provides the general introduction, **section 2** outlines the methodologies applied in this project, which integrates qualitative impact and causal loop analysis with a quantitative system dynamics model. The system boundaries are established based on the qualitative systems analysis from the Foresight on Demand (FOD) project and activities done in 2022 (FoD contract FoD-2018/RTD/A2/OP/PP-07001-2018/LOT). These analyses support the definition of the EU food system and its interactions with the transport (**section 3**) and energy sectors in the quantitative system dynamics model, that is detailed further in section 7. **Section 4** delves into policies related to the EU agri-food system, employing a forward-looking scenario methodology for assessment. The EEA imaginaries are used to interpret a set of assumptions framing the conditions of how a sustainable future is envisioned in each of them. These imaginaries then guide the development of a model scenario structure in **Section 5**. **Section** 6 explores how KPIs for the model scenario outcomes are determined and how the general policy visions, unique for each of the imaginaries, are operationalized through policy 'levers' in the quantitative model. **Section 7** introduces the model, while **Section 8** presents some initial results. Finally, **Section 9** concludes with overall insights and recommendations for further work.

2 Methodology

Based on the insight of the first scoping study in this project (FoD contract FoD-2018/RTD/A2/OP/PP-07001-2018/LOT) and the extended scoping paper delivered end of September 2022, we followed a Systems Thinking approach, which includes conceptual methods such as Causal Loop Diagrams (CLD) (Roberts et al. 1983; Kim D. H. 1994; Haraldsson 2004; Haraldsson and Sverdrup 2021), Impact System modelling (Imodeler), (Neumann et al. 2018) and flow diagrams using Stocks and Flow Diagrams (SFD) (Sterman 2000; Sverdrup et al. 2022). We aimed to identify and understand the behavioural rules of the system, i.e. drivers and feedbacks, stakeholders and their activities that steer system behaviour – in our case, the combined systems of food and mobility. Key attributes of System Thinking are finding simplicity in complexity by defining proper framing in space and time of the problem and defining the key questions associated as well as different perspectives on the problem, such as interconnections and boundaries (Haraldsson & Sverdrup 2021). They also identify the drivers and leverage points in a system. While **Systems Thinking** is a way to describe and define the system boundaries around the problem and understand the causality and interrelations between variables within a system, **System Dynamics** quantifies the impact of those interactions. On the contrary, **Qualitative impact Systems Modelling** is a hybrid method comparable to fuzzy cognitive maps (Qazi and Raza 2021; Felix et al. 2019; Kosko 1986), giving additional information about the connections of the parts of the systems (orientation, direction, delay, and strength compared to other factors).

Conceptual modelling is useful for simplifying highly complex systems, and it is an important step for translating different factors into quantitative system dynamic modelling. In this project, we applied the CLD and causality analysis to conceptualise complex causal relations and feedbacks. Emphasis was put on analysing "cause and effect" relationships between system actors, activities, and items and translating them into mass-flow diagrams and subsequent stock-flow diagrams. This forms the basis for full quantitative model based on the System Dynamics method (Sverdrup et al 2022).

The specifics of the System Dynamics (SD) method is to understanding the nonlinear behaviour of complex systems over time using object oriented diagram modelling of stocks, flows, and internal feedback loops, table functions and time delays. This project uses the quantitative Systems dynamic modelling approach that utilises data-driven information to inform the model building, for model initialisation, and for model calibration (Pruyt 2013). Hence, this project initially sets activities to analyse multiple layered data from different databanks to prepare for model usage. The data was used in combination with the qualitative modelling to derive the indicators, which were systematically verified in the scientific literature, especially in the context of lifecycle assessments, to identify and later be able to quantify environmental effects from the food chain and related transport.

By adopting this methodology, we investigate the environmental impacts within the food chain, integrating findings from diverse studies and the initial outcomes of quantitative modelling. The classification of environmental impacts, as identified in life cycle assessments, serves as a useful baseline for our modelling efforts. Furthermore, the European Commission's Farm to Fork (F2F) Strategy (European Commission 2020) is represented as a qualitative model (chapter 2.1), with its insights contributing to the development of quantitative models. We also review the literature on the systemic analysis of the food system and other case studies to identify applicable patterns and mechanisms for our modelling activities, both qualitatively and quantitatively.

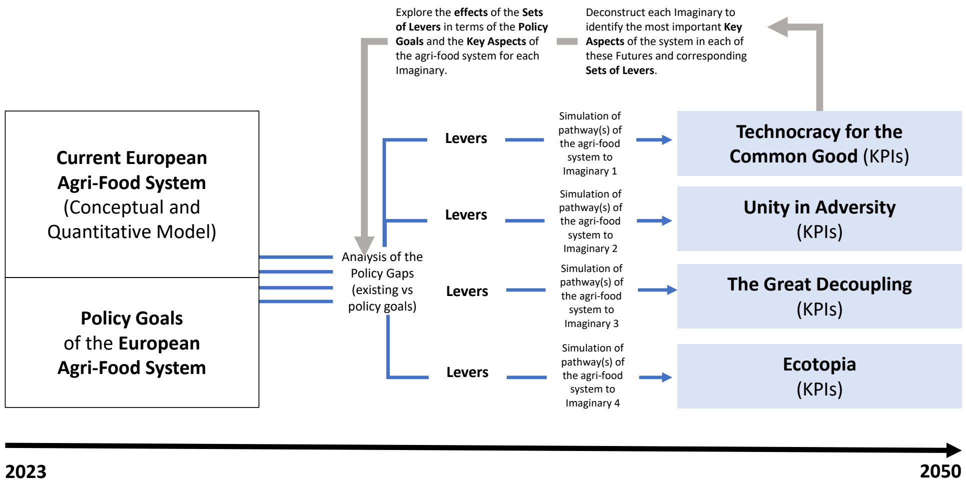
2.1 Methods

2.1.1 Foresight Approach

One of the main challenges of this work was to develop a system dynamics model of the EU agricultural and food system that could allow the assessment of potential policies for a transition to a sustainable the food sector, using the four Imaginaries for the future of a sustainable Europe in 2050.

To understand the Foresight approach of this project, it is important to understand and visualize how we organized the process in two complementary parts (Figure 1). The first one is based in a conceptual and quantitative model, that encompassed the simulation and analysis of the current state of the European agricultural and food system. The second part focused on the way that the system dynamics model could be used to interpret and represent the EEA imaginaries and the capability to identify and act on policy levers that allow a transition to a sustainable food sector in each one of those EEA imaginaries.

Figure 1: Visioning and Foresight Approach.



Source: authors.

Part 1. Conceptual and Quantitative Model and Simulation of the European Food System Today
As mentioned before, to understand the current European food system it was developed a conceptual mapping involving the modelling the EU's Farm to Fork strategy, its affiliated programs, and the application of sustainable finance features within the food system. This allowed the visualization and deep understanding of the foundational structure of the food system, highlighting components integrated into the system dynamics model.
The quantitative modelling, relying on a data-driven multi-scale system dynamics model, delves into the interconnectedness between the food system and related sectors like mobility and energy.

Part 2. The food system dynamics model in the context of four contrasting imaginaries
The study tries to explore how a system dynamics model of the EU agricultural and food system can be developed to assess potential policies for a transition to sustainability for the food sector in 2050

using the four imaginaries that represent four engaging, plausible and contrasting images of what a sustainable Europe could look like in 2050.
The underlying question is how a system dynamics model can be used to interpret and represent the EEA imaginaries. In a complementary way, the analysis tries to include in the system dynamics model the policy levers for transition to sustainability for the food sector in the context of the EEA imaginaries.
It is imperative to note that all four Imaginaries converge on the premise of a sustainable European future. However, the trajectory to that future—i.e., the distinct pathways and dynamic shifts within the food system—varies significantly across these Imaginaries.
To provide a comprehensive understanding we highlight three important steps that formed the basics of the work.

Deconstruction of Each Imaginary
Each Imaginary was meticulously analysed to unearth the Key Factors intrinsic to the system dynamics. These factors encapsulate crucial elements of the foundational system and are seamlessly integrated into the system dynamics model. Furthermore, these factors are intricately connected to Key Performance Indicators (KPIs) that gauge the efficacy of achieving respective policy objectives.

Configurational Analysis of Key Factors
A subsequent step involved the in-depth study of the manifestation of these Key Factors across each Imaginary. This foundational understanding is pivotal as it facilitates the calibration of the model in alignment with each Imaginary. Such calibration, in turn, paves the way for the precise definition of KPIs and the identification of policy levers that can steer the system towards achieving these KPIs within the purview of each Imaginary.

Scenario-Based Model Analysis
The research methodology also incorporated a model-based scenario analysis. This methodological approach is geared towards examining alternative policy paradigms. Furthermore, this analysis synergizes seamlessly with the data-driven multi-scale system dynamics model, providing an exhaustive understanding of the food system's value chain.

2.1.2 Multi-Method Systems Approach

The agri-food system and transportation systems are dynamically complex systems. Jointly they constitute a dynamically complex system-of-systems. When studying such systems, using multiple methods instead of a single method enables one to generate more insights. Hence, the agri-food-transportation system is investigated using complementary systems approaches:

- First, Qualitative Systems Modelling is used to map and link all aspects of these systems and policies targeted at them without quantifying them. Second, this approach allows for assessing whether the systems and policies can be mapped unambiguously or not. Third, Qualitative Systems Modelling is used to assess the extent to which the other approaches used for this research incorporate these aspects and the links between them.
- Qualitative System Dynamics Modelling – specifically Causal Loop Diagramming – is used to distil essential feedback loop mechanisms that endogenously drive the system into (un)desirable directions or keep the system from reaching its goals. These System Dynamics Diagrams differ from the diagrams developed with the first approach in that the Causal Loop Diagrams are stylised diagrams distilled from more complicated underlying systems diagrams.
- Quantitative Data-Rich Multi-Scale System Dynamics Modelling is used to capture the system's multi-scale nature and dynamic complexity. It merges knowledge and data about the system and simulates the dynamics of plausible scenarios and plausible effects of policies over time.

These different techniques are briefly introduced below.

2.1.3 Qualitative Systems Modelling

The qualitative analysis builds on the FoD contract FoD-2018/RTD/A2/OP/PP-07001-2018/LOT 1. A focus is given to the interplay of the factors and assumptions in the Farm to Fork Strategy with accompanying programmes. In addition, the qualitative analysis focuses and concretises the link between the food system - based on the value chain - and selected environmental impacts.
Various sketches of qualitative models have been developed so far:

- One model to collect building blocks for a sustainable food system (normative, mind-map structure).
- One model to capture the concepts of the Farm to Fork Strategy.
- One model – expanding the FoD-Model – to explore the environmental effects of the food system and to connect to policy measures.
- Smaller CLD models to illustrate and understand and analyse loop combinations.

2.1.4 Quantitative System Dynamics Modelling

In this section, a generic introduction to System dynamic modelling is presented. Chapter 7.3 discusses the methodology behind the CROSS-SYSTEMS AGRI-FOOD TRANSITION (CRAFT model).

Quantitative System Dynamics (SD) is a system modelling approach for endogenously modelling and simulating dynamic complexity (i.e., the – mostly nonlinear – dynamics of systems over time). Technically speaking, SD models are models of integral equations (or differential equations). These systems of integral equations are simulated numerically to generate resulting behaviours over time.

Even though SD models are mathematical models, they are mainly developed using specific diagrammatic conventions and communicated by means of resulting so-called Stock-Flow Diagrams. Stock-Flow Diagrams consist of different types of variables: Stock variables (represented with rectangles/blocks) capture accumulations in systems, Flow variables (represented with double flows with valves into/out of stock variables) represent increases and decreases of stocks, auxiliary variables (mostly represented by variable names without specific symbols) are used to capture complex interactions between variables, and constants to include constant values. Even though all variable names in SD models unambiguously relate to real-world concepts and aspects, functions within these variables can be complex and nonlinear, for example, representing a complex delay effect.

Stock-Flow Diagrams can be translated into Causal Loop Diagrams and vice versa. Stock-Flow Diagrams focus on the stock-flow structures, whereas Causal Loop Diagrams focus on feedback loops. Mostly, CLDs associated with quantitative SD models are either high-level representations of the most crucial feedback effects in models and – assuming a correspondence between real-world systems and models-systems, or representations of specific feedback loop mechanisms of interest. The latter type of CLDs was referred to in section 1.4.3. CLDs are essential because they convey an important source of non-linearity (e.g., exponential behaviour). Other significant sources of non-linearity in SD models are: stocks (accumulations or integral equations), delays, nonlinear functions, and nonlinear relations between variables. More on SD modelling can be found in many sources, including (Ford 2010; Pruyt 2013; Sterman 2000; Sverdrup et al. 2022).

SD models are often used to simulate the dynamics of systems away from sustainability (e.g., the Limits to Growth Studies) or towards sustainability. The Limits to Growth Study by (Meadows 1972) for the Club of Rome is one of the most well-known examples of quantitative SD modelling and simulation.

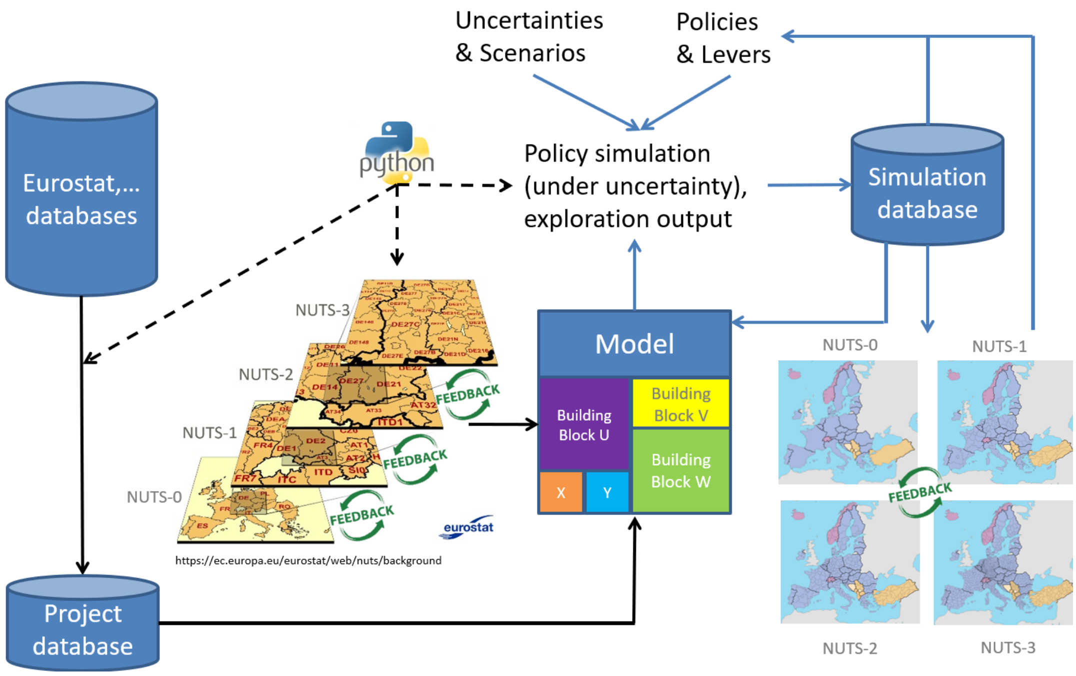
2.1.5 Quantitative Multi-Scale Data-Rich System Dynamics Modelling and Simulation under Deep Uncertainty

Constrained by data availability, computing power, and the state of complementary approaches available at the time, the model developed and used for the Limits to Growth Study was a highly aggregated world model instantiated with little best-guess data. Those only familiar with the first Limits to Growth Study/Model and similar studies and models often criticise SD modelling for being overly aggregated, top-down, and data-poor.

While the SD language (mathematics and diagrammatic conventions) itself has not changed much since the first Limits to Growth Report, for the mathematics behind SD and its diagrammatic conventions are very effective and efficient, the possibilities of the practice of SD have changed significantly over time, especially over the last two decades, with the spectacular increase in data availability and computing power. Today it is possible to use large data sets to build and simulate models with multiple geographic scales and many geographic entities and scan across large uncertainty spaces. Borrowing from the deep uncertainty field, uncertainties that can be dealt with today go beyond parametric uncertainties dealt with before: structural uncertainty, model uncertainty, ambiguity, and outcome uncertainty can be dealt with today – even known unknowns (Figure 2).

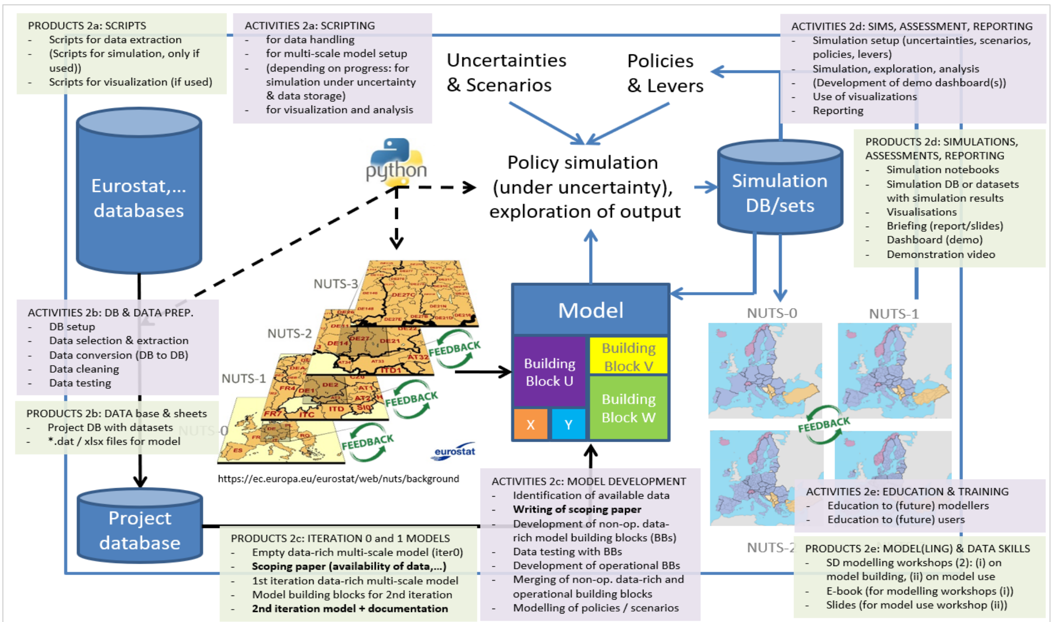
These different innovations are brought together in this study. The type of SD modelling and simulation used here might be referred to as Quantitative Multi-Scale Data-Rich System Dynamics Modelling. Figure 2 shows how this approach is applied in practice: python scripting is used to download data from useful databases (e.g., Eurostat, FAOstat, Copernicus) and handle data, create multi-scale structures linking geographic entities across different scales, and simulate policies/levers across models and across uncertainty/scenario spaces. Models are constructed based on building blocks that can be tested separately and be replaced by better (i.e., more operational) versions. The simulation runs are stored in databases, which are subsequently explored and analysed (using data science and machine learning techniques) and visualised. Exploration and analysis of simulation results often lead to changes in model structures (during the development phase), changes in settings of policy levers (during the use phase) and model building blocks (during further model expansion). To be able to apply this approach, one needs the necessary scripts, data (bases), and model building blocks: Figure 3 shows the activities required to develop scripts, data (bases), and model building blocks. These scripts, data (bases), and model building blocks are intermediate products of the project that need to be developed before a meaningful simulation can take place.

Figure 2: Data-rich multi-scale SD modelling and simulation under deep uncertainty.



Source: Erik Pruyt, unpublished, 2023.

Figure 3: Activities and products required to apply data-rich multi-scale SD modelling and simulation under deep uncertainty.



Source: Erik Pruyt, unpublished, 2023.

3 Qualitative cross-systems analysis

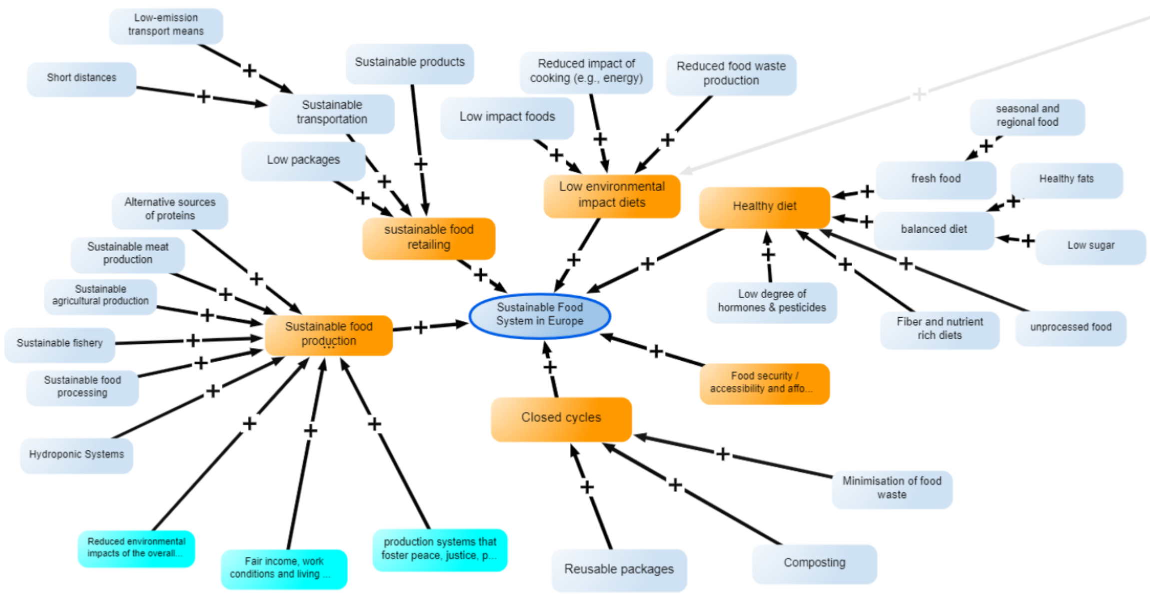
3.1 Overview of causal chains in the food system

3.1.1 Sustainability of the food system – a normative concept

The first steps of the analysis involved the creation of a qualitative mind map to explore the complex relationships between sustainable food systems and transportation networks. This map examines the cause-and-effect links across the food supply chain, environmental impacts, and the crucial impact of policy measures to reduce environmental harm while securing food availability and maintaining high food quality standards internationally.

The initial phase of the analysis included constructing a normative mind map to outline the key concepts related to sustainable food systems (illustrated in Figure 4). This map is not exhaustive but is informed by expert input and serves as a visual guide to the primary elements of sustainability in food systems. The mapping titled "Normative Mind Map of Targets of Sustainable Food System" was derived using the iModeler tool and represents an aggregation of the food system in general and in Europe.

Figure 4: Normative Mind Map for collecting targets of a sustainable food system.



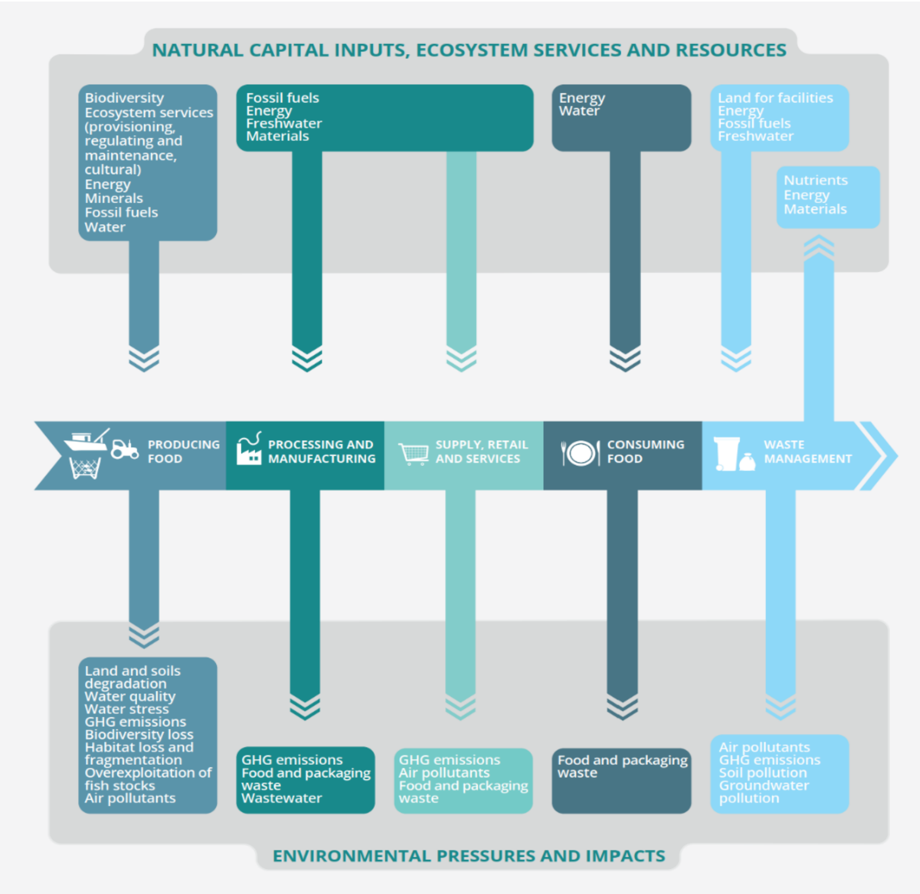
Source: Visualization from iModeler, authors compilation.

While useful for offering an overarching perspective, this mind map has limitations; it does not provide an in-depth rationale for the sustainability of each element, nor the specific measures required to fulfil these objectives. Despite these constraints, this preliminary work is essential for shaping subsequent analysis and identifying specific aspects that require closer examination. Through this process, we can identify critical factors for change and gain insight into the feedback mechanisms and driving forces that are foundational to the sustainability of food systems in conjunction with transportation systems.

3.1.2 Environmental impacts

Food production and consumption have significant impacts on the environment. The value chain of the food system presented in EEA's report "Food in a Green Light" (EEA 2017) (Figure 5) is extended with input and output factors. This representation gives an excellent overview but does not fully show the allocation and balance of the substantial environmental effects.

Figure 5: Value chain of the food system with inputs and outputs (environmental pressures/impacts). Taken from Food in a Green Light, (EEA, 2017).



Source: Taken from Food in a Green Light, (EEA, 2017).

In terms of **climate change**, land-area (and **land use changes**), **freshwater uses**, **water quality**, **eutrophication**, and **biodiversity,** food production is globally responsible for:

- 21% to 37% of global GHG emissions (IPCC 2019; Crippa et al. 2021; Poore and Nemecek 2018) (IPCC, 2019; Crippa et al., 2021; Poore and Nemecek, 2018, see When looking into the environmental impacts of the food value chain, there is an important effect linked to transport and the nature of environmental impacts, which is important to consider: regionalisation. Regionalisation refers to an impact occurring in one region while the product's consumption happens elsewhere. For example, water withdrawals and water pollution can have significant impacts locally (or regionally, i.e., downstream watersheds), but without compromising other regions outside the watersheds (and other parts of the food system). This translocation of effects means that if products are exported, the consumer will be little affected by such environmental impacts. This does not count for other impacts, such as climate change, whose effects are more global and independent of where GHG emissions occur. In this sense, three types of environmental impacts could be distinguished (Turner et al. 1990): global systemic, global cumulative or regional/local:

1. Global systemic changes include local sources of changes leading to global effects and with a global limit. This is the case for **climate change**, **Ocean acidification** and **stratospheric ozone depletion**.
2. Global cumulative changes include multiple transformations having local impacts, which can nevertheless be considered global because they occur worldwide and can have global consequences. This is the case for Nitrogen and Phosphorus Losses (i.e., **eutrophication**), **land cover anthrophization** and **biodiversity loss**.
3. Lastly, there are environmental impacts that, according to current knowledge and data, are at regional or local scales only. This is the case for **air pollution**, **freshwater use** (such as **water withdrawals**), **waste production**, and many other forms of **pollution** (i.e., water and soil). The term 'regional' does not preclude that those regional pollutants can travel or be transported (due to trade) over long distances and can be transboundary, i.e., become a global issue. This is the example of freshwater withdrawals identified earlier, except maybe for oceans (e.g., in the case of heavy metal pollution and plastic/marine litter). For air pollution, the emission of pollutants by traffic of industrial activities can have significant impacts locally, such as a road junction, but without compromising other regions, even within the same city or region.

- Table 1 for a decomposition of these emissions by stage of the food value chain,
- the appropriation of 40% of all habitable land (i.e., excluding glaciers and barren land (FAO 2022).
- 70% of freshwater withdrawals (OECD 2010),
- the main driver of biodiversity loss and tropical deforestation (IPBES 2019).

When looking into the environmental impacts of the food value chain, there is an important effect linked to transport and the nature of environmental impacts, which is important to consider: regionalisation. Regionalisation refers to an impact occurring in one region while the product's consumption happens elsewhere. For example, water withdrawals and water pollution can have significant impacts locally (or regionally, i.e., downstream watersheds), but without compromising other regions outside the watersheds (and other parts of the food system). This translocation of effects means that if products are exported, the consumer will be little affected by such environmental impacts. This does not count for other impacts, such as climate change, whose effects are more global and independent of where GHG emissions occur. In this sense, three types of environmental impacts could be distinguished (Turner et al. 1990): global systemic, global cumulative or regional/local:

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Table 1: GHG emissions by stage of the food value chain, according to different databases.

Stage in the food value chain	Fraction of GHG emissions from the food value chain	
	HESTIA database [a]	**EDGAR-Food database [b]**
Crop production	27% [c]	39%
Livestock and fisheries	30%	
LULUCF	24%	33%
Remaining value chain (processing, manufacturing, packaging, transport and distribution, consumption and end-of-life disposal)	18%	29% total (Increasing trend since 1990) Packaging: 5.4% [d] Transport (regional and local): 4.6% Transport (international): 0.2%
Total	100%	100%

(a) (Poore and Nemecek, 2018); (b) (Crippa et al., 2021); (c) 6% of this value is for feed; (d) mostly due to the pulp and paper industry.

We observe these environmental impacts throughout the food value chain, from global systems down to regional and local levels. Therefore, we need to consider the multiple scales of these environmental impacts. Thinking about the future sustainability of the food system requires looking beyond the direct impacts of food policy. We need to address the influence of food policy on other systems, such as transport and distribution, as these can have significant weight in the overall environmental and social impacts of the food system. In addition to these more direct impacts of transportation and distribution, other indirect impacts result from, for example, the production of capital goods (vehicles, fuels, and transportation infrastructure). If these represent significant impacts for the food value chain, one might ask whether the impacts associated with the mobility system, such as those associated with the production of capital goods (e.g., the production of vehicles and the resources required for those), should be targeted by food policies or if they should remain outside the scope of food policy.

The environmental impacts of the food system vary significantly across the different stages of the value chain. Furthermore, not all food-related policies necessarily reduce the environmental impacts of the food system. Agricultural, water management, mobility, industrial, resource efficiency, and climate policies all have an impact on the food system. One challenge is to identify the specific impact that food policy can have on the food system and how this impact is reflected in environmental target indicators. The complexity of this analysis is further increased by the application of different measures simultaneously (policy mix) and the consideration of spatial and temporal scales (i.e., the sequence of measures). Target indicators are defined in Figure 6.

3.2 The Farm 2 Fork Strategy

The following sections analyze the causal relationships and potential feedback loops within the food system. A qualitative causal-loop (or cause-effect) analysis is essentially built upon the food value chain, linking to environmental effects and bridging to measures/instruments from the Farm to Fork Strategy.

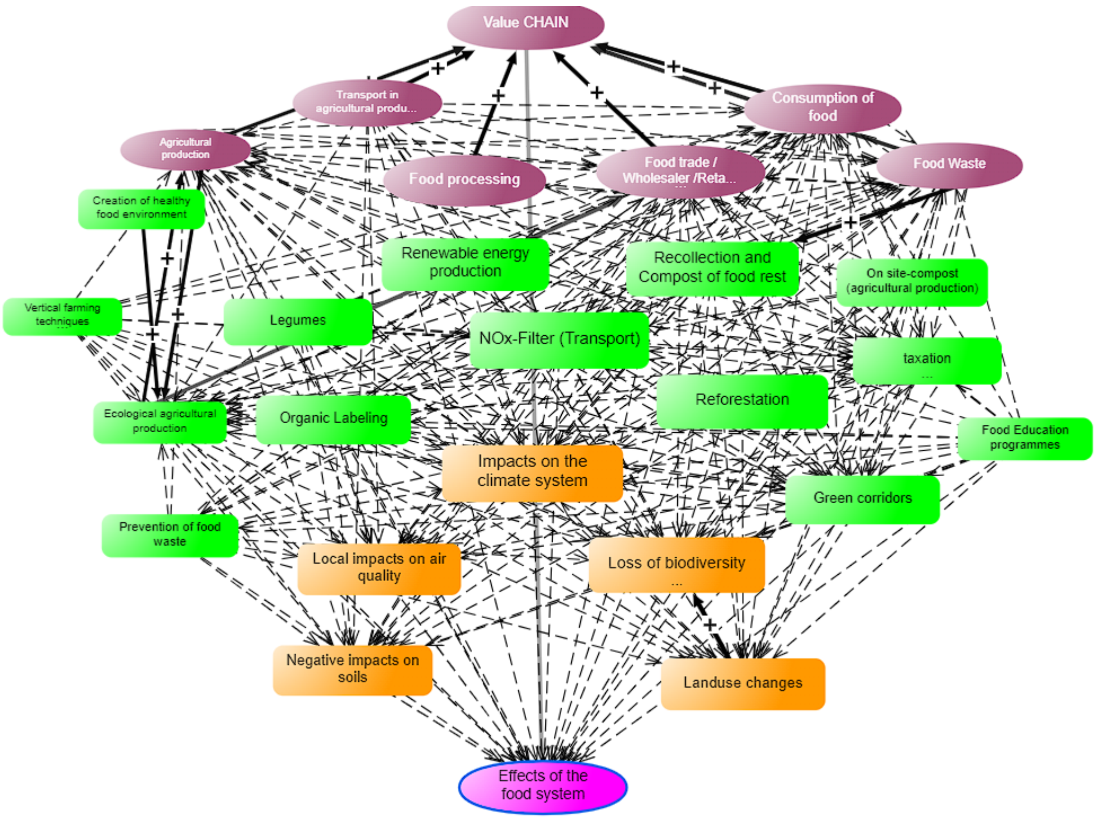
The qualitative analysis of the current state addresses only a subset of the indicators mentioned previously. Some indicators are implicitly integrated within broader factors. Figure 6 provides a clustered overview of the qualitative model within the *"Normative Mind Map of Targets of a Sustainable Food System."* The Figure 6 displays the five environmental impact categories (orange boxes), the measures (green), and the elements of the value chain (wine red). Furthermore, the figure indicates which measures are currently addressed within the model. While not all measures are described in full detail, the model already comprises 175 factors, 321 connections, and over 20,000 loops.

Orange boxes show the environmental impacts, green boxes, measures that are addressed in the model, and dark red boxes indicate the steps of the food system value chain (Screenshot from Imodeler, captured on 28.11.2022).

The core function of this expansive model is to set a conceptual foundation for the causal loop diagram (CLD) analysis, shape the direction of quantitative studies, and pinpoint specific topics for deeper analysis. The model operates as a qualitative mind-map designed to map out connections and provide a broad understanding of the system. It should be noted that such a model is iterative and evolving, intended to be expansive, but it should be acknowledged that it cannot be exhaustive. Detailed examination of particular subjects within the model is essential to comprehend the dynamics of feedback loops, time delays, and multifaceted pathways.

The following sections will utilize various model representations for improved clarity. This will include visualizations of the Imodeler model results for a holistic view and, alternatively, focus on the causal loop diagram analysis to scrutinize the function of selected feedback loops. Where applicable, block diagrams or CLDs from other sources will be incorporated and examined for their contributions to the findings.

Figure 6: Cluster view of the large Imodeler qualitative model of the food system (including some aspects of mobility).



Source: Visualization from iModeler, authors compilation.

Connecting and assessing measures/instruments with a Causal Loop Diagram (CLD)

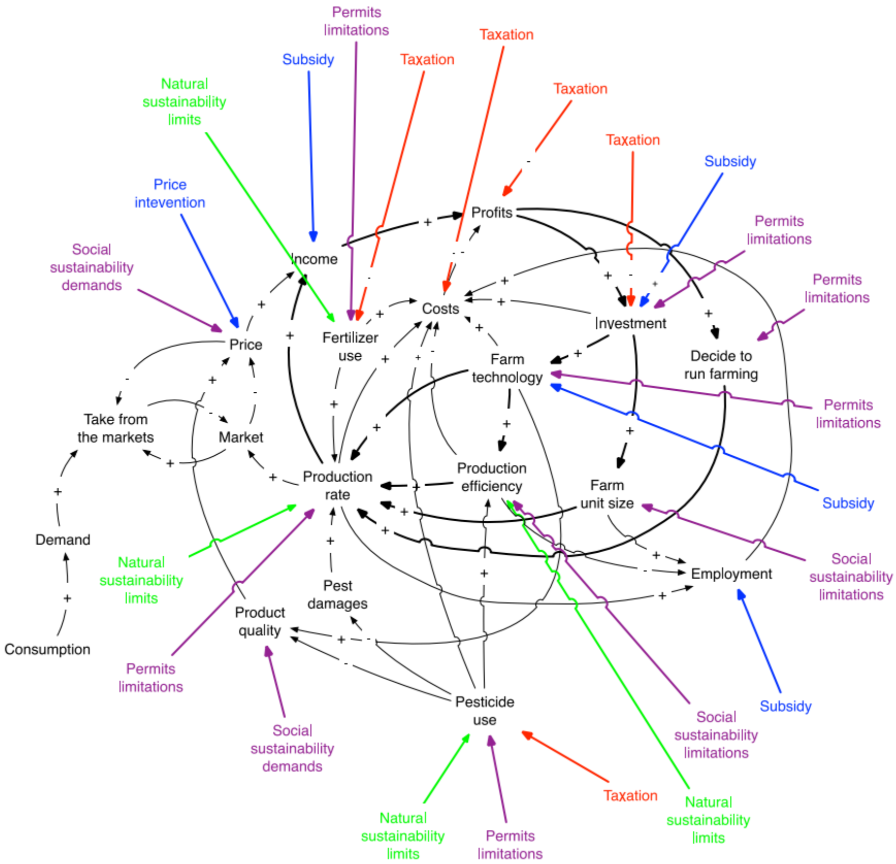
Measures are designed to influence outcomes by creating a cause-and-effect relationship with the elements they target. They can alter a variable or affect a process by either modifying existing flows or introducing new ones. In some cases, this might even lead to the creation of new resource pools. While the specific details of these changes are not crucial for qualitative modelling, understanding them can improve our overall comprehension of the system.

The analytical power of causal analysis is demonstrated when policy interventions influence the system, either directly or indirectly. This shows which specific feedback loops are affected, allowing us to steer the system in the desired direction. The CLD in Figure 7 illustrates how economic or regulatory interventions might integrate with a farm's operations within the broader "Farm to Fork" value chain. This diagram represents a basic farm system, detailing farm production, the farm's economy, and the material inputs and outputs of that system.

The CLD also highlights where policy instruments can intervene in the system, directing its trajectory through finance, fiscal measures, regulation, or voluntary actions. As reported by Koca et al. (2013), Sverdrup et al. (2017), Gudbrandsdottir et al. (2018) and, Olafsdottir and Sverdrup (2019), Sverdrup and Olafsdottir (2019;2020) the transfer of food (and goods/material in general) through the value chain occurs through sales to the processing industry, followed by distribution to wholesalers and consumers.

The CLD provides a systematic way to understand feedback loop dynamics, illustrating how causes and their effects can either move together or in opposite directions. This relationship is marked with a "plus" when changes align and a "minus" when they diverge. When processes reinforce one another, enhancing their effects, they are termed reinforcing processes and labelled with an 'R.' Conversely, processes that lead to opposing changes, thereby mitigating the effect, are known as balancing processes and are denoted with a 'B' (Haraldsson 2004).

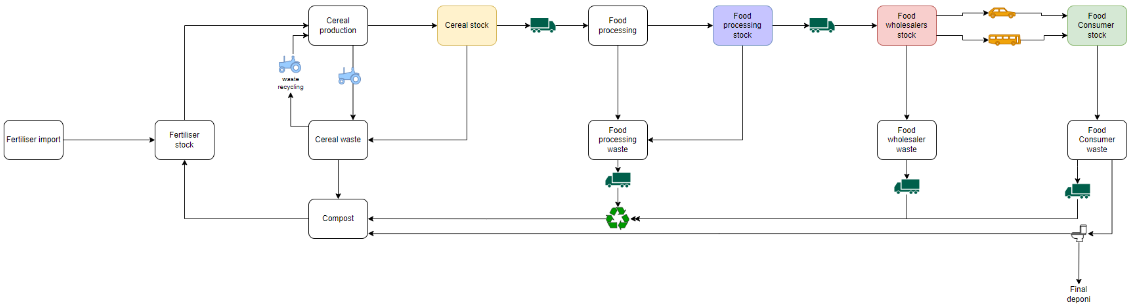
Figure 7: A basic CLD for Agricultural production system with different types of measures/interventions shown.



Source: Adapted from stakeholder workshop results, with contributions by Sverdrup/van Allen and the authors, evolved from original content reported in the internal report Cross-Systems Analysis in WP1.2 in the STPR AP 2022 (Lorenz et al., 2022).

Expanding the farm system to include the whole path from the farm to the consumer is effectively introducing three additional systems from the F2F value chain (Figure 8). The F2F value chain involves a unidirectional flow of materials and a reverse flow of capital. Material begins at 'Primary Food Stocks', undergoes processing, is held in 'Food Processing Stocks', then moves to 'Wholesalers Stock', and finally reaches the consumer as 'Consumer Stock'. Capital, on the other hand, flows in the opposite direction through purchases, starting from the consumer and ending with the farmer.

Figure 8: Simplified flow diagram of "material stocks" and transport modes along the food value chain.



Source: adapted from Koca et al. (2013) and Olafsdottir and Sverdrup (2019).

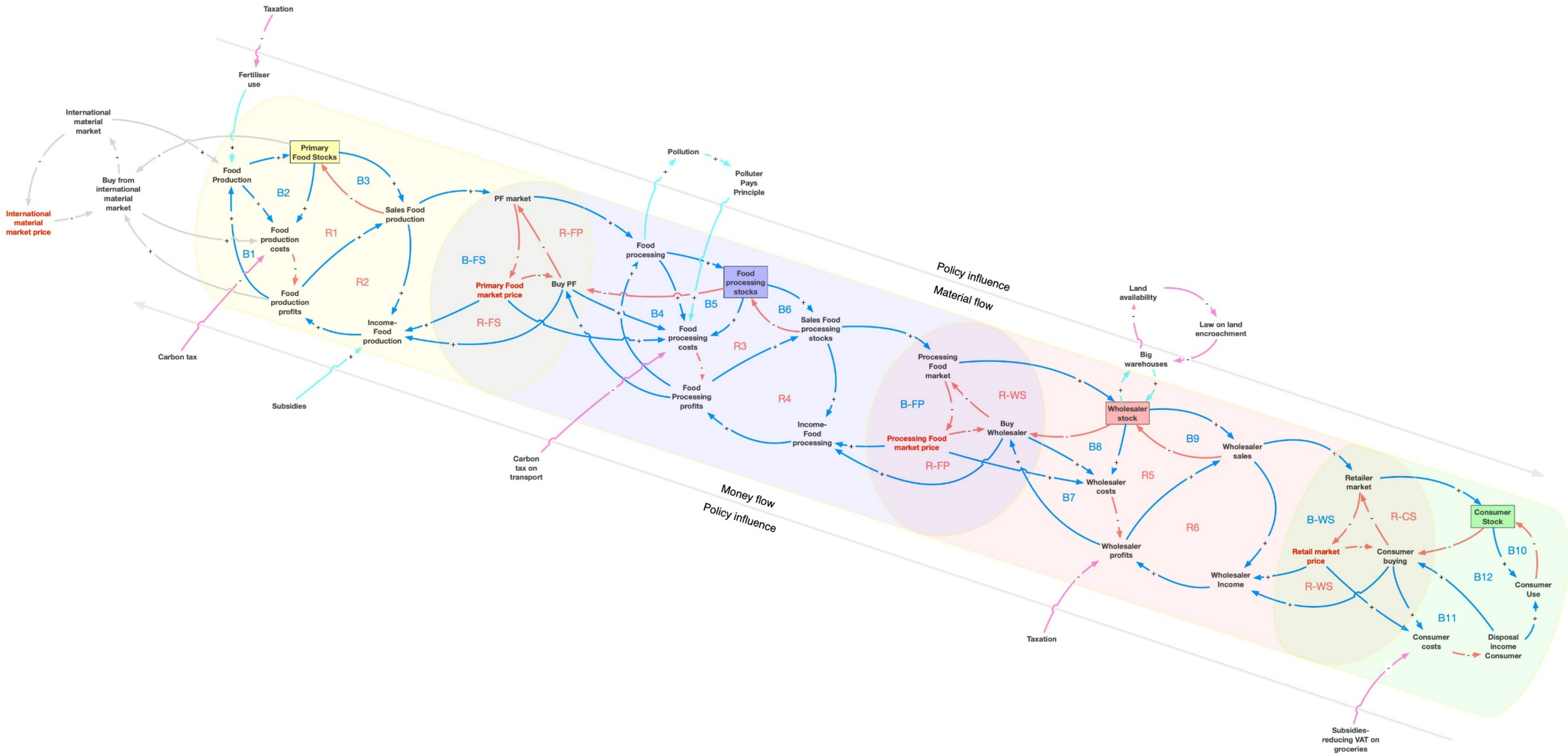
As an example of policy instruments (taxation, subsidies, permit limitations), these are introduced into the CLD as exogenous factors in different parts of the CLD. What the policy instrument illustrates in the CLD is where in the value chain the impact is foreseen, and causality tracing from that impact can be found across factors in the value chain. The policy instrument, as depicted in the Causal Loop Diagram (CLD), identifies the specific points within the value chain where impacts are anticipated. It also enables the tracing of causality, showing how these impacts influence various factors throughout the value chain (Figure 9).

A closer examination of the CLD in Figure 9 reveals the core loop system governing food production and the availability of items in 'Primary Food Stocks', which is demonstrated by feedback loops B1-B3 and R1-2. These loops regulate food production costs and income from selling food products, denoted as 'Income-Food Production'. The transfer of food occurs through sales to the processing industry. The farmer places food from 'Food Processing Stocks' on the market for the processing industry to acquire.

In Figure 9, it is further illustrated that the supply, demand, and pricing mechanism are regulated by three loops (B-FS, R-FS, R-FP). The transaction between the farmer and the food processor industry is facilitated by the combination of loops R2 and B-FS. Prices regulate purchases by the food processing industry, impacting 'Buy PF' and profits, i.e., 'Food Processing Profits'. All components of the value chain, except for consumers, exhibit the basic loop behaviour of production and sales transactions, distinguished by different colorizations.

In summary, the value chain transfer involves the production of food from farmers' 'Primary Food Stocks', influenced by loops B1-3 and R1-2. The transaction from farmers to food processors passes through loops B-FS, R-FS, and R-FP. The food processing industry is influenced by loops B4-6 and R3-4. The transaction from 'Food Processing Stocks' to 'Wholesaler Stock' goes through loops B-FP, R-FP, and R-WS. The wholesaler industry is influenced by loops B7-9 and R5-6. The transaction from 'Wholesaler Stocks' to 'Consumer Stock' passes through loops B-WS, R-WS, and R-CS. Consumers, as the end recipients, are influenced by loops B10-12.

Figure 9: Adaptation of the agricultural production system shown in figure 7.



Note: Now illustrating the CLD of the F2F value chain in its entirety and their individual parts (shaded colours) to showcase how each value chain item interacts (with shaded colour overlaps). These include 'Food Stocks' (yellow), 'Food Processing stocks' (purple), 'Wholesaler Stock' (red), and 'Consumer Stock' (green). The R-loop amplifies the effect of the measure, while the B-loop moderates the effect of that particular loop.

Source: Hördur Haraldsson adaptation of Koca et al (2013), Gudbrandsdottir et al (2018), Olafsdottir & Sverdrup (2019), Sverdrup & Olafsdottir, (2020) and Lorenz et al., (2022).

In the CLD in Figure 9, consumers cannot receive profits like other parts of the value chain, only reduce costs (through savings), thus increasing disposable income, denoted as 'Disposable Income Consumer'. Further analysis of the CLD reveals where policy measures come into play. Policy measures such as taxation (fiscal lever), subsidies (financial lever), and permit limitations (regulatory lever) have different impacts on the value chain components ('Primary Food production', 'Food Processing Stocks', 'Wholesaler Stock', 'Consumer Stock') and the material flow from farmer to consumer.

For example, subsidies positively affect 'income-food production', supporting the reinforcement of the profit loop (R2) and food production overall. Conversely, taxation impacts three feedback loops by constraining their behaviour, such as 'Taxation' on fertilizer use and 'Carbon tax' (B1, B2). The 'Polluter pays principle' increases food processing costs (B4, B5) alongside measures like 'Carbon tax on transport'.

Taxation on profits affects the entire loop system (B7-9, R5-6, R-WS), making it a key lever for influencing wholesalers (as well as consumers). Another example is restricting wholesalers by limiting land encroachment (Land availability).

Addressing consumers involves subsidising excess food costs passed down the value chain, akin to existing practices like food stamps in industrialised countries. These subsidies reduce 'Consumer Costs', thus increasing disposable income, i.e., 'Disposable Income Consumer'.

Nonetheless, the strategies linked to the Causal Loop Diagram (CLD), as shown in Figure 9 and in Figure 7, require further incorporation of different type of policies into a broader qualitative or quantitative framework. This brief illustration highlights the intricacies involved in outlining potential points for policy intervention (levers) and in developing a cohesive policy approach.

3.2.1 The production side of the food value chain: ecological vs. conventional agriculture

The food system fundamentally involves the transformation and translocation of carbon. It alters the natural carbon cycle at different stages, primarily through the process of photosynthesis in agricultural systems. Beyond altering the natural balance, the introduction of pollutants exacerbates environmental impacts. From an economic standpoint, the food system can be viewed as a sequence of resource and financial exchanges, with materials, pricing, and capital moving between stages of the entire food value chain.

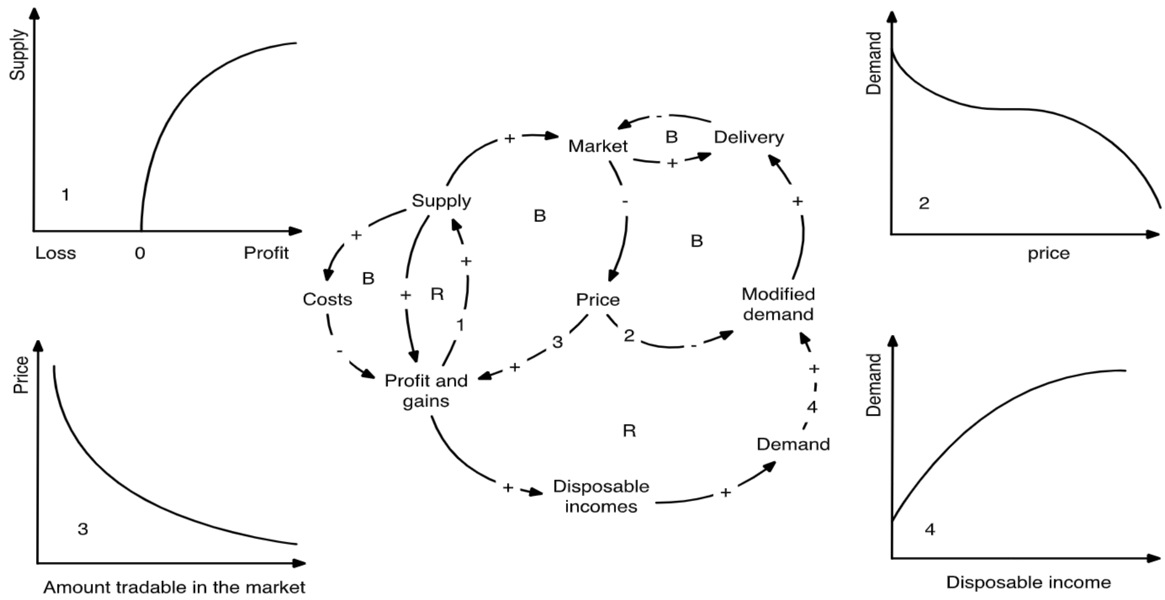
The system operates on energy and is subject to entropy, yet photosynthesis is the singular process within this system that decreases entropy and energizes the cycle. A simplified view of thermodynamics demonstrates that while the total energy input remains constant, the variables of carbon concentration, spatial distribution, and temporal factors are crucial. These aspects are key to understanding the finite nature of resources and the trajectory of their distribution, as detailed in the research of Dennis Meadows (Meadows 1972).

Agricultural intensification is proposed to meet the nutritional needs of a growing global population (Tilman et al. 2011; Gerten et al. 2020). This is not to engage in debates on growth limitations or Malthusian perspectives (Kallis 2019), but to acknowledge that efficiency improvements alone do not address the issue of limited resource availability. Analyses must also incorporate temporal and spatial dimensions.

As illustrated in Figures 7 and 9, the economic relationship between supply and demand governs price determination. Supply is determined by the availability of resources, the value added through labour, and transportation costs, all of which collectively shape price formation. Within this context, monetary exchange can be likened to the energy required to sustain the system's functioning at a general level.

Recent studies employing detailed feedback loop analysis (Sverdrup et al., 2012; Koca et al., 2013; Sverdrup et al., 2017; Gudbrandsdottir et al., 2018; Olafsdottir & Sverdrup 2019; Sverdrup & Olafsdottir, 2019; Sverdrup & Olafsdottir, 2020) provide a framework for understanding how prices are formulated through causal loop diagrams within system dynamics models. This methodological approach circumvents the complexities inherent in econometric theories while underscoring a fundamental concept: the system operates within growth limitations. This insight is vital for acknowledging the finite capacity of any system to expand, which is a critical consideration in the dynamics of economic models (Figure 10).

Figure 10: A more complex CLD of market dynamics.

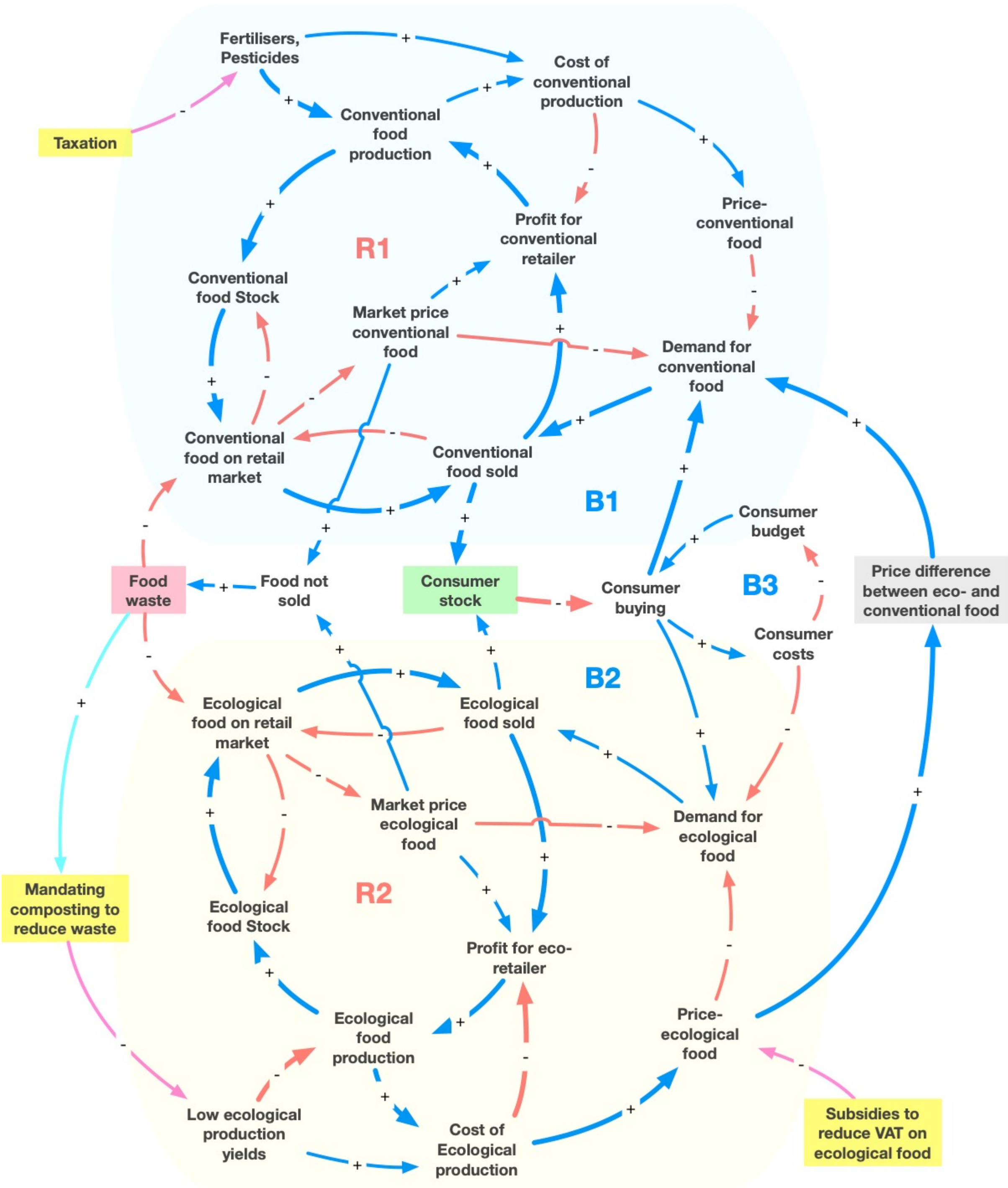


Source: Sverdrup & Olafsdottir (2020).

Comparing industrial and ecological agricultural production, we have to assume that yields per hectare are lower in ecological agricultural practice (Reganold and Wachter 2016). Economically, if the offer is lower, the intensity of work and the price will be higher, which will impact the demand side. If prices are too high, people will buy less. If prices are lower, consumption rates will be higher (but not unlimited). In the case of food, we do not have "perfect" markets, as naturally, the stocks are limited on one side and food is essential for humans (so demand will not be zero). We have to assume that the producer wants to get profit at least in a way he can compensate all the costs (production costs, and including overhead for investments or transport but also all living costs).

Building upon the normative mind-map (Figure 4) and the previous the knowledge from the value-chain illustrated in figures 7-9 as well price mechanism in Figure 10, it is possible illustrate how the transitioning from conventional food production to ecological food production can take place. The following CLD in Figure 11 shows the conventional food production (shaded blue) vs ecological food production (shaded light yellow) and the competing market/price mechanisms for ecological and conventional food production. It demonstrates the market interplay of ecological agricultural practices and conventional agricultural practices.

Figure 11: A CLD showing conventional vs ecological food production showing competing market/price mechanisms for ecological and conventional food production. Policy instrument (in yellow) show where intervention is used to increase market competence for ecological food.



Source: Hördur Haraldsson, adaptation of Sverdrup & Olafsdottir (2020) and Ullrich Lorenz.

Shifting food production towards ecological methods, as outlined in the F2F policy objectives, requires making ecological food more price competitive. The higher production costs of ecological food are due to its lower efficiency compared to conventional production, which relies on fertilizers and pesticides to maximize output but leads to pollution. Shifting production towards ecological methods necessitates reducing or eliminating the use of these chemicals. However, this presents a challenge in the market, as ecological food is priced higher due to lower yields and increased production costs. To encourage the shift towards ecological food consumption, the price difference between ecological and conventional food needs to be minimized, allowing consumers to make informed choices based on their budgets.

Figure 11 illustrates the two food production systems and how consumers interact with them. The R1 and B1 loops drive conventional food production, reinforced by the significant price difference between conventional and ecological food. The R2 and B2 loops represent the uptake of ecological food production, which is hindered by low ecological production yields, leading to increased production costs and a higher price difference between ecological and conventional food. To increase the uptake of ecological food production and achieve the F2F policy objectives, several policy measures (shown in yellow in the CLD) can be considered:

1. **Taxation on Fertilizers and Pesticides**: This policy instrument aims to increase the cost of conventional food production, thereby narrowing the price gap with ecological food production. By imposing taxes on chemical fertilizers and pesticides, the economic advantage of conventional farming is reduced. This measure not only discourages the use of environmentally harmful substances but also indirectly supports ecological food production by making it more price competitive.
2. **Mandating Composting to Reduce Waste**: Mandating the composting of food waste enables the recycling of organic waste back into farm production, replenishing the nutrients that fertilizers originally supplied. This process not only contributes to soil health but also has the potential to enhance the yields of ecological farming.
3. **Subsidies to Reduce VAT on Ecological Food**: Offering subsidies to lower the Value Added Tax (VAT) on ecological food directly reduces its retail price, making it more accessible to consumers. This financial incentive is crucial for encouraging consumer uptake of ecological foods by minimizing the price difference with conventional options. Lowering the financial barrier for consumers is important for increasing the market share of ecological food.

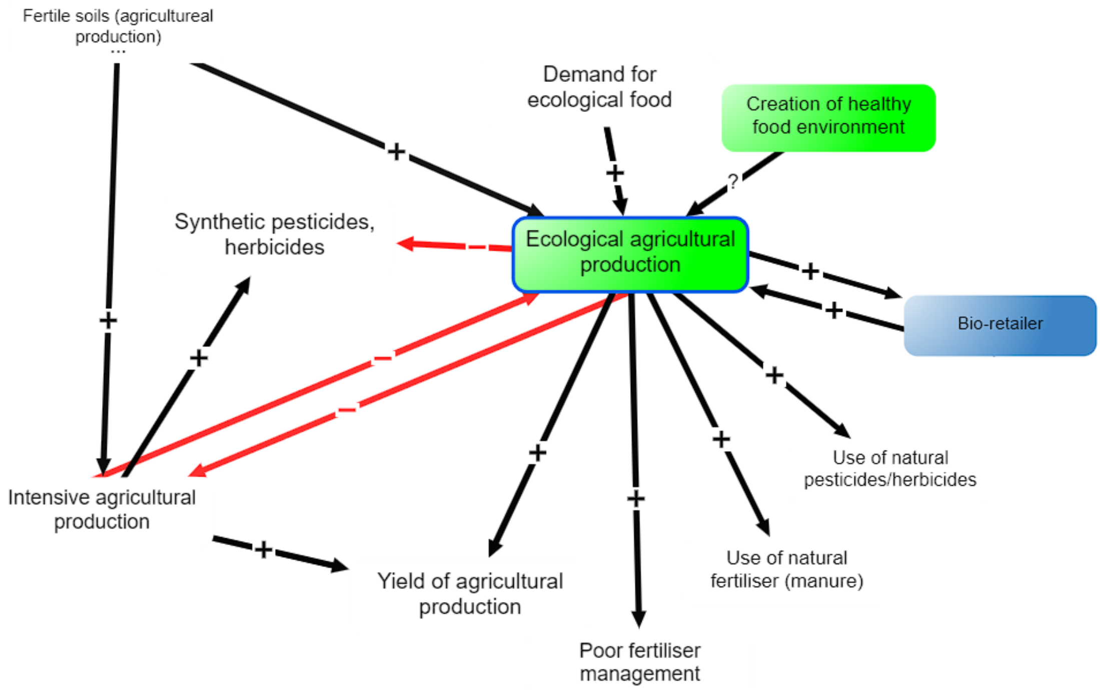
These combined measures seek to balance the market forces, making ecological food more financially appealing to consumers(B3). Levelling the playing field between the two production methods and facilitate a ‘just’-market-uptake of the ecological food production, and ultimately facilitates transitioning towards the policy aims of the F2F.

The price of a product is determined by the profit and production cost, as well as the product's availability, regardless of whether it is ecologically or conventionally produced. Assuming the overhead is identical, production cost directly influences the price for the customer. The consumer's decision is based on their preferences and budget constraints (preferences -> see chapter 0). Once the budget is spent, it cannot be used for further purchases. The causal loop diagram (CLD) in Figure 11 contains a price-building mechanism and "bullwhip-effects" as described in studies by (Novitasari and Damayanti 2018; Osadchiy et al. 2018). The detailed analysis of bullwhip effects in relation to value chains and logistics management is not included in this report. However, it is essential to address this effect in a comprehensive quantitative model based on the model's spatial and temporal resolution. Value chain management significantly impacts waste generation, whether the food is produced ecologically or conventionally (Otero-Diaz et al. 2021). Any intervention that influences demand can heavily impact consumption and waste generation rates. Due to the involvement of several balancing loops, a thorough quantitative analysis is crucial (Alabdulkarim 2020). When balancing structures are involved, it is important to carefully assess policy interventions to avoid rebound effects, "shifting the burden," or "fixes that fail" (refer to the archetypes in (Senge 1991)).

The following sections present additional visualizations from the IModeler qualitative model to further analyze the relationship between ecological and conventional agricultural practices. Ecological agricultural production does not exist in isolation; there must be a market (i.e., demand) for this agricultural production. Therefore, demand needs to be present, along with the necessary soils and resources for ecological agricultural production. This means that soil quality and productivity are also key variables for ecological agricultural production.

Organic farming practices are considered to reduce the environmental impacts of agriculture. However, pest management and the application of fertilization also occur in ecological agricultural production. Depending on the agricultural practice, the management of natural pesticides and fertilizers might be poor, leading to environmental harm (Figure 12).

Figure 12: Screenshot from the qualitative iModeler CLD showing factors influencing ecological agricultural production.



Source: Visualization from iModeler, authors own compilation.

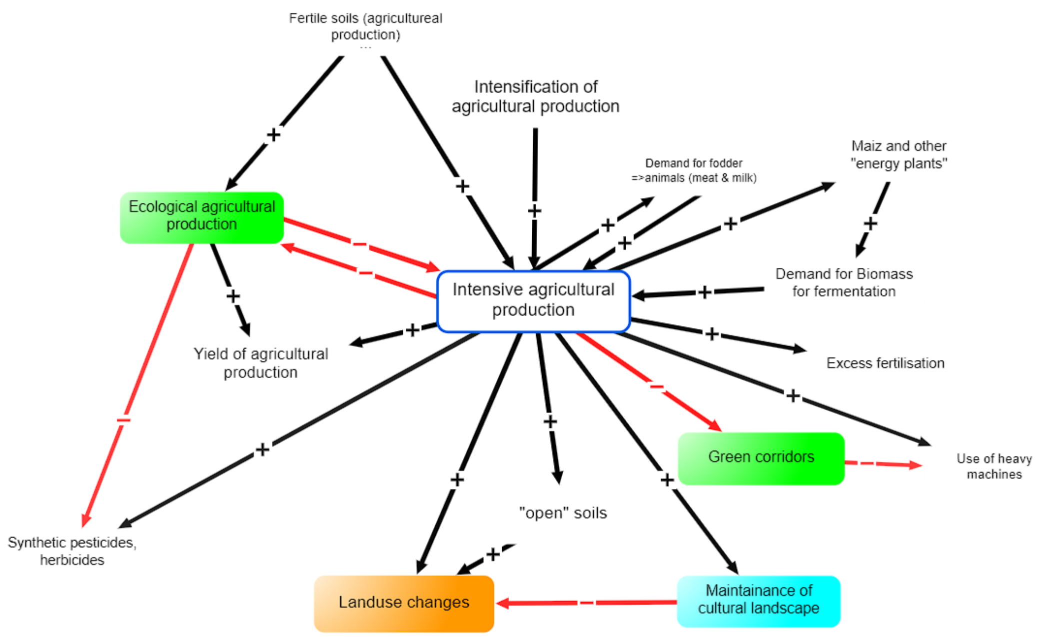
The following sections present additional visualizations from the IModeler qualitative model to further analyze the relationship between ecological and conventional agricultural practices. Ecological agricultural production does not exist in isolation; there must be a market (i.e., demand) for this agricultural production. Therefore, demand needs to be present, along with the necessary soils and resources for ecological agricultural production. This means that soil quality and productivity are also key variables for ecological agricultural production. Organic farming practices are considered to reduce the environmental impacts of agriculture. However, pest management and the application of fertilization also occur in ecological agricultural production. Depending on the agricultural practice, the management of natural pesticides and fertilizers might be poor, leading to environmental harm (Figure 12).

There is an ongoing debate about the sustainability of intensive industrial agriculture versus small-scale ecological production schemes on a global scale. On one hand, powerful vested interests with close ties to the government, media, and academic institutions advocate for high-input technology-based solutions, speculative and neoliberal "market-based" solutions, and export-oriented agricultural models. On the other hand, an international scientific and grassroots Food Movement has emerged, calling for a redesign of the global food system in support of small-scale agroecological farming systems (Valenzuela 2016).

The study by (Tuomisto et al. 2012) conducted a comprehensive analysis of published studies comparing the environmental impacts of organic and conventional farming in Europe. The findings indicated that organic farming practices generally have a positive impact on the environment per unit of area, but not necessarily per product unit (as indicated in Figure 11). Specifically, organic farms tended to exhibit higher soil organic matter content and lower nutrient losses (such as nitrogen leaching, nitrous oxide emissions, and ammonia emissions) per unit of field area. However, when considering emissions per product unit, organic systems had higher levels of ammonia emissions, nitrogen leaching, and nitrous oxide emissions. Additionally, organic systems showed lower energy requirements but higher land use, eutrophication potential, and acidification potential per product unit (Tuomisto et al. 2012; Świtek et al. 2019). Therefore, it is not feasible or advisable to make a blanket generalization that ecological agricultural practices are inherently more environmentally friendly.

One of the primary drivers for the adoption of intensive or industrial agricultural practices is the demand for affordable food, particularly meat, and consequently, inexpensive fodder for livestock such as beef and pigs. Furthermore, there is a growing demand for "energy" plants for biogas fermentation. According to a study by Greenpeace, data reveals that over 71% of all agricultural land in the EU, including both arable land for crop production and grassland for grazing or fodder production, is dedicated to feeding livestock. When focusing solely on land used for growing crops, it becomes evident that over 63% of arable land is utilized for producing animal feed rather than food for human consumption (Greenpeace 2019).

Figure 13: Visualization from iModeler model, showing incoming and outgoing factors of intensive agricultural production.



Source: Screenshot from iModeler, Authors own compilation.

Intensive, super-intensive and compact modes of production are typically more energy and additive intensive. They are associated with poor air quality compared to organic or extensive modes of production (IPES-Food 2022) than organic farming and other ecological modes of production. However, these intensive, super-intensive and compact forms of production also have higher productivity (Seufert et al. 2012; Garnett et al. 2017; Tal 2018). This means that intensive, super-intensive and compact modes of production will require less farmed area (and the environmental impacts associated with these) for the production of the same amount of food; and could allow for land-sparing rather than land sharing (Phalan et al. 2011), which could significantly reduce greenhouse gas emissions from farming (Lamb et al. 2016).

Recommendation 1: For modelling analysis, the production per unit area of different modes of production need to be included in modelling exercises. Productivity and environmental impacts need to be measured in both per unit of product and area.

Recommendation 2: Research is required to increase productivity in ecological modes of production without diminishing their environmental benefits

Recommendation 3: Incentives/pressure for continuous environmental improvements in intensive and super-intensive modes of production are essential.

Recommendation 4: A whole food system analysis is needed to understand the efficiency of the system and to understand the demand for food. This needs to account for food losses within the food chain (and how to minimise these) and the production and consumption of nutrient-poor foods (and how to minimise these).

3.2.2 The demand side of the food value chain

Contextualizing the consumer in the EU's Farm to Fork

The Farm to Fork (F2F) Strategy is an integral part of the European Green Deal and focuses on creating equitable, healthy, and sustainable food systems. It emphasizes a detailed approach to food production, with the goal of promoting economic growth, enhancing public health, and safeguarding the environment (European Commission 2020). The strategy aims to build a more resilient and ecological agricultural sector, while prioritizing the well being of consumers and the European environment within the limits of planetary boundaries.

The F2F's goal on promoting sustainable food consumption and facilitating the shift to healthy, sustainable diets opens the F2F strategy to account for the demand side of the food value chain. The linkage to the consumer is made through the links between consumer choices and (1) health and (2) environmental impacts of food production.

Regarding the first link, the EU's average energy intake, red meat, sugars, salt and fats exceed health recommendations, while whole-grain cereals, fruit and vegetables, legumes and nuts are insufficient. Willett et al. (2019) showed that if consumers were to follow national health guidelines in their diets, this would significantly reduce the environmental impacts of the food system, thus showing a clear link between the health impacts of diets and the environmental impacts of diets. It also shows that the demand side of the food value chain, although with little direct environmental impact (Poore and Nemecek 2018; Crippa et al. 2021), can be a leverage for the reduction of the environmental impacts of the food supply chain. This takes us to the second link to the consumer referred to in the EU's F2F. For the second link, the link between the consumer and the environmental impacts of food systems, the F2F strategy considers that consumers have enough power to affect the supply chain through their choices (i.e., that demand has enough power to shift supply). Studies such as the EAT Lancet (Willett et al. 2019; Moran et al. 2020; Aleksandrowicz et al. 2016) have found that a shift to a higher plant-based diet can provide many environmental benefits, such as leading up to 80% reductions in land use, 25% reduction in GHG emissions and 50% reductions in water use, as well as modest benefits to mortality risks. This reduction in environmental impacts is assumed to occur through the change in the type of foods consumers select for their baskets.

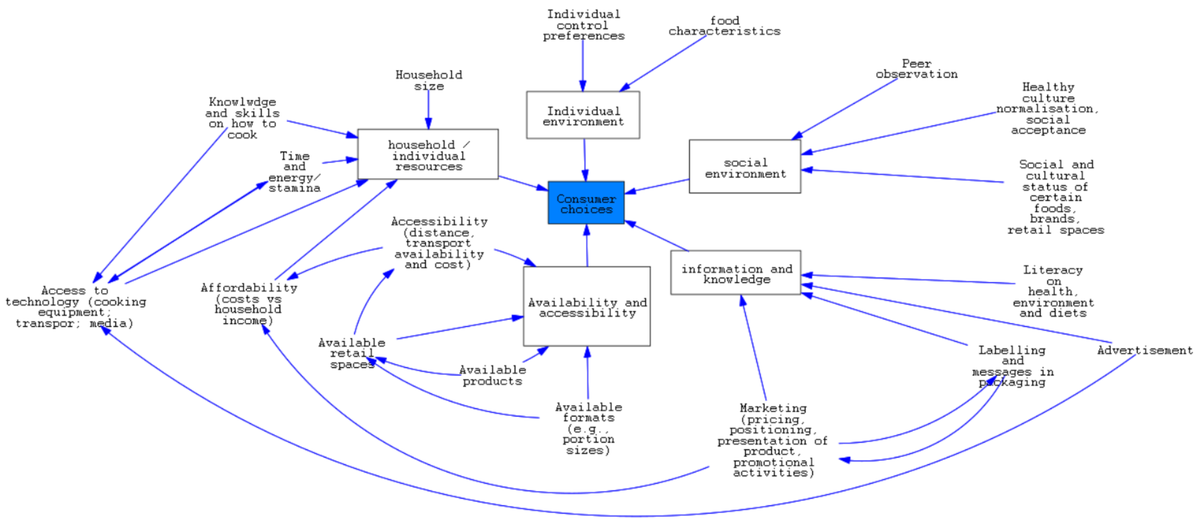
Changing the environmental impacts of the supply chain is partially covered in the F2F by ensuring sustainable food production. This covers primarily domestic production. Tackling the demand side allows for dealing with food imports (where the EU has less control), their environmental impacts, and domestic production.

In addition to the aspects identified above, research has found that the consumer side has a relevant role in food waste reduction. Caldeira et al. (2019) have found that it is in the consumption stages of the food chain, in particular in households, where most of the food waste is generated. Tackling food loss and waste is key in the F2F strategy. The EEA and the European Topic Centre for Sustainability Transitions (ETC ST) are preparing an assessment of the EU policy mix driving the transformation of Europe's food system (EEA 2023b). Amongst other aspects, the report analyses the demand side of EU food policy by assessing how consumers are addressed in EU's food policy and proposing policy tools for food system transformation. In the present report, we do not intend to repeat information but to complement those results, but bringing a cross-system perspective into it.

Factors affecting consumer food choices - overview

The literature on food environments shows that Individual food choice has a multifactorial nature. Some studies have identified over 60 variables shaping consumer choices (e.g., (Chen and Antonelli 2020; Friel et al. 2017; UK's Government Office for Science 2007). These factors include food related features such as information, sensory features, the social and physical environments, but also, individual features (biological, physiological and psychological aspects, together with habits, experiences, knowledge and skills, attitudes and preferences, personal identities) and socioeconomic factors (culture, economic variables, policies and regulations), see Figure 14.

Figure 14: Impact diagram showing summary of the factors affecting consumer food choices.



Source: Author own compilation.

In figure 14 the following food factors can be identified:

- Food characteristics represent factors such as food sensory features (e.g., taste, smell, texture) and perceptual features (e.g., colour, portion size, nutrition and health value, and quality).
- Individual control or preferences represents biological features (genetic disposition for obesity; metabolic rate; health in general); physiological aspects (e.g., level of primary appetite control in the brain); psychological aspects (self-control over purchasing, level of acceptance of different (new, unfamiliar) foods); stress; habits and experiences.
- Social environment represents factors such as peer observation (including parents, social groups and schools); healthy culture normalisation, social acceptance of obesity; social or cultural status by buying specific foods (e.g., branded items, fast food) or visiting certain shops; using food as a marker of good parenting.
- Information and knowledge represent marketing (pricing, positioning, presentation of the product itself, promotional activities); advertisement (linked with media availability (e.g., TV) and media consumption (e.g., time spent watching TV)); labelling and messages in packaging; and, the literacy on health and food. E.g., the level of understanding of nutritional information and health messages, as well as the availability of healthy food curriculums, cooking classes, and cooking resources.
- Availability and accessibility refer to factors such as accessibility to retail outlets, restaurants and cafés selling healthy foods (vs. non-healthy), availability of healthy food products in retail outlets, retail environments (e.g., location of products within retailers' spaces, and portion sizes of food sold or served.
- Finally, individual or household resources refer to factors such as affordability of foods (costs of foods, household income and food budget), and of transport to reach retail; access to equipment (transport, cooking equipment, media); time and fatigue (to cook, to travel, to be exposed to media, to learn how to cook); knowledge and skills on how to cook; and household size (number of children under 5yoa).

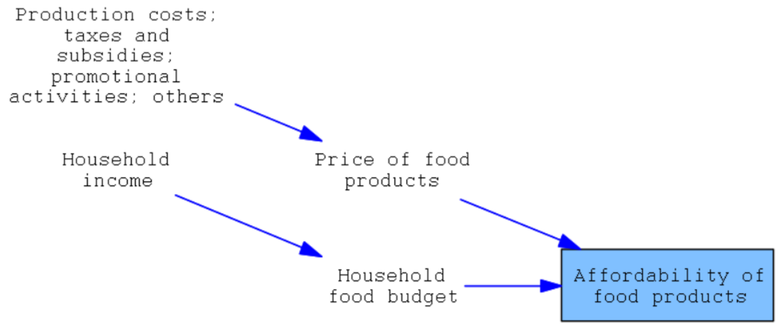
The way these factors influence food choices is not linear. Together, these factors form a web of interactions, resulting in complex causal chains, at times, leading to reinforcing and balancing loops (Allender et al. 2015; Gerritsen et al. 2019; Sawyer et al. 2021; Friel et al. 2017; UK's Government Office for Science 2007; Chen and Antonelli 2020). These loops are not shown in Figure 14 as the figure is meant to provide an overview/ list of the different factors affecting consumers' choices. Examples of balancing and reinforcing loops are, for example, reduced demand for fruit and vegetable, will lead to reduced availability of these foods, which in turn, it will limit food choices, leading to a reduction on fruit and vegetable intake. Factors such as job/employment conditions, transport, level of education of mothers, all influence food choices (Gerritsen et al. 2019; Friel et al. 2017; Allender et al. 2015). For example, employment influences income, which affects the affordability of food. Employment conditions (such as shift work, overtime work, and job security) can also affect accessibility (depending on the opening hours of retail facilities and transport availability), affecting food choices. Additionally, the distance between workplaces and retail outlets affects time available to shop and to cook.

Accessibility, availability and affordability

Accessibility, availability and affordability are three key factors affecting consumers' behaviour (Cervigni et al. 2020; Chen and Antonelli 2020; Gerritsen et al. 2019; Friel et al. 2017; Díez et al. 2017). Availability refers to the availability of certain food products in retail outlets, cafés, and restaurants, but also at work and in schools, community events or extended family events. Available portion sizes of food sold or served (in retail outlets, cafés, restaurants, workplaces, schools, events, etc.) is also a key factor linked to availability.

Accessibility refers to access to retail outlets, restaurants and cafés selling foods. This includes distance, availability (and cost) of transport/ walkability, time of travel and opening hours of outlets. Accessibility can also refer to, within retail spaces, product placement/positioning).
Affordability refers to food products (healthy or environmentally friendly products) and modes of transport to reach retail spaces. Affordability is a relative concept as it depends on the price of food products (linked with costs of production, but also, with promotional activities and government taxes, for example) the household income, in a relationship that can be represented as in Figure 15.

Figure 15: Flow chart of impact factors affecting the affordability of food products.



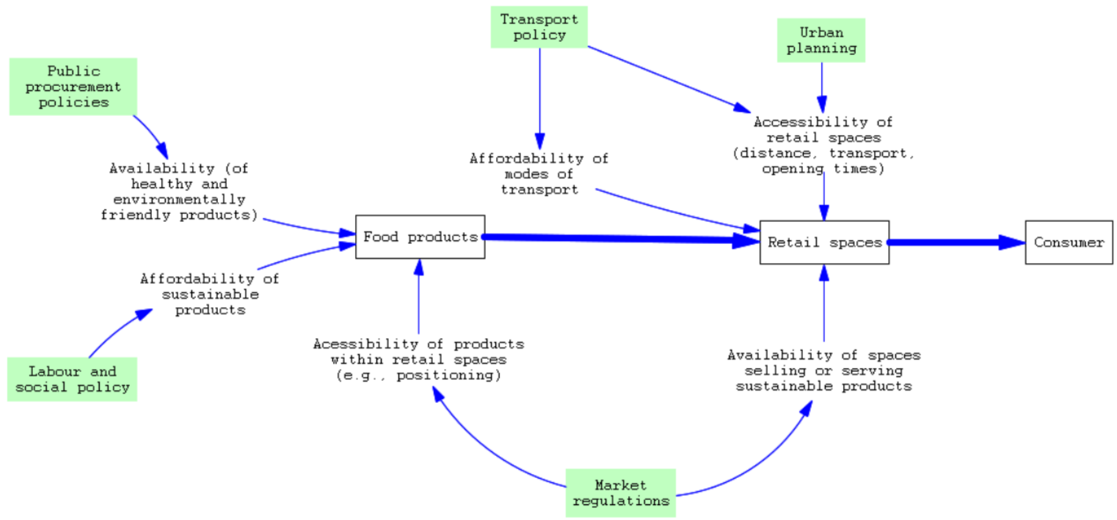
Source: Authors own compilation.

It is clear that for policy interventions to be effective in addressing accessibility, availability and affordability, these need to include:

- Urban planning instruments to ensure that physical environments make sustainable food choices accessible (in terms of proximity), and open during the hours a consumer may need to retail and that the retail environment is conducting sustainable food shopping;
- Transport policy to ensure availability and cost of transport and reasonable times of travel to retailers with sustainable food options;
- Public procurement policies to establish criteria for the availability and portion size of sustainable food products in public places such as schools, hospitals, and canteens, amongst others;
- policies on labour and social policy, ensuring that low socioeconomic status households can afford healthy and sustainable food products, are of relevance.

Figure 16 summarises the impact flowchart depicting availability, accessibility and affordability concepts in relation to food environments and presents different types of policy interventions that could be sought of when dealing with these concepts. The three concepts are strongly linked. For example, affordability can be seen as a form of accessibility, and availability can refer to affordable, healthy and environmentally sound products.

Figure 16: Availability, accessibility and affordability in food choices and their relation to different policy sectors.

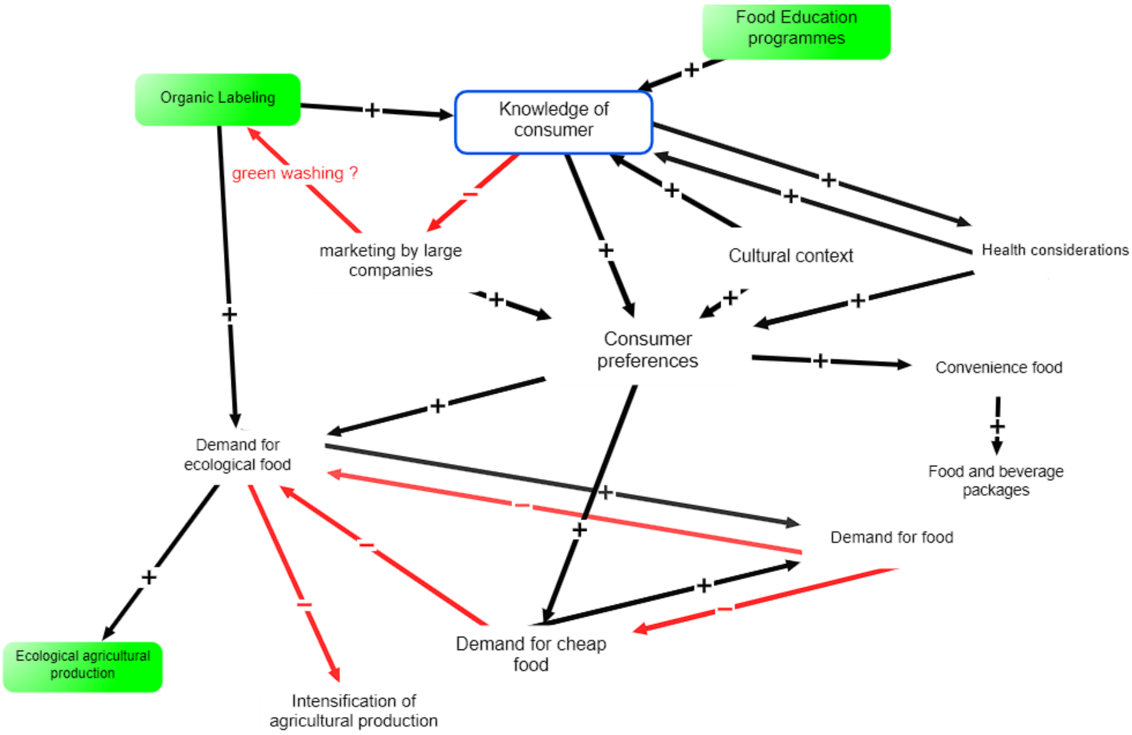


Source: Authors own compilation.

The concept of affordability (and accessibility) are not just linked with the food products and retail spaces. These can be linked with: (1) marketing, which can alter food prices, and product positioning, (2) accessibility to media such as TV, affecting the exposure to the advertisement and (3) accessibility/affordability to/of cooking equipment. These factors relate to the "information and knowledge" and "household resources" depicted in Figure 14.

In this context, the possible effectiveness of organic labels needs to be evaluated. As depicted in the impact CLD in Figure 17, an ecolabel is expected to directly influence the demand for ecological food. A recent study by (Nguyen-Viet 2022) indicated the positive effect of a green label on green purchase intention (see also (Donato and D'Aniello 2022)). Nonetheless, as mentioned before and shown in the ecological vs conventional food production CLD (in figure 12), the demand is formed not only by the knowledge of the existence but also generally by the product's availability on the market and other consumer preferences. The food label might be necessary, not alone sufficient, to increase sustainable food consumption.

Figure 17: CLD Showing the possible connections of the causal impact of organic labels.



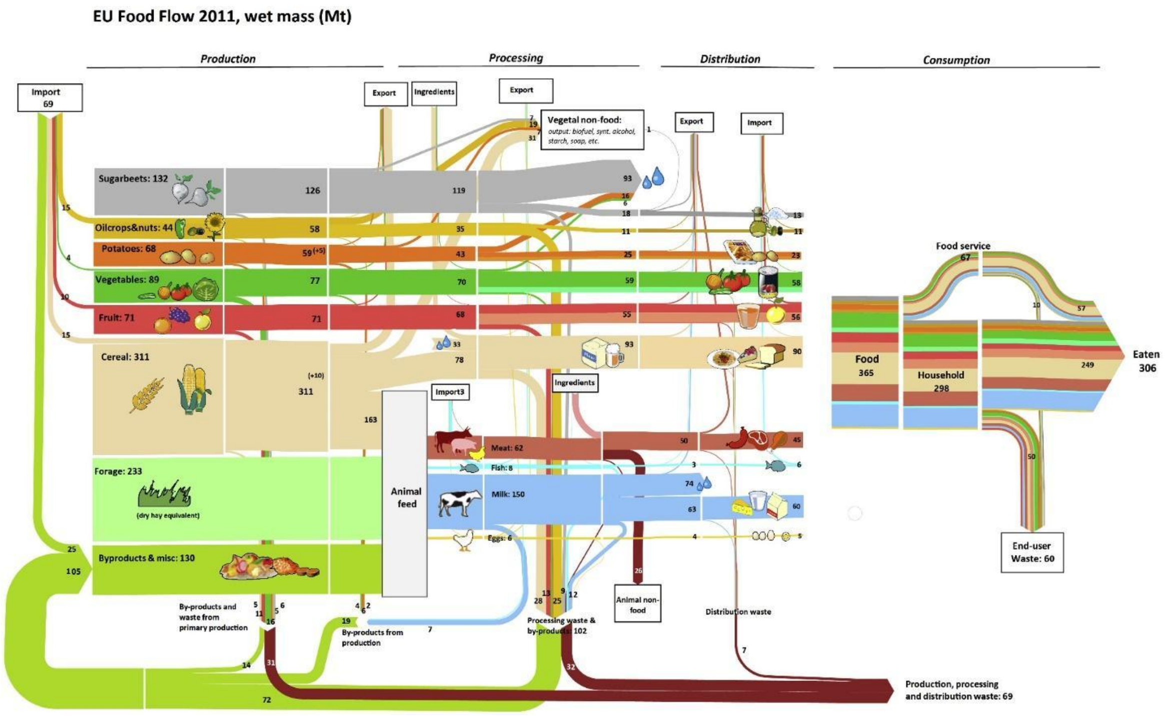
Source: Screenshot from qualitative iModeler, Authors own compilation.

Competition for Food waste

Addressing food waste prevention is one of the Sustainable Development Goals (SDGs) targets and a significant task for the UN Environmental Programme and the European Commission. It is promising in terms of its environmental saving potential. However, it also leads to consumers being able to save money, which they then are likely to spend, thus again causing a negative environmental impact (EEA 2020). Bio-waste – mainly food and garden waste – is a critical European waste stream. Across the European Union, somewhere between 118 and 138 million tons of bio-waste arise annually. Currently, about 40% of the waste is recycled and digested into high-quality compost. Implementation of separate collection of bio-waste in all EU member states as laid down in the Waste Framework Directive is a key for diverting organic waste from landfills and to guarantee that high-quality secondary raw materials (composts and digested) are consistently manufactured so that they can be placed on the European fertiliser market. [1] Mass flow analysis of the food system marks a good starting point for model building and simulations. Figure 18, reproduced by (Caldeira et al. 2019), shows the mass flow balance of EU food based on data from 2011.

1 https://www.compostnetwork.info/policy/biowaste-in-europe/

Figure 18: Mass flow balance EU 2011.

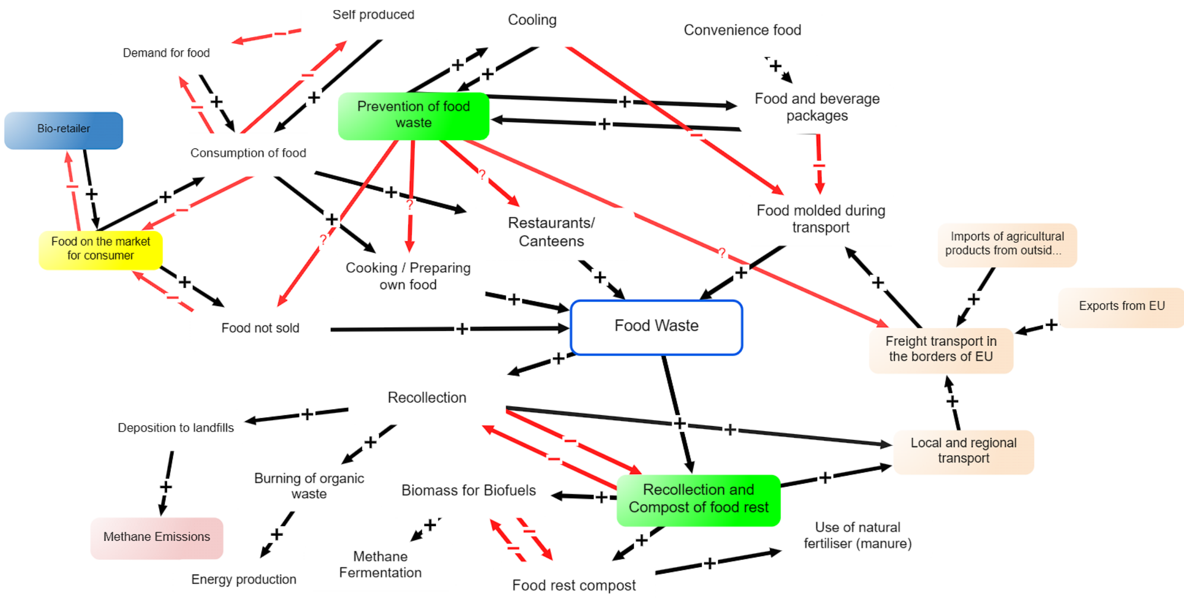


Source: Caldeira et al., 2019

However, mass flow modelling does not include the mechanisms that change these flows from changing (e.g., decision mechanisms), nor do they keep track of the accumulations ("stocks") or delays in the system. Beyond focusing on flows, Quantitative System Dynamics Modelling also requires incorporating accumulations, delays, decision mechanisms, and causal and feedback effects for the entire value-chain.

The Farm2Fork Strategy (European Commission 2020), p. 8) lays out: “(…) The circular bio-based economy is still a largely untapped potential for farmers and their cooperatives. For example, advanced bio-refineries that produce bio-fertilisers, protein feed, bioenergy, and bio-chemicals offer opportunities to transition to a climate-neutral European economy and create new jobs in primary production. Farmers should grasp opportunities to reduce methane emissions from livestock by developing the production of renewable energy and investing in anaerobic digesters for biogas production from agriculture waste and residues, such as manure. Farms also can produce biogas from other sources of waste and residues, such as from the food and beverage industry, sewage, wastewater and municipal waste. (…)" Further on, the "Farm2Fork-Strategy" (European Commission, 2020, pp 13) points out (…) Tackling food loss and waste is key to achieving sustainability. Reducing food waste brings savings for consumers and operators, and the recovery and redistribution of surplus food that would otherwise be wasted has a significant social dimension. It also ties in with policies on the recovery of nutrients and secondary raw materials, feed production, food safety, biodiversity, bio-economy, waste management and renewable energy. (…)". The following Figure 19 shows these connections, already giving an idea of the mutual effects.

Figure 19: CLD showing how "food waste" is represented and connected in the model. Source: Authors own representation.

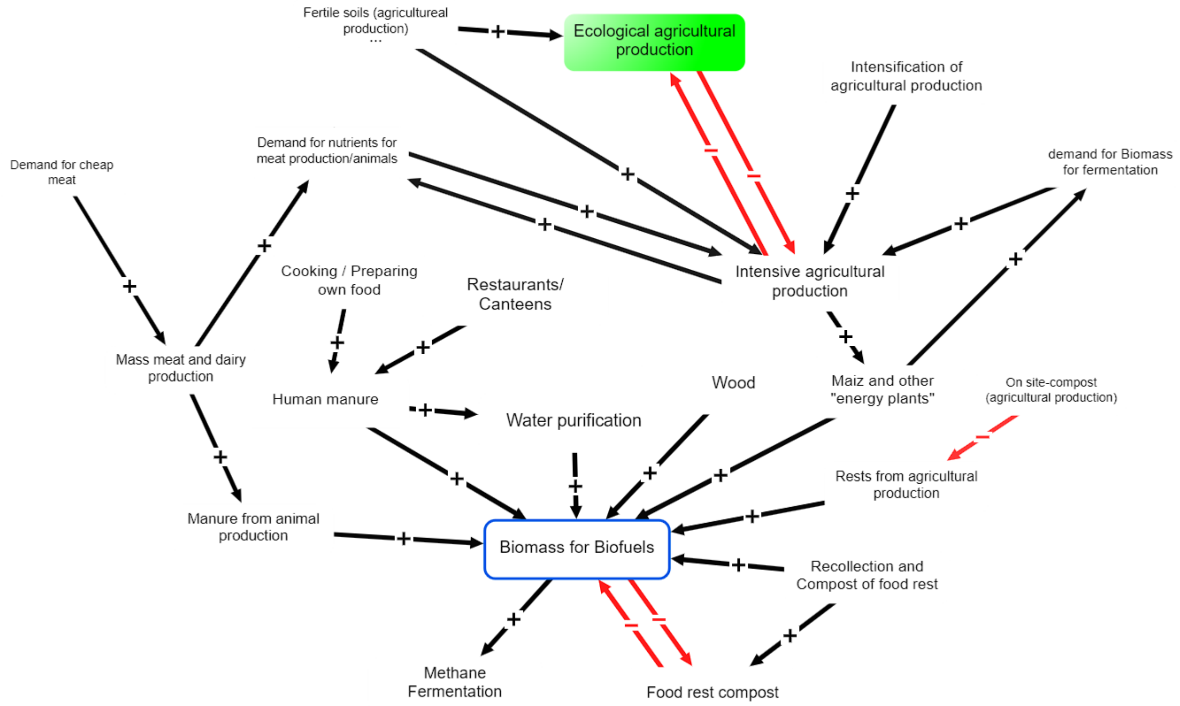


Source: Screenshot from iModeler. Authors own compilation.

Statistically, more than half of the food waste/bio waste ends on a landfill or in incineration. On a landfill, the organic rest will be "fermented", likely creating methane released uncontrolled to the atmosphere. Respectively, there are initiatives to use landfill gas, most recently the EU strategy to reduce methane emissions (European Commission 2020). In the case of incineration, energy (heat) is created, often in waste incineration plants with combined heat and power. Another stream of food waste goes into recollection and composting, closing a loop, and using the compost in gardening or agricultural production (As mentioned in Farm2Fork, see above). Nonetheless, the recollected food/bio waste might be fermented in a fermenter under controlled conditions. Here we see competing mass flows. Installations, like incineration plants, food compost plants or fermenters, are infrastructures that create investments and require a more or less constant flow of biomass. While reducing food waste would limit the possible material flow, a synergistic effect would occur by the reduced need for recollection systems (transport), see Figure 19.

Figure 20 extends the perspective shown in Figure 19, by focussing on the factor "Biomass for Biofuels". The biomass used in a fermenter to build methane can come from different sources, from manure from animal production (meat and milk) to sludge from wastewater, wood, and energy plants. Next to methane, ethanol fermentation is also possible (but not marked in the model). Again, when the infrastructure and a demand for the end product (methane, ethanol) are set up, there is a lock-in effect, as a constant flow of biomass is needed from a technical and economic perspective. If food waste is not part of the mass flow anymore and even rests from agricultural production are composted instead of fed into bio-fermenters, the mass flow from maize and energy plants might compensate. As maize is typically produced in intensive agriculture, the pressure to maintain the share of intensive cultures is likely to remain. This is a sort of "rebound effect", keeping the share of intensive agricultural areas constant, although less food might be needed.

Figure 20: CLD, showing the factors impacting the biomass for biofuels.



Source: Screenshot from iModeler. Authors own compilation.

In the model, we briefly mention three direct measures to reduce food waste:

- Cooling
- Food package
- Consumer behaviour

Cooling will directly consume more energy. Food package also requires energy and create a waste "problem" on their own (Sjölund 2016; Wilson et al. 2015; Ncube et al. 2021) . "Consumer behaviour" is more complex to address and is discussed in more detail in chapter 3.1.2.
The prevention of food waste is expected to create positive environmental effects (Sjölund 2016; Kummu et al. 2012; Hagedorn and Wilts 2019; Moraes et al. 2020):

- Direct positive effects can be expected mainly in reducing uncontrolled methane emissions. A small fraction might contribute to the relief of eutrophication of surface waters.
- Indirect positive effects occur through the potential reduction of transport and reduced emissions.
- Balancing effects might occur with substituting the food waste in use-streams of biomass (mainly growing of more maize in intensive agriculture). Also, packaging and cooling are ambivalent effects that require quantification to determine the effect clearly.

Recommendation 5: the competition for the resource "food waste/biomass" should be further assessed in the quantitative assessments. Data sources and additional information can be found on the EU Platform on Food Losses and Food Waste[2].

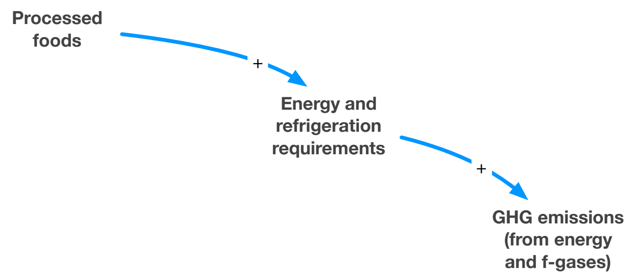
Recommendation 6: Food waste reduction reduces transport activity and should be incorporated in analyses of the food system.

Recommendation 7: Packaging and cooling (during transport) need to be balanced carefully in the quantitative models.

3.2.3 Processing and manufacturing

The heaviest environmental impacts from food products take place before the farm gate. In terms of GHG emissions, 71% of emissions came from these stages, mostly due to methane and nitrous oxide emissions (Figure 21). Interestingly, emissions from the remainder of the value chain, alongside with emissions from energy production and use in the food value chain have been increasing. Between 1990-2015, this represented a 31% increase. F-gases (used in refrigeration), which represent only 2% of emissions, have doubled between 1990-2015. These trends show an increase in energy usage in food systems and refrigeration.

Figure 21: A simplified causal link between processed foods and GHG emissions.



Source: Autors own compilation.

This goes in paired with the increased use of some ultra-processed foods. Ultra-processed foods are ready-to-eat or ready-to-heat industrial formulations made mainly with ingredients refined or extracted from foods and contain additives but little to no whole foods.
The environmental impacts of food processing stages are expected to continue to rise, surpassing the impacts of more efficient and less environmentally intensive food production systems. This increase in the environmental impacts of the food value chain can undermine the efforts to reduce the impacts of the production stages of food.

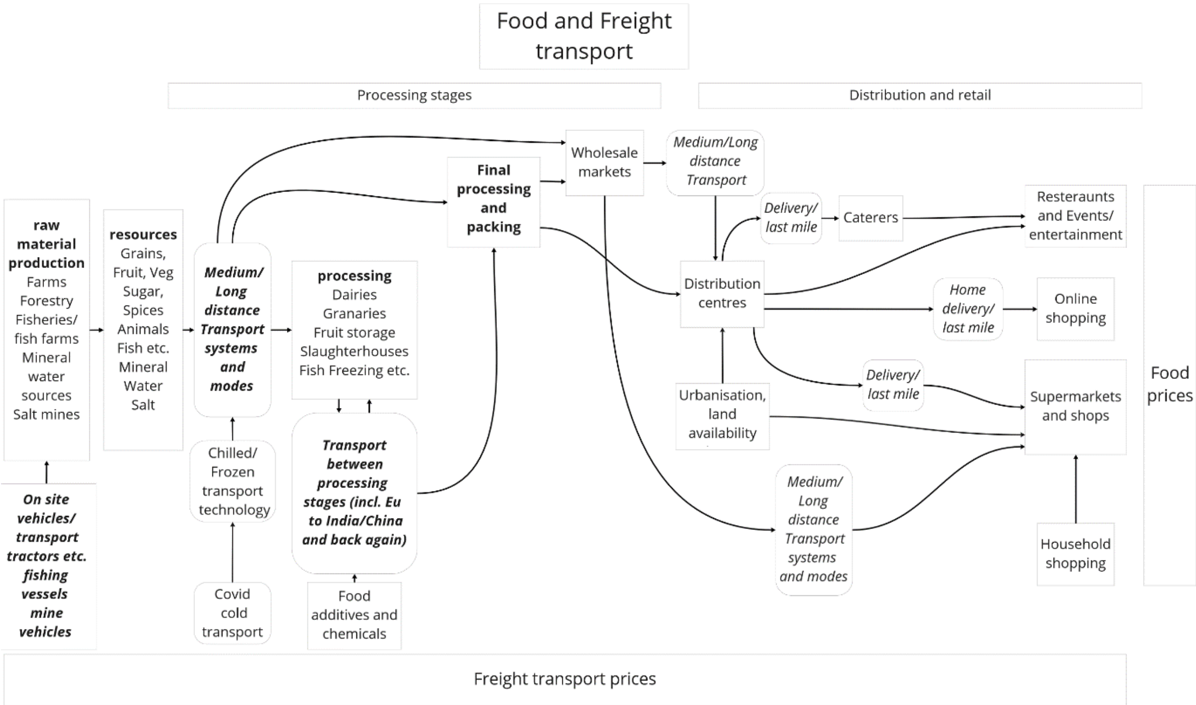
3.2.4 Food and mobility

The overall scope of such an analysis is to analyse the interrelationships of the food and mobility systems, particularly concerning environmental impacts. The analysis should enable greenhouse gas emissions due to transport for the food supply chain and, where data is available, consider local air emissions. A further issue is land use for supply chain activities, particularly logistics or warehouse/distribution centres, but data on the local environmental impacts would have to be

2 https://food.ec.europa.eu/safety/food-waste/eu-actions-against-food-waste/eu-platform-food-losses-and-food-waste_en

collected. The FOD[3] project considered the relationships between food and freight transport using a supply chain approach, as shown in Figure 22.

Figure 22: Block Model giving an overview about the connection of food and freight transport system.



Source: Taken from FoD-2018/RTD/A2/OP/PP-07001-2018/LOT.

Identifying variables and causal connections for a System CLD

From Figure 22, the main structure of the supply chain can be seen to cover the variables:

Food production from agriculture, drinks and fisheries -> transport of fresh products and intermediate products -> distribution.

Distribution includes:

- Online supply
- Distribution to supermarkets

A further group of variables is required to include consumption (final demand) variables:

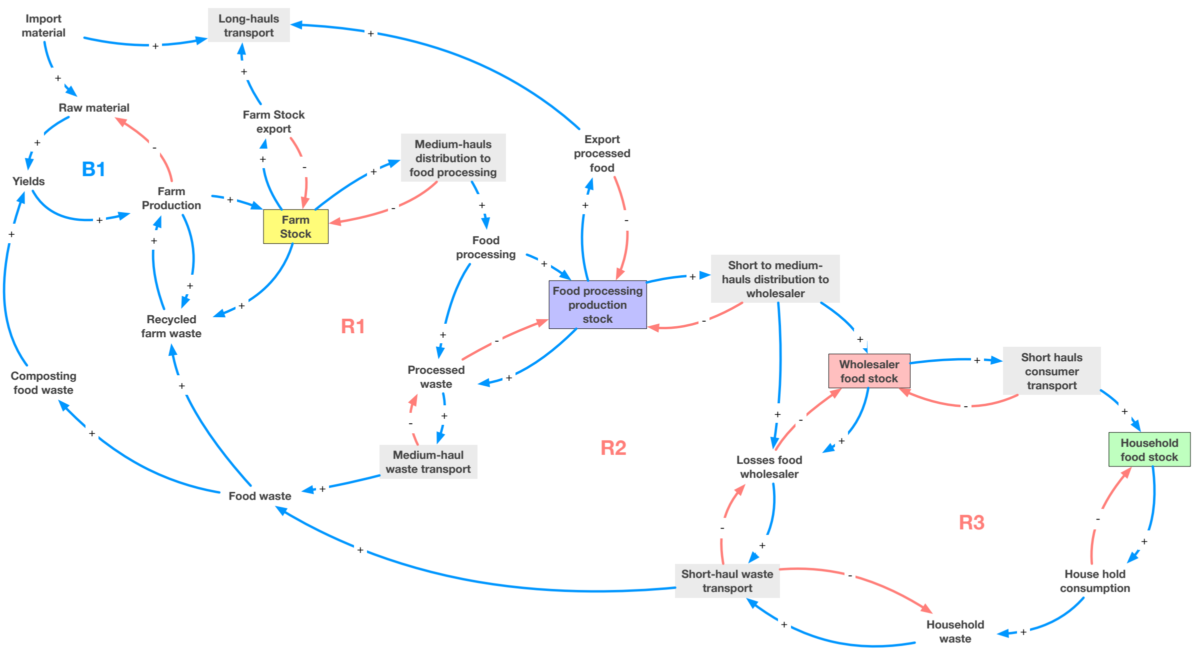
- Eating out: Consumption in restaurants and events
- Eating at home – supermarket shopping, online shopping

Figure 22 also indicates that transport prices have a significant impact on the supply chain, in comparison to labour costs. In particular, high local (European) labour costs and low transport costs lead to transport of intermediate food products internationally for intermediate processing which are then re-imported to the EU. These variables can be included in the system analysis of the food system. Analysing the supply chain in figure 23 in more details we can use the freight costs per tonne and the related environmental impacts as food products move from origin to the consumer.

3 FoD contract FoD-2018/RTD/A2/OP/PP-07001-2018/LOT

At the Farm level: the cost initially per tonne is low, solely including the production expenses. The environmental footprint here includes the use of natural resources and the release of emissions from farm the operations.
Transport to food processors: This stage shows an increase in freight costs per tonne due to the need for fuel, labour, and vehicle maintenance. The primary environmental concern is the emission of pollutants from the vehicles used, which contributes to air quality degradation and GHG emissions.
Food processing: Additional freight costs per tonne are included for energy and labour to process the food. The processing phase also contributes to the environmental impact, mainly through energy consumption and the generation of waste.
Packaging and Finishing: The freight cost per tonne rises with the inclusion of packaging expenses. The environmental impact includes the resources used to create packaging materials and the waste generated for post-consumer use.
To the Stores: As goods are transported to retail locations, freight costs per tonne increase due to logistics and warehousing demands. This phase adds emissions, in addition to transportation, energy use in storage facilities.
In Stores: The cumulative freight cost per tonne is highest, cumulating all previous transportation and handling stages. Environmentally, the stores impact is primarily energy consumption and waste management, thus transport impact is much lower.
Throughout the supply chain, freight costs per tonne accumulate progressively with each transition and the environmental impact per tonne intensifies, through GHG emissions at each transport stage.
Figure 23 shows an initial draft of a CLD for the food value chain and transport system interactions and the figure illustrates on an overarching level how the transport of food and food intermediate products is interlinked into the food value chain. It is dependent on the demand from retail in response to demand from end consumers.

Figure 23: CLD food and transport system interactions. Grey boxes show where transport interacts in the food value chain from 'Farm-stock, Food processing production stock, Wholesaler stock, and Household stock', and furthermore, where policy levers for influencing transport modes would occur.



Source: Hördur Haraldsson, synthesis of FoD-2018/RTD/A2/OP/PP-07001-2018/LOT and (Köhler et al. 2020).

From a transport perspective, the main loops that move the food material between the value-chain items are shown as reinforcing R1, R2 and R3. The loops illustrate the feedback from move material ultimately to the consumer, and back ultimately as waste, back to the farm production. The most essential causal loops are, therefore, resulting from Households 'taking from the wholesalers' through consumer buying food, which effects, cascade through the whole value chain to farm production. The supply from agriculture and intermediate processing then generates transport activity, both global and intra-EU (long-haul transport), which generates food waste in transport and emissions from vehicles and logistics (indicated with grey boxes in fig. 23). Transport costs have only an indirect effect on these feedback, because consumers do not see the explicit transport costs of the food products. Transport costs may also be a relatively small proportion of the purchase price of food. Transport activity therefore has little impact on the choice between 'conventional' and organic foods, again because transport's price and environmental impacts are not visible to the consumer. However, adding the information from figure 23, we can see that the transport prices and environmental impacts increase through each value chain stages.

From this analysis, KPIs for the Modelling can be identified. In addition to the agricultural and food system KPIs, the following are relevant:

- Emissions from transport activity, both within the EU and from global transport of food with end consumers in the EU – per tonne of food delivered to the user
- Food waste in processing and transport

Outputs of the cross-system analysis of food and transport.

The scope of the initial analysis should cover an approximate assessment of the overall transport activity for agriculture, fisheries, and food in the EU and the resulting GHG emissions. Transport outside the EU should be considered, as there are global supply chains for products such as wine, fruit, fish and prepared food as well. The two main factors changing freight transport are currently assessed to be the requirement for emissions reductions and the continuing digitalisation of logistics (Köhler et al. 2020) ((Köhler J. and Brauer C., 2022)). While there is an extensive literature on reducing emissions from freight transport and in particular low carbon fuels, the fundamental changes taking place in logistics through digitalisation have not been fully understood. Indeed, models which represent digitalisation in logistics at a policy – i.e. aggregated level – do not exist (Köhler J. and Brauer C. 2022). Such new systems include:

- Logistics control towers
- Blockchain supply chain relationships
- Synchro-mobility, the Internet of Things (IoT) and the physical internet -> reduced warehousing

Conclusion/Recommendation: There are connections between the food system and freight transport, which involve a large, global freight transport activity and GHG emissions. Li et al. (2022) argue that the contribution of transport to food system emissions is much higher than previously estimated. The future change to digital, low-carbon logistics systems requires considering how these systems will change supply chain structures in the agricultural and food systems and how the associated GHG emissions may change.

3.3 Using the qualitative CLD analysis to structure the quantitative model development

The CLD analysis has identified the main areas of the food system. The first elements comprise the production of food and the consumption of food. Linked to this is the issue of food waste. This involves a value chain starting with agriculture and fisheries, through food processing and manufacturing, to distribution and consumption, with aspects of waste. Transport along the supply chain is an important factor. These structural components of the food system are the result of many factors in terms of technology, culture, and population. They form the structure of the quantitative model. The quantitative model, while of necessity simplifying some aspects of these CLDs, uses the elements identified for the model structure.

The development of the food system is also strongly influenced by policies reflecting the goals of EU society. In terms of the analysis, the policies form inputs to the food system structure and change the outputs and development of the system in a dynamic analysis. Therefore, it is necessary to consider the policy context for the food system and its potential influence on the food system dynamics, given the food system structure. We now review the EU food policy context. Food policy includes the identification of objectives for food policy, in particular meeting demand and ensuring a path towards a sustainable food system (European Commission 2020; European Parliament 2022).

Given the policy context reviewed in section 4, the objectives of the quantitative modelling are defined. This pilot project implements the EEC imaginaries (EEA 2023a), as desirable scenarios for the achievement of sustainability. Since the imaginaries are not food sector specific, section 5 explains how the imaginaries were interpreted as scenarios for the quantitative modelling of the food system. The scenarios were used to determine the required final states of the food system in 2050, in terms of KPIs identified through the policy analysis and in discussion with EEA experts. Section 6 then explains how policies are represented in the quantitative modelling through 'policy levers', which are model variables representing the policies and their influence on the food system.

4 European food and mobility policies

4.1 Farm to Fork Strategy and the logics of Intervention

The "Farm to Fork" (F2F) Strategy (https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en#documents) is at the heart of the European Green Deal – the New Growth Strategy of the European Union and a key to the implementation of Sustainable Development Goals (SDGs). The F2F Strategy is designed to build a fair, healthy, and environmentally friendly food system with an integrated food safety policy in the EU. The Commission sees new opportunities for all operators in the European food chain to tackle pollution, biodiversity loss, climate change, food waste, and unhealthy diets. The F2F Strategy is meant to pave the way for this transition. The strategy was presented on the 20th of May 2020 with an action plan consisting of 27 measures. The F2F Strategy targets the whole value food chain, from production to waste generation. This is one of the main features of this policy strategy. The first two actions described in the strategy are rather general: a proposal for a legislative framework for sustainable food systems and the development of a contingency plan to ensure food supply and food security.

The following sets of actions in the F2F strategy are connected through their collective aim of ensuring sustainable **food production**. The F2F strategy, in line with the European Green Deal, does not only aim to improve the sustainability of production methods in the EU farming sector but to transform Europe's food systems in the broadest sense. The renewed Common Agricultural Policy for 2021-2027 will play an essential role in this, as well as a review of pesticides, animal welfare, food additives legislation and the introduction of a new EU carbon farming initiative to reward farming practices that remove CO_2 from the atmosphere. The F2F strategy also includes actions that aim to stimulate **sustainable food processing**, **wholesale**, **retail**, **hospitality,** and **food services** practices.

At the core of the F2F Strategy are key domains designed to enhance the sustainability of the EUs food system:

- **Sustainable Food Production**: This domain focuses on promoting eco-friendly farming practices that preserve biodiversity and natural resources. It aims to reduce the dependency on chemical pesticides and fertilizers and increase organic farming.
- **Sustainable Food Processing and Distribution**: Here the emphasis is on making the food processing, packaging, retail, and distribution sectors more sustainable. This involves adopting circular economy practices, reducing carbon footprints, and improving food packaging sustainability.
- **Sustainable Food Consumption**: The strategy encourages a shift towards diets that are both healthy and sustainable, emphasizing plant-based foods to reduce environmental impact. Enhanced labeling will provide consumers with the information needed to make informed, sustainable food choices.
- **Food Loss and Waste Prevention**: A significant goal is to halve the per capita food waste at the retail and consumer levels by 2030, addressing food losses throughout the production and supply chains.

The ambition of the F2F strategy is underpinned by five quantitative targets that serve as milestones towards its overarching objectives. These targets, particularly focusing on primary producers and food waste reduction are instrumental in driving the EUs efforts in building a sustainable food ecosystem:

1. **Pesticides Reduction**: Aiming for a 50% reduction in the use and risk of chemical and hazardous pesticides by 2030. It underscores the dedication to minimizing the environmental and health impacts associated with pesticide use. This target is pivotal in promoting safer, alternative pest management practices.

2. **Nutrient Management and Fertilizer Reduction**: The dual goals of cutting nutrient losses by at least 50% and reducing the use of fertilizers by at least 20% by 2030. This highlight the strategy's approach to enhancing soil health while mitigating environmental pollution. These targets are essential for balancing agricultural productivity with ecological preservation.
3. **Antimicrobials in Farming**: By targeting a 50% reduction in the overall EU sales of antimicrobials for farmed animals by 2030, addresses the issue of antimicrobial resistance. This objective not only promotes animal health and welfare but also safeguards public health.
4. **Organic Farming Expansion**: The ambition to increase EU agricultural land under organic farming by 25% by 2030. This reflects the commitment to sustainable agriculture practices. Organic farming is recognized for its benefits in enhancing biodiversity, reducing environmental pollution, and supporting soil fertility.
5. **Food Waste reduction**: Reduce per capita food waste by half at retail and consumer levels by 2030. This aligns with global efforts to achieve more efficient food systems. This target is important for reducing environmental impacts and improving food security.

By analyzing the strategic domains and the quantitative targets set for the F2F, the project consulted experts at the EEA as part of formulating policy objectives to frame the entire value chain for production-consumption system in the project. These objectives were designed to encapsulate the essence of the Farm to Fork Strategy and align with the EEAs areas of focus. These policy objectives served as the foundation for framing and defining success for the policies, as well as for establishing KPIs to measure the success. Additionally, they were instrumental in identify the types of policy instruments that could be suitable for scenario analysis for the pathways towards the imaginaries. The following nine policy objectives include:

Organic Farming: This goal encourages farming methods that are in harmony with nature and reduce impact on the environment. Organic farming plays a key role in decreasing the use of synthetic chemicals like pesticides and fertilizers. It promotes the responsible use of land.

Reducing GHG: Reducing GHG emissions in the food sector is essential for fighting climate change. The strategy aims to cut emissions from farming, food production, and transportation. This is part of a larger effort to achieve carbon neutrality in the EU.

Energy Use: Improving energy efficiency and adopting renewable energy in agriculture and food processing helps lower the food sector's impact on the climate. This includes developing better farming equipment, food production methods, and distribution systems.

Biodiversity: Protecting and reviving the diversity of fauna, flora affected by farming is a priority. A healthy ecosystem is important for growing food, supporting pollinators, managing pests, and helping control the climate.

Pesticides: Reducing chemical pesticides is good for both nature and human health. The strategy encourages less pesticide use and looks for other ways to manage pests.

Chemicals: Reducing harmful chemicals in farming for safe food and a healthy environment. The strategy supports the EUs plan to minimize dangerous substances in food.

Water: Using water wisely in farming is in dry areas or where water is scarce. The strategy supports efficient water use, protecting water sources, and reducing pollution from farms.

Food Waste: A major goal is to cut food waste in half at the retail and consumer levels by 2030. This includes actions throughout the food supply chain to lessen waste and make food distribution more efficient.

Transport: Changing transport to cut emissions. This means improving logistics, sourcing food locally to reduce travel distance, and using cleaner ways to move food.

4.2 Sustainable and Smart Mobility Strategy together with an Action Plan

Even though transport emissions are a small part of food system emissions, they are still part of a freight transport system that is 8% of global GHG emissions and 11% of global GHG emissions including logistics sites and equipment (DHL 2022 https://www.dhl.com/global-en/delivered/sustainability/carbon-insetting-freight-forwarding.html).

The current EU policy context for considering interactions between the food and mobility systems is, from the viewpoint of transport, the EU Green Deal and the proposals for implementation in the 'Fit for 55' proposals, the 'Sustainable and Smart Mobility Strategy' and the associated action plan and policy 'Flagships'. The proposals were presented in the European Green Deal 'Fit for 55' actions (European Parliament 2022).

4.2.1 Cross systems Analysis of EU transport policy and transport in the food system

Two Flagships are relevant for freight transport. There are no policies that specifically consider transport of agricultural products or food and drink.

FLAGSHIP 4 – GREENING FREIGHT TRANSPORT
This Flagship continues the general goal of EU environmental policy in freight transport of promoting modal shift to rail and inland waterway freight transport away from road freight. An important policy has been the infrastructure support through the TEN-T (Trans-European Networks-Transport) programmes, which have provided limited support for rail and road infrastructure. They have not yet significantly changed the dominance of road freight in the EU. This applies particularly to distribution, because rail and IWW have almost all activities in freight transport in long distance, mainly international traffic. Concrete actions are indicated in Flagship 5 PRICING CARBON AND PROVIDING BETTER INCENTIVES FOR USERS.

FLAGSHIP 5 – PRICING CARBON AND PROVIDING BETTER INCENTIVES FOR USERS
The EU is concentrating on market-based measures for changing the structure of economic incentives for freight transport. The European Commission proposes more ambitious targets for reducing the CO_2 emissions of new cars and vans (EU Fit for 55):

- 55% reduction of emissions from cars by 2030,
- 50% reduction of emissions from vans i.e. light duty freight vehicles by 2030,
- Zero emissions from new cars by 2035.

A further policy objective for low-carbon vehicles is promoting the growth of the market for zero- and low-emissions vehicles through the provision of charging infrastructure for short and long journeys. The following measures have been proposed:

- include aviation in the EU ETS,
- include road transport in the EU ETS,
- remove current tax exemptions, including for aviation and maritime fuels,
- update distance-based road charging.

Up to 2022, the European Parliament has passed legislation for including road passenger and road freight in the EU ETS: EU ETSII (EU Parliament 2022). This is implemented through a new system for the CO_2 price for fuel sales, which is authorised to start in 2024 for fuels in freight vehicles.
Of these specific measures, the most significant for the EU food system is the introduction of CO2 pricing for road freight vehicles in the EU ETS, putting a price on the CO2 content of fuels in road freight. This is the only measure that has been approved by the European Parliament so far.

Summary

This policy summary is used in an analysis of policy requirements or policy 'gaps' in section 6 below. The policies need to be considered in relation to the imaginaries analysed and the policy levers implemented in the model to determine potential pathways to realise the imaginaries for a sustainable EU food system.

5 Interpreting the EEA imaginaries for the system dynamics modelling of transitions to a sustainable food system

5.1 The food system in the 'Technocracy for the common good' imaginary

In the "Technocracy for the common good" imaginary, the food system is characterized by a strong influence from national governments directing national food systems towards sustainability. These governments utilize digital tools to monitor and control relevant activities, ensuring the internalization of external health and environmental costs of nutrition. This encompasses dynamic food pricing and nudging consumer diets.

The economy predominantly consists of large businesses. These are substantially influenced by the state to ensure their activities serve the common good. However, they also maintain a persistent lobbying presence, holding significant political influence. Member states exercise a dominant influence over large food companies specializing in digital agriculture and food manufacturing. Sustainable food innovations are rapidly patented by startups, with larger companies acquiring the rights to mass-produce them. The agricultural landscape features large agri-businesses employing regionalized/localized franchising models and employing few due to high levels of digitalization and automation. As food production shifts towards urban areas, rural income and employment opportunities decrease. In contrast, urban areas become hotbeds for startups innovating in alternative foods.

Regarding food value chains and trade, food commerce primarily occurs nationally and within Europe. Agriculture is geared towards meeting domestic demand without focusing on import or export surpluses. The emphasis on domestic growth is supported by deglobalization and protectionism. The production takes a digital and innovative turn, with techniques like vertical farming becoming essential. The previous global animal-based food system evolves into national-scale chains providing alternative nutrients.

The vision for production includes an emphasis on intensive mono-cropping, precision agriculture, and a shift from animal-based nutrition. High-performance seeds adapted to local climates reduce the need for pesticides and fertilizers. The landscape sees a rise in alternative protein sources, less extensive animal grazing, and a focus on the 'maximum sustainable yield' paradigm. Innovations in farming techniques and machinery contribute to environmental conservation, and novel value chains, including seaweed and algae, become more prevalent. Urban areas become central hubs for food production, benefiting from large-scale digital technology deployment. Genetic modifications are employed to enhance nutritional values.

In terms of dietary habits, people primarily consume locally produced food, leading to diets rich in seasonal and national produce. The consumption of animal-based proteins, dairy, and certain seafoods sees a reduction, replaced by alternatives like algae and artificial meats. Health becomes a paramount concern, leading to the elimination of unhealthy diets. Advanced digital technologies play a role in personalized nutrition and health regimes, prioritizing nutritional value over traditional taste and food culture.

Lastly, food policies are bolstered by strong national economies, enabling strict governance of the food system, including digitally identifying and addressing food shortages. Interlinkages between food, land-use, and energy policies focus on decarbonization, leveraging practices like agroforestry. Digital monitoring aids in managing sustainability indicators, ensuring a balanced approach that considers aspects like soil health and biodiversity.

5.2 The food system in the in the 'Unity in adversity' imaginary

The "Unity in adversity" imaginary highlights a period marked by significant climate disasters, geopolitical challenges, and financial downturns. In response, the EU takes a united stance, adopting a common constitution that emphasizes stringent, top-down regulations for economic activities. The focus shifts from GDP as a primary indicator of economic health to prioritizing the environment and ensuring stakeholders adhere to strict environmental limits.

Agriculture and food production at the EU level undergo a shift towards large scales, heavily impacting global trade and consumption patterns. This centralized European food governance results in friction with global regional blocks like China and India. Despite the challenges, significant investments are made in nature, promoting resilient infrastructures, effective disaster relief systems, and cooperative European strategies in various fields, including foreign and security policies. Urban landscapes feature networks of natural and designed elements, like water bodies and green spaces, but restructuring cities for a changing climate remains a challenge even in 2050. In contrast, many rural areas integrate agriculture and nature, employing strategies like agroforests to enhance farming outputs and counteract natural hazards. This includes practices like soil management geared towards increasing soil biodiversity and enhancing nutrient cycling.

In terms of food production, the agricultural practices and food processing undergo significant changes, with a primary orientation towards food security and availability. Given the top-down governance approach, it becomes crucial to engage civil society in decision-making processes. The production landscape diversifies, with large-scale, small-scale, and family-owned farms coexisting. While large-scale entities embrace sustainable practices, smaller farms receive increased support from the EU. Producers are held accountable for their environmental impact, adhering to stringent laws and comprehensive sustainability requirements. The integration of agriculture with nature becomes prominent in rural areas. Urban and peri-urban agriculture, including vertical farming and community gardens, rises in urban regions, offering fresh, local produce. This shift accompanies a move towards organic and precision agriculture, leveraging technological innovations like agri-drones and agri-bots. However, the focus isn't on intensive farming but innovative, regenerative methods that connect urban spaces with nature, proving resilient against extreme climate events.

As for dietary preferences, a European-centric food system with decreased imports leads to a rise in alternative protein sources, such as insects, algae, and artificial meat. Dairy products see substitutions from plant-based alternatives, and legumes play a significant role due to their environmental and health benefits. Innovative food technologies emerge, offering personalized nutrition and artificial food options. The governance model imposed by the EU results in a resilient agricultural system, reviving ancient grains and cereals from perennial crops. Cultural shifts lead to reduced sugar consumption and healthier ready-made food choices. The "less but better meat" approach becomes prevalent, and an emphasis on health and wellness encourages people to consume nutritious foods. Regional supply chains bolster, offering locally sourced and seasonal produce, reducing environmental impacts, and supporting local communities. Consumers favour organic and regenerative agriculture products, leading to reduced food waste and more conscious consumption.

Lastly, food policy and monitoring emphasize a regional and secure supply chain, ensuring food availability and access. Establishing solid European governance structures provides the foundation for creating public crisis reserves and private mechanisms, focusing on regional self-sufficiency. Regulation and effective financing play vital roles in transitioning to food safety, catering to an aging society's needs. There isn't a pronounced issue of food inequality. Solidarity-focused policies aid in the transition of agricultural leadership from the older to the newer generation. The robust presence of European institutions facilitates the redistribution of activities and functions between cities and rural areas.

5.3 The food system in the 'The Great Decoupling' imaginary

The food system in the 'The Great Decoupling' imaginary is defined by a liberalized global market economy. This economy is primarily driven by a strong private sector dominated by large multinational cooperation, especially in the biotech and agri-food industries which rely on technological breakthroughs. Nation states play a significant role in wealth distribution and in ensuring the proper functioning of a liberal market economy. They promote disruptive innovation and entrepreneurship while ensuring market failures, such as monopolies, are minimized. Without the Euro, Europe takes a backseat in global affairs, leaving the European Union with a diminished role. Its institutions and regulations largely cater to the needs of major global players. Nature is utilized for its ability to provide ecosystem services that spur green growth. Technological developments in the bioeconomy, ranging from primary production to consumption, have become the main drivers of this great decoupling. These technological advances come as a response to the global food crisis. Despite the challenges posed by climate change, crop yields continue to increase. Large farms utilize data analytics, improved sensor technology, and drones to gather essential data. The rise of agro-ecosystem designs, some based on genetically modified species, represents a new wave of technoscience, pushing agricultural automation beyond precision farming. Biotechnological advancements not only facilitate environmental restoration but also provide solutions for rural and urban pollution. These technological strides have revolutionized food production, potentially ushering in new sustainable nutrition sources. The climate crisis is managed by addressing its peripheral effects. However, the availability of land for biofuels and biobased materials is compromised by environmental disasters. The detachment of GDP growth from environmental impacts aids in environmental rejuvenation, although it results in unequal well-being distribution, leading to isolated regions and unstable work environments. For those with satisfactory living conditions, a green lifestyle is standard. This bioeconomy, rooted in circular business models, is accelerated through the twin transition of the agri-food sector with modern digitalized production and monitoring techniques.

Food production in this imaginary is founded on a market-oriented economy teeming with technological innovations. Competition for resources constrains open markets and the drive for technological and economic development. The increased demand for metals and minerals, essential for advancing digital technologies and society's electrification, indicates that while the economy grows, energy availability is limited compared to 2022. Global companies create product ecosystems tailored for specific demographics. The entire production and consumption system is circular, and the flourishing bioeconomy hinges on biotech and digitalization. These influence agricultural practices, optimizing resource use and carbon sequestration. Farming has become intensive, transitioning indoors and adopting vertical strategies using resource optimization technology. Precision farming leverages all available digital tools, and urban areas witness the rise of cellular agriculture and micro-companies. Aquaculture sees growth, introducing innovative sea value chains and closed-loop systems. Industrial production is dispersed, with multinational corporations overseeing globally distributed but localized production facilities. To thrive amidst constraints, major players capitalize on short transport distances, spreading across entire value chains and territories, often employing franchising business models.

Regarding dietary choices, biotechnological advancements introduce alternative protein sources like lab-grown meat, plant-based proteins, and insect-derived proteins. These not only diversify diet options but also offer environmentally-friendly choices. Widespread GMO use in agriculture can potentially produce nutritionally enriched crops resistant to diseases, leading to increased GMO food consumption. Urban vertical farming provides city dwellers with fresh local produce, promoting a vegetable-rich diet and reducing transportation's environmental impact. Algae cultivation for food might become popular given their nutritional value, as the push for circularity makes upcycled ingredients or waste stream products more common. Technological and data advancements might enable personalized nutrition plans tailored to individual health needs, preferences, and genetic predispositions. Green lifestyles may promote more plant-based diets or environmentally friendly food choices. The thriving bioeconomy and innovation focus could result in novel food products by 2050, such as new plant-based alternatives, functional foods, or innovative food processing techniques enhancing nutritional value or product longevity.

Food policy and monitoring perceive food security as an equilibrium between availability, access, and affordability. The state's limited resources often compromise food quality due to low safety standards. Companies dominate the conversation regarding quality food's affordability and accessibility. While caloric diet affordability is not an issue due to innovations, healthy food access varies significantly across societal groups. Energy prices, a key factor in food accessibility and affordability, influence logistics and production structures, making local production more profitable. This results in regional energy price disparities, causing unequal access to non-local foods. Food availability is complex, impacted by weather extremes and regional production disparities. European policy-making mainly manages this, emphasizing the importance of solidarity within the relatively inactive European Union. Precision farming, especially precise fertilizer application, significantly relieves this. Reduced fertilizer requirements decrease CO_2 and N_2O emissions from fertilizer production and agricultural lands, affecting hydrogen demand. Water quality also improves in rural areas. However, water access remains a concern, particularly fresh water quality and availability, as competition between humans, agriculture, and industry intensifies, causing tensions within the EU and globally.

5.4 The food system in the ‘Ecotopia’ imaginary

In the "Ecotopia" imaginary, local communities reconnect with nature, and technology is sparingly utilized to foster sustainable lifestyles. Consumption and resource use have been considerably curtailed, and the primary socio-economic paradigm has transitioned from profit and consumerism to sufficiency and frugality. Nature is valued intrinsically. The reduction in resource use and economic activity has relieved ecosystems but has also diminished governmental resources. Power is now largely vested in local communities and civil society organizations, which play a prominent role in fulfilling collective needs like health and social care. Many people have transitioned from city life to ecovillages, resulting in a dispersed population. Economic activity is fragmented and localized, with sectors like energy and agriculture often managed by small-scale cooperatives. Europe has become more insular and less integrated into global economic networks.

Regarding food production, agriculture is predominantly smaller in scale, diverse, and organized around locality, place, and season. Many Europeans have become "prosumers," producing some of their own food, like fruits and vegetables. The energy sector is decentralized, with private and commercial entities producing and storing energy from renewable sources. Food chains have shortened, and food imports into Europe have reduced due to a preference for local products. Ecotopian society is highly aware of sustainable food, thanks to strong civil society influence. Markets have evolved to become hubs for idea exchange. Economic sectors remain fragmented and localized, and decentralized digital currencies are common. Businesses are frequently managed by stakeholders, including customers and local communities. Since local and organic food production is costly, food prices have risen. Organic farming and agroecology are standard practices, and technology, like precision farming and agri-drones, aids resource-efficient cultivation. Food is produced harmoniously with nature, and many previously abandoned agricultural regions are now inhabited again. Resources are managed to boost biodiversity and ecosystem health. The concept of consumers has evolved, with many now producing some of their own food. Community brokers facilitate knowledge exchange and trade between regions, often in exchange rather than monetary transactions.

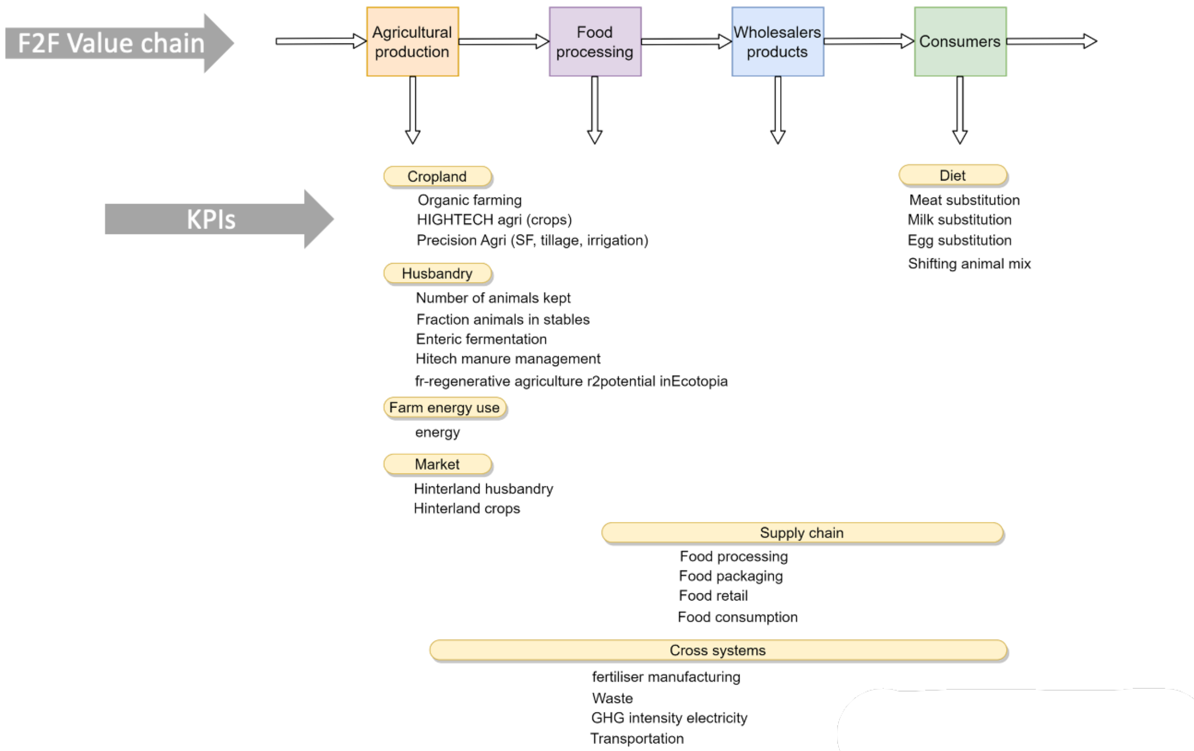
People in Ecotopia consume food that is locally sourced, seasonal, and less processed. Diets are primarily plant-based, with protein sourced from legumes and soy. Agrobiodiversity is prominent, and there is cultural diversity in place-based food production. Animal-based product consumption has plummeted, and animal rights are held in high regard. Genetic plant and seed diversity aids adaptation to changing climate conditions. Legumes serve both as a dietary staple and a means to replace synthetic fertilizers. Active lifestyles mean higher calorie consumption, but diets are healthier, leading to fewer obesity cases. Nutrition is a health cornerstone, with a focus on raw foods rather than supplements. Life cycle assessments ensure the sustainability of novel foods, and the consumption of animal-based products, like meat and dairy, is greatly reduced. There is less reliance on artificial meat and superfoods, and citizens yearn to understand their food's origins.

Food policy and monitoring emphasize short supply chains and close producer-consumer relationships. However, with more fragmented food supply chains, there is an uptick in food safety concerns. As a countermeasure, robust food safety protocols are in place. Retail is diversified, no longer monopolized by large entities, and community-supported agriculture is prevalent. Food prices are higher due to sustainable practices, so ensuring food access for the impoverished is crucial. Some communities even recognize the "right to food." Innovative models enable even those with low incomes to obtain food non-monetarily. Non-carbon intensive agricultural methods are mainstream, and a dietary shift towards plant-based foods has environmental benefits. In Ecotopia, previously farmed lands are often restored to their natural state. Community approaches to environmental challenges can be fragmented, but the EU continues to push for sustainability. Carbon pricing and innovation incentives are common, and many regions invest heavily in decarbonization and environmental preservation.

6 Policy and policy levers

The imaginaries described in section 5 above need to be interpreted to assess policy actions to achieve them. This involves considering the impacts of the policies summarised in section 4 above on the Farm2Fork value chain. A preliminary version of the policy levers in the model is shown in Figure 24 below.

Figure 24: Specific KPIs that connect to policy levers for testing in a simulation model.



Source: Authors own compilation.

This structure was used for a policy gap analysis.

6.1 Policy Gaps: Performance of the System versus Desired Performance of the System

The overall goals of the system (and model) and policies to steer the system are healthy, safe, secure food production, supply, and consumption with minimal climate change impact and minimal negative impacts on other systems including nature. The agri-food system might even have positive climate change impacts and positive impacts on nature. To assess the impact in the real world as well as in the modelled world (i.e., in the model discussed here), Key Performance Indicators (KPIs) that capture the goals and can be measured and simulated need to be identified. The model is set up such that following useful dimensions/aspects and associated KPIs can be assessed using data and simulations:

- Food production
  - Conventional versus organic / ecological agricultural production and land use.
  - Food production in terms of the main food types and domestic supply (also: security of supply, and self-sufficiency).

    - Diets: climate friendly versus climate unfriendly (in terms of GHG emissions), eco-friendly versus eco-unfriendly (nature and biodiversity), and healthy versus unhealthy (in terms of effects on consumers, rural population, and farmers).
    - Food waste: in terms of streams, inputs to other processes (circularity), and losses of nutrients.
- Extent of inputs used by the agri-food system:
    - land use.
    - amount of organic fertiliser use versus synthetic fertilizer use.
    - amount of pesticide use.
    - amount of labour needed/used.
    - cross-systems inputs: energy, transportation, *etc.*
- Extent of the (side) effects:
    - Contribution to the climate change problem and solution (net GHG emissions).
    - Contribution to climate adaptation.
    - Water quality (and quantity), Soil quality, Air quality, Ecosystem quality.
- Intrinsic dimensions:
    - Nature: negatively impacted <> no impact <> positive impact.
    - Biodiversity: negatively impacted <> no impact <> positive impact.
    - Wildlife: negatively impacted <> no impact <> positive impact.
    - Human health and wellbeing (farmers, consumers, rural population).

The model contains many data sets that can be used to assess the current state of the world, EU27, and all countries in the world on several of these KPIs.

In terms of food production, organic / ecologically friendly (in which chemical fertilisers and antibiotics are not used and land use is changed to ensure the continuing quality and productivity of land in the future), is marginal compared to conventional farming. Diets are very climate unfriendly as well as unhealthy for consumers, farmers, and the rural population. Security of supply (self-sufficiency) of many countries is low. Food waste is high, and circularity is low. In terms of inputs, land use is very high due to the large land use requirements for meat production (cattle), synthetic fertilizer use is high even though manure applied to soils is high too, pesticide use is high. Consequently, GHG emissions are high, water quality is bad and lots of fresh water is impacted, air quality is bad, and Nitrogen deposition in nature is high, which results in a strong negative impact on nature, biodiversity, wildlife, and land use, as well as on human health and wellbeing. These statements can be substantiated by the data (see the analysis based on model and data due early 2023).

The current system scores badly on many KPIs. The main question is then: how to change the agri-food system into a sustainable system, one with only favourable scores on all KPIs? The analysis and simulation model developed should be able to help answer this question. Changes in food demand are included in the model, so different changes in demand can be investigated to see what changes in food production they would require. To do so, we can use the operational structures developed in this model to identify levers that might allow for changing aspects of the system into a desired direction and use the model to assess to what extent they would. For example, levers can be identified to reduce the climate change impact of the agri-food system (see Figure 24 and table 2). Only looking for levers to deal with the climate change effects of the food system would disregard other aspects that require improvement. An integrated analysis is needed. A start is made below by looking at levers to reduce GHG emissions of the Agri-Food system.

6.2 From imaginaries to policy levers methodology

One way to organise the levers is to match policy areas of the F2F to the value chain. The table 2 is set up to match different policy areas from the F2F strategy with stages in the food value chain, pointing out where specific actions, or "levers," should come from.

Table 2: Policy levers and value chain structuring.

F2F Policy	Food Production	Food Processing	Food Wholesaler	Food Consumer	KPIs (Example Indicator)
Transport	Sustainable transport infrastructure	Energy-efficient processing facilities	Low-emission distribution networks	Access to low-carbon transportation options	Modal share (Share of public transport in total transportation)
Organic farming	Increase in organic farming area	Adoption of organic processing methods	Support for organic food supply chains	Demand for organic food products	Organic farmland (% of total agricultural land)
GHG	Reduction in GHG emissions from agriculture	Lower emissions from food processing	Decreased GHG emissions in logistics	Lowering carbon footprint of food consumption	Carbon footprint (CO_2 equivalent emissions per capita)
Energy	Adoption of renewable energy in agriculture	Energy efficiency improvements in processing	Use of renewable energy in distribution	Energy-conscious consumer behaviour	Renewable energy share (% of total energy consumption)
Biodiversity	Promotion of agrobiodiversity	Biodiversity-friendly processing methods	Support for biodiversity-preserving supply chains	Demand for biodiversity-friendly products	Biodiversity Index (e.g., Shannon index)
Pesticides	Reduction in pesticide use	Decreased reliance on harmful chemicals in processing	Promotion of pesticide-free food supply chains	Demand for pesticide-free products	Pesticide application rate (kg/ha)
Chemicals	Reduced chemical inputs in agriculture	Chemical efficiency in processing	Preference for low-chemical supply chains	Demand for chemical-free products	Chemical footprint (kg of chemicals used per capita)
Water	Sustainable water use in agriculture	Water efficiency in processing	Water-conscious distribution networks	Water-saving consumer behaviour	Water use efficiency (cubic meters of water used per ton of crop)
Food waste	Reduction in food waste at production	Minimization of waste in processing	Efficient waste management in distribution	Lowering food waste at consumption	Food waste reduction (% of food waste reduced)

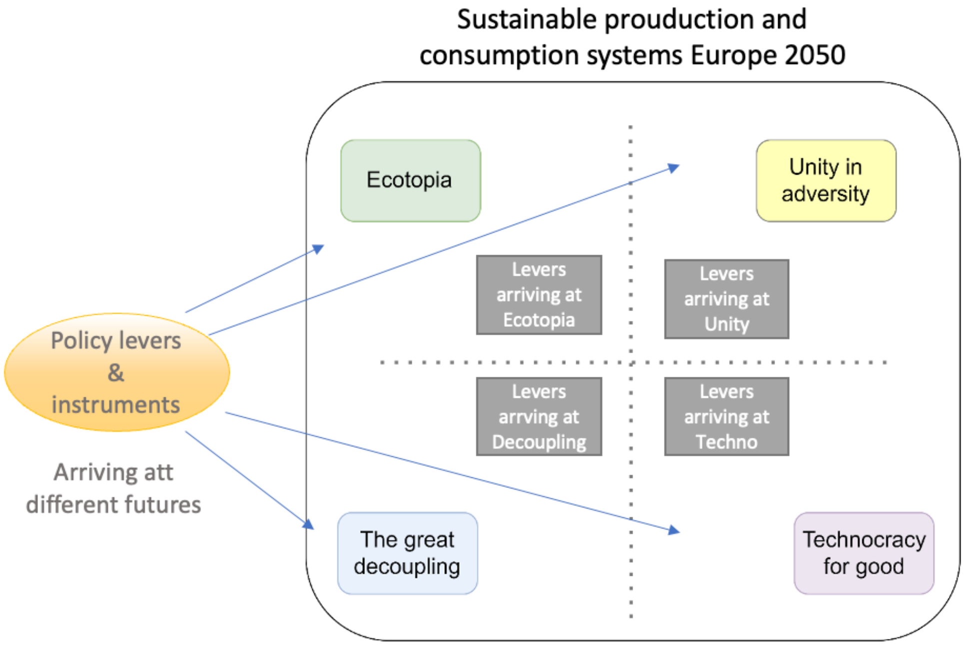
Source: Authors own compilation.

For example, within the Food Production section of the value chain, the F2F policy on Transport would aim at developing sustainable transport infrastructure as a primary action. Continuing with the Transport policy example, as we move along the value chain, we would establish specific KPIs related to each stage. The table provides example KPIs for reference, such as the 'Modal share' for the Transport policy, which measures the use of sustainable transportation methods. This approach allows for a systematic organisation of actions and measurable outcomes across the entire F2F strategy.

The method here is to use the Farm2Fork goals as an exogenous 'target' for the model simulations to achieve. Since the model to be developed is intended to be a dynamic simulation SD model, it has to be able to run in an exploratory mode: defining policy inputs to the model that can be varied to achieve the Farm2Fork policy goals.

The Farm2Fork policy goals set forth a vision for reaching sustainable states by 2050. These states don't dictate the specific appearance of the world; rather, they emphasize the aim of achieving sustainability down the line (stand alone). This concept remains distinct from the process of attaining sustainable levels within the four Imaginaries (arriving at different futures). While the definition of success and the key performance indicators (KPIs) for each Imaginary are the same, the approaches and policy tools (levers and instruments) employed to achieve them differ. This process is illustrated in Figure 25 below.

Figure 25: Policy option analysis for F2F – "stand alone" vs "arriving" at different imaginaries futures.

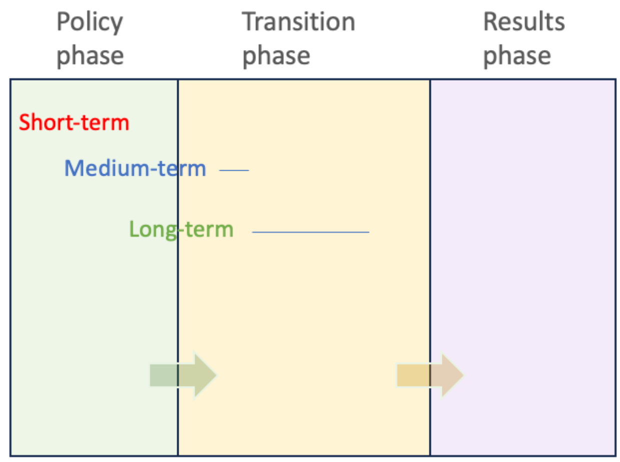


Source: Authors own compilation.

The practical application of policy instruments over time needs to consider how they are needed to be strategic tailored for each imaginary. As such, while each imaginary may need different levers to achieve the same sustainability, the continuous feedback obtained from monitoring policy success is instrumental in shaping and adjusting policies over time, ensuring they remain effective toward reaching specific goals of the individual imaginaries.

In the context of implementing different policy instruments over time, it is crucial to understand feedback mechanisms in order to evaluate the effectiveness of these instruments. Evaluating effectiveness requires understanding framework spanning over time that includes the Policy phase, Transition phase, and Results phase (Figure 26). Within these phases are different time horizons—short-term, medium-term, and long-term, that are marked to indicate the typical implementation window for various policy instruments. As policies unfold in the short, medium, and long term, their impacts on the system and the pathway towards desired goals need to be monitored. This monitoring allows policymakers to adjust strategies based on real-world outcomes and emerging challenges. For example, short-term instruments may reveal unintended consequences that necessitate adjustments in medium-term strategies. Similarly, the success of medium-term instruments can inform the scalability and focus of long-term investments. Understanding this approach facilitates a more adaptive and responsive policymaking process, where strategies are not static but evolve over time in response to system feedback, ensuring that policy instruments remain effective and aligned with overarching goals.

Figure 26: Policy option analysis for F2F – "stand alone" vs "arriving" at different imaginaries futures.



Source: Authors own compilation.

6.2.1 Policy Levers to Mitigate GHGs

The policy levers are chosen to reflect the requirement to address a series of policy domains defined in discussion with EEA experts. These are summarised in Table 3 below. Table 3 also shows the indicators i.e. output variables to be included in the model to represent progress towards sustainability in the policy domains defined.

The model integrates policy levers, as illustrated in Figure 27, where the building block accepts time series data as input (purple variable on the top left), calculates statistics, replicate the data (until the end of the data series), and generate different future evolutions (constant behaviour as well as a continuation of the dynamics in the data), but most importantly, it allows for inclusion of goals and goal seeking behaviour. This means policy effects can be added and be evaluated within the bigger model. Note that policy instruments (e.g., a subsidy or a tax) and the effects of policy instruments on effects in the system are not included yet. Including effective and efficient policy instruments in the model and analysis requires time and resources.

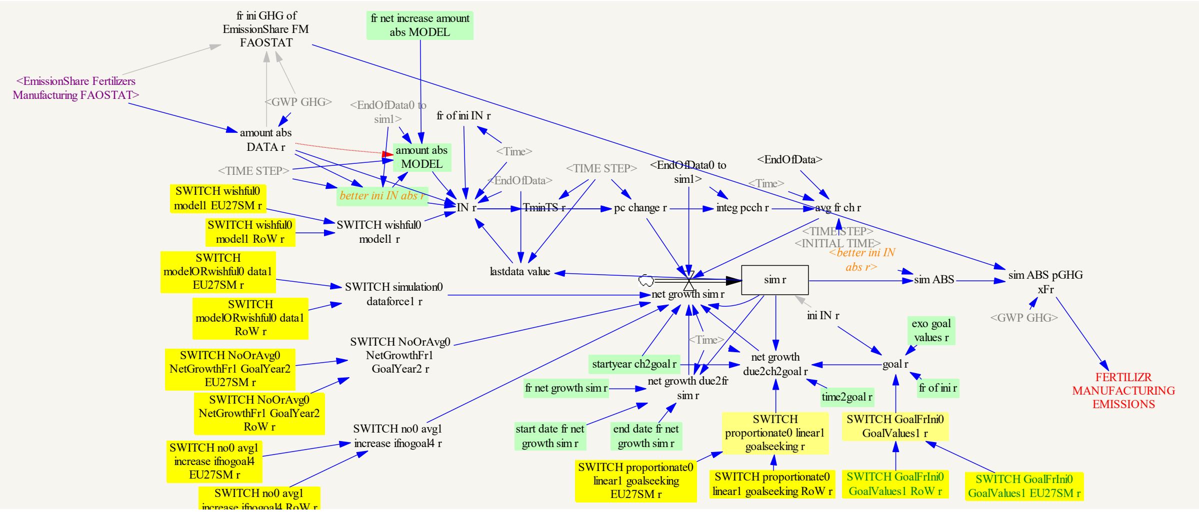
Table 3: List of Levers and KPIs.

Domain	Category	Indicator
Biodiversity conservation and restoration of natural resources	Headline	Size of natural grassland, cultivated, extensive pastures and meadows.
Air (GHG emissions)	Headline	GHG food system emissions
	Secondary	Greenhouse gas emissions from agriculture
	Secondary	Net GHGs Emissions from LULUCF sector
Consumption footprint	Headline	Consumption Footprint - Food
	Secondary	Per Capita Agri-Food PRODUCTION emissions, for all countries & EU27. Land use for Agri-Food PRODUCTION , for all countries & EU27.
	Secondary	
Food waste and use	Headline	Food waste generation reported by Member State
Pollution	Headline	Use and risk of chemical pesticides (F2F pesticide reduction target 1)
	Headline	Use of more hazardous pesticides (F2F pesticide reduction target 2)
Energy	Headline	Probably, need to check and do some more calculations
Soil and land	Headline	
	Headline	Share of agricultural area under organic farming
	Secondary	Land cover - Agricultural areas
Trade	Placeholder	Import dependency
Effective implementation	Placeholder	Number of hectares under environmental practices
	Placeholder	Reducing emissions in the livestock sector

Note: Domains from discussion with the EEA experts/JRC (adopted from JRC 2023).

6.2.2 The Policy Lever Building Bloc

Figure 27: Model building block to simulate the effect of policies.



Source: Screenshot from the Vensim-Simlation Model, Erik Pruyt.

6.2.3 Levers and Leverage

We can now use the model to identify levers that may lead to substantial reductions in GHGs in the agri-food system.

Some of the strongest levers in the agri-food system are related to diets. Diets can be change in multiple ways. In other words, there are multiple levers.

- The amount of food consumed could be reduced, especially of high-impact food types (e.g., meat, especially beef from meat cattle). By extension, the amount of Domestic Supply (which includes more categories) could be reduced by reducing food waste and agri-food losses along the supply chain.
- Apart from reducing the amount of food, one could shift to other food types (e.g., from meat-based proteins to pulse-based proteins).
- Apart from shifting between food types, one could also shift between products within food types (e.g., from beef to chicken meat)
- Apart from these shifts at the consumer side, producers can shift modes of production of the same food types to more sustainable production. There is a big difference in environmental effects between sustainable production and unsustainable production (see https://ourworldindata.org/less-meat-or-sustainable-meat).
- Finally, food could be sourced from different locations with different climates and other resources: local production reduces transportation, but it might have many other effects. In that respect: the effects of transportation are mostly small compared to effects of primary production.

The model contains a module to assess the effects of high protein foods in diets. The GHG emission effects of the module are larger than the ones obtained with the supply chain structures. Before being able to firmly conclude anything about the shift in diets, these two calculation approaches need to be compared and assessed – which takes time.

The protein data shows that there is a large variation in daily protein intake and source (plant based, meat based, eggs, dairy, fish and seafood) of the daily protein intake between different countries. Moreover, there is a large variation within and between different food types (see table 4): shifting within and between food types makes a big difference.

Table 4: kgCO_2eq emissions per 100g proteins for main food types in the model

kgCO_2eq emissions per 100g proteins	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH
Cereals	1,29	2,7	6,27	Wheat and rye	Grains	Rice
Pulses	0,44	0,84	1,98	Peas	Other pulses	Tofu
Starchy Roots	2,71	4,3	14,67	Potatoes	Root vegetables	Cassava
Nuts	0	0,26	1,23	Nuts on former Cropland	Nuts	Groundnuts
Vegetables	1,79	3,85	19	Maize	Onions and leeks	Tomatoes
Fruits	6,55	9,56	15,3	Avocado	Bananas	Berries and grapes
Meat	5,7	19,85	49,89	Poultry meat	Mutton Lamb	Beef <> Dairy herd: 16,87
Alt. (lab grown & plant based) meat	0,9	1,98	6,2	Insects; Sust. lab meat 1.1	Plant-based meat	Lab grown meat
Milk (dairy)	0,3	9,5	10,82	Ferm.pro.0.3, Yoghurt 2.7	Milk	Cheese
Eggs	2,5	4,21	9	Guestimate	Eggs	Guestimate
Fish Seafood	1,71	5,98	18,19	Farmed bivales	Farmed fish	Prawns

Sources: own calculation and https://www.bbc.com/future/article/20221214-what-is-the-lowest-carbon-protein, https://ourworldindata.org/environmental-impacts-of-food#carbon-footprint-of-food-products

Animal products, especially of ruminants, have the biggest climate impact. However, that does not necessarily mean that the agri-food system needs to eliminate beef production. To the contrary: cattle can provide useful functions in the agricultural system. Hence, let's have a closer look at some of the levers related to animal related GHGs

The main source of GHG emissions from farm animals is enteric fermentation by ruminants (about 20% of EU27 agri-food emissions). Levers to reduce "Enteric Fermentation" GHG emissions include:

- Reducing the number of animals. Consequently, there will be a reduction in beef/sheep/goat production (and consumption per person per annum, and less manure to fertilize fields.
- There could be a shift in the type of animals kept. Poultry birds have much lower GHG emissions than ruminants (especially in terms of enteric fermentation, especially for cattle).
- However, lower enteric fermentation intensity could also be achieved by changing fodder. One of the consequences would be lower milk production for dairy cows.
- Alternatively, CH_4 emissions could be captured in stables, used energy (biogas), after which the CO_2 emissions may be used to accelerate crop growth in greenhouses.
- Finally, ruminants may be kept in stables with CH_4 capturing instead of in pastures.

Levers to reduce "manure related GHG emissions" (in total about 14.5%) include:

- Reducing the number of animals (=> beef & pork consumption pp pa, less manure)
- Shifting the type of animals kept (specific emissions of cattle are much higher than of poultry)
- In terms of manure management, manure on pastures (i.e., of free grazing animals) is, contrary to emissions from enteric fermentation, less harmful for the climate than manure from animals in stable that is subsequently treated and applied to soils
- Changing the N content of (power) feed (i.e., more grazing). However, this affects the production of milk per cow.
- Applying more sustainable manure treatment practices (separating excrements, air washing, treatment with reduced emissions, and storage with reduced emission).
- Capturing emissions and flows in stables and conversion them to energy.
- Although not captured in the model yet (leaching and volatising are included with fixed fractions), the amounts and ways in which nitrogen is applied to soils makes a difference too.

- Finally, nitrogen could be recovered from sewage [circularity of domestic wastewater], to replace nitrogen inputs via organic fertilizers and synthetic fertilizers.

Levers to reduce GHGs from primary (vegetal) production include:
- Shifting from feed production to more vegetal food production: although this leads to more cropland for food production, it may well free up large areas for other functions (e.g. nature).
- Shifting from conventional to ecological production (note however, that it is easy to fall in the trap of produce more than less emissions).
- Shifting to more local sourcing (accompanied with dietary changes) or to more global sourcing (e.g., importing tomatoes from the south of France instead of producing them in gas-heated greenhouses in the Netherlands).
- Reducing the amount of consumption, and shifting within and between vegetal food types.

Levers to reduce GHGs from On Farm Energy Use include:
- Shifting to different types of land use (e.g., towards wet peatland agriculture) or agriculture practices (e.g., to regenerative agriculture) with effects on amounts and types of production
- Reducing specific activities (in terms of uses and number of times per growth cycle) that require energy:
    - Use of engines (conservation vs conventional tillage, types of irrigation).
    - Heating (greenhouse heating for crops vs transportation from warmer climates).
    - Electricity (e.g., vertical farming | greenhouse lighting vs lower yields).
- Shifting to more energy efficient appliances (e.g., engines, heating, and electric devices).
- Changing the energy mix used on farm (e.g., from coal to natural gas, and possibly to electricity, but only if the specific emissions of electricity are lower).
- Changing the GHG intensity of energy types (e.g., of electricity which is a function of the mix of power generation technologies used, losses, and life cycle emissions).
- Re-using GHGs and heat produced on the farm or close to the farm.

Levers to reduce GHG emissions due to Processing, Packaging, Food Retail, and Household Food Consumption (some 30% of the EU27 agri-food emissions):
- Reducing the amounts that are being processed / packaged / funnelled through retail / consumed.
- Reducing the fraction (of the underlying amounts of drivers like consumption) that are being processed / packaged / retailed / consumed.
- Increasing the energy efficiency of processing / packaging / retail / consumption.
- Changing the energy mix used for processing / packaging / retail / consumption.
- Changing the GHG intensity of the energy mix used for processing / packaging / retailing / consuming.

Levers to reduce GHG emissions due to agri-food related transportation (some 8.5% of the EU27 agri-food emissions):
- Reduce the amount of agri-food goods consumed that are being transported.
- Change the location of sourcing (origin-destination), this may include *increasing* the amount of goods transported instead of locally produced if local production is more inefficient.
- Change the mode of transport (train versus truck, water versus air).
- Change the energy carrier used for modes of transportation (diesel versus electricity, if and only if electricity is generated sustainably).
- Increase the efficiency (of the mode) of transportation.
- Increase the GHG emission intensity of the energy carrier used (esp. electricity and H2).

Note that pulling some of these levers has consequences for other parts of the system. Some of these are already included in the model, but more need to be added. Note also that levers for some parts of the system still need to be analysed and included (e.g., waste and crop residues).
It is not necessary to pull all levers simultaneously. In many cases, it is enough, per aspect that requires change, to entirely pull one lever with extremely high leverage or to somewhat pull a few levers with high leverage.

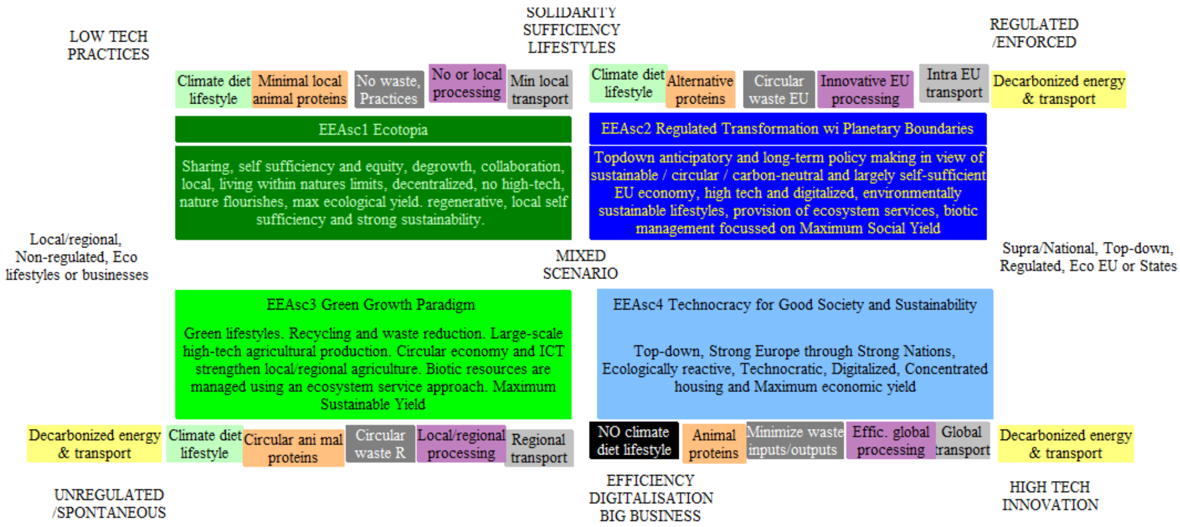
Some levers are counterintuitive, i.e. shifting from conventional to organic agriculture results in many improvements, such as reduced pesticide use, but not across all KPIs—more land may be required to produce the same output. Achieving positive effects on all KPIs may require pulling multiple levers simultaneously.

Pulling some levers may be counter-effective with pulling others. Levers therefore need to be consistent with each other. Finally, pulling different consistent sets of levers may all result in sustainable futures. However, what these futures look like to live in may be radically different. This is what we will turn to now (Figure 28).

6.2.4 The EEA Imaginaries Interpreted for Agri-Food Systems

Figure 28 shows an early interpretation of the imaginaries developed by the EEA. These imaginary future worlds are equally plausible, yet not equally likely to materialize. Some require strong top-down intervention and steering, others a breakdown of society and top-down power, and some require large technological innovations. The model developed for this cross-systems project essentially is a computational System Dynamics model. That is, a simulation model that can be used to simulate from today on into the future. One of its uses could be to identify (i.e., simulate) pathways from today towards these futures.

Figure 28: Interpretation of the EEA imaginaries for the agri-food system.



Source: Authors own compilation.

In the previous section, we listed levers for different aspects of the agri-food system to close the policy gap related to GHG emissions and climate change. That is, what levers can be pulled to substantially reduce GHG emissions. For most of the subsystems studied, there are several alternative levers that can be pulled. Some of these alternative levers are reinforcing, others are countering each other. Also, they either open up a pathway towards a specific EEA imaginaries and block pathways towards other EEA imaginaries. Interestingly, for each of the problem areas, i.e. tiers of the supply chain or activities that generate GHG emissions, there are levers that correspond well with each of the EEA imaginaries. In the next section, we assess how well each of the levers corresponds to each of the imaginaries.

Fit between Levers and EEA Imaginaries

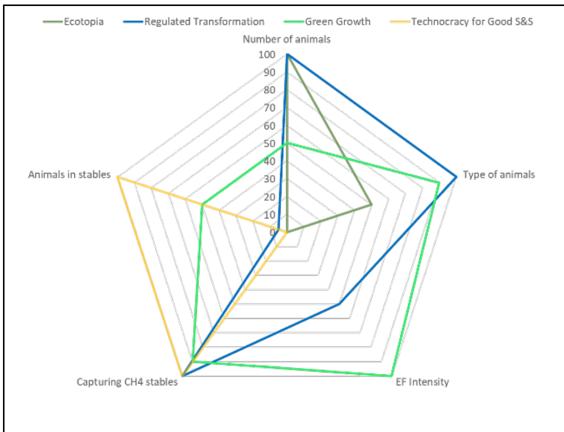
First, we assess how well each of the levers discussed above corresponds to each of the imaginaries. Next, we assess the resulting sets of levers.

Figure 29 (a) shows how each of the levers for Enteric Fermentation GHG Emissions discussed above either corresponds perfectly well (score 90-100, outer side of the spider diagram), or not (score 0-10, middle of the spider diagram), or somewhat (score between 20 and 80) to these imaginaries.

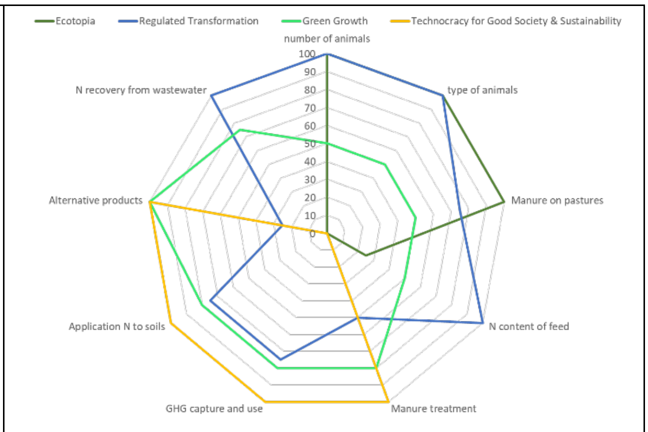
Ecotopia and Regulated Transformation are both consistent with a strong reduction in the number of animals, especially ruminants. In Ecotopia, ruminants are still needed to some extent for regenerative agriculture as well as for manure to organically fertilise (some) cropland. Manure from largely reduced livestock is insufficient though, especially because manure is not captured, treated, and applied there where most needed: animals are not kept only in stables. In Ecotopia, all nutrients – including those in human faeces – therefore need to remain in a *local* closed loop. In a Regulated Transformation world, fewer animals are needed due to a large-scale shift to alternative proteins, a shift to different types of animals (from ruminants to poultry and insects), and technical solutions to capture CH4 in stables and reduce the GHG intensity through balanced feed.

In the Technocracy for Good Society and Sustainability world, even more GHGs from enteric fermentation are desirable, since/if all ruminants are kept in stables, all CH4 emissions are captured and used, for instance as green gas, and the resulting CO2 emissions from burning CH4 are used to accelerate plant growth. This world is dominated by large integrated highly efficient farming systems. The Green Growth world is characterized by fewer ruminants, a larger fraction of ruminants kept in stables (but not all) to capture CH4 in stables, as well as a shift in the types of animals kept (from ruminants to poultry, insects, fish farmed on closed-loop fish farms).

Figure 29: Levers consistent with the EEA imaginaries to reduce GHG emissions due to enteric fermentation (a) and manure related GHG emissions (b).



(a) Levers to reduce enteric fermentation GHG emissions



(b) Levers to reduce manure related GHG emissions

Source: Authors own compilation.

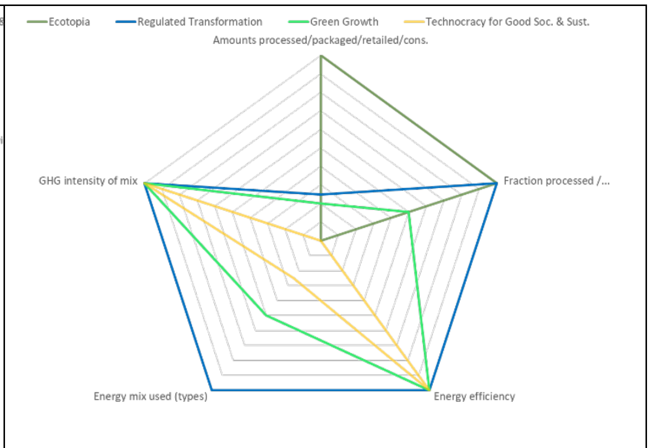
Figure 29 (b) shows the correspondence between levers to reduce “manure related GHG emissions” and the four imaginaries. In Ecotopia, manure related GHG emissions are largely dealt with by substantially reduced livestock, a shift towards different types of animals, but also by keeping animals out of stables, and somewhat changing the N content of additional feed.

The Technocracy for Good Society and Sustainability world is completely opposite to the Ecotopia world in terms of levers, as was the case with the levers to deal with enteric fermentation. In the Technocracy for Good Society and Sustainability, more animals in stables leads to more manure treatment, with very efficient and sustainable techniques, more GHG capture and use, more precision application of organic N to crops (with less leakage and volatising) and the development of alternative products with manure rest products.

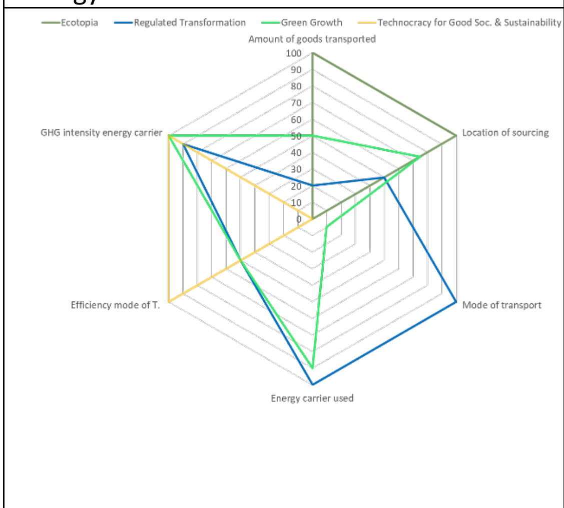
The Green Growth (Great Decoupling) world and Regulated Transformation (Unity in Adversity) world are also more balanced across the levers to reduce manure related GHG emissions.

Figure 30: Levers consistent with the EEA imaginaries to reduce GHG emissions due to on farm energy use (top left), to processing, packaging, retailing, household consumption (top right), agri-food transportation (bottom left), and diets (bottom right).

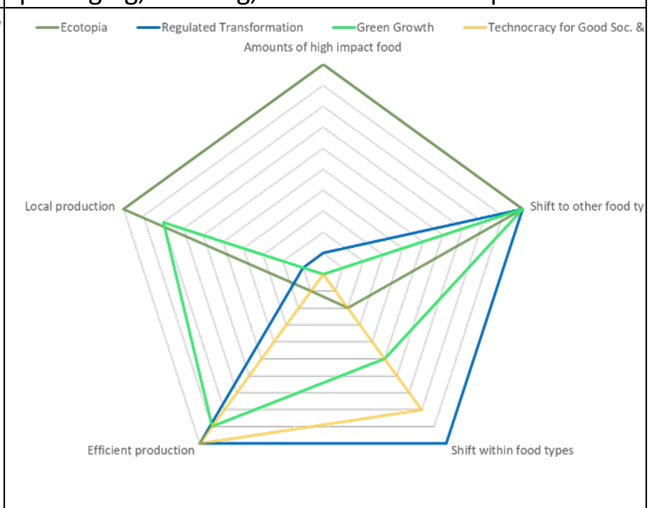
Levers to reduce emissions from “On Farm Energy Use”



Levers to reduce emissions from processing, packaging, retailing, household consumption



Levers to reduce emissions from agri-food related transportation



Levers to reduce emissions from high-impact diets and lifestyles

Source: Authors own compilation.

Figures 29 and 30 together highlight the contrasting approaches to lever sets across different scenarios. Figure 29 establishes the foundational differences, showing how levers favorable to Ecotopia often directly oppose those aligned with the Technocracy for Good Society and Sustainability world. Expanding on this, Figure 30 provides a detailed breakdown of these lever sets within specific domains, on-farm energy use, food processing, agri-food transportation, and dietary shifts, illustrating how each scenario prioritizes distinct emission reduction strategies. The charts in Figure 30 reveal that while Ecotopia emphasizes levers like local production and reduced GHG intensity, the Technocracy model places a stronger focus on energy efficiency and scalable production. Additionally, (The Great Decoupling (Green Growth) and Unity in Adversity (Regulated Transformation) appear more balanced across these areas, suggesting potential overlap. These figures collectively underscore the complexity of achieving universally positive outcomes across all KPIs, as certain levers benefit one model while proving less effective in others.

Fit between Levers and EEA Imaginaries

Table 5 provides an overview of the levers discussed above: a score of 100 means that the lever seems to be consistent and required for the specific imaginary; 50 means the lever needs to be engaged, but a substantial reduction of GHGs will also happen without pulling it; 0 means the lever does not seem to be required. The information in the table is used to set the many levers in the simulation model (Regulated transformation = Unity in Adversity, and Green Growth = The great Decoupling). The implementation of these levers in the model is discussed below in section 7 below, tables 6 and 7.

Table 5: summary of the analysis of imaginaries and levers.

	Ecotopia	Regulated Transf	Green Growth	Technocracy4GSS
Amounts of high impact food	100	0	0	0
Shift to other food types	100	100	100	0
Shift within food types	0	100	50	100
Efficient production food	0	100	100	100
Reduction of number of animals	100	100	50	0
Shift in type of animals	100	100	100	0
Manure on pastures	100	100	50	0
Change in N content of feed (EF)	0	100	100	0
Innovation in manure treatment	0	50	100	100
GHG capture and use (EF & MM)	0	100	100	100
Innovation in N application to soils	0	100	100	100
Alternative products from manure	0	0	100	100
N recovery from wastewater & use	0	100	100	0
Animals in stables (Enteric Ferm.)	0	0	50	100
Amounts processed/packaged/retailed/consumed	100	50	50	0
Fraction processed/packaged/retailed/consumed	100	100	50	0
Energy efficiency processing/.../retail/...	0	100	100	100
Energy mix used -> electricity	0	100	50	0
GHG intensity of electricity mix	0	100	100	100
Local production	100	50	50	0
Amount of goods transported	100	50	50	0
Mode of transport	0	100	50	0
Energy carrier in mode of transport	0	100	50	0
Efficiency mode of transport	0	50	100	100
GHG intensity energy carrier	0	100	100	100

Source: Authors own compilation.

7 Implementation of a system dynamics model- The CRAFT model

This chapter will give an overview of the development of the system dynamic model developed for the Agri-food systems related to the F2F which led up to the development of the The **CR**OSS-SYSTEMS **A**GRI-**F**OOD **T**RANSITION model (**CRAFT model** in short).

The CRAFT model is designed to be a dynamic model of the EU food system. It uses the results of the CLD analysis to inform the choice of variables in the model and the causal dependencies between the variables. The modelling used a 'data-rich' approach, explained in section 7.2, with the implementation in the CRAFT model in section 7.3. The structure includes the interpretation of policies as policy levers, which are used to represent policy measures and their impacts in the model. The model was developed to illustrate different transition pathways to a sustainable EU food system. The general idea of sustainability was made specific by interpreting the EEA imaginaries for the food system. The model was then developed to represent policy actions than could achieve the visions of sustainability described in the imaginaries. This was implemented through the policy levers.

7.1 Overview of the model structure

This part reports on the data-rich quantitative systems modelling, simulation, and quantitative analysis of the project that was pre-stage for the development the CRAFT model. The goal of this part of the project is to analyse the agri-food system and its crossovers with other important consumption-production systems starting from the data, using modelling to connect the dots across these systems, and ultimately using simulation to test the effectiveness of policies. Doing so for a large and complex system like the agri-food system (and related cross systems) requires analysing and modelling different subsystems as well as all important aspects within these subsystems, identifying and including KPIs, and adding important (a)cross systems effects and feedback effects.

Data from relatively large databases are used to this end. Different from data analysis and visualization, data is used here to analyse how the world works in view of buildings systems models that function like the real world, to explore potential futures, to answer "what-if" questions, and to test the effectiveness of potential policy levers. The resulting model is, in that sense, a synthesis of knowledge and data gathered during the qualitative work and quantitative research.

An advantage of the data-rich quantitative approach used here is that orders of magnitude become clear (e.g., the orders of magnitude of GHG emissions emitted by different parts of the value chain), that levers and their respective leverage can be assessed, and that plausible dynamics over time could be simulated, not just for the world at large, or the EU27, but for all entities represented in the model (in this case, 217 countries and higher level regions).

For this approach to be useful, one needs to understand the methods and models used well enough to understand the results and assess their usefulness. Hence, we will first discuss the modelling approach (Quantitative Data-Rich Systems Modelling), the different stages of the modelling process (From Data Model to Data-Rich Systemic Model to Data-Rich Systemic Policy Model to Data-Rich System Dynamics Policy Model), the agri-food system as captured in the current model, the policy gap between the desired state of the world (in terms of major KPIs) and the current state of the world (based on the data), and alternative policy levers to close the policy gaps. Since there are many levers, the policy gaps can be closed in different ways. Pulling different sets of levers result in alternative sustainable futures. These alternative futures can be very different: one of the main messages of our analysis is that pulling different consistent sets of levers leads to very different futures, all to a large degree sustainable in terms of food production, GHG emissions, and their environmental impacts. The sustainable futures considered in our analysis are limited for the time being to four EEA Imaginaries. The policy levers are assessed in view of reaching these EEA Imaginaries. Finally, the model has been used to simulate potential futures by projecting from today's data toward the imaginaries, assessing to what extent these imaginaries could theoretically be realized. The next steps are then discussed.

7.2 Quantitative Data-Rich Systems Modelling

Quantitative Data-Rich Systems Modelling requires many activities, including:

- Developing data scripts and setting up databases.
- Identifying data sources: In this case, we decided to start with the FAOSTAT databases and gradually extend and improve the data with EEA & Eurostat data. The reason for starting with the FAOSTAT databases is that these databases are relatively complete, well developed, and provide data for most countries in the world. Even though the European agri-food system is the subject of this study, many food products are imported into Europe and exported from Europe. Limiting the analysis and model to Europe alone would result in overly narrow systems boundaries.
- Downloading data, storing data, converting data, importing data, testing completeness and usefulness of data, and finally, filling data gaps.
- Analysing data over time and space to figure out how the numbers relate to each other.
- Constructing data-rich structures that replicate the logic of the data and testing the logic.
- Identifying levers (by adding policy structures and sliders) and assessing potential leverage.
- Developing model structures to link different parts of the system (effects and side effects).
- Simulating combinations of levers and assessing their system wide effects.
- Theoretically testing whether different futures (in this case the EEA imaginaries) could possibly be reached or not (and what else might be needed to reach them).
- Closing the feedback loops (e.g., via prices) within and across different systems, and practically testing whether the different imaginaries might be reached in the presence of all sorts of systemic feedback effects.
- Simulating adaptive pathways towards desirable futures/imaginaries.

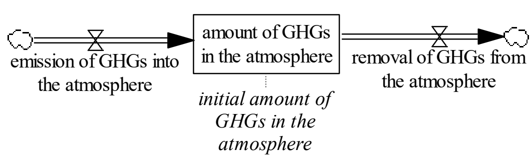
To construct the quantitative systems model discussed here, we used the System Dynamics formalism/language (see (Forrester (1968), Ford (2009), Pruyt (2013)). System Dynamics allows for rapid model development, fast simulation, and transparent communication about the system represented in the model – also to non-modelers. Rapid model development and transparent communication are due to the object-oriented representational techniques used (*causal loop diagrams* and *stock-flow diagrams*). *Causal diagrams* were introduced and used in section 3.2. *Causal diagrams* with a specific focus on the feedback loops in systems are called *feedback loop diagrams.* These diagrams are mostly drafted at the beginning of a quantitative modelling journey (to identify the system, its elements, and their relations) and at the end of the quantitative modelling journey (to summarize models or explain dynamics in relation to the underlying structure of the system). Quantitative SD models, however, are drafted and represented with so-called *stock-flow diagrams*. The reason is that SD models consist of different types of variables (*stocks*, *flows*, auxiliary variables, and constants). Their difference is conceptually so important that they are represented differently:

- Stock variables (aka *Levels*), which are represented by variables in rectangles, are accumulations or memories in the system (like state variables). Metaphorically speaking, they are the bathtubs of the system. Mathematically speaking, stock variables are integral equations: they sum everything that flows into them minus everything that flows out of them over time, starting from an initial value. Examples of typical stock variables are populations in countries/regions, the amounts of Greenhouse Gases (GHGs) in the atmosphere, the amount of carbon captured in soils, land use, human capital stocks (trained workforce), nature capital stocks (number and size of ecosystems) and invested capital stocks (buildings, installations, trucks). Important KPIs are often stocks.

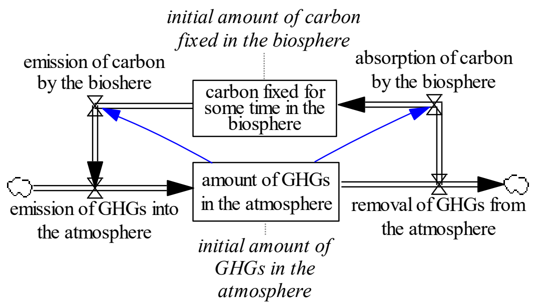
- Flow variables – represented by double arrows with valves going into or out of stock variables – change stock variables over time. No other variables do. Mathematically speaking (and if the system is written as a system of differential equations), they are differential equations. The sum of all inflows and outflows into one stock variable determine how the stock variable changes over time. Examples of typical flows are the increase (births and immigration) or decrease (deaths and emigration) of populations, the emission of GHGs into and the absorption of GHGs out of the atmosphere, the absorption or emission of carbon by soils, the increase or decrease of (conventional or organic) crop land / pastures / forest land / other land, the increase/decrease of the size of trained (agricultural) workforce, of specific ecosystems, and of existing buildings/installations/trucks. In many cases, flow variables need to be targeted by policies to change the values of KPIs captured by stock variables.
- Auxiliary variables and constants (no special symbols are used) are variables with equations or constants that might have been integrated in the flow equations, but are not, to keep models understandable. Auxiliary variables either correspond to real-world concepts or perform technical functions in a model.
- Within equations of auxiliary variables (and flow variables), functions are used. In this model, only a handful of basic pre-defined functions[4] are used to keep the model understandable.

Given that simulation models contain more variables than conceptual causal loop diagrams, and that they contain different symbols (for stocks and flows), less (visual) attention is given to the feedback loops. Of course, they are still there. The focus is simply on stock-flow structures.
The use of these different variables and the representational differences between them are useful in two respects: (i) practically, they enable one to understand so-called *stock-flow* structures without having to resort to the underlying mathematical equations, (ii) philosophically, they clearly distinguish systems elements with very different dynamics over time (i.e., stocks display slow changing dynamics of accumulations, whereas auxiliaries and flows display rapid or even instant dynamics). For example, the amount of Greenhouse Gases (GHGs) in the atmosphere (represented by stock variables) changes much slower than the emissions of these GHGs into the atmosphere (represented by inflows into the corresponding stock variables) as in Figure 31.

Figure 31: SD model building by building up a Stock-Flow diagram.

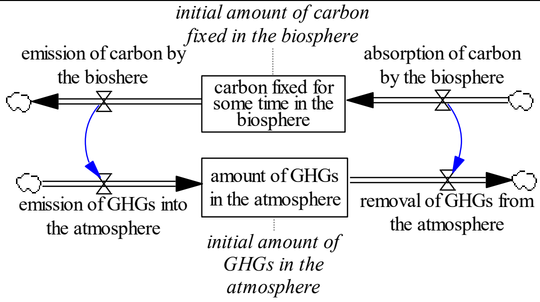
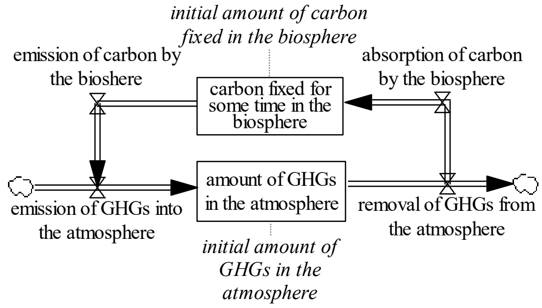


a. A stock variable (amount of GHGs in the atmosphere) and two connected flows.



d. Adding causal effects between system elements: a larger amount of GHGs in the

4 Often used functions in this model are the ZIDZ, XIDZ, MAX(0,x), MIN(y,1), STEP(), PULSE() and delay (SMOOTH) functions. For more information about these functions, see Pruyt (2013).

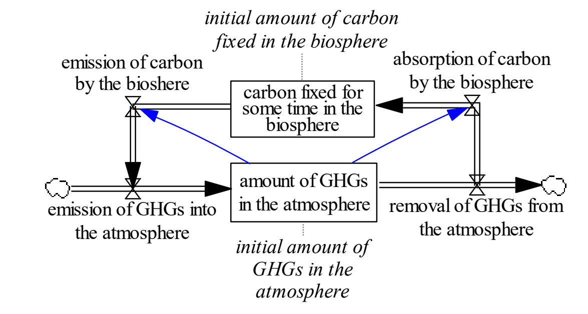
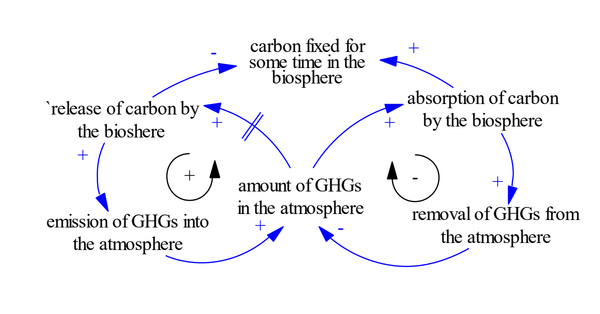
	atmosphere leads to more absorption of carbon by the biosphere (all else remaining the same), and (over time) to more emissions of carbon by the biosphere.
	
b. Adding another part of the overall system, and linking variables: absorption by the biosphere leads to removal from the atmosphere and emissions from the biosphere add to the amount of GHGs in the atmosphere.	c. In fact, they are part of the same system, and the causal links (blue arrows) are flows between the subsystems, which is why it is best to connect their flows. There are still emissions coming from elsewhere (cloud on the left) and removals by other parts of the system (cloud on the right).

Source: Screenshots from Vensim Simulation Model. Erik Pruyt.

Due to their different nature, they require different levels of intervention to change their behaviour: halving GHG emissions obviously halves GHG emissions, but halving GHG emissions does not half the amount of GHGs in the atmosphere. Far from it. GHG emissions need to be brought down to the rate of GHG absorption by biosphere and oceans out of the atmosphere (which requires much more than halving emissions) only to halt the further increase of the total stock of atmospheric GHGs (and therefore their concentrations). It would take many decades to half the stock of GHGs in the atmosphere, even if GHG emissions are miraculously brought down to zero today and remain zero afterwards: it takes as much time as the biosphere and hydrosphere (oceans) need to absorb excess GHG in the atmosphere. These processes are dynamic and are expected to slow down. The concept of *net-zero* emissions is, from this angle (i.e., compared to *absolute zero* emissions), a dangerous one which will slow down the reduction of atmospheric concentrations: credit schemes in which for instance existing forests are sold as credits to emitters who can greenwash their emissions and keep on emitting, comes down to an accounting trick in which an existing outflow of sold as a negative inflow (which then supposedly cancels out a real inflow). If all existing outflows were packaged as credits and sold to emitters who were then allowed to keep on emitting claiming their emissions are net-zero, would at most lead to stabilizing atmospheric GHGs (and their concentrations). Any repackaging of outflows as negative inflows that can be used to compensate for real inflows, reduces the outflows that are necessary to bring down the stock values over time. The stock-flow perspective shows that only real *additional* and real *long-lasting* GHG removals from the atmosphere should be considered for credits in such schemes.

The stock and flow variables of Figure 31 (d) are readily understood by system dynamics modellers. The focus in stock-flow diagrams is on stock and flow variables. Normal causal links, represented by single (mostly blue) arrows connecting variables (the causal link indicates that a change in the value of a variable causes the other variable to change too), are less prominent, and feedback loops are often hard to spot right away. There is nevertheless a correspondence between Stock-Flow Diagrams (SFDs) and Causal Loop diagrams (CLDs). Figure 32 shows the correspondence between the SFD from Figure 31d and a CLD (Figure 32b). Note that this is merely an example to illustrate the use of and correspondence between CLDs and SFDs. The system in these diagrams is much bigger and more complex. These two loops are by no means the only loops in the system. That also means, we cannot conclude anything about the non-linear dynamics this system will display. Note also that feedback loops cause non-linear behaviour, but that they are by no means the only elements that cause non-linear behaviour. Stock-flow structures, delays, non-linear functions also cause non-linear dynamics.

Figure 32: Correspondence between Incomplete Stock-Flow Diagram and Causal loop diagram.

	
a. Incomplete Stock-Flow Diagram	b. Corresponding incomplete causal loop diagram

Source: Screenshots from Vensim Simulation Model. Erik Pruyt.

SFDs be used in the remainder of this part. Behind these structures are equations, and in the case of this model, so-called *subscripts*. Subscripts are vectors that allow one to use one structure or equation for many entities at the same time. In this model, subscripts are used to represent 217 countries, 22 different food types, 3 types of GHGs, 3 types of nutrients, 9 different energy types, 6 types of farm animals, 9 different types of top-level pesticides (and many lower-level ones), etc. Subscripts can be combined to create multidimensional variables, for example Food demand for 22 different food types for 217 different countries. Aggregator functions (like sum functions) are used on these variables to aggregate them[5]. In Vensim DSS, the SD software used to build and simulate the quantitative model described here, subscript mapping enables for building multi-scale models. The current model is a multi-scale model due to the fact that the 217 countries are flexibly grouped in higher level regions. Consequently, data can be pulled up and analysed for specific countries but also for each desirable grouping of countries (e.g., for the Benelux, for the EU27, or for the EU27 countries plus Single Market countries).

The model is fed with data from FAOSTAT from 2011-2021 (in some cases up to 2019), after which simulation starts. Databases are mostly very incomplete. That is, many important pieces of data that are needed to quickly construct good models are often not available. That is also the case for FAOSTAT: for example, in the absence of drivers underlying the agri-food system, data on GHG emissions from different parts of the agri-food system have been used to reconstruct (reverse engineer) the drivers underlying the agri-food system.

7.2.1 From Data Model to Data-Rich Systems Model to Data-Rich Policy Simulation Model to Data-Rich System Dynamics Policy Model

After cleaning data, we first use the data to construct Data Models that are used to identify and/or test relations between variables. Once relations are found and a proper functioning data model is

5 For example, SUM(variable X[subscript U, subscript V!]) sums the two-dimensional variable X across dimension V, resulting in a one-dimensional "variable X summed across dimension V[subscript U]".

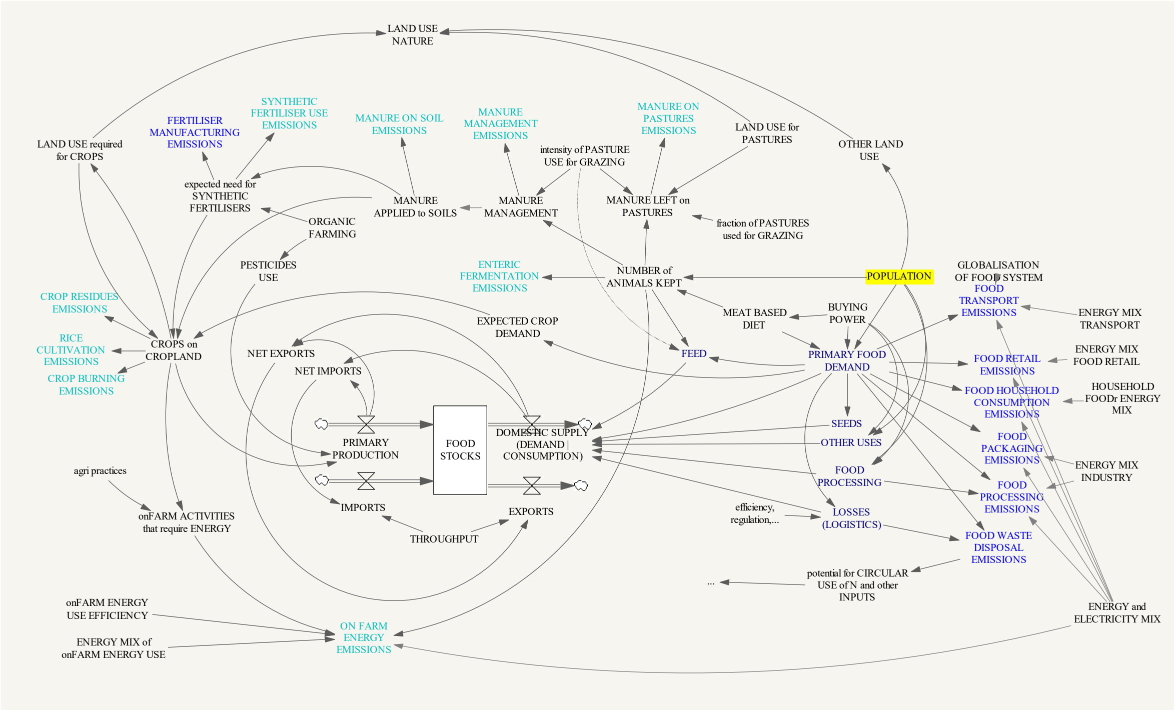
constructed (convincingly connecting the data), we use the information about these relations to build corresponding Data-Rich Systems Models which replicate the data when data is available but simulates model-generated dynamics afterwards. Next, we extend this model with policy structures that allow for simulating different plausible dynamics and different policies. This is what we call a Data-Rich Policy Simulation Model. Finally, when a Data-Rich Policy Simulation Model is extended with all sorts of systemic effects (including feedback loops), it becomes a full-fledged Data-Rich System Dynamics Policy Simulation Model (or Digital Twin).

An important point to stress here is that systems models are iteratively developed and gradually refined: it is normal practice to first develop models with broad systems boundaries but relatively simple structures, and later refine important parts of the model with more detailed structures. Data-rich systems models are developed based on information, but especially based on data. Since not all data about all parts of a system are available or easily accessible, and systems modelling is a time-consuming activity, parts of a system that are not (easily) accessible might be underrepresented at first. In other words, data availability influences model development, especially at the beginning of a substantial modelling processes like the one for this project. This is most certainly the case for modelling of the agri-food and associated cross-systems: data availability and the quality of available data is very different for different countries, parts of the overall system, aspect systems, and effects/variables. Even though the FAOSTAT databases contain lots of data for many countries in the world, not all data required to make a balanced agri-food systems model is available. For example, although data regarding the GHG emissions for different aspects of the agrifood supply chain is available in the FAOSTAT databases, there is no data regarding water pollution (or water quality and quantity), local air pollution, or data regarding many of the causes of pollution, let alone behaviours of actors in the system. Inputs needed or used for primary production (e.g., yields or nutrients) and effects (e.g., GHG intensities) are often only available on the aggregate level or for a subset of items, while they are required on the level of separate agricultural products, for all such agricultural products.

This means that additional data needs to be found and added, or (proxies for) values need to be calculated from other data or information. Since this takes a lot of time, some aspects are not equally well represented at first. This is clearly the case for this first iteration model discussed here.
Many of the aspects discussed before – in the qualitative analysis – are represented in the model though. However, in this first version of the model, many structures are still represented with “first iteration” model structures – structures built to replicate the data and allow for calculation of effects of policies. In that sense, the current model should still be seen more as a “data model”, built with and containing large amounts of data, that allows for testing what-if assumptions starting from the data (e.g., what happens if from year A till year B, values of stock variable X fall by Y percent per year) than a full-fledged Data-Rich System Dynamics Policy Simulation Model or Digital Twin of the agri-food system. Developing the latter is nevertheless one of the goals.

Figure 33 shows a high-level representation of the current model. Population and buying power (GDP/Capita), and starting data, determine primary food demand for different food types, including demand for vegetable and meat products food products, and via animals, feed, but also for other uses, for food processing, etc. Domestic supply (which really is “domestic demand supplied”) is the sum of domestic demand for food, feed, other uses, food processing, seeds, tourist consumption and losses in the supply chain. Domestic demand supplied also creates expectations about future crop demand, and consequently production of crops on cropland, and animals kept for meat and other animal products. This influences Primary production. Based on primary production and domestic supply – and knowing how much throughput there is per country – one can calculate Imports and Exports – which is checked with data on stocks and stock variations. Primary production requires inputs, for example cropland. Depending on the amount of organic farming and manure produced and used, primary agricultural production uses synthetic fertilizers and pesticides. The application (and amounts) of organic and synthetic fertilizers and pesticides has “side” effects. Moreover, all activities create GHG emissions. All blue variables are GHG emissions that are attributed to the agri-food supply chain. All turquoise variables are GHG emissions that can be attributed to primary agricultural production.

Figure 33: A high-level overview of the quantitative systems model.



Source: Screenshots from Vensim Simulation Model. Erik Pruyt.

7.2.2 The Agri-Food System

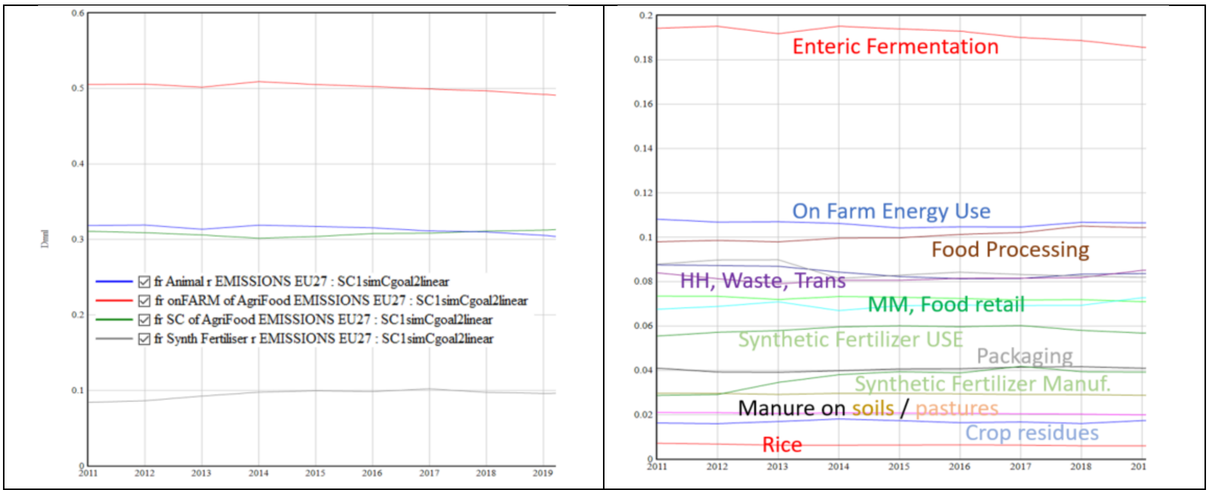
We will now discuss some of these subsystems in more detail, using the data models created from the data in the FAOSTAT databases.

GHG Emissions – the Big Picture

Given the large contribution of the agri-food sector in GHG emissions, and the need to mitigate these emissions, GHG emissions are a good entry point to look at the agri-food system. Leaving land use changes aside (which are also part of the model), there are a few big contributors to GHG emissions in the EU27 agri-food system (see Figure 34(a)):

- Primary agricultural production accounts for some 50% of all CO2eq emissions in the EU27.
- Some 30% of GHG emissions are related animal husbandry (animals included in the analysis are Camels and Llamas, Cattle, Mules and Asses, Poultry Birds, Sheep and Goats, Swine).
- The agri-food supply chain without synthetic fertiliser manufacturing also accounts for some 30% of GHG emissions, with manufacturing of synthetic fertilisers this amounts to some 34%.
- Emissions related to synthetic fertilisers manufacturing and use amount to 10%.

Figure 34: GHG emissions by main parts of the agri-food supply chain (left) and by detailed activities in the Primary Production and Supply Chain parts of the Agri-Food system.



(a) GHG emissions by main activities	(b) GHG emissions by detailed activities

Source: Simulation results. Erik Pruyt.

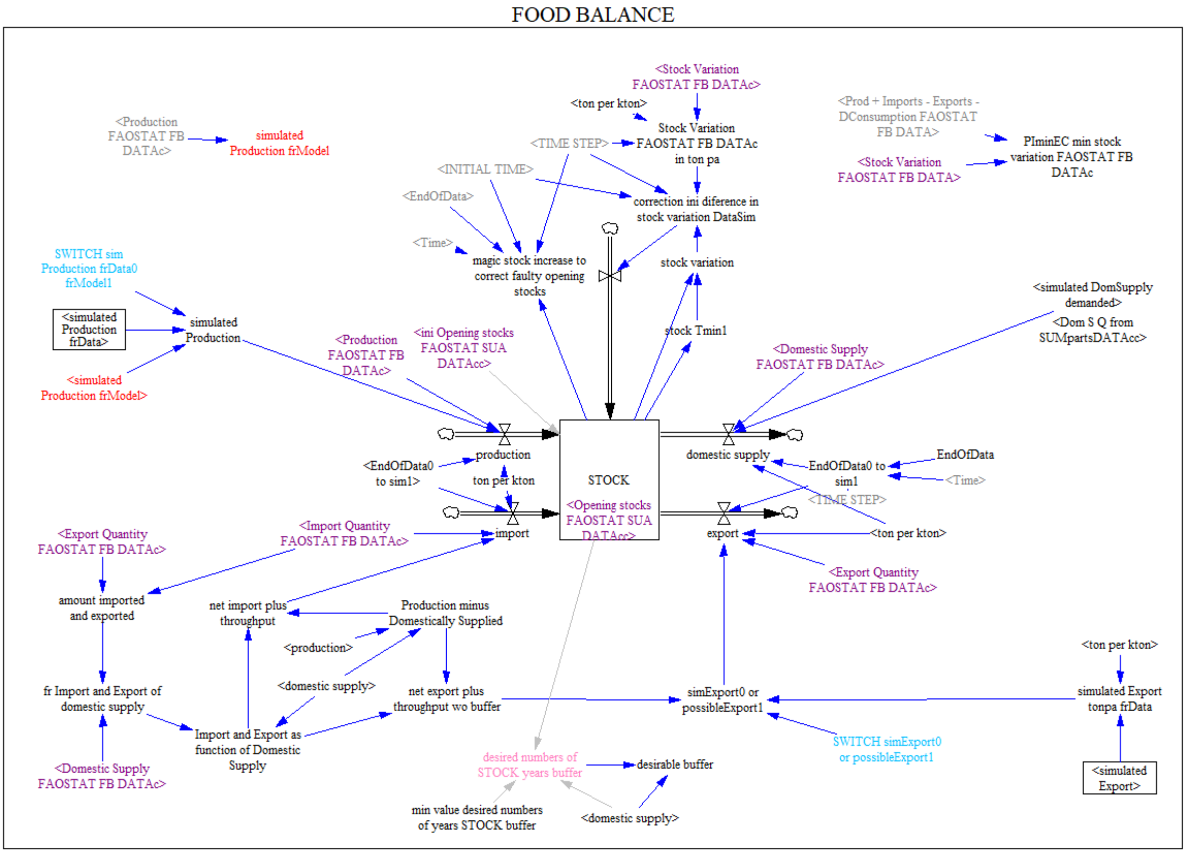
However, as Figure 34 (b) shows, this does not mean there is one single aspect of the agri-food supply chain that needs to be addressed to mitigate climate change in the agri-food system. To the contrary, most aspects need to be addressed to mitigate emissions.

In primary agricultural production, enteric fermentation (CH4 from ruminants) is responsible for most CO2eq emissions, followed by on farm energy use. After those two, there are several aspects that have to do with manure and fertilizers: manure management (MM), synthetic fertilizer use, and to a smaller degree, manure on soils and manure on pastures. Emissions due to crop residues and rice production are small. In the agri-food *supply chain*, most tiers (Food processing, Transportation, Food retail, Household consumption, Waste management) cause a comparable slice of the overall agri-food GHG emissions. Packaging and Synthetic fertilizer manufacturing are smaller contributors.

Domestic Demand, Import/Export, Primary Production, Supply Chain

Moreover, only looking at EU27 primary production hides part of the big picture: apart from emissions related to primary production and the supply chain in Europe, emissions related to import, export, and throughput need to be looked at, to assess the real contribution by the EU27 but also to assess whether there is GHG leakage. Given that all countries in the world are included in this model, this is possible (but has not been done yet). Figure 35 shows the model structure the “Food Balance” in the model (Figure 35). Although it is called Food Balance – after the FAOSTAT DB name – it balances more than food alone.

Figure 35: the “food balance” structure in the model unites all FAOSTAT Food Balance databases and some of the Standard Utilization Accounts databases.



Source: Screenshot from Vensim Simulation Model. Erik Pruyt.

The demand side of the Agri-Food value chain

The demand side of the Agri-Food value chain is captured by Domestic Supply. Domestic Supply consists of demand for Food, demand for Feed, demand from Processing, demand from other uses, demand for seeds, losses (in transport and storage), tourist consumption, and residuals – each for 12 agri-food products (Cereals Excluding Beer, Pulses, Starchy Roots, Tree nuts, Vegetables, Sugar crops, Oil crops, Fruits Excluding Wine, Meat, Milk Excluding Butter, Eggs, Fish Seafood). Residuals is a non-demand item introduced by FAOSTAT to balance Domestic Supply, Imports, Exports and Primary Production. All categories are explicitly modelled except for residuals.

Food and Feed are the main categories and are modelled more in-depth than the other categories.

Food corresponds to all direct consumption by consumers. It is modelled such that diets can change, both in terms of amounts consumed, in terms of the mix of food products, in terms of the choice of mode of production (organic or conventional), and in terms of the choice of the provenance of domestic supply (local versus EU and global) – be it because of autonomous change (for instance towards climate-friendly diets) or because of policies.

Indirectly, feed is also food since it is used to grow animals whose products (predominantly) constitute the future supply of animal products to humans. Feed is combined with information and data about animals and manure to calculate grazing in pastures and feeding of grass to animals.

The production side of the food value chain

<u>Primary Production in General</u>

Primary production is based on primary production data of 217 countries for 12 aggregated food types (Cereals, Pulses, Starchy Roots, Tree nuts, Vegetables, Sugar crops, Oil crops, Fruits, Meat, Milk, Eggs, Fish Seafood). Some of these aggregated types, like Fish Seafood, are further subdivided.

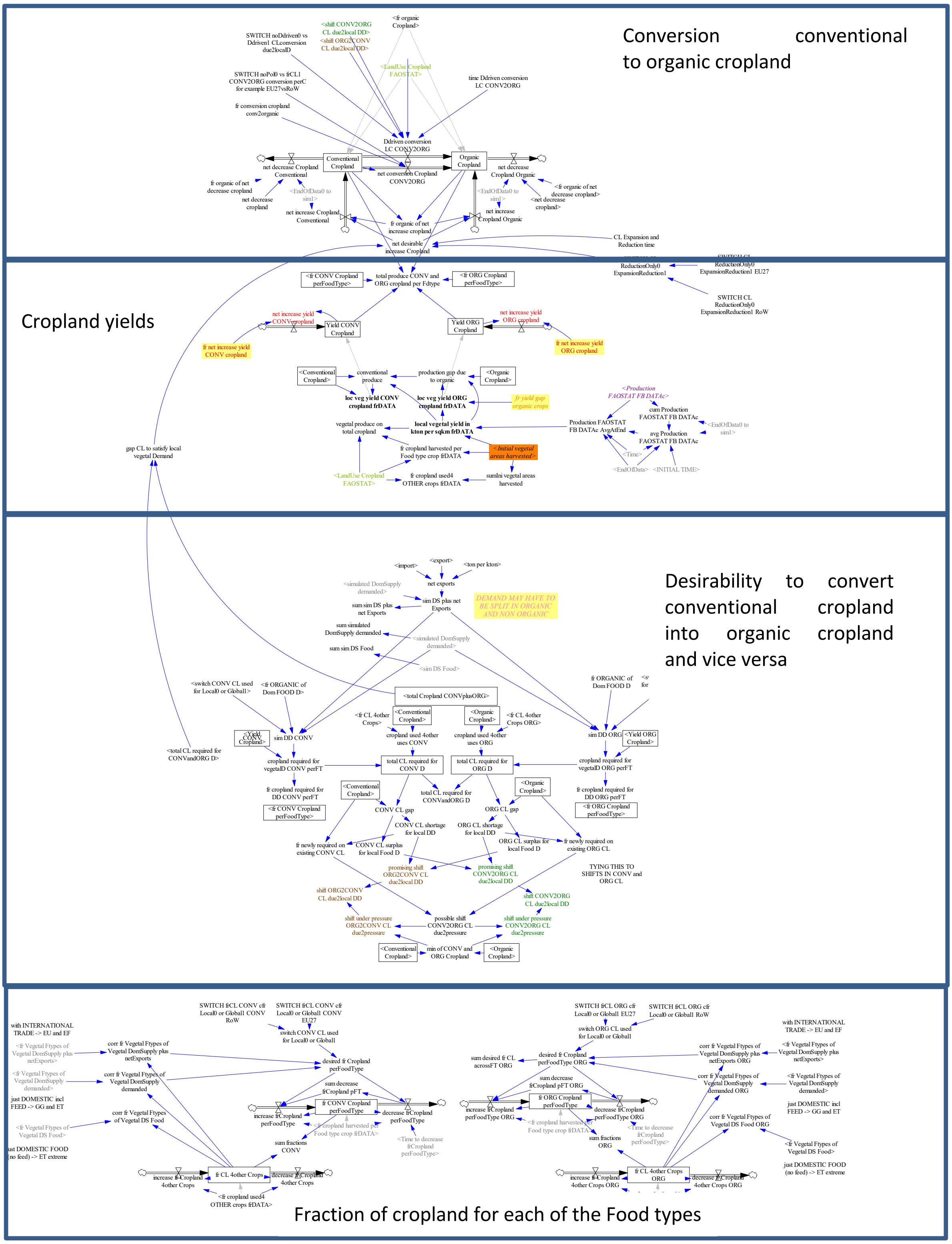
During simulation time, primary production is calculated based on the size of cropland, the share of cropland dedicated to each food type, agricultural practices (conventional versus organic farming), the amount of pesticides used, and the amount of manure and synthetic fertiliser (N contents) used.

<u>Conventional versus Organic Farming</u>

The area used for conventional agriculture and organic agriculture could increase (if switched on in the model), decrease, and conventionally farmed areas can be converted into areas that are farmed organically (and vice versa). Figure 36 shows the model structure developed to distinguish between conventional and organic agriculture. Apart from that, effects on required cropland, the amount of organic and synthetic fertilizer use, and the amount of pesticide use are calculated. Currently, we are looking into the effects of organic and synthetic fertilizer use, and the amount of pesticide use on farmers, rural population, consumers, and nature. Effects on water quality and quantity should be added in 2023.

For animal husbandry, based on numbers of manure and manure that is left in pastures and meadows, the model calculates how many animals graze (partly) outside, how many animals are permanently in stables. These results of these calculations are then used to calculate additional feed needs (beyond the separate domestic supply category), how much of that need can be satisfied by grass harvested from meadows, and how much additional feed is lacking. Note in this respect that rest streams are not incorporated in the current model (yet).

Figure 36: model structures to capture conventional and organic cropland, potential conversion between conventional cropland and organic cropland (top), their yields for each of the 12 food types, the willingness to convert cropland, and the fraction of each of the food types.



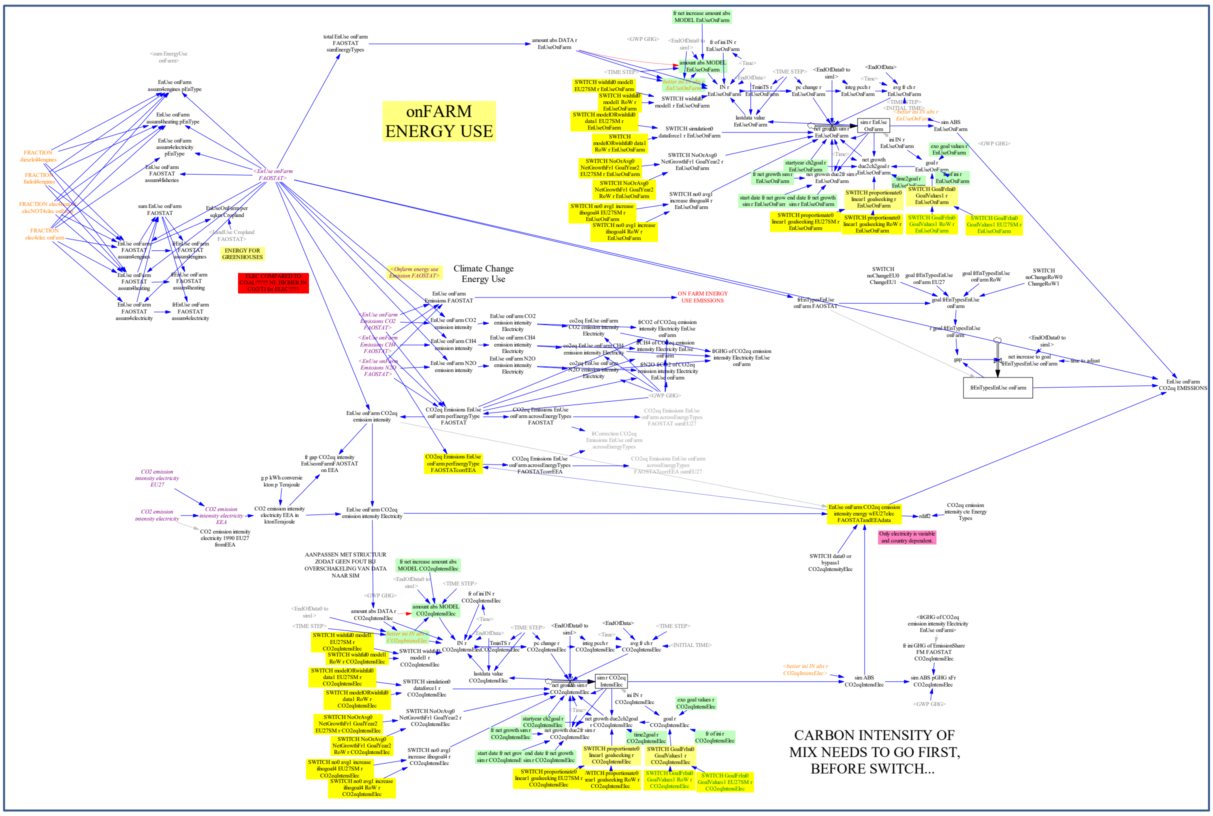
Source: Screenshots from Vensim Simulation Model. Erik Pruyt.

As already mentioned before, primary agricultural production is a large contributor to GHG emissions in Europe (and most places in the world). These emissions can be largely attributed to (1) animal farming, and (2) on farm activities that require energy.

On Farm Energy Use

Ideally, On Farm Energy Use is split out in terms of energy use for different on farm activities (e.g., energy use for engines, energy use for heating, energy use for electricity) so that these activities could be reduced, or alternative technologies would be coupled to these activities. Since data related to these different uses is not available in FAOSTAT, adding it in a reliable way requires some reverse engineering (which might be done later). Instead, energy use for these on farm activities is provided for 9 different energy types (Gas Diesel oil, Motor Gasoline, Natural gas, Coal, Electricity, LPG, Fuel oil, Gas Diesel oil fisheries, Fuel oil fisheries). Moreover, emission intensities of these different on farm energy types is provided by FAOSTAT. Finally, GHG emissions are available too (Figure 37).

Figure 37: Model structures to change the level of activities and the energy required for them, to change the energy efficiency of these activities, to change the energy mix used for these activities, and to change the emission intensity of the energy types used.



Source: Screenshots from Vensim Simulation Model. Erik Pruyt.

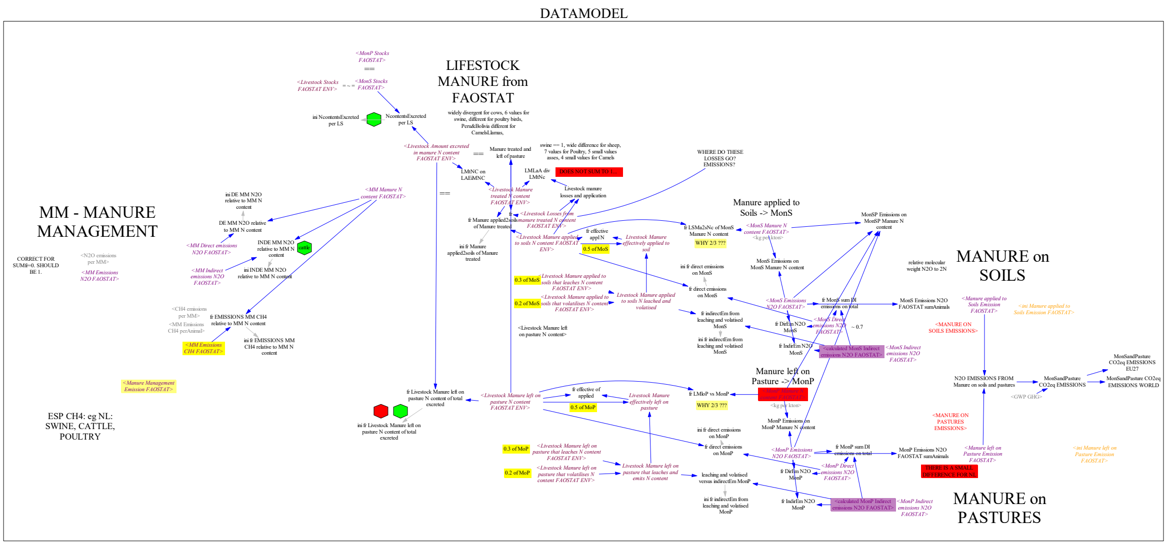
With these three pieces of data, a model structure is constructed that splits out total energy demand for on farm activities, the efficiency of energy use for these activities, the emission intensities of these energy types, and the mix used. In other words, there are several levers: reducing the activity level (and consequently using less energy, e.g., from tilling to no tilling), increasing the energy efficiency of these activities (e.g., investing in new conventional tractors), and changing the energy mix by shifting to electricity, see Figure 38. The building blocks (with many yellow policy/decision variables) in Figure 37 enable to test the effects of policies that activate these levers.

At first, FAOSTAT data was used to assess the effects of levers to reduce emissions from on farm energy use. However, for many countries, the emission intensity of electricity was higher than other energy types, even higher than coal. Hence, EEA data was added for European countries. Results were even worse for some countries like the Netherlands. Given the conversion losses to turn energy types into electricity, grid losses, and conversion losses when turning electricity into the energy required for the energy use at hand (e.g., heating), electricity mixes with rather high fractions of fossil fuels perform badly. Shifting to electricity is in these cases not a good idea, yet. First the mix behind electricity needs to become (largely to fully) sustainable in such countries, before considering electrification of on farm energy use.

<u>Animal-related GHG emissions</u>

Animal-related GHG emissions comprise enteric fermentation emissions (about 20% of EU27 primary agricultural production plus agri-food supply chain emissions), manure management (about 10.5% of total EU27 agri-food emissions), emissions from the application of manure on soils (2%) and manure on pastures (2%), and emissions due to synthetic fertiliser use (8.5%) (excluding synthetic fertilizer use) – in total some 43%. On farm energy use amounts to some 11% of the total primary production plus agri-food supply chain emissions in the EU27. This means they may provide substantial leverage.

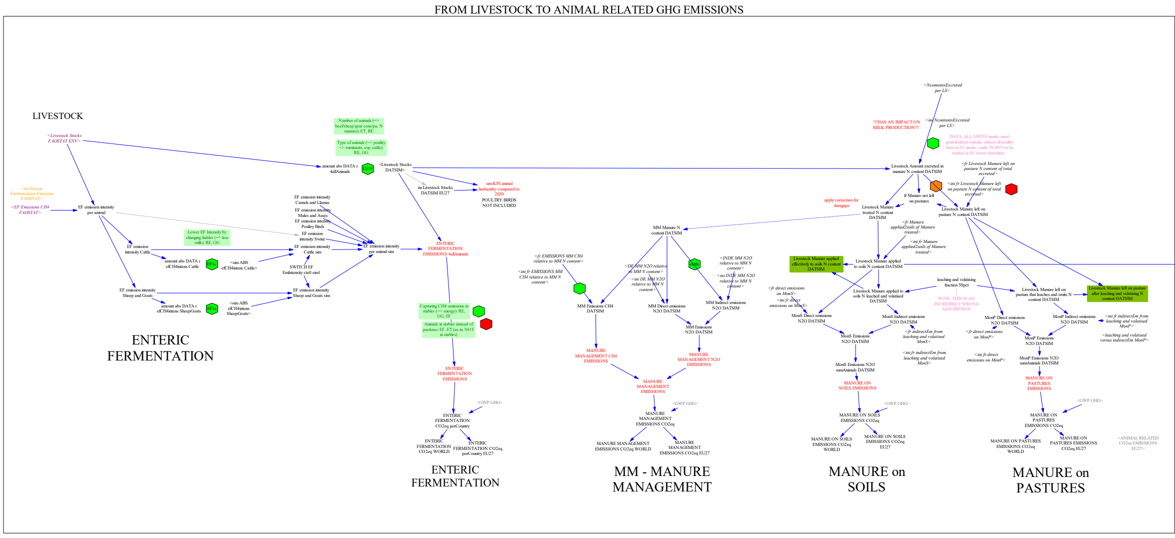
Figure 38: Data model to connect the dots for all animal stocks and animal related GHG emissions.



Source: Screenshot from Vensim Simulation Model. Erik Pruyt.

Figure 38 shows the data model (all purple variables are data imports from FAOSTAT). This data model was subsequently turned into the simulation model in Figure 39 and allowed for identifying potential leverage points. These leverage points are indicated with green and red hexagons. Policy building blocks were subsequently added there (not visible in this figure) to pull these levers.

Figure 39: Simulation model based on the data model, with structures to test policies and leverage.



Source: Screenshot from Vensim Simulation Model. Erik Pruyt.

Synthetic Fertilizer Use

In the current version of the model, synthetic fertilizer (SF) use, account for some 6% of agri-food GHG emissions in the EU27, and is not elaborated operationally (yet) due to a lack of time and the complexity of interactions with manure production and use, modes of cropland use, and SF manufacturing. Currently, emissions can be turned off but it should/could be included. Supporting model structures include structures to calculate: (i) livestock (and manure) on pastures and meadows and in stables, (ii) feed, grass, and other fodder inputs as well as outputs in terms of organic fertiliser, (iii) possible and needed animals for agriculture without Synthetic Fertilisers, (iv) yields of bio organic agriculture (without synthetic fertilisers and pesticides) versus yields of conventional agriculture with synthetic fertilisers (and pesticides), (v) soil nutrient balances. These pieces of the puzzle still need to be combined in view of calculating the need for and use of synthetic fertilisers.

Crop Residues, Burning Crop Residues, Rice Cultivation

In the current version of the model, Crop Residues, Burning Crop Residues, and Rice Cultivation, accounting together for some 3% of agri-food GHG emissions in Europe, is not elaborated operationally.

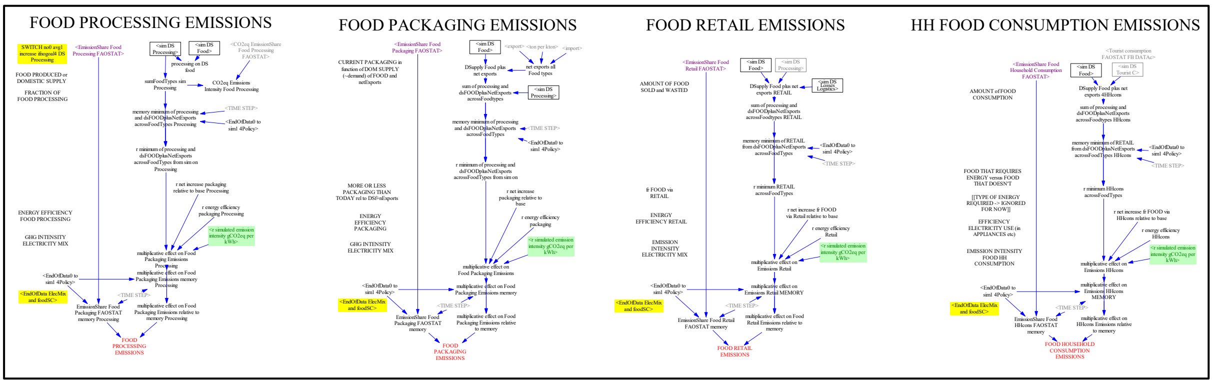
The Agri-Food Supply Chain

Figure 34 showed that many tiers of the EU27 agri-food supply chain have about the same annual GHG emissions. GHG emissions from food processing amount to 10.5% of all emissions of primary agri-food production and the agri-food supply chain, transportation amounts to 8.5%, household consumption to 8.5%, waste to 8.5%, food related retail to 7%, and packaging and synthetic fertilizer manufacturing both to 4%. To substantially reduce supply chain emissions, all these emissions need to be reduced substantially, which requires pulling levers to minimize each of these emission gaps.

Emissions related to Food Processing, Packaging, Food Retail, and Household Food Consumption

Four tiers of the supply chain – namely Food processing, household food consumption, food related retail, and packaging – which together cause some 30% of EU27 GHG emissions from agricultural production and the food supply chain, have similar drivers and levers, and are therefore included with the same (relatively simple) building block in the model (Figure 40).

Figure 40: model structures with levers for food processing, packaging, retail, and consumption.



Source: Screenshot from Vensim Simulation Model. Erik Pruyt.

Figure 40 shows the four structures: the structures start – on the top left – with country-level GHG emissions data and (top right) with simulated drivers for these emissions. These drivers are:

- for Food Processing Emissions: the simulated amount of Processing from Domestic Supply (<sim DS Processing>);
- for Food Packaging Emissions: the sum of simulated Domestic Supply of Food, net Exports, and Processing in Domestic Supply;
- for Food Retail Emissions: the sum of simulated amounts of Domestic Supply of Food, Processing, and Losses in logistics (<sim DS Losses Logistics>);
- for Food Consumption Emissions: the sum of simulated amounts of Domestic Supply of Food and Tourist Consumption.

The absolute values of the summed drivers are turned into relative values with base value 100% from the moment the simulation model takes over from the data. From then on, lower (higher) values for drivers drive the relative value down (up). That is, 20% increase of the underlying drivers results in a relative value of 120%. These underlying drivers are also the first lever: their values could be brought down, which results (in the current simple set-up of the model) in fewer GHG emissions from these tiers of the agri-food supply chain. From there on, other levers – similar across the different tiers of the supply chain represented with this structure – come into play:

- for Food Processing Emissions: apart from the amount of food processed, which might actually be broken down in demand for food and the fraction of that food demand being processed, levers include the energy efficiency of food processing, and the GHG intensity of the energy mix used for food processing (which is assumed here to be electricity only);
- for Food Packaging Emissions: apart from the demand for (possibly packaged) food (assumed here to be the sum of domestic supply of food, net exports, and food processing) and the amount of packaging that is associated to it, levers include a lever for more or less packaging than today (relative to the demand for (possibly packaged) food), a lever for the energy efficiency of packaging, and a lever for the GHG intensity of the energy mix used in the packaging industry (which is assumed here to be electricity only, albeit country-specific);
- for Food Retail Emissions: apart from the amounts of (pure and processed) foods sold and losses in the supply chain, levers include the fraction of food passes through retail channels, the energy efficiency of retail, and the emission intensity of the electricity mix used;
- for Food Consumption Emissions: apart from the amount of (regular and tourist) food consumption, levers include the fraction of food consumption that requires energy or causes GHG emissions when consumed at home compared to the base year, the primary energy type

used (assumed here to be electricity only), the efficiency of energy use (e.g., by appliances), and the emission intensity of food consumption by households.

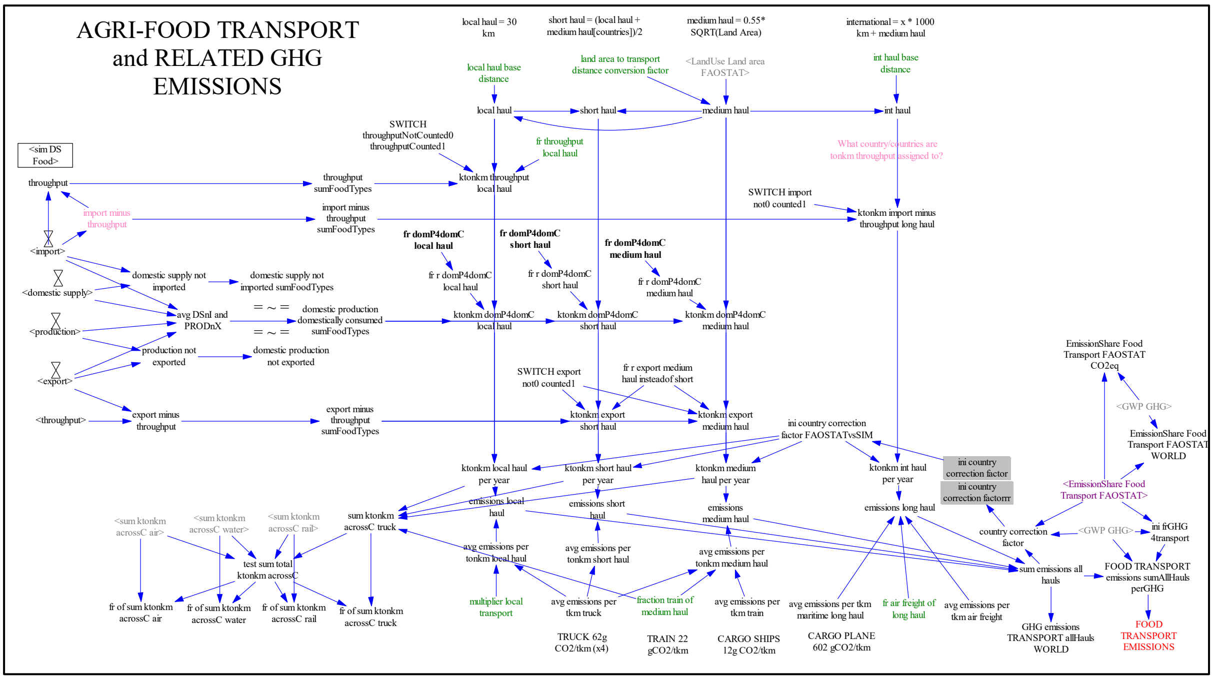
Each of these tiers has more or less the same levers: emissions (and other environmental side effects) can be reduced (increased) by less (more) of the underlying driver, a smaller (bigger) fraction of the driver treated in a way emissions are generated, a larger energy efficiency, and a cleaner energy mix. In the current version of the model, the energy used in these tiers is assumed to be electricity. The main reason for this choice is that electricity is predominantly used as energy input in these tiers of the supply chain. Since electricity mixes strongly differ across different European countries (and ever more so across the world), the resulting GHG intensity of the electricity used also strongly differs – but is the same across these different tiers for the same country.

The GHG emission intensity of electricity generation (the variable "*r simulated emission intensity gCO2eq per kWh*" displayed in green) is therefore an important input into these calculations of the GHG emissions of these different tiers. Given that all tiers include this "GHG emission intensity of electricity generation" lever and knowing that these specific emissions of electricity generation can be brought down substantially, being able to change the GHG emission intensity of electricity generation is an important *cross-systems lever* for the overall agri-food system (potentially reducing some 30% of European agri-food emissions). The electricity generation module is discussed below.
All levers are expressed in relative terms (starting at 100% when simulation takes over from the data), and simply multiplied. The total relative effect of these levers (compared to the base year) is subsequently multiplied by the GHG emissions in the base year (left hand side of the model structure) to calculate the GHG emissions caused by these tiers of the supply chain.

Cross Systems Electricity Mix and Associated GHG Emission Intensity of Electricity Generation
The electricity mix – and associated to that, the GHG emission intensity of electricity – is an important input (and lever) for Food Processing, Packaging, Food Retail, Household Food Consumption, and for On Farm Energy Use. These Cross-Systems inputs are currently represented relatively simplistically, starting from longitudinal data on electricity mixes in each country in the world and EEA data on CO2eq emission intensity of electricity generation. The fractions of each electricity generation technology are calculated and used as memory variable (i.e., in a stock variable). These fractions can change according to data, stay constant, or change non-linearly or linearly to future goal values from a start year to a goal year. From these mixes (different for each country in the world), emission intensities of electricity are calculated by multiplying them with constant GHG emission intensities of electricity generation (e.g., coal ~ 860 g CO2eq/kWh, gas ~ 360 CO2eq/kWh, etc.). These constants (assumed here to be the same for all countries in the world) could later be made country specific or could be turned into variables. Data on CO2eq emission intensity of electricity generation from the EEA is used to correct these GHG emission intensities of electricity generation for European countries. The outcome of this structure is the variable "*r simulated emission intensity gCO2eq per kWh*", where *r* stands for relative.

Cross-Systems Agri-Food Transportation Emissions
Based on the FAOSTAT data, EU27 food related transportation accounts for 8.5% of the total value chain emissions. Given the cross-over aspect of the project, modelling food transportation well is important. However, the current setup only uses high-level data from FOASTAT on food related transportation, more precisely the Emission Share of Food Transport (GHG emissions in tonnes per year) per country in the world (Figure 41). There was not enough time for proper analysis of very detailed data for low level origin-destination couples.

Figure 41: model building block to simulate GHG emissions from agri-food related transportation.



Source: Screenshot from Vensim Simulation Model. Erik Pruyt.

To make the high-level data operational and add levers to assess effects of shifts from local sourcing to regional sourcing to global sourcing, of shifts in modes (e.g., truck to train), and GHG intensity of different modes, assumption-based structures have been included (in the sub model displayed in Figure 41):

- Four typical distances are considered: local haul, short haul, medium haul, and international (or long) haul. Local haul transportation is assumed to amount to 30km (or the medium haul distance discussed below if it is smaller than the base local haul distance). Short haul transportation is assumed to amount to the average of local haul and medium haul. Medium haul is calculated as the square root of the land area of a country, times a further 55% land-area-to-transport-distance conversion factor. International haul is assumed to amount to 9000km.
- Domestic supply, exports, imports minus throughput, and throughput are treated distinctly in the model. Domestic supply is assumed to be 10% local haul, 30% short haul, and 60% short haul. Export is assigned to medium haul transportation. International long-haul emissions are attributed to the importing country (to avoid double counting). Throughput is not assigned to long haul, since they are attributed to the importing country, not to the throughput country, except for 20% of throughput which are assumed to be transported over a short haul. Import (minus throughput) is assigned to the long haul.
- Transportation on local and short haul, medium haul, and long haul are also treated differently in terms of modes used and the associated CO2eq emissions. Local and short haul are assumed to be transported by truck at 62g CO2eq per tonne-kilometre (tkm), with local transportation emissions estimated to be 4 times higher than emissions of short and long-haul transportation by truck). Slightly less than 30% of medium haul is assumed to be transported by train, the rest by trucks. Long haul is assumed to be transported by air and by water. Only 2% of long-haul transportation is assumed to be transported by air (although island and small rich nations have much higher percentages of transportation by air) at 602

gCO2 per tkm. The rest is assumed to be shipped with cargo ships which are assumed to generate 12g CO2eq per tkm of goods shipped.

In the current version of the model, these numbers are constant that are applied to all countries in the world, which is a blunt simplification. Moreover, the constants are simply guestimates. Emissions due to food transportation per country are then calculated as the sum-product of type of stream (domestic supply/import/export/ throughput), the corresponding hauls, the modes used per haul, and the emissions per tkm transported. The calculated country totals are compared to the FAOSTAT country totals to calculate a correction factor per country. The tkm values for local/short/medium/inter-national haul per country are corrected by multiplication with this country-specific correction factor.

Although all values are guestimates, their country and global totals correspond to the country and global totals from FOASTAT (due the country-specific correction factors), and the calculate global fractions correspond well to the real-world global fractions. However, this is by no means proof that the assumed values have anything to do with the real values: More detailed data is needed to improve this building block and the conclusions that can be derived from it. The reason why food transportation is modelled in an elaborate way while being based on very limited data, is that it is important to already add the levers. These levers are (i) the different amounts per food type that are transported, (ii) the distances over which these amounts are transported, (iii) the modes of transport used for these amounts over these distances, and (iv) the emission intensity per tkm of the different modes in different countries). That is, amounts transported could be reduced, the transport distances could be reduced, modes with smaller environmental impacts could be used, and specific emission of the modes used could be reduced.

Food Waste Disposal Emissions
In the current version of the model, Food Waste Disposal, accounting for some 8.5% of agri-food GHG emissions in Europe, is not elaborated operationally.

Synthetic Fertilizer Manufacturing Emissions
In the current version of the model, Synthetic Fertilizer Manufacturing, accounting for some 4% of agri-food GHG emissions in Europe, is not elaborated operationally.

7.3 Description and the methodology of the CRAFT Model

The **CR**OSS-SYSTEMS **A**GRI-**F**OOD **T**RANSITION model (**CRAFT model** in short) is a **systems model** that allows for in-depth system-wide what-if investigations of the Agri-Food system and related cross Systems (like the energy system and the transportation system). Even though it was built using the System Dynamics language and is simulated with System Dynamics simulation software (Vensim DSS), it is *not* a typical System Dynamics model. It differs from traditional System Dynamics models in that it has been developed specifically to simulate from today's world towards specific sustainable futures, by pulling sets of levers. Where traditional System Dynamics model focus on discovering an endogenous "structural" explanation of system dynamics over time due to feedback effects and accumulations, the System Dynamics language and System Dynamics simulation software were used in this project to develop structures to investigate large amounts of data and derive information from it, link data and information to connect dots within subsystems and between subsystems, identify levers of change, and above all, to simulate dynamic pathways between today's world and alternative sustainable futures enabled by well-chosen sets of consistent levers. To arrive at the current what-if model, a lot of data science, time series analysis, systems analysis and policy analysis was required. The model is, in a sense, the result of those analyses. But it is first and foremost an instrument to investigate what levers can and need to be pulled to attain alternative sustainable futures. Any lever, any value, any assumption, and function in the model can be varied to assess their impact on the overall system dynamics. Simulation of one simulation run takes about 1 minute (compiled simulation will be faster) of which most time is required for loaded large amounts of data. The current version of the model is most appropriate for cross-system what-if testing. If desirable, future extension of the model (e.g., with important feedback effects and endogenous dynamics instead of assumed transient behaviour) could turn it into a full-fledged System Dynamics model. That would be a next step, useful for other purposes. However, for the purpose at hand, the current set-up of the model is most appropriate.

The CRAFT model is a *data-rich* model. Most **data** originate from the FOASTAT DATABASES. The model is a highly subscripted (i.e., vectors are used intensively) entity-based model: the same structures/equations are used to represent many entities (e.g., countries, grouped in regions). An equation in the model with the subscript *countries*, automatically applies to all 217 countries in the model, except for explicitly defined exceptions to the equation (e.g., the levers in the current version of the model are defined for the EU27SingleMarket countries only, which means that many variables have an equation for all countries except the EU27SingleMarket countries, and separate equation for all EU27SingleMarket countries). An equation for a particular *region* applies to all countries in that region, but not to other countries: the *EU27* region subscript allows one to activate equations or pass values to the 27 EU countries and not to others, or to group values across the EU27 region (e.g., SUM(EU27!) sums the values of all EU27 countries inside an equation). Vector notation is used extensively in this model, including for:

- 12 different Food types (*Cereals Excluding Beer, Pulses, Starchy Roots, Treenuts, Vegetables, Sugar crops, Oil crops, Fruits Excluding Wine, Meat, Milk Excluding Butter, Eggs, Fish and Seafood*),
- 6 classes of Animals (*Cattle, Poultry Birds, Sheep and Goats, Swine, Mules and Asses, Camels and Llamas*),
- 12 alternative Land Uses[6],
- 9 Energy types (*GasDiesel oil, Motor Gasoline, Natural gas, Coal, Electricity, LPG, Fuel oil, GasDiesel oil fisheries, Fuel oil fisheries*)
- 7 energy types used to generate Electricity (*Elec from coal, Elec from gas, Elec from oil, Elec from solar, Elec from wind, Elec from nuclear, Elec from hydro*),
- 9 groups of pesticides, 7 insecticides, etc., as well as the chemical substances listed in the Rotterdam Convention,
- 5 types of Proteins in terms of their origins (plant-based, meat, milk, egg, fish), and
- 3 greenhouse gases (CO2, CH4, N2O).

Starting from the multidimensional FAOSTAT data (e.g., combining the *countries* subscript with the *Food types* subscript), data structures were modelled and used to investigate the data, resulting in data models to infer information about the system, which were subsequently used to develop data-rich sub-models to simulate system dynamics over time starting from the data.
The main purpose of the **CRAFT model** is to investigate what is required to attain **sustainability** in agri-food production-supply-consumption. A sustainable agri-food system is defined here as an agri-food system that:

- ***Guarantees sufficient food production*** (in the face of climate change) and (security of) supply
- ***Provides healthy*** food and a healthy work and living environment (e.g., to rural populations)
- Strongly ***mitigates*** emissions of ***greenhouse gases*** (GHGs) – the focus in this model is on just three GHGs (CO2, CH4, N2O)
- ***Reverses biodiversity/nature loss*** by creating necessary conditions for resilient ecosystems:

6 Forest Land natural, Forest Land planted, Agricultural Land permanent crops, Agricultural Land temporary crops, Agricultural Land temporary fallow, Agricultural Land temporary meadows and pastures, Agricultural Land permanent meadows and pastures cultivated, Agricultural Land permanent meadows and pastures natural, Agricultural Land market and kitchen gardens, Agricultural Land other, Other Land built environment, Other Land non built environment.

- Either through land use changes in favor of nature, or through bio-inclusive farming
- By eliminating the use of, or effects on, nature of (harmful) pesticides and chemicals, pollution (also of nutrients), and waste, and
- By restoring water quality, soil quality, and air quality.

- ***Eliminates losses and externalities*** (e.g., elimination of material loss by circular use of nutrient flows (in the current version of the model, only Nitrogen), waste, materials).

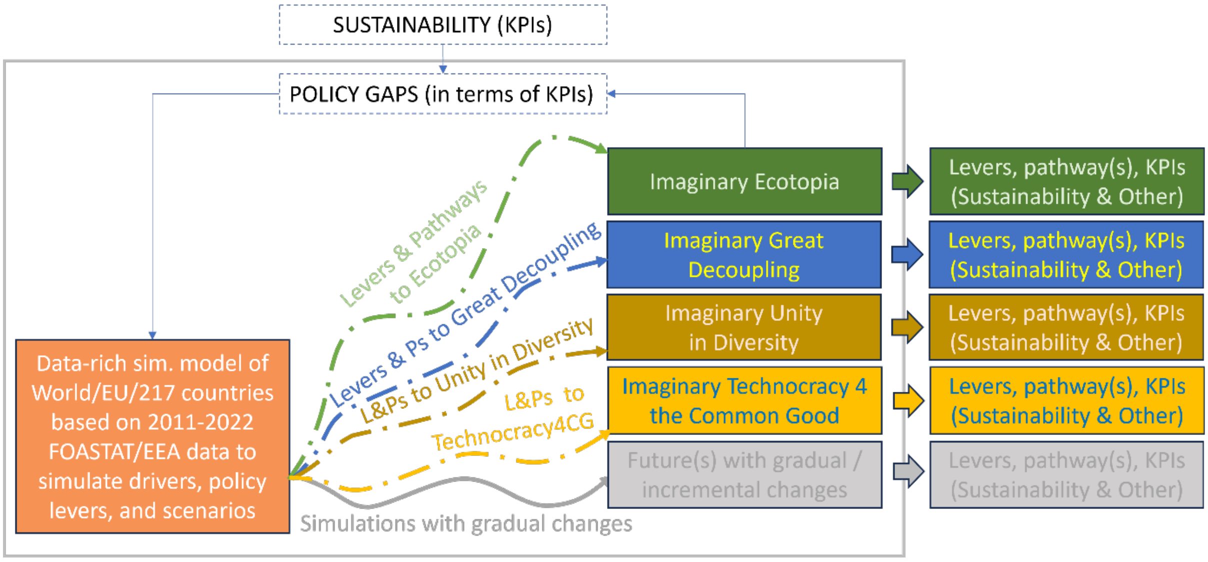
There is not just one and only sustainable future that satisfies these criteria. Without explicitly considering alternative sustainable futures, incremental developments will (hopefully) take us to a particular one. However, that might not be the most desirable one. To end up in a good future, we need to first know where we want to go. This requires imagining alternative futures that satisfy particular criteria, in this case that these futures are sustainable. These alternative futures might be wildly different on other criteria. Four **Imaginaries** – in this case, four very different futures, all *sustainable* – were provided by the EEA. Even though they satisfy sustainably criteria, these imaginaries are completely different in terms of their functioning, the work and living environments they provide, and the drivers and policies that might get us to them. These Imaginaries are described in more detail in Chapter 5. In short, these imaginaries are:

- The first Imaginary is called The Great Decoupling.
- The second Imaginary is called Unity in Adversity.
- The third Imaginary is called Technocracy for the Common Good.
- The fourth Imaginary is called Ecotopia.

Although these imaginaries all describe sustainable futures on specific core criteria/KPIs, they differ on many criteria, including density of human settlements, integration of food production and nature, dietary composition and amounts of consumed per capita, efficiency and human work required, reliance on high-tech systems and innovative solutions, amount of energy used, local production or global markets, size of circular flows, *et cetera*.

The question for this model-based part to the overall Cross-Systems program was: How could each of these imaginaries be attained, starting from today's world? This required understanding – and in-depth analysis – of the current world (in terms of underlying structures and data), of these future worlds, of the policy gaps between today's world and these futures, and the levers that can be pulled to steer today's world towards each of these imaginaries, and their leverage (Figure 42). Advantage of using a data-rich model-based approach to do so, are that this approach requires one to elicit definitions and assumptions, and that this approach allows one to systemically analyse all available levers.

Figure 42: Data-rich model-based simulation from today towards the imaginaries.



Source: Authors own compilation.

Levers are policy or decision points in systems that might strongly change the system (i.e., have leverage). The model contains some 60 policy levers (see section on Levers).

Simulation from today's world in data to each of the four imaginaries: The sets of levers and goal values associated to these levers (i.e., the leverage they have) that are consistent with each of these imaginaries were pre-specified in the model. Imaginaries can be selected with the "SWITCH None0 IMAGINARY1234 EU" – setting the SWITCH value to 4 will select all pre-defined settings for the fourth Imaginary ('Ecotopia'). Note that any of these values or any setting could be changed to assess the effects of alternative goal values or settings. Note also that not only the goal values for each of these levers needs to be selected – the dynamics towards these goal values also needs to be selected. In terms of the dynamics over time of the effects on the levers, two options are currently built into the model: the same dynamics can be simulated across all levers in each of the domains of the system (namely: Diets, Target market for the agri-food system, Agricultural production itself, the Supply Chain, Cross Systems), or the same dynamics can be simulated for all levers across the entire system (to do so, make sure the "SWITCH TRANSITIONS ifALLinSYNC0 ifNOTinSYNC1" is set to 0). The dynamics can be different for the different imaginaries. In the simulation runs in the current version of this document, all imaginaries and levers across the entire system have the same dynamics. Simply modifying the assumed transient dynamics would result in different dynamics across imaginaries and/or domains of the system. These exogenous transient dynamics could be replaced by endogenous dynamics when turning the model into a full-fledged system dynamics model.
Note also that the behaviours in this report are preliminary simulations.

Key Performance Indicators:
Most KPIs are provided for countries, the EU27 as a whole and the world (as a whole). To be able to make sense of these hundreds of KPIs, and their interconnections, they have been bundled in sub views, with a logical sequence between the sub views. Not all KPI sub views are fully elaborated yet. The ones in green are fully elaborated, the ones in orange need to be filled in, the ones in red require quite some work to make them correspond to the real world. More on these KPIs can be found in the KEY PERFORMANCE INDICATORS appendix. In short, the following KPI views and KPIs are available:

1. The “Human population and their Built Environment” sub view comprises KPIs regarding human populations (equal across the imaginaries) and the built environment they occupy.
2. The “Diets” sub view (associated to the population in the previous bullet for all food items in the model) covers KPIs that relate to the food demand from these human populations.
3. “Demand (Domestic Supply)”, which comprises Food demand (for humans), Feed demand (for animals), demand for Seeds, demand emanating from the Processing sector, Logistics Losses in the food supply chain, Tourist Demand, and demand of the Food types for Other Uses. Food demand (for humans) results from the domestic human population and their diets, Feed demand from the animals kept in the agricultural sector that are not fed through grazing and other feed, etc. These KPIs show that the demand for these Food types is not just direct demand for food. The demand for feed is substantial, as are losses and other uses.
4. The “Demand for Agriculture” view comprises KPIs that indicate how much of the Domestic Supply in the previous sub view ends up as demand to the domestic agricultural sector in each country. How much of the Domestic Supply ends up as demand for the domestic agricultural sector depends on the market the agricultural sector produces for (e.g., just for domestic demand or for demand from international markets), as well as the competition from abroad (via import and export). There is a major difference between the imaginaries in terms of their “Demand for Agriculture”. In the Great Decoupling, the market for domestic agricultural producers is assumed to be the sum of Domestic Supply and net Exports to the whole world. In Unity in Adversity, the market for domestic agricultural producers is assumed to be the sum of Domestic Supply and net Exports to the EU27 only. And in Technocracy for the Common Good and in Ecotopia, the market for domestic agricultural producers is assumed to equal Domestic Supply.
5. The “Demand for Agriculture” in the previous bullet drives (but does not determine) the “Agricultural production” in this model: Agricultural production is split up in Vegetal production (permanent and temporary crops, in 10 Vegetal food classes) and production of Animal products (Meat, Milk, Eggs) and production of Fish and Seafood. Animal products are assumed to be produced by Animal Husbandry (6 animal classes). Although the food production sub models are quite extensive, this KPI sub view only reports on production per Food type and across Food types, as well as the expected surplus Meat production (which reacts to demand with a delay due to the need to keep breeding animals), and the fractions of meat from different animals in the overall meat production.
6. The “Processing, Packaging, Retail, Household Consumption” sub view covers KPIs that characterize the Processing, Packaging, Retail sectors and Household consumption, their GHG emissions, and the effects of alternative levers to drive the GHG emissions of these sectors down.
7. The KPIs in the “Import, Export, Throughput, Import Dependency Ratios” sub view cover country and EU27 import, export, throughput of each of the Food types and across all Food types, as well as the resulting dependency ratios (defined as production outside of the country or EU27 over consumption).
8. The “Animals kept, Animals Slaughtered, and Meat” sub view contains KPIs that characterize how many animals (per animal class) are kept, slaughtered, and how much meat is produced.
9. “Livestock on Pastures and Meadows versus Livestock in Stables” (available in the model).
10. The “Land Use and Land Use Change” sub view shows the plausible impact on Land Use and Land Use Changes on the alternative Land Use categories.
11. “Conventional versus Organic”: Conventional versus Organic and Intensive versus Extensive is available in the model.
12. “Manure and Synthetic Fertilizers” (is in the model, but requires further investigation)

13. “Nutrient Balance and Soil Nutrient Budget”
14. “Pesticides” (in the model (although data completeness is poor and effects on ecosystems and health hard to assess on a country level.
15. “Energy / Electricity Sector (Cross System)” (available in the model)
16. “On Farm Energy Use” – More operational modelling should be possible and data issues may need to be solved. KPIs are nevertheless available.
17. “Transportation (Cross Systems)” (available in the model, not translated to the EU27 yet)
18. “Waste” – Wastewater KPIs are available. KPIs regarding the Circularity need to be created.
19. “Greenhouse gas emissions”. This is the core KPI sub window. KPIs regarding all emissions from Agricultural production and the Supply Chain are available, for each country, the EU27 and the world at large, both in absolute terms and in relative terms. The Land Use and Land Use Change emissions need to be used with care, since the underlying data is limited. UNFCCC data can be used for more detailed investigations.

This CRAFT model is structured in following VENSIM views:

- DASHBOARD
- HUMAN POPULATION
- DIETS, PROTEINS, GHG EMISSIONS
- DOMESTIC SUPPLY (ELEMENTS)
- BALANCE (Domestic Supply, Production, Export, Import)
- ANIMAL HUSBANDRY and MEAT MILK EGG PRODUCTION
- ANINALS FEED, MANURE, NUTRIENTS, NUTRIENT BALANCE
- VEGETAL AGRI PRODUCTION (CONV vs ORG)
- LAND, LAND USE, LAND USE CHANGE
- WATER AVAILABILITY and WATER QUALITY
- AGRI-FOOD SUPPLY CHAIN
- WASTE, CIRCULARITY, BIOECONOMY
- KEY PERFORMANCE INDICATORS
- FAOSTAT DATA INPUTS

7.3.1 Cross-systems: electricity sectors across the EU27

The electricity sector itself is included in the model too, in a relatively simple way given that it is a cross-system that requires as big a model as the agri-food one, so that changes in the electric power sector in each country are translated in CO2eq emission intensity of the electricity used on farm and in the supply chain. Figure 43 (right-side graph) displays the 2011-2019 data on CO2eq emission intensity of the power sector. Availability of electricity (due to generation and grid capacity) and prices are not included, but might be added later.

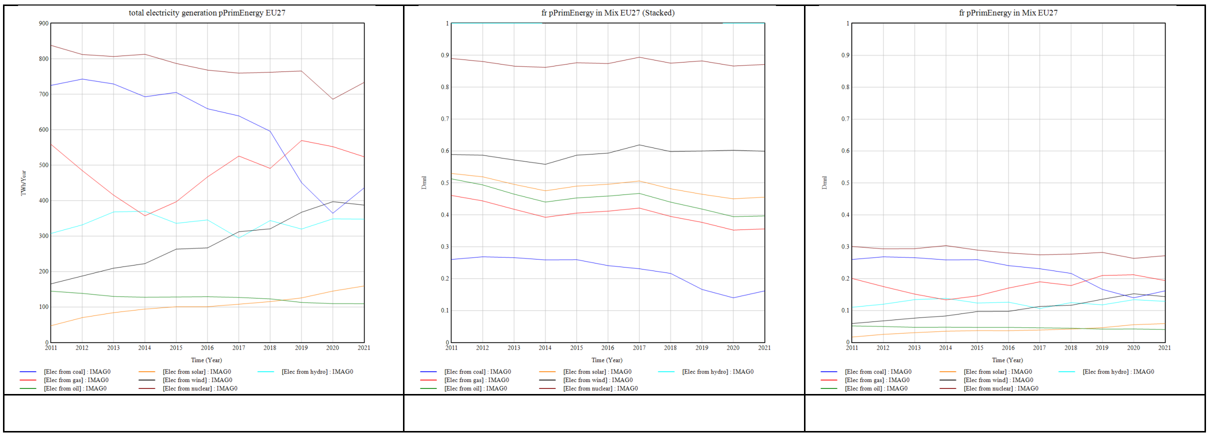
Electricity generation is included. Figure 43 displays the EU27 electricity generation per primary energy source, in absolute terms (left), in relative terms, stacked (middle), and in relative without stacking (right). From the graphs in Figure 43, the following could be concluded:

- Total EU27 electricity supply increased from 2786 TWh/Year in 2011 to 2697 TWh/Year in 2019.
- Since on farm electricity use amounted to 168295 TJ/year (46.75 TWh/Year) in 2011 and 187854 TJ/year (52.18 TWh/Year) in 2019, EU27 on farm electricity consumption was 1.68% of EU27 total electricity supply in 2011, and 1.93% in 2019.
- If all on farm energy was provided by the electricity sector, ignoring additional on farm transformation losses, what would be the impact on the electricity sector? Total on farm energy supply amounted to 1177350 TJ per year or 327.04 TWh per year in 2011, which was 11.74% of

total electricity generation in the EU27. In 2019, this was 1165710 TJ/year or 323.81 TWh per year, which was 12.01% of total electricity generation in the EU27. In other words, electrifying farm energy would require an increase in total EU27 electricity generation in the order of 12%.

- The data also shows that electricity generated with nuclear and coal and oil decreased over the data period. The relative contribution of fossil based electricity production decreased from 50% in 2011 to 40% in 2021. Fractions of electricity from wind and (to a lesser extent) from hydro and solar power increased somewhat.
- The contribution of each of the primary sources to EU27 power generation is relatively small. No technology or primary source contributed to more than a third of total generation. In 2021, electricity from nuclear amounted to 27.19%, electricity from gas to 19.42%, electricity from coal to 16.17%, electricity from wind to 14.37%, electricity from hydro to 12.90%, electricity from solar to 5.91%, and electricity from oil to 4.06%.

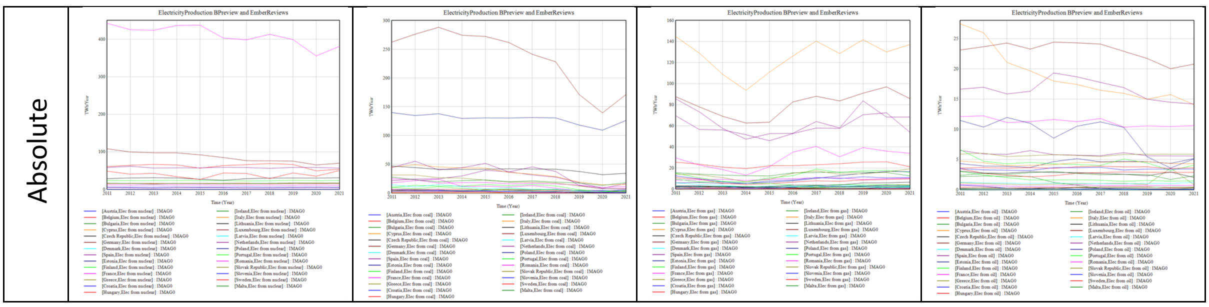
Figure 43: EU27 electricity generation per primary energy source: absolute (left), relative stacked (middle), relative (right).

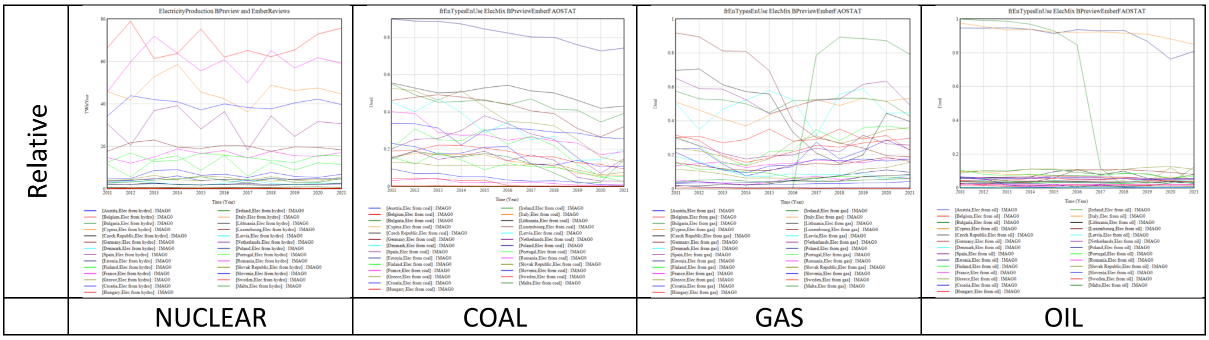


Source: Simulation results from Vensim Model. Erik Pruyt.

On the EU27 Member State level, things are quite different and diverse across EU27 Member States. Figure 44 and Figure 45 show the contribution of EU27 Member States in absolute terms (top) and in relative terms (bottom). The "absolute"comparison (top row) shows which countries contribute most to the use that primary energy source on the EU27 level. The latter (second row) shows how important primary energy sources are for each of the individual Member States.

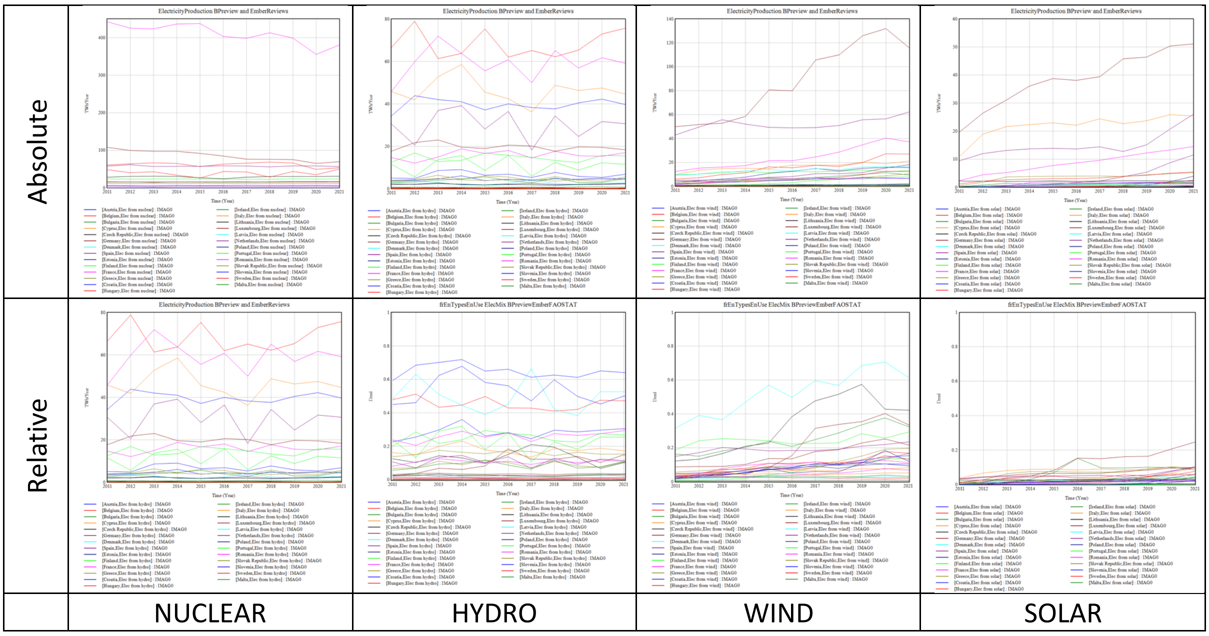
Figure 44: Absolute (top) and relative (bottom) contributions by different primary energy sources (Nuclear, Coal, Gas, Oil) to electricity generation from 2011 to 2021.





Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 45: Absolute (top) and relative (bottom) contributions by different primary energy sources (Nuclear, Hydro, Wind, Solar) to electricity generation from 2011 to 2021.



Source: Simulation results from Vensim Model. Erik Pruyt.

From Figures 44 and 45, the following conclusions can be drawn regarding the EU27 electricity generation landscape in 2021:

- **Nuclear Power**: In 2021, France led the EU27 in nuclear power generation, with a substantial contribution from nuclear-fired power plants. Germany, Spain, Sweden, and Belgium followed but at a significant distance. Relative to national power generation, nuclear's contribution was notably high in France, as well as in the Slovak Republic, Belgium, Hungary, Finland, the Czech Republic, Bulgaria, Romania, and Sweden.
- **Coal Power**: Germany and Poland had the highest absolute contributions from coal-fired power plants. In relative terms, coal's role in national electricity generation was exceptionally large in Poland.
- **Gas Power**: Gas-fired power plants contributed significantly in absolute terms in Italy, Germany, Spain, the Netherlands, and France. Relatively, the national grid in Malta (following a shift from oil to gas in 2016-2017), Italy, and the Netherlands showed high dependence on gas power.

- **Oil Power**: The largest contributions from oil-fired power plants were in Germany, Italy, Spain, and France. Relative to total national generation, oil-fired power was particularly significant in Cyprus and Estonia. Malta also relied heavily on oil until 2017.
- **Hydropower**: The largest absolute contributions from hydropower were observed in Sweden, France, Italy, Austria, and Spain. In relative terms, Austria, Latvia, Croatia, and Sweden had the highest shares of hydropower in their national grids.
- **Wind Power**: Wind energy contributed most to electricity generation in Germany, Spain, France, and Sweden. Relatively, Denmark, Lithuania, Luxembourg, Ireland, and Portugal saw the highest shares of wind power in their national electricity generation.
- **Solar Power**: Although smaller than other primary sources, solar power made a growing contribution across the EU27, with Germany, Italy, Spain, France, and the Netherlands leading in absolute terms. Luxembourg had the highest relative contribution. In most other EU countries, solar power's share remained below 12% in 2021, but it showed an upward trend.
- **Other Renewable Sources**: The current model does not account for electricity generation from biomass, wave, geothermal, or other alternative sources.
- **Nuclear Power in the Energy Transition**: Nuclear represents part of the traditional electricity generation system. While its role in the future energy mix is still debated in many EU27 member states, understanding the transition from fossil-fuel technologies to non-fossil-fuel sources remains crucial. This transition should be evaluated in terms of the specific greenhouse gas emissions from electricity used on farms and across the supply chain.

7.4 Levers

This chapter contains a discussion of levers that might close the gaps identified in the previous chapter, and the identification of alternative sets of levers that are consistent with the alternative imaginaries discussed in chapter 5.

Some levers discussed below are inferred directly from the gap analysis in chapter 6. They correspond directly (1-on-1) to the policy gaps.

Some levers are theoretic levers in the sense that the technical solution they "offer" does not exist in practice yet (e.g., "indirectEmMonS r2baseyear IMAGx"). They are discussed here irrespective of their technical and/or economic feasibility. Their development may be required for one or more imaginaries to materialize. In addition to the effect of the lever, the lever itself needs to be made technical and economic feasibility.

Some levers are "multi-levers" that address many aspects of the system or close many gaps at the same time (e.g., electricity and regenerative farming). They have multi-leverage, although some leverage may be in an undesirable direction, countering the desired effects.

In many cases, there are several levers that could close one and the same gap. These levers may be supplementary to each other: Pulling one of these levers entirely may do the job, pulling another lever entirely may also do the job, or pulling both (but not entirely) may also do the job.

Different levers may also be inconsistent with each other: pulling lever may reduce the basis for the other one or counter it entirely. For instance, not keeping ruminants in stables means their enteric fermentation emissions cannot be captured. So, if capture and use is the lever to be pulled to deal with enteric fermentation, then ruminants need to be kept in stables that allow for capturing CH_4 and using it. If there are alternative levers that could close the same gap, then a lever could be chosen that is consistent with the imaginary of choice. Since, different people may prefer different imaginaries, it makes sense to identify sets of levers that are consistent with the four imaginaries.

The list of levers covered here is not exhaustive. Any missing lever can be added at a later moment in time. Some levers listed below are not simulated yet in the next chapters.

In many cases, levers cannot "just be pulled" in practice. For instance, there is no "lever" to change the real diet of all real citizens of a EU27 Member State. It takes policies and measures to seduce individuals and/or organizations to change their individual behaviours. If enough individuals change their behaviours, then all these changes together result in systemic change with a particular leverage.

7.5 Levers implemented in the CRAFT model

The levers discussed here are ordered along the supply chain: starting with diets and the markets that are open to domestic agricultural production ('demand side and market levers'), followed by primary agricultural production ('on farm levers'), supply chain levers, cross systems levers, and finally by cross domain levers ('land use and land use change').

7.5.1 Demand side and market levers

All "demand side and market" (DM) levers are multi-levers: they affect multiple GHG gaps as well as land use.

LEVER DM01 – Dietary intake and Composition: This lever is a powerful multi-lever in that it affects *all* GHG sources, both the Agricultural Production ones and Supply Chain ones, both domestically (X) and in other countries (Y) from which the country imports. Effectively steering diets towards less demand per capita, healthier demand, and demand that is more environmentally friendly significantly affects the whole agri-food system and GHG emissions caused by it.

LEVER DM02 – Meat substitution: Substituting meat by alternative protein sources (e.g., vegetal proteins, synthetic proteins, low-impact proteins) is a powerful super lever. It affects all agricultural GHG emissions except rice cultivation. However, whether enteric fermentation emissions are mitigated depends on which meat is substituted (ruminants). Effects on GHG emissions from manure management, manure on soil, manure on pastures, and synthetic fertilizer use also depend on other choices (whether animals are kept in stables, whether reductions in manure application are compensated for by synthetic fertilizer application). If meat substitution leads to more synthetic fertilizer use, then there are also more GHG emissions from fertilizer manufacturing. Depending on the substitutes (e.g., plant-based non-processed non-packaged versus processed and packaged), there may (or may not) be indirect effects along the supply chain too.

LEVER DM03 – Milk substitution: Substituting dairy by alternative protein sources (e.g., plant-based proteins, synthetic proteins, or low impact animal-based proteins instead of ruminant-based dairy) is a powerful super lever, with a double dividend. Not only does it have a direct effect in terms of emissions from keeping animals for milk, but milk substitution also results indirectly in a reduction of meat animals that are the by-product of milk production. This indirect effect may be (at least) as important as the direct effect. Moreover, a large share of milk is processed into dairy. Depending on the substitutes (e.g., plant-based non-processed non-packaged versus processed and packaged), there may (or may not) be indirect effects along the supply chain too.

LEVER DM04 – Egg substitution: Substitution of eggs by vegetal or synthetic proteins, reduces the need for poultry farming and its impacts. These effects may be substantial for poultry and/or egg farming on the environmentally harmful side of the spectrum, but egg substitution may result in higher environmental damage, when egg from the environmentally side of the spectrum are substituted by substitutes with larger environmental impacts.

LEVER DM05 – Shifting animal mix: Shifting meat production from cows, sheep/goats, pigs to poultry meat or insect meat results, on average, in substantial emission reductions. Note, however, that in practice there is quite some variance in impacts for most of them – so much even, that the worst practices for the (on average) most sustainable type of animal farming perform worse than the best practices for the (on average) least sustainable type of animal farming.

LEVER DM06 – Markets for animal-based production: Producing animal-based products for the world market, only for the EU27 market, or only for domestic supply affects the amounts of agricultural products that are imported and exported, and therefore transported. It also affects each country's husbandry-related emissions, but also the agricultural emissions in the countries that otherwise would be exported to. Without additional measures, emissions and environmental impacts may decrease in one place to increase disproportionally in other places. Without changes in diets, aggregated effects may actually be adverse.

LEVER DM07 – Markets for crop production: Producing plant-based products for the world market, only for the EU27 market, or only for domestic supply affects the amounts of agricultural products that are imported and exported, and therefore transported. It also affects each country's agricultural emissions, but also the agricultural emissions in the countries that otherwise would be exported to. Without additional measures, emissions and environmental impacts may decrease in one place to increase in other places. Without changes in diets, aggregated effects on emissions and land use may actually be adverse in many places, but beneficial in countries that are cutting down forests for palm oil plantations or soja production for the west. Note, however, that currently the levers are defined for EU27 MSs, not for Brazil or Indonesia.

7.5.2 On farm emission levers

LEVER AG01 – Organic farming: Organic farming is a multi-lever with effects in multiple directions (i.e., not resulting in better outcomes on all KPIs). More organic farming reduces the use of synthetic fertilizer and of (particular types of) pesticides (although not all) and improves the long-term soil quality, but in the short term, it requires more land for the same amount of production, albeit with fewer inputs, or less production on the same amount of land.

LEVER AG02 – Large-scale high-tech high-efficiency crop farming: This lever relates to efficiency improvements due to the use of (ever more) larger and more efficient high-tech machinery (e.g., GPS combine harvesters). It could either lead to an increase in scale of operations and more mono-cropping, resulting in products with a lower per unit footprint and less land use for the same amount of production. In the current version of the model, it affects the specific N2O emissions of Synthetic Fertilizer use ("specific N2O emissions of SFuse IMAGx"), and it should be extended to other inputs (e.g., energy) in future versions of the model. This lever affects the same KPIs as Lever AG03.

LEVER AG03 – Precision agriculture: This lever relates to efficiency improvements due to the use of technologies and practices to supply **precise**ly the required agricultural inputs (water, nutrients, fertilizer, crop protection) and **precise**ly when they are needed, thereby reducing external inputs to the absolute minimum. Examples include indoor farming, hydroponics, drone-based farming, and drip irrigation. Precision agriculture requires more technology, monitoring and control, and in most cases more electricity, although it does not necessarily require large-scale operations as in Lever AG02. In the current version of the model, it affects Synthetic Fertilizer use ("ktonSFuse per ktonCROP IMAGx"). In a next version of the model, this lever should be extended to other inputs (pesticides, manure, water via irrigation, etc.). This lever affects the same KPIs as Lever AG02. It is not mutually exclusive.

LEVER AG04 – Vertical/Indoor Farming or Land Use/Location Decoupled Farming: This lever captures the space reduction from growing crops and possibly animals in vertical farms / indoor production. To account for the full power of vertical farming, this lever could/should be used together with LEVER AG03 (Precision agriculture) and with **LEVER CS09 – Domestic haul to NO Haul**

LEVER AG05 – Integrated Nature-Based Farming [yet to be implemented in the model]: This lever increases the use of integrated nature-based solutions, like regenerative agriculture (agriculture with cover crops and mixed crops, with livestock to clear new cropland instead of tilling, and with reduced use of pesticides and synthetic fertilizers), agrosilvipastoral systems (combining trees, crops, and animals), aquaponics (combining aquaculture (i.e., raising aquatic animals) and hydroponics (i.e., cultivating plants in water)) or aquaforestry (i.e., fish in ponds fed by leaves from the surrounding forest). Many of these systems integrated crop farming and animal farming (as much as, but not more than, needed).

LEVER AG06 – Number of animals kept: Although in the current version of the model, the numbers of animals kept follows (with a delay) changes in population times average diet and markets served (Levers DM01 to DM07) – it may as well be seen and used as a lever by regulators. Note, however, that the leverage is weak if demand does not adapt, and imports could compensate reductions in animal-based production. The number of animals kept is a super lever in that it influences many sources of GHG emissions in primary production (emissions from enteric fermentation, manure management, manure on soil, and manure on pastures) and possibly synthetic fertilizer use and production (in the wrong direction, although alternatives for synthetic fertilizers are available).

LEVER AG07 – Fraction of animals in stables: This lever is a lever that may be a precondition for other levers to work. It could affect emissions from enteric fermentation, manure management, manure on soil, manure on pastures, and the availability of land for different land uses. To capture enteric fermentation emissions, animals need to be kept in stables that allow one to capture them. Moreover, it is the fraction of animals kept in stables time the number of animals times the manure per animal per year that determines how much manure is available for manure management and how much manure could be applied to soils and pastures, versus how much is left in the fields. This lever needs to be as low as possible for Ecotopia (to use animals for regenerative farming) and as high as possible for Technocracy for the Common Good (to capture CH_4 and used it).

LEVER AG08 – Fraction of meadows and pastures used for intensive husbandry: This lever determines what fraction of temporary and permanent cultivated meadows and pastures is used for intensive husbandry. The rest of the temporary and permanent cultivated meadows and pastures and natural meadows and pastures are not used for intensive husbandry. This lever affects Land Use and Biodiversity – not GHG emissions.

LEVER AG09 – Maximum LSU kept on meadows and pastures for intensive husbandry: This lever sets an upper limit to the number of LSU kept (of all LSU kept except the ones that are kept permanently in stables – see LEVER AG07) on meadows and pastures used for intensive husbandry (LEVER AG08). This also determines (together with AG06, AG7, and AG08) how many LSU are kept on meadows and pastures that are not used intensively and how much land is used for keeping animals. This lever affects Land Use and Biodiversity – not GHG emissions (at least not in the current version of the model).

LEVER AG10 – Enteric fermentation avoidance/mitigation: This lever reduces enteric fermentation emissions of ruminants, for example through changes in feed or through food additives.

LEVER AG11 – Enteric fermentation CH4 capture and use: This lever reduces the climate impact of enteric fermentation emissions (CH4) from ruminants by capturing and using them (e.g., by burning them for energy production). This lever requires high values of LEVER07 and is supplementary to lever AG10.

LEVER AG12 – Manure management emission reduction: This lever reduces GHG emissions of Manure Management [how precisely needs to be elaborated].

LEVER AG13 – Direct manure emissions avoidance/mitigation: This lever reduces GHG emissions of direct manure on soils and manure on pastures emissions [how precisely needs to be elaborated, most likely through injection or other "precision farming approaches"].

LEVER AG14 – Indirect manure emissions avoidance/mitigation: This lever reduces GHG emissions of indirect manure on soils and manure on pastures emissions (better practices, cover crops that absorb nitrogen).

LEVER AG15 – Total On-Farm Energy Use: This lever relates to reducing total on-farm energy use. At a later stage, this lever could/should be split out in different activities and machinery used on farm that require different sorts of energy (pure electricity (light and digital), engines, heating).

LEVER AG16 – Fraction electricity in the On Farm energy mix: This lever relates to the fraction of electricity use in the total on-farm energy mix. This lever needs to be consistent with the Cross Systems lever on specific GHG emissions of the electricity sector. Shifting to more electricity in the on-farm mix only makes sense if the electricity sector has sufficiently greened and if sufficient electricity can be generated.

7.5.3 Supply chain emissions levers

The supply chain levers across the various tiers are quite similar. However, different levers influence each tier differently. For instance, the overall amounts can be reduced, particularly through levers in the diets and market segments. Following this, the fractions contributing to emissions—such as the portion that is processed, packaged, etc.—can be further minimized.
LEVER SC01 – Fraction being processed (relative to 2019): This lever relates to reducing the fraction that is being processed relative to today's fraction.
LEVER SC02 – Food processing efficiency of energy use: This lever allows for increasing the energy efficiency of food processing relative to today's values.
LEVER SC03 – Food processing energy mix (assumed in current version: 100% electricity): This lever allows for increasing or reducing the fraction of electricity in the energy mix relative to 2019 values.
LEVER SC04 – Fraction being packaged (relative to 2019): This lever relates to reducing the fraction that is being packaged relative to today's fraction.
LEVER SC05 – Food packaging efficiency of energy use: This lever allows for increasing the energy efficiency of food packaging relative to today's values.
LEVER SC06 – Food packaging energy mix (assumed in current version: 100% electricity): This lever allows for increasing or reducing the fraction of electricity in the energy mix relative to 2019 values.
LEVER SC07 – Fraction being distributed via retail stores. This lever relates to reducing the fraction that is being distributed via retail stores relative to today's fraction.
LEVER SC08 – Food retail efficiency of energy use: This lever allows for increasing the energy efficiency of the food retail sector relative to today's values.
LEVER SC09 – Food retail energy mix (assumed in current version: 100% electricity): This lever allows for increasing or reducing the fraction of electricity in the energy mix relative to 2019 values.

LEVER SC10 – Fraction of food household consumption with energy use (relative to 2019). This lever relates to reducing the fraction of food household consumption for which energy is used to store and prepare it relative to today's fraction.
LEVER SC11 – Energy efficiency of food household consumption: This lever allows for increasing the energy efficiency of food processing relative to today's values.
LEVER SC12 – Energy mix of food household consumption (assumed in current version: 100% electricity): This lever allows for increasing or reducing the fraction of electricity in the energy mix relative to 2019 values.

7.5.4 Cross systems levers

LEVER CS01 – Total Synthetic Fertilizer Manufacturing relative to 2019 values (from the INDUSTRY cross system).
LEVER CS02 – Energy efficiency Synthetic Fertilizer Manufacturing relative to 2019 values.
LEVER CS03 – GHG intensity Fertilizer Manufacturing relative to 2019 values.
LEVER CS04 – Food waste disposal relative to 2019 values.
LEVER CS05 – Waste losses logistics, relative to 2019 values.
LEVER CS06 – Waste Other Uses, relative to 2019 values.
LEVER CS07 – GHG intensity electricity mix: The GHG intensity of the electricity mix is an extremely important multi-lever, since on farm energy, all tiers of the supply chain, and Fertilizer manufacturing use electricity. By sufficiently greening the electricity mix and subsequently electrifying these sectors, GHG reductions can be achieved. However, electrifying without prior greening, may well result in more overall GHG emissions.
LEVER CS08 – Amounts transported, throughput: This lever reduces the amount of throughput on the national level and forth and back movements of agri-food items across the world (e.g., for processing).
LEVER CS09 – Domestic haul to NO Haul: This lever reduces the amounts of agri-food products that are transported domestically. In other words, own or local production is favoured instead of production elsewhere in the country. This lever is relevant for Ecotopia.
LEVER CS10 – Modes of transport Medium Haul: This lever allows for switching medium haul modes of transport (from truck to train). ("MHaulMODALshiftTRANSP rate of gapclosing r2potential").
LEVER CS11 – Modes of transport Long Haul: This lever allows for switching long haul modes of transport (from plane to ship). ("LHaulMODALshiftTRANSP rate of gap closing r2potential").
LEVER CS12 – GHG Intensity Transport: This lever allows for reducing the GHG intensity of transportation (across modes) relative to the base year.

7.6 Levers and KPIs

These levers impact directly or indirectly affect Key Performance Indicators (KPIs). Table 6 sketches how levers (grouped according to their main sub system) are directly (or indirectly) affect KPIs. Note that this is work in progress: the grey parts in the table still need to be elaborated (either in the table or both in the model and in the table).

Different symbols are used in Table 6 Major (direct) effects in a Member State are indicated by 'X'; possible yet uncertain direct/substantial effects in a Member State by '?X?'; minor direct effects or major indirect effects in a Member State by 'x'; effects in Member State(s) X and elsewhere Y by 'XY'; effects in Member State X and the opposite effect in country Y by 'X<>Y'; minor direct effects or major indirect effects on Member State X and other countries Y by 'xy'; a possible effect, although uncertain because of the existence of other options by 'uvw'; and effects that are not included in the model yet by 'nyiM'.

Table 6: Levers and KPIs affected [Grey -> to be implemented].

	SUB SYSTEM	LEVER	ON FARM EN USE	ENTERIC FERMENT	MANURE MGT	MANURE on SOIL	MANURE on PAST	SYN FERTILISER USE	CROP RESIDUES	CROP RESID BURN	RICE CULTIVATION	SYN FERT MANUFAC	PROCESSING	PACKAGING	FOOD RETAIL	HH CONSUMPTION	FOOD WASTE	AGRI-F. TRANSPORT	LAND USE	PESTICIDES USE	BIODIVERSITY	SOIL QUALITY	WATER QUALITY	FOOD SECURITY	IMPORT DEPEND.	HEALTHY FOOD	HEALTHY ENV.	ANIMAL WELFARE
DM01	DIET	Dietary intake and composition	nyiM	XY	XY	XY	XY	XY	xy	xy	xy	xy	xy	xy	xy	xy	xy	X	X									
DM02	DIET	Meat substitution	nyiM	X	X	X	X	X	xy	xy		nyiM							X									
DM03	DIET	Milk substitution	nyiM	X	X	X	X	X	xy	xy		nyiM	?X?						X									
DM04	DIET	Egg substitution	nyiM		x	x	x	X				nyiM																
DM05	DIET	Shifting animal mix		X	X	X	X	x																				
DM06	MARKET	Markets for animal-based production	nyiM	X<>Y	X<>Y	X<>Y	X<>Y	X<>Y				nyiM	nyiM	nyiM	(x)			X	X									
DM07	MARKET	Markets for crop production	nyiM						X<>Y	X<>Y	X<>Y		X	X				X	X									
AG01	Cropland	Organic farming						X				X							X	X								
AG02	Cropland	Large-scale high-tech high-efficiency crop farming	X					nyiM	nyiM	nyiM																		
AG03	Cropland	Precision agriculture	nyiM					nyiM	nyiM	nyiM																		
AG04	Integrated	Vertical/Indoor or Land Use/Location-decoupled farming																	X	x								
AG05	Integrated	Integrated Nature-Based Farming	nyiM	nyiM	nyiM	nyiM	nyiM	nyiM	nyiM	nyiM		nyiM	nyiM	nyiM	nyiM	nyiM	nyiM	nyiM			nyiM							
AG06	Husbandry	Number of animals kept		X	X	X	X	uvw				uvw																
AG07	Husbandry	Fraction of animals in stables		?X?	X	X	X	?X?				?X?							X									
AG08	Husbandry	Fr meadows and pastures for intensive husbandry																	X									
AG09	Husbandry	Maximum LSU on Intensive Meqadows Pastures																	X		X							
AG10	Husbandry	Enteric fermentation avoidance/mitigation (fodder)		X																								
AG11	Husbandry	Enteric fermentation CH4 capture and use		X																								
AG12	Husbandry	Manure management emission reduction			X																							
AG13	Husbandry	Direct manure emissions avoidance/mitigation				X																						
AG14	Husbandry	Indirect manure emissions avoidance/mitigation				X	?X?																					
AG15	OnFarm EnUse	Total On-Farm Energy Use	X																									
AG16	OnFarm EnUse	Fraction electricity in the On Farm energy mix	X																									
AG17	Fisheries	Shift from MSY fisheries to Ecosystem-based Fisheries																	nyiM		nyiM							
AG18	Fisheries	Shift from Fisheries to Aquaculture and Blue Economy																	nyiM		nyiM							
AG19	Fisheries	Energy Mix Fisheries	nyiM																									
SC01	Supply chain	Fraction being processed											X															
SC02	Supply chain	Food processing efficiency of energy use											X															
SC03	Supply chain	Food processing energy mix (assumed for now: 100% elec.)											X															
SC04	Supply chain	Fraction being packaged												X														
SC05	Supply chain	Food packaging efficiency of energy use												X														
SC06	Supply chain	Food packaging energy mix (assumed: 100% electricity)												X														
SC07	Supply chain	Fraction being distributed via retail stores													X													
SC08	Supply chain	Food retail efficiency of energy use													X													
SC09	Supply chain	Food retail energy mix (assumed for now: 100% electricity)													X													
SC10	Supply chain	Fraction of food household consumption with energy use														X												
SC11	Supply chain	Energy efficiency of food household consumption														X												
SC12	Supply chain	Energy mix of food household consumption (100% elec.)														X												
CS01	Cross Systems	Total Synthetic Fertilizer Manufacturing										X																
CS02	Cross Systems	Energy efficiency Synthetic Fertilizer Manufacturing										X																
CS03	Cross Systems	GHG intensity Fertilizer Manufacturing										X																
CS04	Cross Systems	Food waste disposal circularity															X											
CS05	Cross Systems	Waste losses logistics															X											
CS06	Cross Systems	Waste Other Uses															X											
CS07	Cross Systems	GHG intensity electricity mix	X									X	X	X	X	X	X											
CS08	Cross Systems	Amounts transported, throughput																X										
CS09	Cross Systems	Domestic haul to NO Haul																X										
CS10	Cross Systems	Modes of transport Medium Haul																X										
CS11	Cross Systems	Modes of transport Long Haul																X										
CS12	Cross Systems	GHG Intensity Transport																X										
LU01	Cross Domain	Fr land covered with forests																										
LU02	Cross Domain	Fr land covered with natural meadows and pastures																										
LU03	Cross Domain	Fr total land (incl agri land) in line with nature																										
LU04	Cross Domain	Specific biodiversity measures																										
LU05	Cross Domain	Land use for bioeconomy																										

LEGEND				
	X	major (direct) effect	x	minor direct effect or major indirect effect in MS
	?X?	possible yet uncertain effect	X<>Y	effect X in MS opposite to effect Y elsewhere
	XY	effect in Member State(s) X and elsewhere Y	xy	minor direct effect or major indirect effect
	nyiM	not yet in Model	uvw	possible effect, but other options available

Source: Authors compilation.

7.7 Levers and imaginaries

Not all levers should be activated together. Pulling different levers leads to different developments and ultimately to different futures. To end up in a particular future (imaginary), one should only pull sets of levers that are consistent with that future (imaginary) and drive the overall system towards that future (imaginary).

Table 6 shows how levers and imaginaries might be connected. Different values for these levers may work too. The values in Table 7 are merely a starting point to explore pathways between the present and plausible futures and/or imaginaries.

Table 7: Levers and Imaginaries.

CODE	SS	LEVER - NAME	Explanation and/or Principle	PRE and NO IMAGINARY	Type of goal (Final, r2baseyr)	IMAG1: Great Decoupling	IMAG2 Unity in Adversity	IMAG3: Tech 4 CommonGood	IMAG4: Ecotopia
DM01	DIC	Dietary intake and composition	Abundance local MS		Func of prod 2019	no restriction	25% MS, 75% EU, m50% M150%	no restriction	100% MS, m10% M110%
DM02	DIC	Meat substitution	Substitution alternative protein s.	Initial value	Goal r2baseyear	50%	50%	25%	75%
DM03	DIC	Milk substitution	Substitution alternative protein s.	Initial value	Goal r2baseyear	50%	50%	25%	75%
DM04	DIC	Egg substitution	Substitution alternative protein s.	Initial value	Goal r2baseyear	50%	50%	25%	75%
DM05	DIC	Shifting animal mix	More to less polluting or to needs	Initial value					
DM06	MK	Markets for animal-based production	Func. of World, EU, MS FF or Food			DS + net Export	DS+X to EU only	DS FoodFeed	DS food only
DM07	MK	Markets for crop production	Func. of World, EU, MS FF or Food			DS + net Export	DS+X to EU only	DS FoodFeed	DS food only
AG01	CL	Organic farming	Art fertilizer (pesticides to do)		Final goal value	95%	50%	25%	100%
AG02	CL	Large-scale high-tech high-efficiency crop farming	Less due to scale and efficiency		Goal r2baseyear	50%	50%	10%	100%
AG03	CL	Precision agriculture	Less due to precision and tech		Goal r2baseyear	5%	25%	50%	50%
AG04	INT	Vertical/Indoor or LU/Location-decoupled farming							
AG05	INT	Integrated Nature-Based Farming	Regenerative, etc.			0%	0%	0%	90%
AG06	HB	Number of animals kept	Function of diets & market, Govt?			=F(diets)	=F(diets)	=F(diets)	=F(diets)
AG07	HB	Fraction of animals in stables	EF capture, N2O emis. Soils&pastures		Absolute fraction	25%	75%	100%	5%
AG08	HB	Fr meadows and pastures for intensive husbandry							
AG09	HB	Maximum LSU on Intensive Meqadows Pastures							
AG10	HB	Enteric fermentation mitigation (e.g., fodder)	CH4 intensity due2: fodder, additives	-1% per year		50%	100%	25%	100%
AG11	HB	Enteric fermentation CH4 capture and use	CH4 emis. capture and use =f(AG07)			50%	50%	5%	100%
AG12	HB	Manure management emission reduction	MM emissions relative to base year		Goal r2baseyear	5%	50%	5%	95%
AG13	HB	Direct manure emissions avoidance/mitigation	directEmMonS r2baseyear IMAGx		Goal r2baseyear	25%	75%	5%	5%
AG14	HB	Indirect manure emissions avoidance/mitigation							
AG15	OF	On-Farm Energy Use (light, machines, heating)	Relative to base year (2019)	+1% per year		25%	100%	400%	10%
AG16	OF	Fr electricity in the On Farm energy mix (100%)	Energy mix (electricity in ~)			Elec mix	Elec mix	Elec mix	Elec mix
AG17	FI	Shift from MSY to Ecosystem-based Fisheries							
AG18	FI	Shift Fisheries to Aquaculture & Blue Economy							
AG19	FI	Energy Mix Fisheries							
SC01	SC	Fraction being processed	Fraction being processed	+1% per year	Final goal value	200%	100%	50%	10%
SC02	SC	Food processing efficiency of energy use	Energy efficiency -> GHG emissions	-1% per year	Final goal value	0.9	0.5	0.9	0.1
SC03	SC	Food processing energy mix (assumed: 100% elec.)	GHG intensity elec processing			Elec mix	Elec mix	Elec mix	Elec mix
SC04	SC	Fraction being packaged	Fraction being packaged	+1% per year	Final goal value	2	1	0.5	0.1
SC05	SC	Food packaging efficiency of energy use	Energy efficiency -> GHG emissions	-1% per year	Final goal value	0.9	0.5	0.9	0.1
SC06	SC	Food packaging energy mix (assumed: 100% elec.)	GHG intensity elec packaging			Elec mix	Elec mix	Elec mix	Elec mix
SC07	SC	Fraction being distributed via retail stores	Fraction sold via retail	+1% per year	Final goal value	2	1	0.5	0.1
SC08	SC	Food retail efficiency of energy use	Energy efficiency -> GHG emissions	-1% per year	Final goal value	0.9	0.5	0.9	0.1
SC09	SC	Food retail energy mix (assumed: 100% electricity)	GHG intensity elec retail			Elec mix	Elec mix	Elec mix	Elec mix
SC10	SC	Fr food household consumption w energy use	Relative to base year (2019)	+1% per year	Final goal value	2	1	0.5	0.1
SC11	SC	Energy efficiency of food household consumption	Energy efficiency -> GHG emissions	-1% per year	Final goal value	0.9	0.5	0.9	0.1
SC12	SC	Energy mix of household consumption (100% elec.)	GHG intensity elec consumption			Elec mix	Elec mix	Elec mix	Elec mix
CS01	CS	Total Synthetic Fertilizer Manufacturing	(Partly a Func. of husbandry & uvw)						
CS02	CS	Energy efficiency Synth. Fertilizer Manufacturing	GHG intensity elec consumption			Elec mix	Elec mix	Elec mix	Elec mix
CS03	CS	GHG intensity Fertilizer Manufacturing	GHG intensity FM			0.1	0.5	0.1	1
CS04	CS	Food waste disposal circularity	Food waste disposal						
CS05	CS	Waste losses logistics	Losses logistics	+0% per year	Goal r2baseyear	100%	50%	50%	1%
CS06	CS	Waste Other Uses	Other uses	+2% per year	Goal r2baseyear	200%	100%	50%	200%
CS07	CS	GHG intensity electricity mix	GHG intensity of the electricity mix		Goal r2baseyear	10%	25%	10%	50%
CS08	CS	Amounts transported, throughput	Amounts transported, throughput	+2% per year	Goal r2baseyear	50%	25%	150%	10%
CS09	CS	Domestic haul to NO Haul	Domestic NO haul	+2% per year	Fin goal r2potential	50%	10%	0%	95%
CS10	CS	Modes of transport Medium Haul	Modes of transport MEDIUM HAUL	starting 0.29	Fin goal r2potential	100%	50%	90%	50%
CS11	CS	Modes of transport Long Haul	Modes of transport LONG HAUL	starting 0.98	Fin goal r2potential	100%	98%	98%	100%
CS12	CS	GHG Intensity Transport	GHG intensity TRANSPORT r2baseyear	-1% per year	Fin goal r2potential	0.1	0.25	0.1	0.5
LU01	LU	Fr land covered with forests							
LU02	LU	Fr land covered with natural meadows and pastures							
LU03	LU	Fr total land (incl agri land) in line with nature							
LU04	LU	Specific biodiversity measures							
LU05	LU	Land use for bioeconomy							

Source: Authors compilation.

8 Results

8.1 Exogenous transition dynamics

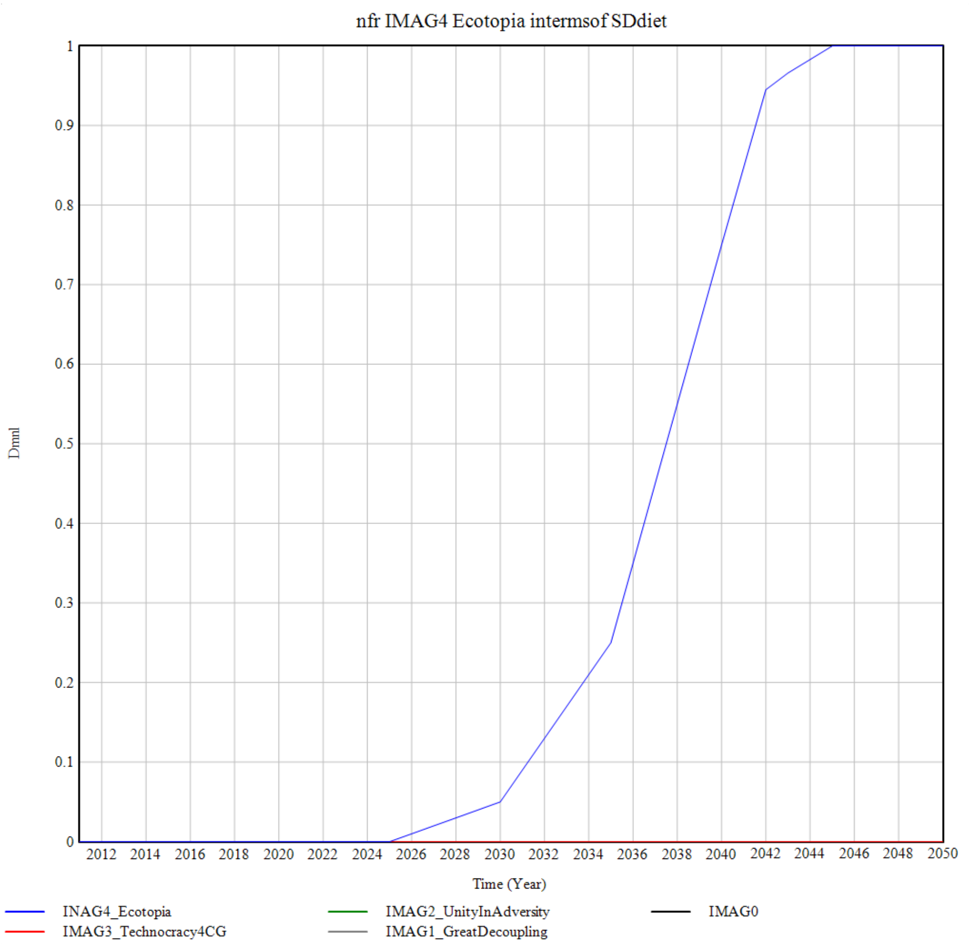
It is important to understand that the temporal transition dynamics exogenously enforced upon the levers in the model strongly influence the results. S-shaped behaviour is implemented here. Different dynamics may occur and can easily be implemented. These exogenous temporal transition dynamics could be substituted by endogenous dynamics by simulating different rates of change instead of transitions towards goal values, or by adding endogenous structures to simulate these dynamics endogenously (e.g., of the change in behaviour by individuals and organizations due to policies, measures, instruments).

The transition dynamics for Ecotopia is visualized on the right-hand side of Figure 46. In the base simulations in this background report, the same exogenous dynamics is used for all levers in all domains, and therefore for all four imaginaries. The reason is that, else, the impression might be given that one of the imaginaries reaches the end state faster or with a different transition dynamic than the other imaginaries. That may well be the case, and that may be simulated with the current model, but in the current simulation runs, we do not have reason to implement these transition speeds nor dynamics differently for different imaginaries.

Also note that, in the simulations displayed in Figure 46, the transition dynamics are purposefully made “discrete” (i.e., discrete jumps in 2025, 2030, 2035, 2042 and 2045): Until 2025 there is no evolution towards the Ecotopia imaginary yet (or any other imaginary), from 2025 it starts to rise to 5% in 2030, 25% in 2035, 75% in 2040, 95% in 2042, and 100% in 2045. The way this is implemented in the model is that, say, in 2030, a particular goal value, 5% of the value comes from the imaginary, and 95% of the value from the value it would assume without imaginary. Gradually the No Imaginary values are therefore replaced by the chosen imaginary values. This is shown in Figure 46.

Note that, in the simulations shown in Figure 46, the transition dynamics are intentionally set to occur at discrete intervals (i.e., discrete jumps in 2025, 2030, 2035, 2042, and 2045). Up until 2025, there is no shift toward the Ecotopia imaginary or any other imaginary. Starting in 2025, the Ecotopia imaginary begins to influence the model, reaching 5% in 2030, 25% in 2035, 75% in 2040, 95% in 2042, and ultimately 100% by 2045. In the model, this transition is implemented such that, for instance, in 2030, 5% of the goal value is derived from the imaginary scenario, while 95% remains based on the ‘No Imaginary’ baseline . Over time, the ‘No Imaginary’ values are progressively replaced by values from the selected imaginary. This gradual replacement process is illustrated in Figure 46.

Figure 46: One of many plausible transition dynamics to simulate pathways between real values and future goal values associated to the imaginaries.



Source: Screen shot from Vensim Simulation Model. Erik Pruyt.

The reason for purposefully working with these discrete jumps in 2025, 2030, 2035, 2042 and 2045 is that, by doing so, it is clearly visible (in all subsequent graphs) that there is an exogenous influence on the rest of the model behaviour. Note also that the discrete S-shaped behaviour in 46implies that the strongest change is happening between the start of the years 2035 and 2042. S-shaped behaviour implies that change starts slowly (it is rather hard to get started), then accelerates, to balance out at the end of the transition (it gets gradually harder to reach the aim). That does not need to be the case. Other shapes could easily be implemented to assess the effects of different dynamics on overall system behaviour and the behaviours of specific KPIs.

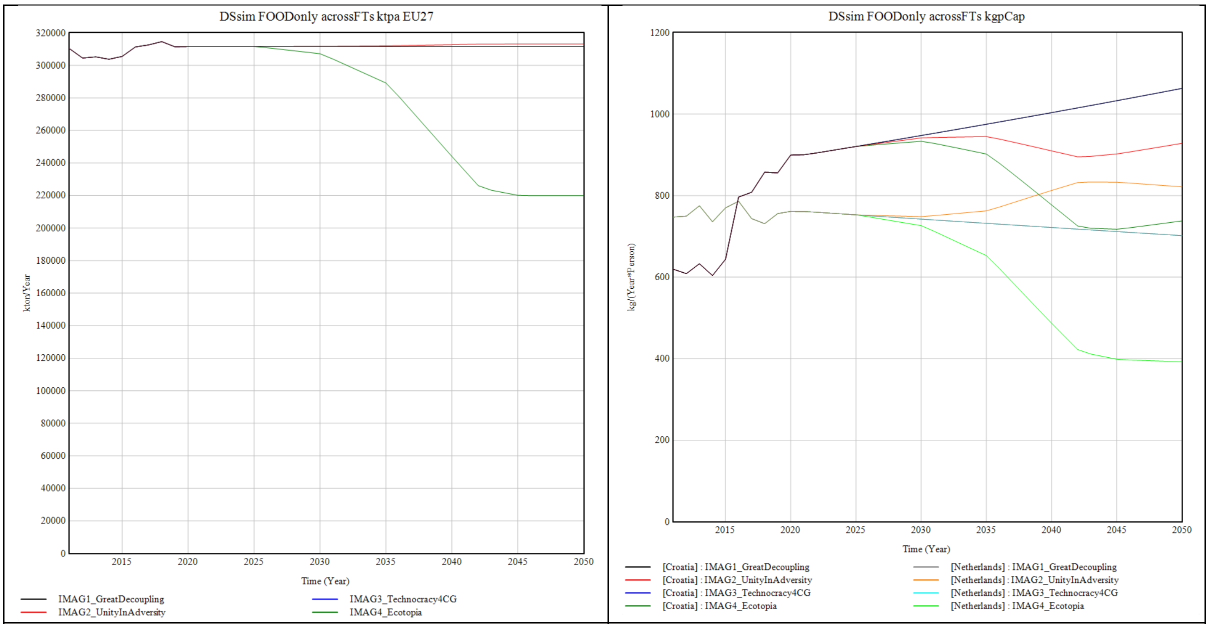
Finally, note that goal values might also be changing over time. That is, goal values in the Ecotopia imaginary also change over time, say, from 0% in 2025 to 100% in 2035.

8.2 Humans and built environment

In this model, the causal chains start mainly with human populations. For the sake of comparison between the imaginaries, we do not assume differences in population dynamics between the alternative Imaginaries. In terms of diets, there is a big difference across the imaginaries for individual countries though (see left hand side figure below, for two EU27 countries). Even though there are differences for individual member states, there is hardly any difference in terms of total amount of food, between the imaginaries on the level of the EU27, except for Ecotopia. In Ecotopia, the total amount of food demanded per capita falls from 700 kg pppa (per person per annum) to some 500 kg pppa. In terms of dietary composition, there are quite significant changes between today and these imaginaries, and between the different imaginaries.

The results on the left side of Figure 47 show that, although there are differences among individual Member States, there is minimal variation at the EU27 level in the total amount of food across three of the four imaginaries (Ecotopia, Great Decoupling, Technocracy for the Common Good, Unity in Adversity). However, this does not imply an absence of significant shifts in per capita consumption within individual Member States across these scenarios. On the right side of Figure 47, the results indicate that overall per capita demand in Croatia increases in the Great Decoupling and Technocracy for the Common Good scenarios, while it decreases in the Netherlands. In contrast, the opposite trend is observed in the Unity in Adversity scenario.

Figure 47: Large differences between countries in changing food demand being supplied (right), seem to cancel out on the EU27 level (left), except in case of Ecotopia in which food demand supplied drops significantly.



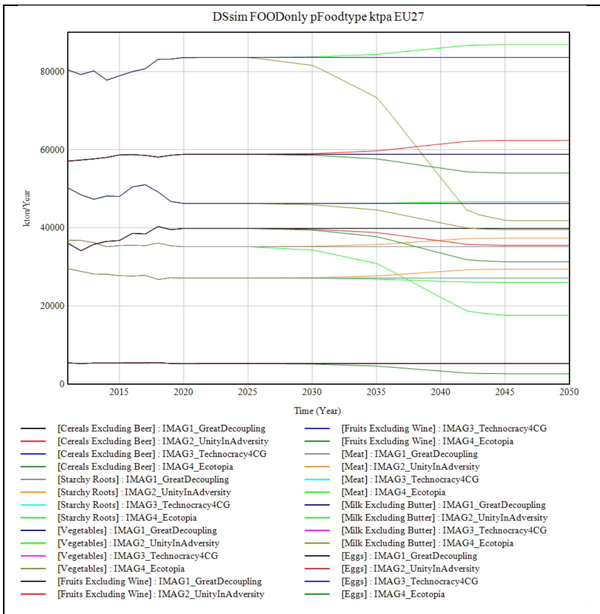
Per capita demand (in kton/year) remains rather stable at the EU27 level in all scenarios except for Ecotopia	… which does not mean that there are no major shifts in consumption in different Member States.

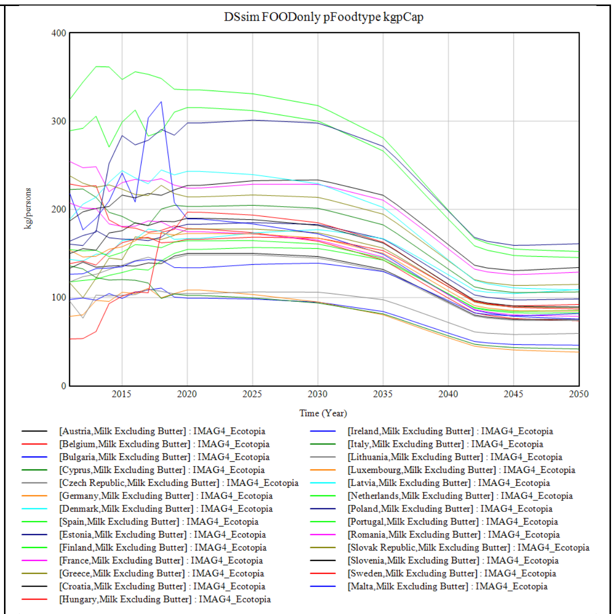
Source: Simulation results from Vensim Model. Erik Pruyt.

The Ecotopia scenario is different, due to its settings for the DM01 Lever. Because of its settings for the DM01 Lever, it is the only scenario with dietary restrictions on the Member State level if domestic production does not cover the needs (possibly down to 10% of 2019 per capita consumption). The Great Decoupling and Technocracy for the Common Good have no restrictions, and Unity in Diversity still allows for intra-EU production and trade (up to 75% of domestic supply) and restricts to a maximum of 50% of 2019 per capita consumption.
Note that the simulated changes in dietary composition could be improved by feedback and inputs from nutritional experts. For example, minimum values for food demand per capita are required, for instance for Luxembourg that, following historic data only, did not produce enough to avoid a major drop in food demand supplied (“DSsim FOODonly”). Right now, these are just 4 scenarios to demonstrate one possible use of the model.
In Ecotopia, the total amount of food demanded per capita in the EU27 falls from 700 kg pppa to less than 500 kg pppa. There are significant changes in terms of dietary composition between historic per capita demand and per capita demand in these imaginaries, and between the per capita demands of the different imaginaries.

The biggest drops per domestic supply (i.e., demand effectively supplied) across food types in the EU27 are those of Milk and Meat in the Ecotopia scenario (see left-hand side graph in Figure 48). This is partly due to the additional restrictions for meat and milk in the Ecotopia scenario. The effect on Milk and dairy (except butter) is visualized in the right-side graph in figure 48. This is milk/dairy including milk substitutes. In case of Ecotopia, substitution is relatively low (25% in 2045) though. Still milk consumption is 25% lower by 2045 than in the right-side graph in figure 48.

Figure 48: EU27 Domestic Supply per Food type (left), EU27 MSs Domestic Supply of Milk (ex butter) for the Ecotopia scenario (right).



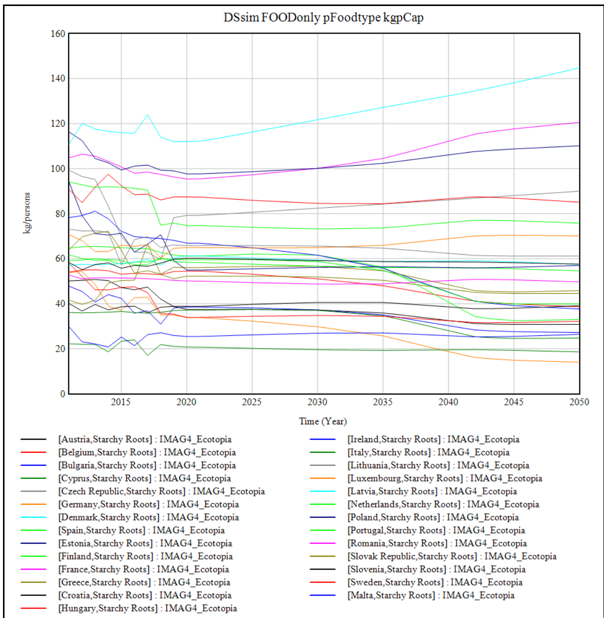


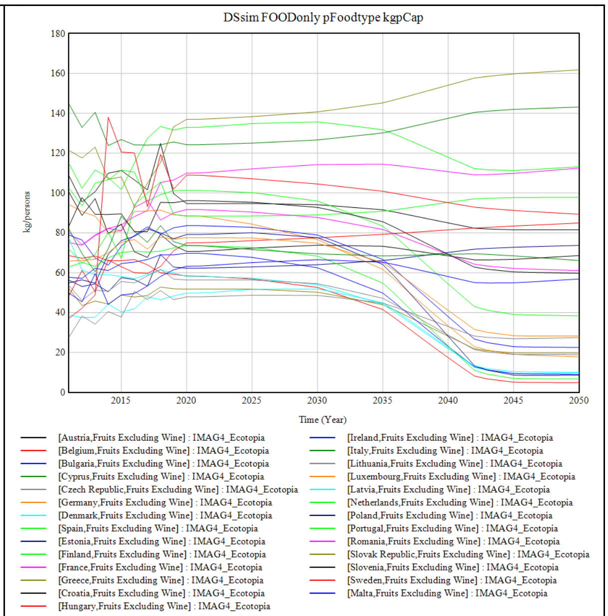
Domestic Supply per Food type in kton/year across the EU27 for 4 imaginaries	Domestic Supply Milk/Dairy (exc butter) in kg/person/year across EU27 MSs for Imaginary 4 - Ecotopia

Source: Simulation results from Vensim Model. Erik Pruyt.

Not all consumption of all food types decreases in all EU27 as in the right-side graph in Figure 48. Figure 49 shows, for Ecotopia, that per capita consumption (Domestic Supply Food-only) of some food types increases in some countries and decreases in other countries.

Figure 49: Domestic supply per capita of Starchy roots (left) and Fruits (right) across the EU27 in the Ecotopia Scenario.



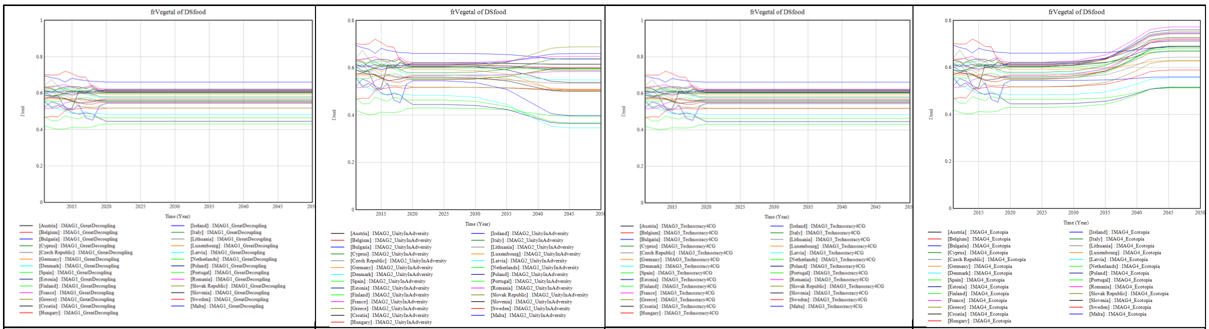


Starchy roots consumption in EU27 MSs for the Ecotopia scenario	Fruits consumption across the EU27 for the Ecotopia scenario

Source: Simulation results from Vensim Model. Erik Pruyt.

Vegetal fractions (and compositions) of EU27 diets in the Great Decoupling and Technocracy for the Common Good do not change (today's diets are continued), whereas they change for the Unity in Adversity and Ecotopia scenarios. In Ecotopia, all diets become substantially more vegetal, whereas in Unity in Adversity, it depends on the country (whether circumstances are more in favour or vegetal or animal-based consumption). Note, however, that the vegetal fraction is higher if meat substitutes are vegetal too (not specified yet -> need to add some additional levers for that).

Figure 50: Fraction vegetal of Domestic Supply Food-only (meat substitution is included in animal products).



Great Decoupling	Unity in Adversity	Technocracy for the Common G.	Ecotopia

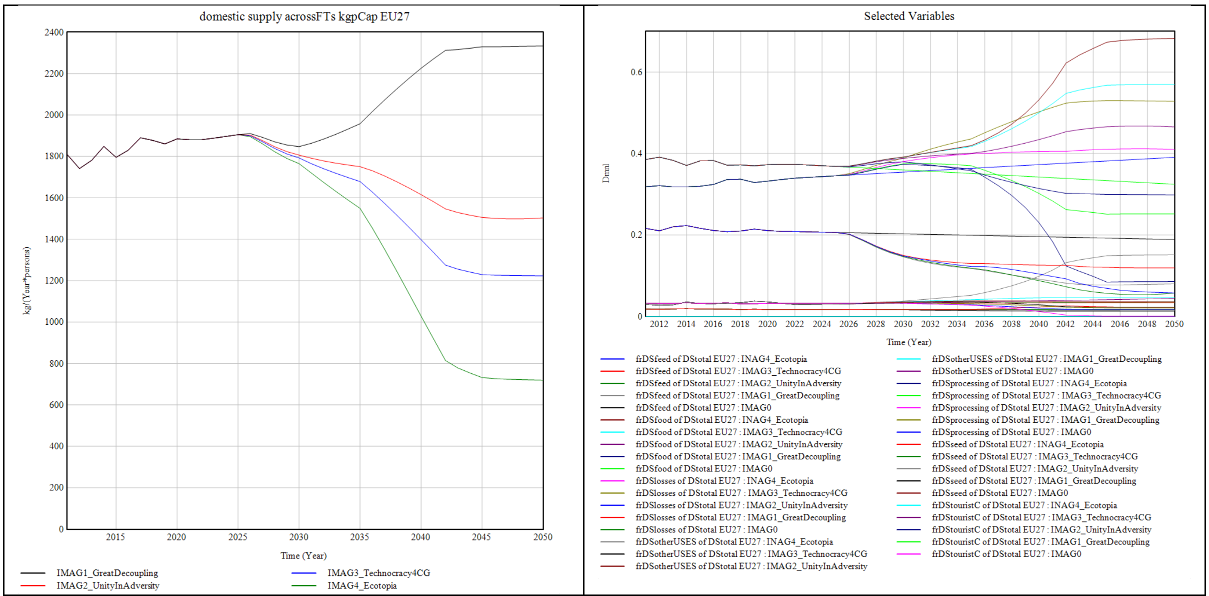
Source: Simulation results from Vensim Model. Erik Pruyt.

8.3 Domestic supply and agricultural production

Domestic Supply for food is only part of the story. Total domestic supply consists of demand for Food, Feed, Seeds, Tourist Consumption, Logistics Losses, and demand for Other Uses. Note that evolutions in Other Uses are not included in what follows.

Figure 51 shows that, overall, Domestic Supply falls most in Ecotopia (esp. due to a drop in demand for Food and Feed), followed by Technocracy for the Common Good, Unity in Diversity, and rises after a small dip in the Great Decoupling scenario. This is the result of the combined effects on elements of Domestic Supply (demand for Food, Feed, Seeds, Tourist Cons., Losses, Other Uses).

Figure 51: EU27 Domestic Supply per Capita (left) and EU27 Fractions of Components of Domestic Supply (right).

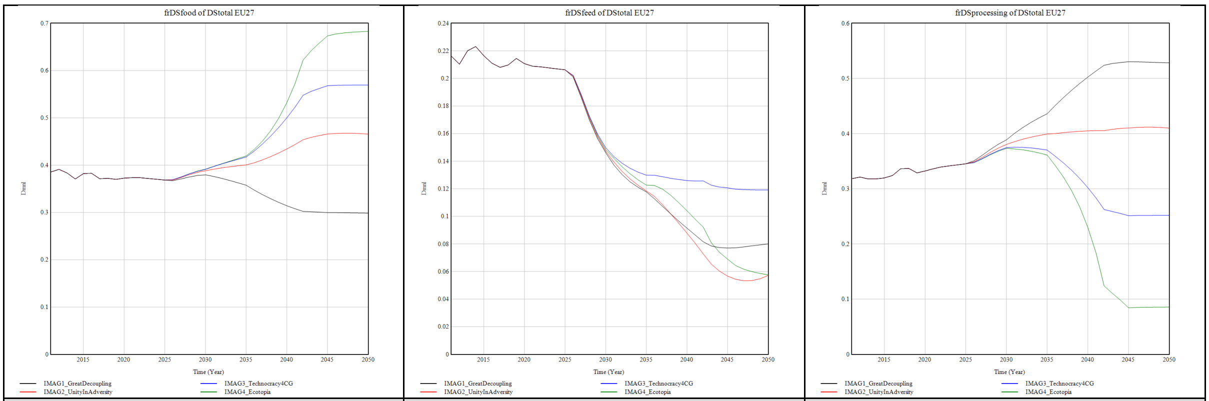


EU27 Domestic Supply per Capita [kg/person/year]	Fractions of Components of Domestic Supply

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 52 splits out the main fractions: the fraction of the Food component significantly increases in the Ecotopia scenario, followed by the Technocracy for the Common Good scenario, and the Unity in Adversity, whereas it decreases in the Great Decoupling scenario. The relative contribution of Feed drops in all scenarios. And the relative contribution of processing drops in the Ecotopia scenario, followed by the Technocracy for the Common Good scenario, and the Unity in Adversity, and increases in the Great Decoupling scenario. Note that this is without processing related to meat/milk/egg substitutes.

Figure 52: EU27 Fractions of Components of Domestic Supply – Food (left), Feed (middle), Processing (right).

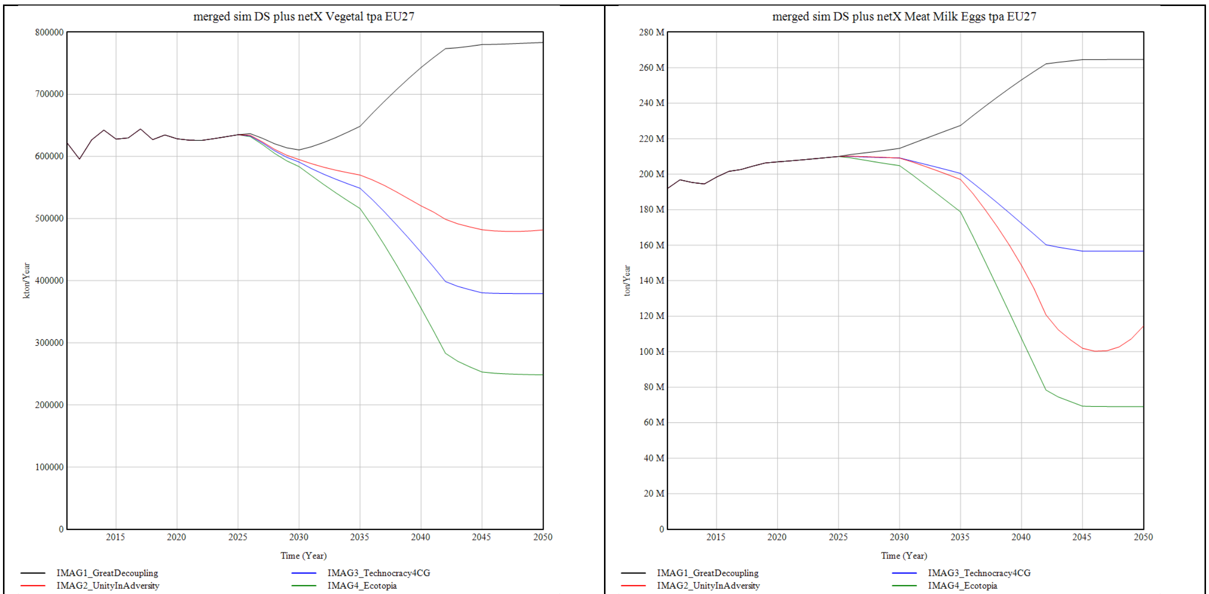


Fraction Food of Domestic Supply	Fraction Feed of Domestic Supply	Fraction Processing of Domestic Supply

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 53 shows the total demand (without meat/milk/egg substitutes) supplied by the agricultural sector (i.e., the sum of Domestic Supply and net exports), which largely follows Domestic Supply. Animal-based production (including substitutes) in the EU27 and the production of different vegetal food types is also affected by changing markets (e.g., in case of Ecotopia, international servicing is replaced by local demand and production only).

Figure 53: Demand for vegetal excluding substitutes (left) and animal-based including substitutes (right) production.

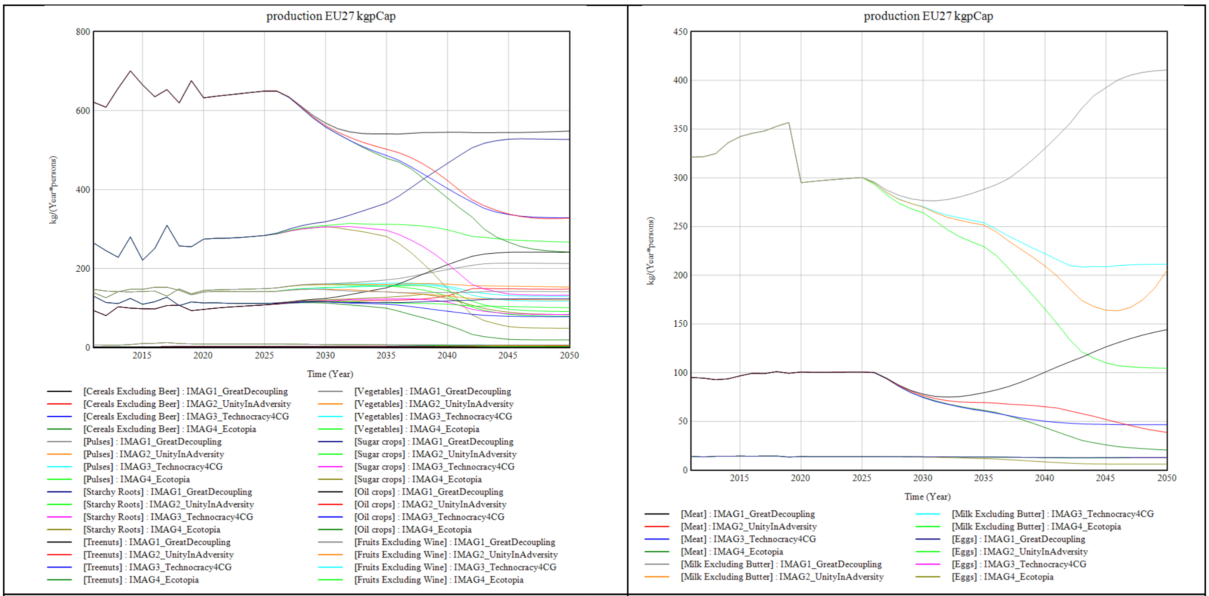


Demand for the vegetal agricultural sector (excluding meat/milk/egg substitutes)	Demand to animal-based production sector (including meat/milk/egg substitutes)

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 54 shows detailed vegetal production excluding meat/milk/egg substitutes (left) and detailed animal-based production including meat/milk/egg substitutes (right) for the EU27 as a whole, across the four imaginary scenarios.

Figure 54: Detailed vegetal production (left) and animal-based production including meat/milk/egg substitutes (right) for the EU27 as a whole, across the four imaginary scenarios.

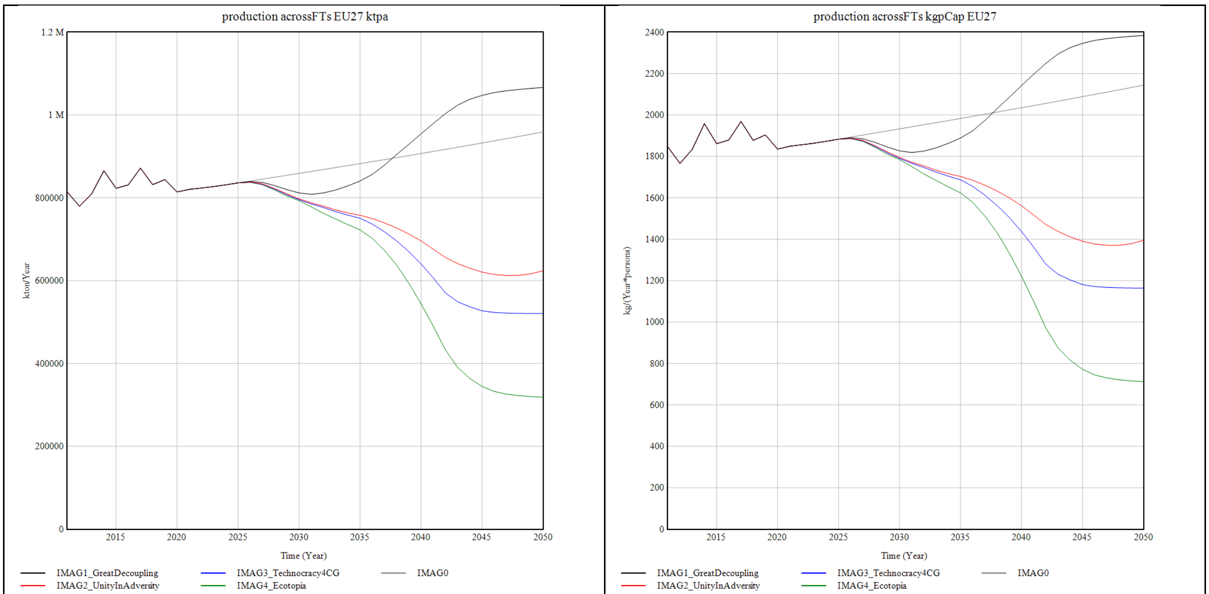


EU27 vegetal production (details) without meat/milk/egg substitutes	Animal-based production including meat/milk/egg substitutes

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 55 shows the resulting total agricultural production and total agricultural production per capita.

Figure 55: total EU27 agricultural production (left) and total EU27 agricultural production per capita (right).

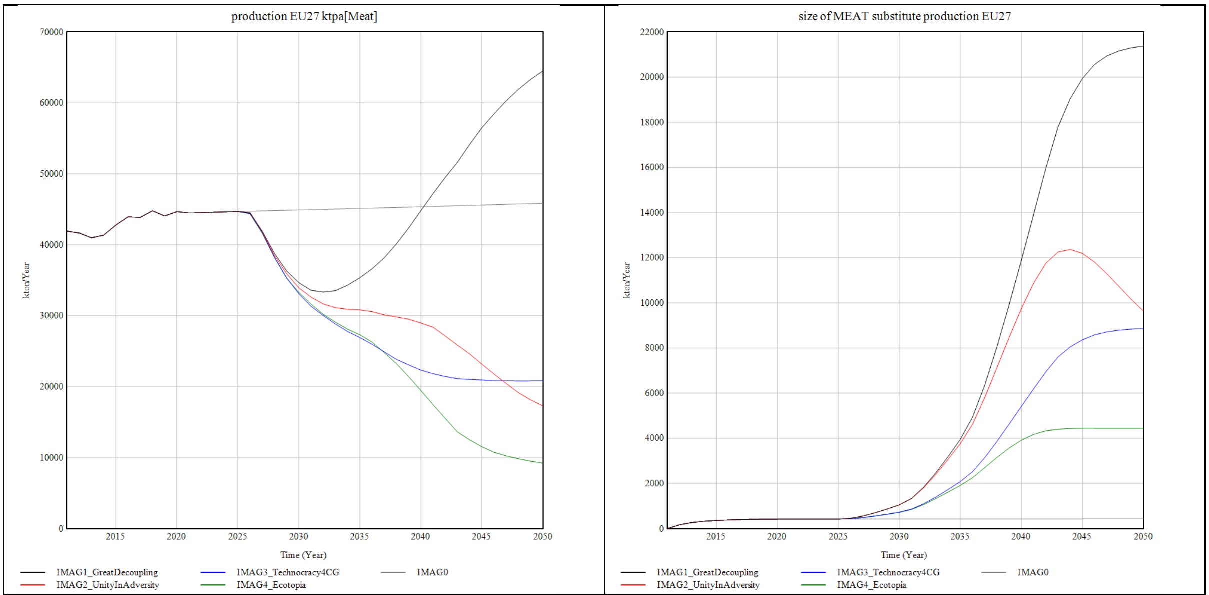


total agricultural production EU27	total agricultural production per capita EU27

Source: Simulation results from Vensim Model. Erik Pruyt.

Meat (including substitutes) production of the imaginary scenarios is displayed in Figure 56 (left), with the associated fractions of animal types (right).

Figure 56: Meat production including meat substitutes (left) and meat substitutes (right) per imaginary scenario/pathway.

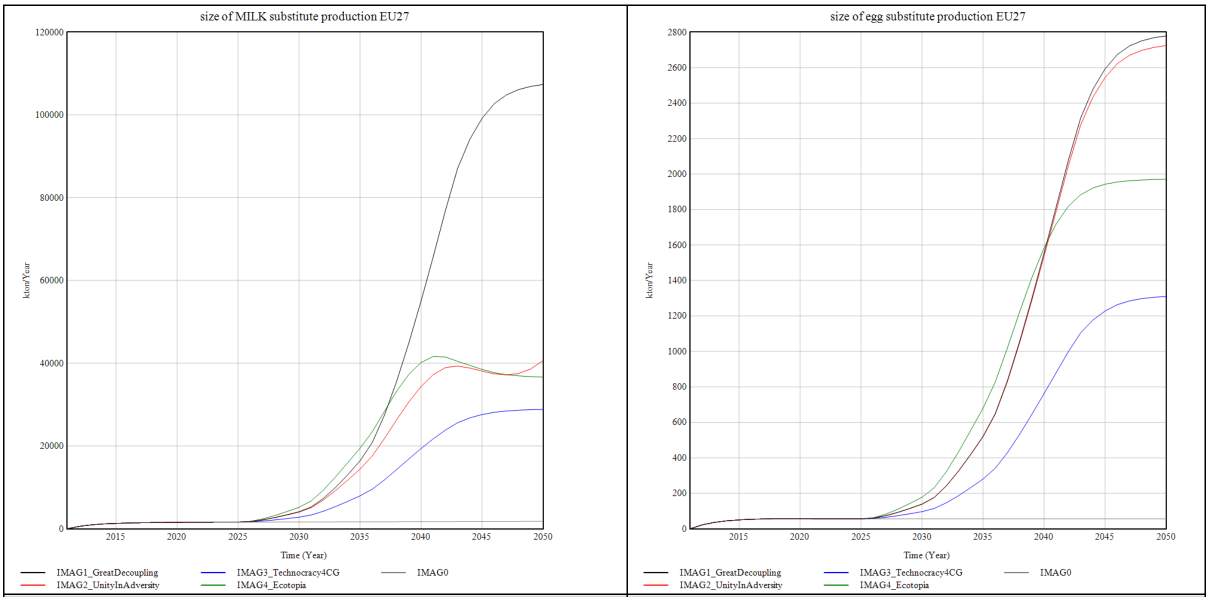


Meat production (including meat substitutes)	Meat substitutes

Source: Simulation results from Vensim Model. Erik Pruyt.

Note that total meat production displayed in the left-side graph Figure 56 includes meat substitutes displayed in the right-side graph Figure 56. Milk substitution and egg substitution are displayed in Figure 57. Note how large milk substitution would be even in when total milk demand (including milk substitutes) would go down. Note that this is the effect of a two-step calculation of substitution starting with diets (without making a difference between meat/milk/eggs and their substitutes) and the subsequent calculation of meat/milk/eggs and the substitutes for meat/milk/eggs (Figure 58).

Figure 57: Milk substitution (left) and egg substitution (right).

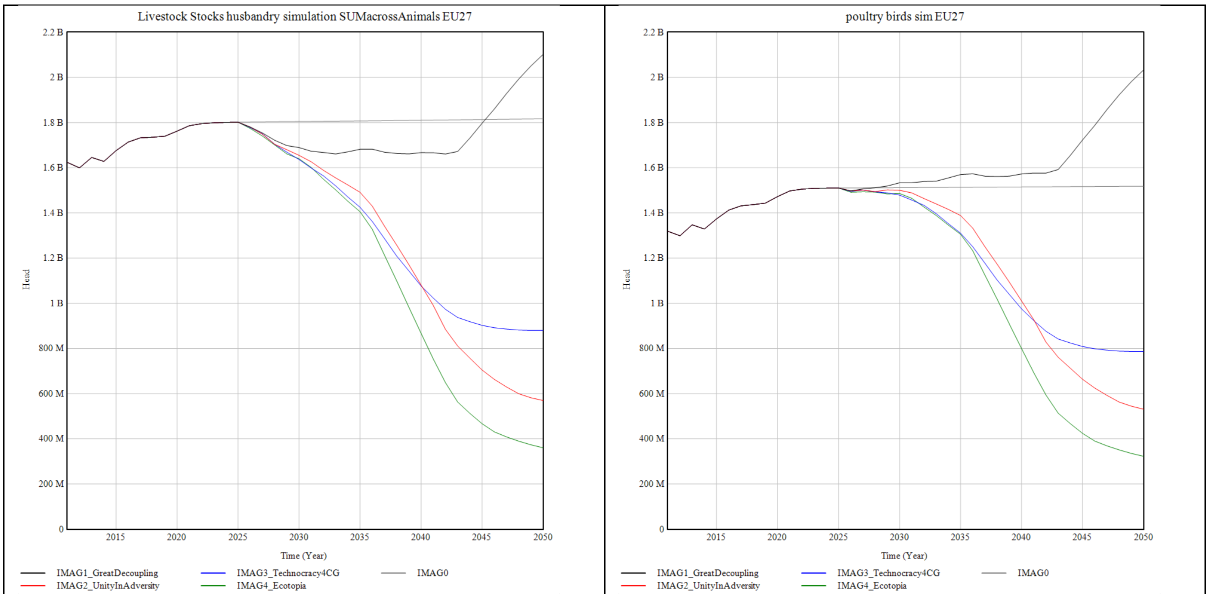


Milk substitution in the model	Egg substitution in the model

Source: Simulation results from Vensim Model. Erik Pruyt.

These two effects together (decreasing overall demand and substitution) strongly affect the livestock stocks (Figure 58). Figures 58 and 59 show the resulting EU27 livestock stocks across all animals, and the livestock stocks of poultry birds and Figure 59 shows the effects on cattle and sheep and goats shows these combined effects on swine and mules and asses. Note that except for one imaginary scenario (Great Decoupling) and one animal stock (poultry birds), overall livestock are dramatically reduced.

Figure 58: total EU27 livestock stocks across all animals (left), and for poultry birds (right).

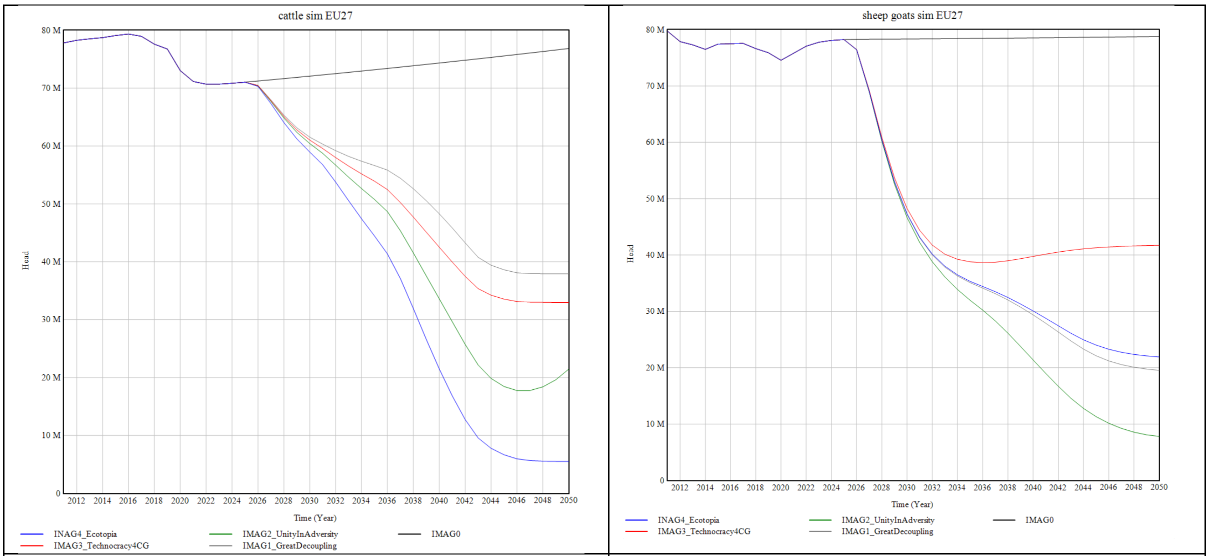


Significant drop in animals kept, except in the Great Decoupling…	…for poultry birds (due to a major shift to poultry)

Source: Simulation results from Vensim Model. Erik Pruyt.

Figures 59 and 60 show the drastic drop in husbandry populations of most animals that is due to the combined effect of changing diets (most in Ecotopia, least in Great Decoupling), the substantial shift to consumption of meat substitutes, and the shift to poultry meat (esp. in the Great Decoupling).

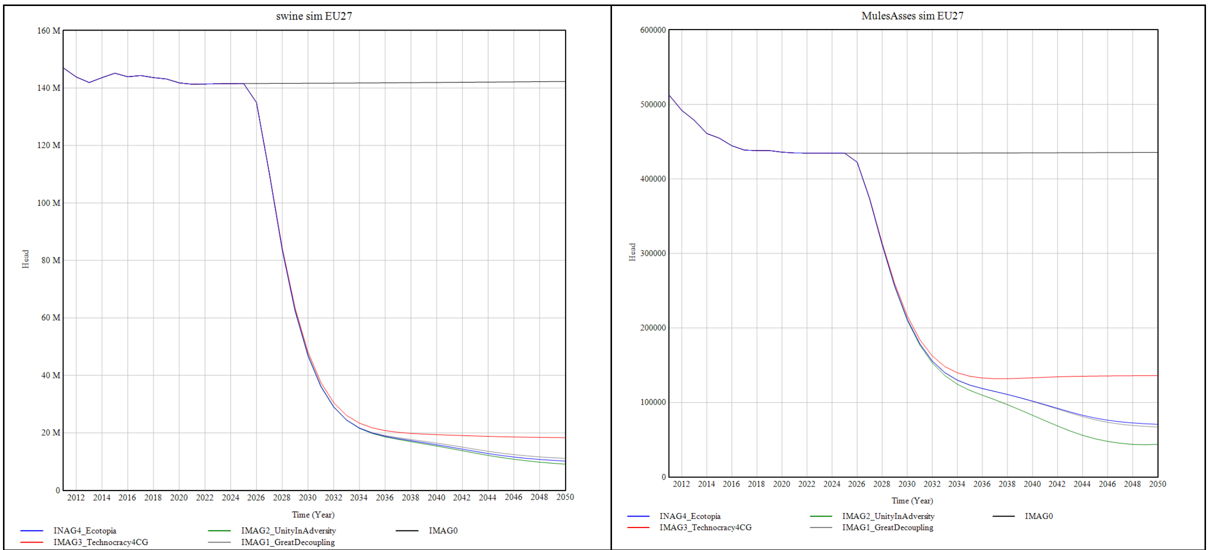
Figure 59: total EU27 livestock stocks of cattle (left), and sheep and goats (right).



Cattle in the EU27	Sheep and goats in the EU27

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 60: total EU27 livestock stocks of swine (left), and mules and asses (right).

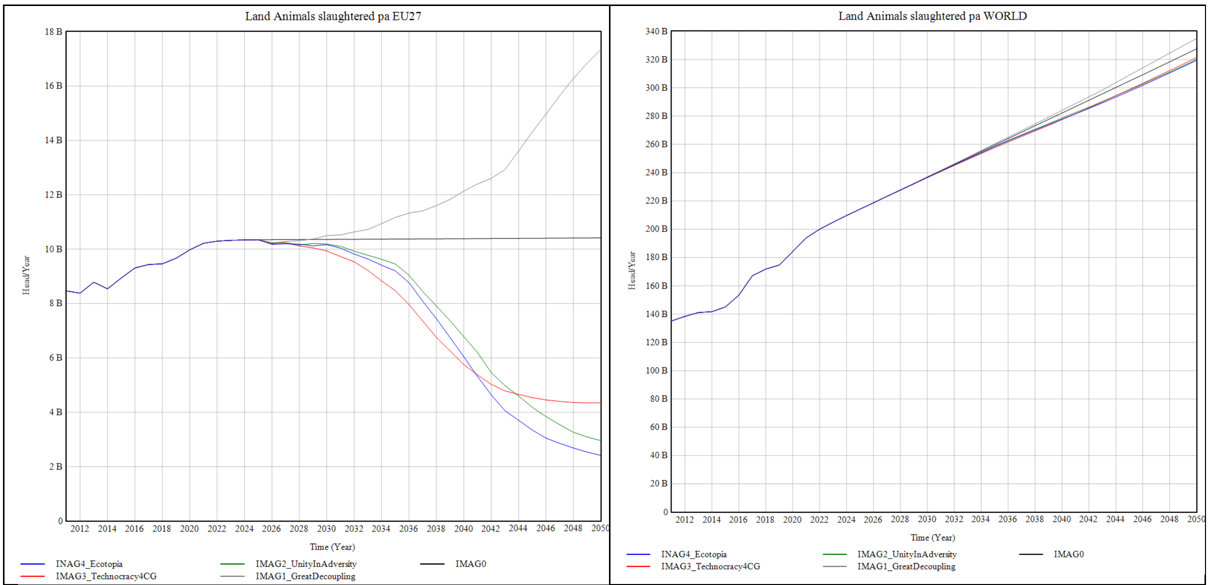


Swine in the EU27	Mules and asses in the EU27

Source: Simulation results from Vensim Model. Erik Pruyt.

This also leads to a drop in animals slaughtered per year in the EU27 (left-side graph in Figure 61), except in the Great Decoupling imaginary where slaughtering rises due to the shift to poultry bird meat (and the fact that it takes a whole lot more poultry bird slaughtering for the same amount of meat than slaughtering of the other larger animals. Note, however, that on the global scale, the decreases in animals slaughtered in the EU27 are hardly visible (right-side graph in Figure 61).

Figure 61: Animals slaughtered per year in the EU27 (left) and across the globe (right).



Animals slaughtered pa in the EU27 drops, except in the Great Decoupling imaginary where slaughtering rises due to poultry	Note, however, that on the global scale, the decreases in animals slaughtered in the EU27 are hardly visible.

Source: Simulation results from Vensim Model. Erik Pruyt.

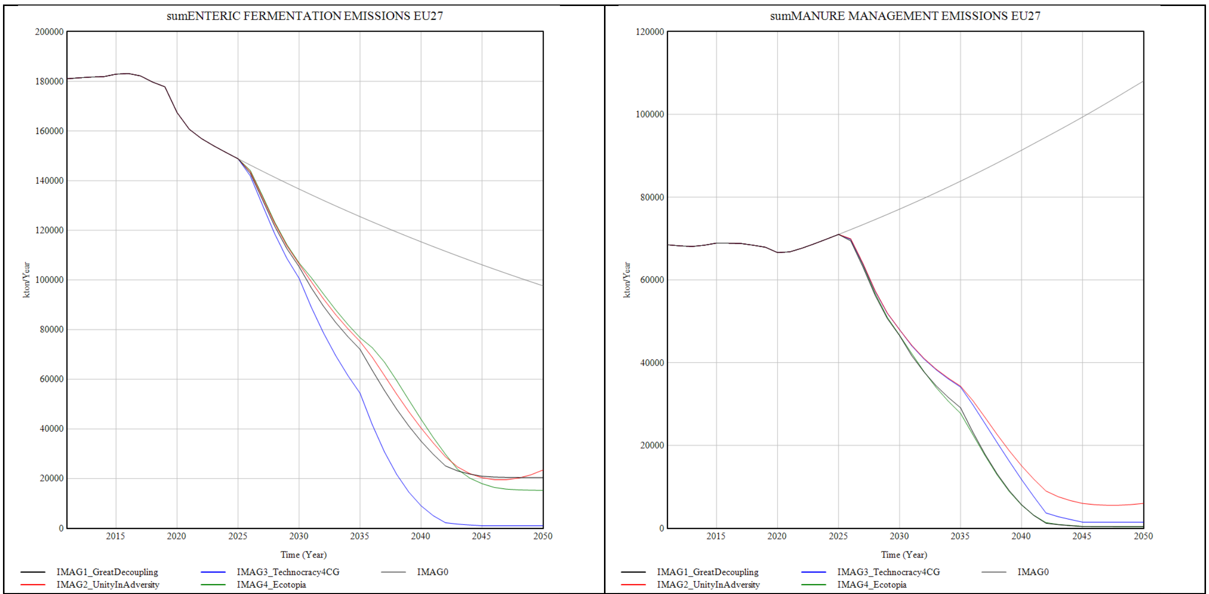
8.4 Emissions GHG Emissions of agricultural production and agri-food supply chain

The evolutions discussed above for the transitions towards the Great Decoupling imaginary, the Unity in Adversity imaginary, the Technocracy for the Common Good imaginary, and the Ecotopia imaginary have very substantial GHG emissions effects. These effects are displayed in Figure 62 to 72.

Figure 62 displays EU27 Enteric Fermentation CO2eq emissions (left) and EU27 Manure Management CO2eq emissions (right). While enteric fermentation emissions were already decreasing, each of the transitions towards the imaginaries does so faster. Manure management emissions were not decreasing yet. The levers activated for the different imaginaries pull CO2eq emissions related to manure management down.

Figure 63 displays that the EU27 Manure on soils CO2eq emissions (left) are more easily dealt with than the EU27 Manure on Pastures CO2eq emissions (right). Although these emissions were already dropping, all imaginaries at first speed up the decrease. However, the reduction in case of the Great Decoupling transition then halts, bounces back and forth, and remains higher than without transition. Manure on pastures emissions towards Ecotopia halt too, but then continue to fall. Unity in Adversity and Technocracy for the Common Good keep on dropping.

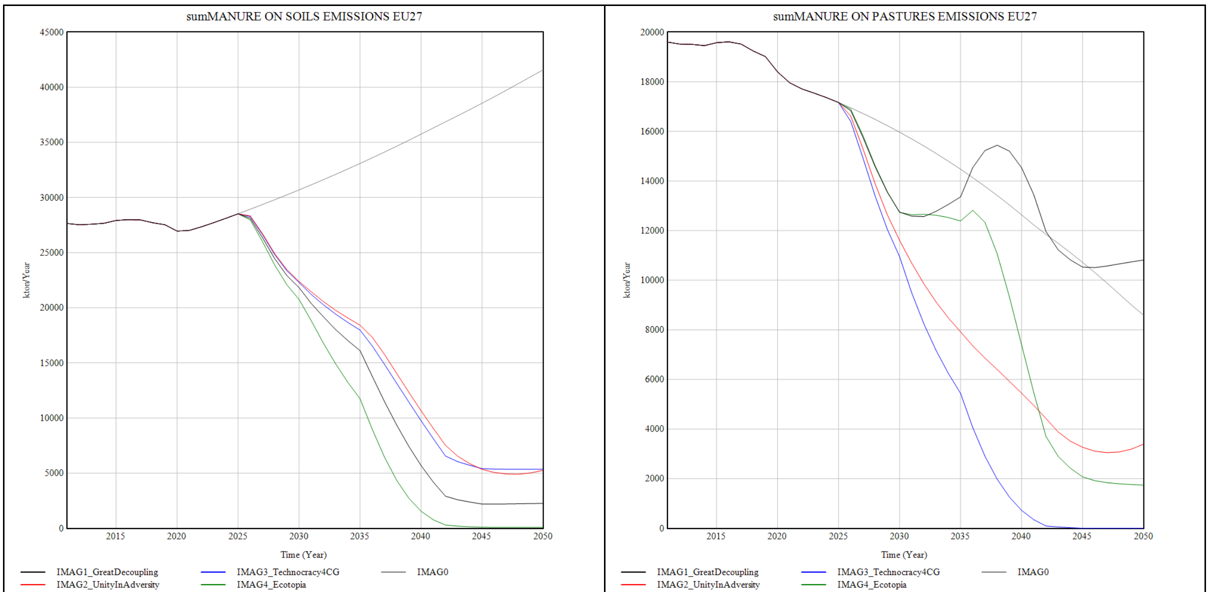
Figure 62: EU27 Enteric Fermentation CO2eq emissions (left) and EU27 Manure Management CO2eq emissions (right).



EU27 Enteric Fermentation CO2eq emissions	EU27 Manure Management CO2eq emissions

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 63: EU27 Manure on soils CO2eq emissions (left) and EU27 Manure on Pastures CO2eq emissions (right).

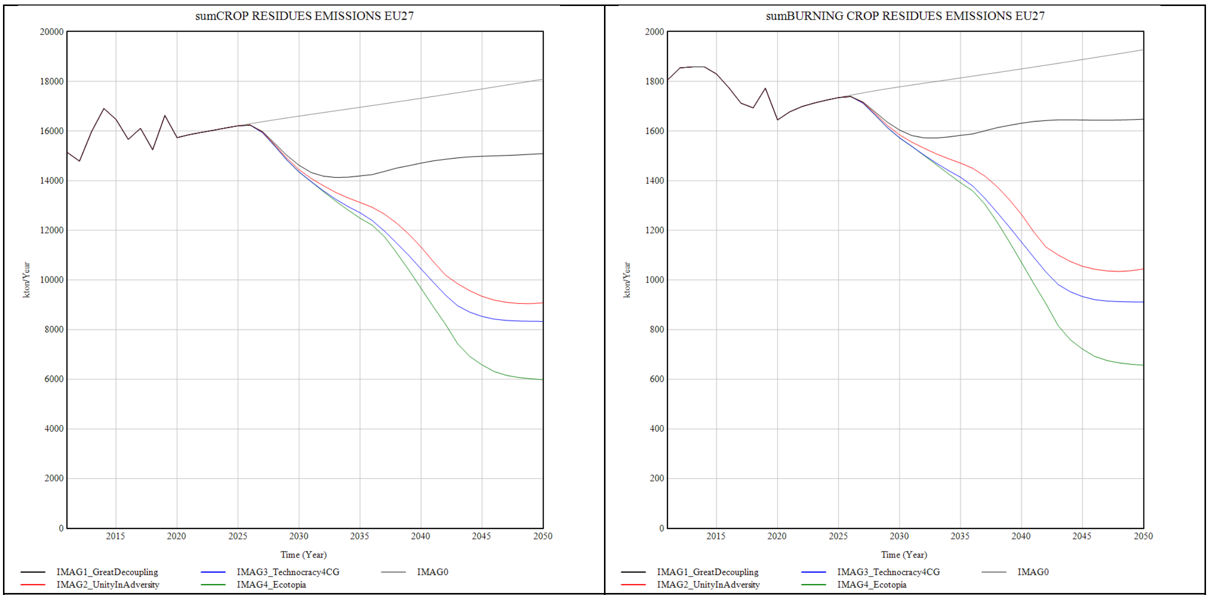


EU27 Manure on soils CO2eq emissions	EU27 Manure on Pastures CO2eq emissions

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 64 displays EU27 Crop Residues CO2eq emissions (left) and EU27 Burning Crop Residues CO2eq emissions (right).

Figure 64: EU27 Crop Residues CO2eq emissions (left) and EU27 Burning Crop Residues CO2eq emissions (right).

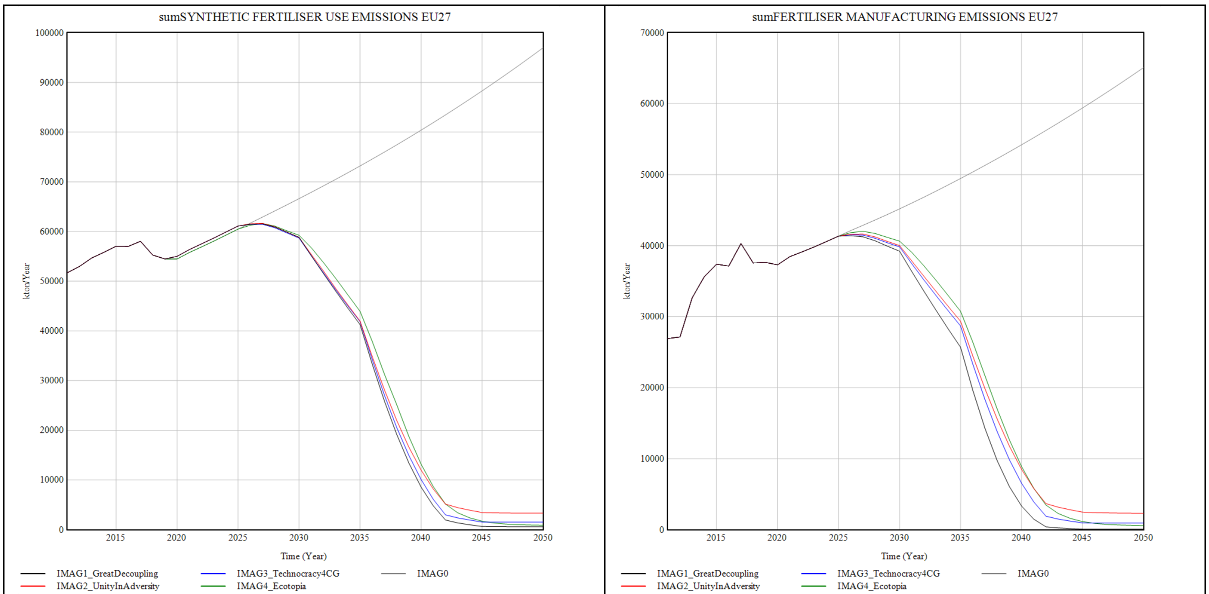


EU27 Crop Residues CO2eq emissions	EU27 Burning Crop Residues CO2eq emissions

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 65 displays EU27 Synthetic Fertilizer Use CO2eq emissions (left) and EU27 Synthetic Fertilizer Manufacturing CO2eq emissions (right).

Figure 65: EU27 Synthetic Fertiliser Use CO2eq emissions (left) and EU27 Synthetic Fertiliser Manufacturing CO2eq emissions (right).

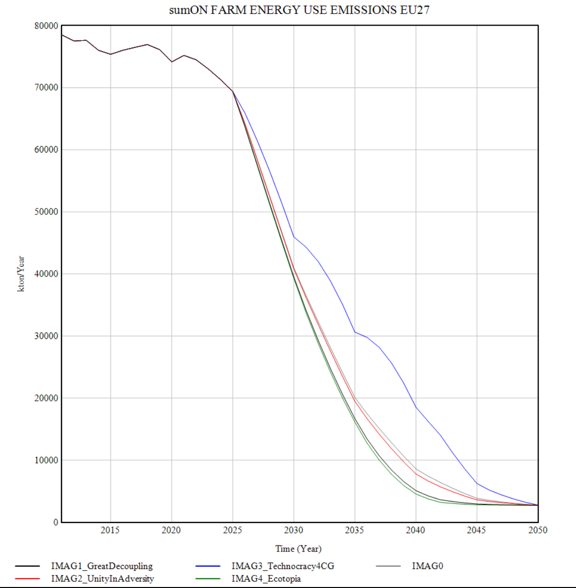


EU27 Synthetic Fertiliser Use CO2eq emissions	EU27 Synthetic Fertiliser Manufacturing CO2eq emissions

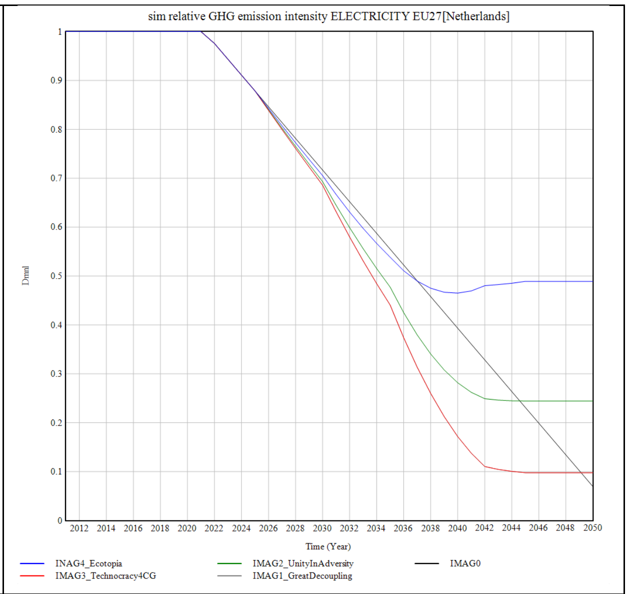
Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 66 displays EU27 on Farm CO2eq emissions (left), and Relative GHG emission intensity electricity NL -> EU27 (right).

Figure 66: EU27 on Farm CO2eq emissions (left), and Relative GHG emission intensity electricity NL -> EU27 (right).



EU27 on Farm CO2eq emissions

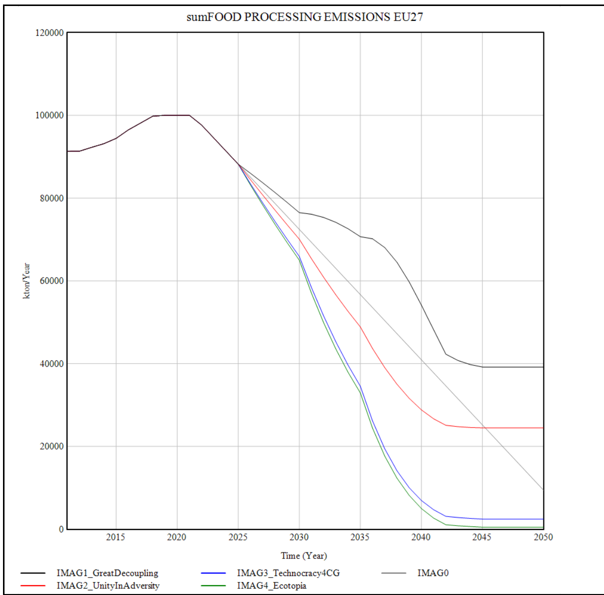


Relative GHG emission intensity electricity

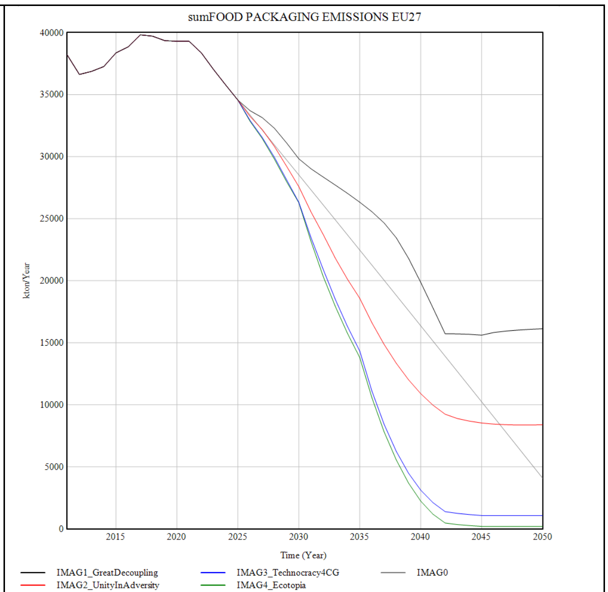
Source: Simulation results from Vensim Model. Erik Pruyt.

The main contributor to this evolution in the supply chain comes from the electricity cross-system, namely the continued drop in GHG emission intensity of electricity. This cross system is assumed to influences many supply chain tiers, discussed below. Figure 67 displays EU27 Food Processing CO2eq emissions (left) and EU27 Food Packaging CO2eq emissions (right).

Figure 67: EU27 Food Processing CO2eq emissions (left) and EU27 Food Packaging CO2eq emissions (right).



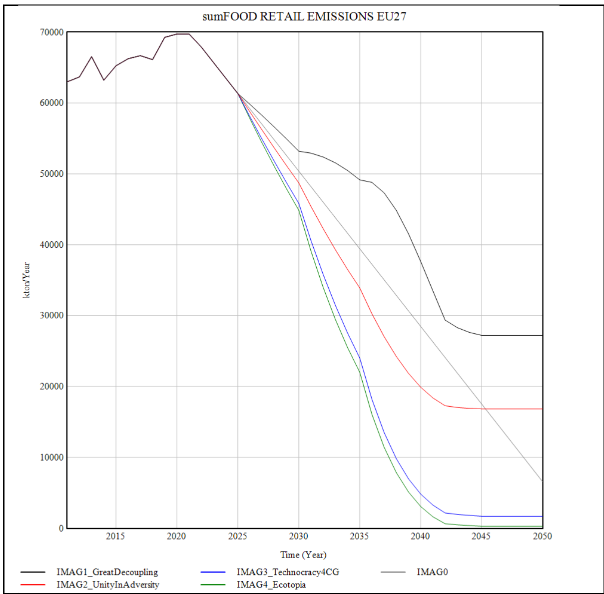
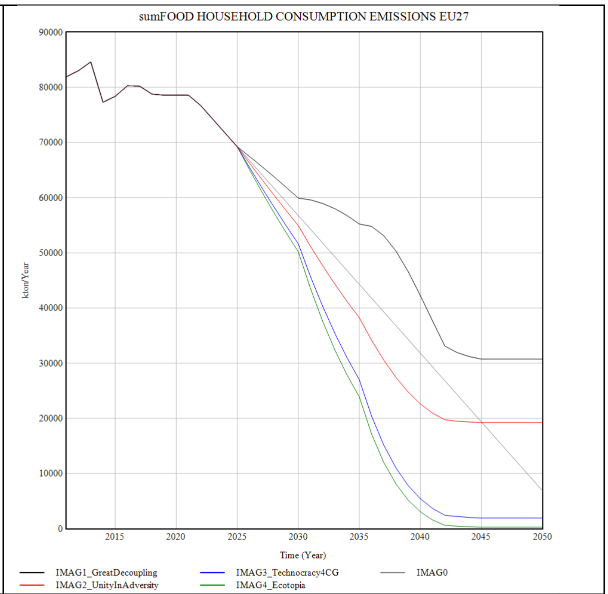
EU27 Food Processing CO2eq emissions



EU27 Food Packaging CO2eq emissions

Source: Simulation results from Vensim Model. Erik Pruyt.

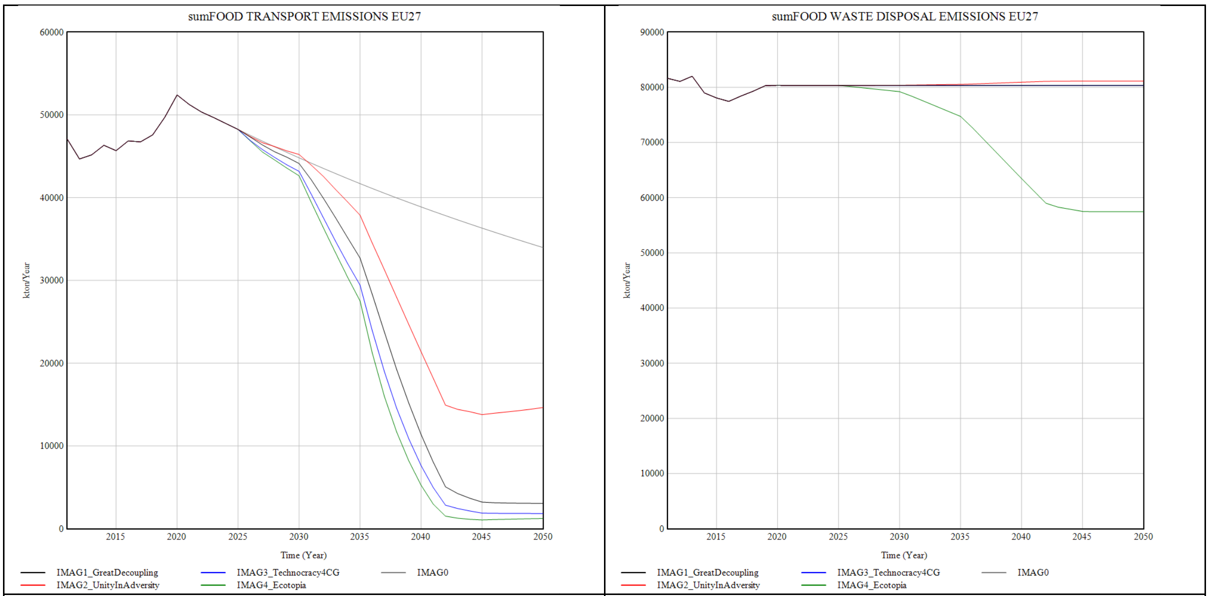
Figure 68: EU27 Food Retail CO2eq emissions (left), and EU27 Food Household consumption CO2eq emissions (right).

	
EU27 Food Retail CO2eq emissions	EU27 Food Household consumption CO2eq emissions

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 69 displays EU27 Agri-Food Transport CO2eq emissions (left) EU27 Food Waste Disposal Emissions (right). Figure 70 displays the sum of all EU27 on-farm CO2eq emissions (left) and the sum of all EU27 agri-food supply chain CO2eq emissions (right). These graphs show that in all transitions towards the imaginaries, agricultural emissions significantly drop. Emissions from the supply chain would already drop in the base case, but on-Farm emissions would a bit, but would subsequently rise.

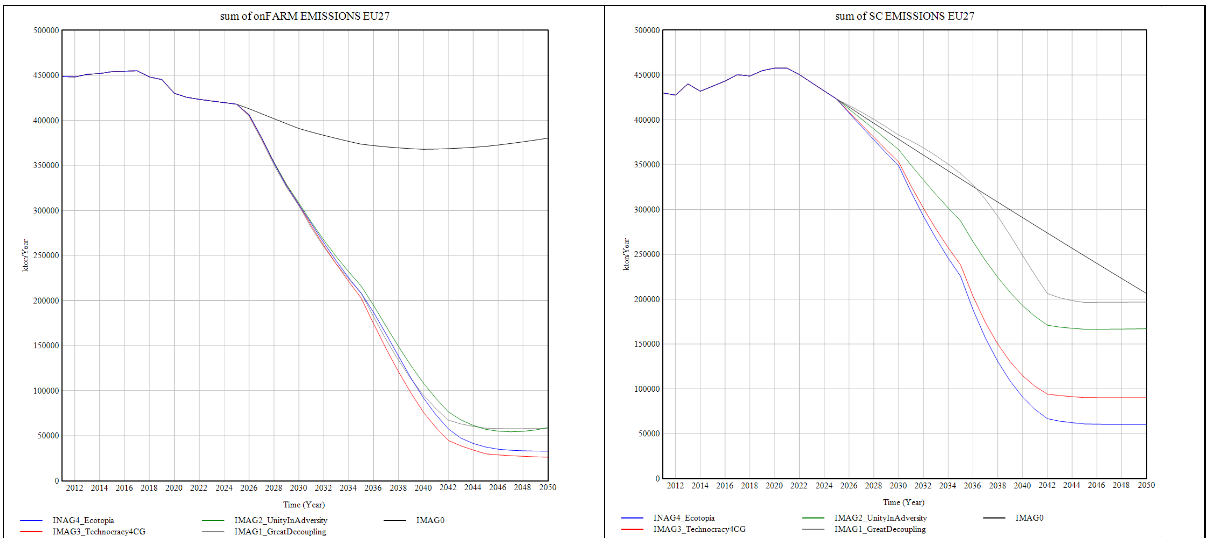
Figure 69: EU27 Agri-Food Transport CO2eq emissions (left) EU27 Food Waste Disposal Emissions (right).



EU27 Agri-Food Transport CO2eq emissions	EU27 Food Waste Disposal Emissions

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 70: Sum of all EU27 on-farm CO2eq emissions (left) and sum of all EU27 agri-food supply chain CO2eq emissions (right).

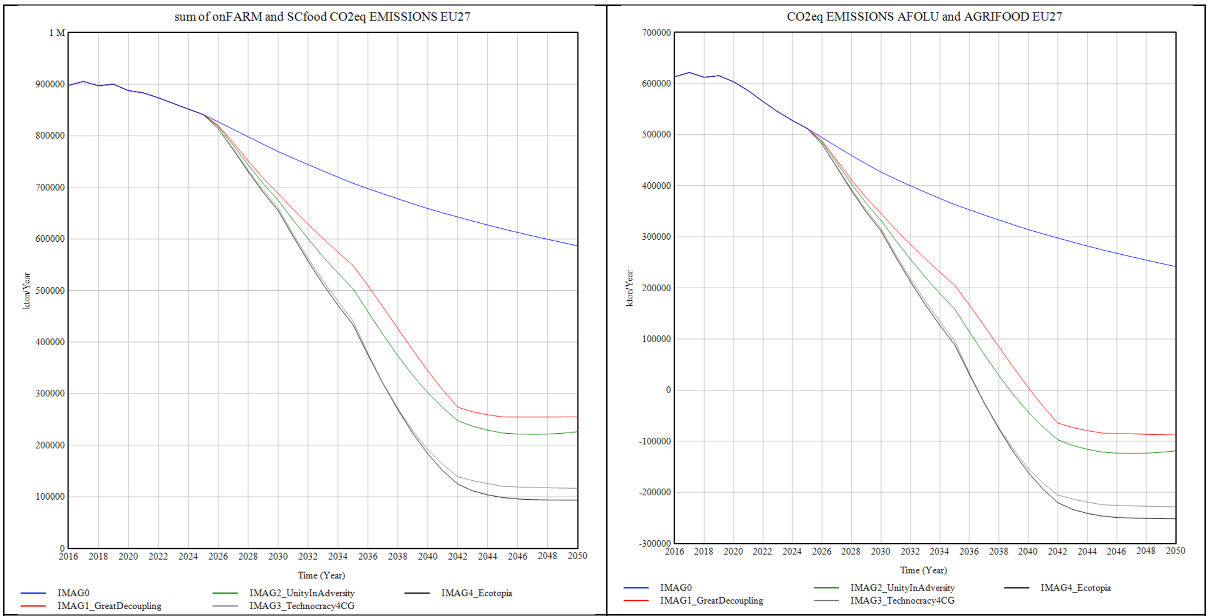


In all transitions towards the imaginaries, agricultural emissions significantly drop…	More so than the emissions from the supply chain, which would already drop in the base case.

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 71 shows the sum of all EU27 on-farm and agri-food SC CO2eq emissions (left), and the sum of EU27 on-farm, agri-food SC, and AFOLU CO2eq emissions (right). The sets of Levers for the 4 imaginaries were designed such that they would reduce (but not fully eliminate) GHG emissions across the Agri-Food System (below, left). In combination with (negative) Land Use and Land Use Change (LULUC) emissions, they may lead to net negative emissions (below, right).

Figure 71: Sum of all EU27 on-farm and agri-food SC CO2eq emissions (left), and Sum of EU27 on-farm, agri-food SC, and AFOLU CO2eq emissions (right).

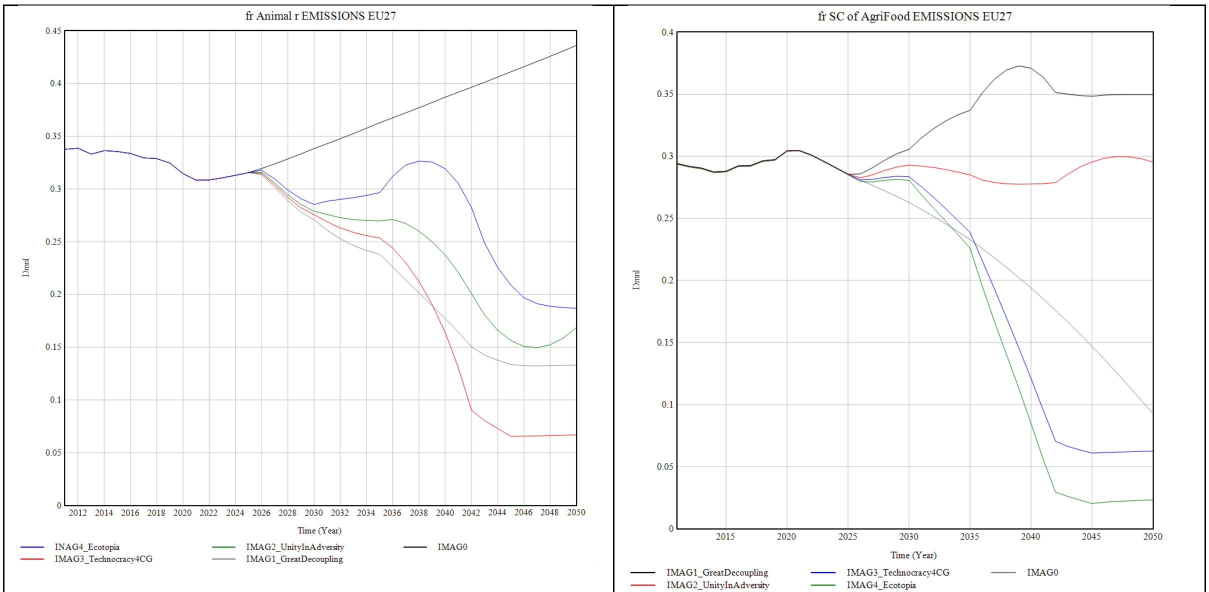


Sum of all EU27 on-farm and agri-food SC CO2eq emissions	Sum of EU27 on-farm, agri-food SC, and AFOLU CO2eq emissions

Source: Simulation results from Vensim Model. Erik Pruyt.

Note, however, that one needs to be cautious with these LULUC emissions: Apart from apparent issues with the data underlying the LULUC emissions (we need to implement a version with UNFCCC data instead of FAOSTAT Tier1 data), there is another problem with this reasoning: These negative emissions from Forestland (i.e., absorption by the biosphere) may be needed to compensate for many other sectors too.

Figure 72: Fraction of EU27 animal related CO2eq emissions (left) and fraction of EU27 AfriFood SC related CO2eq emissions (right).



Fraction of EU27 animal related CO2eq emissions	Fraction of EU27 AfriFood SC related CO2eq emissions

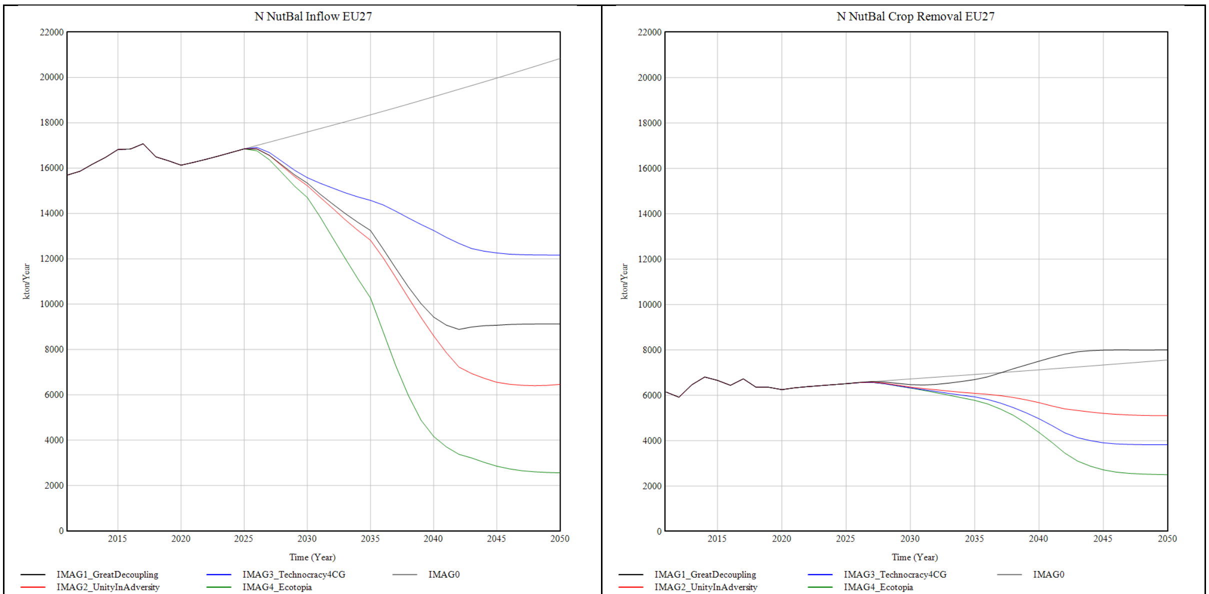
Source: Simulation results from Vensim Model. Erik Pruyt.

Finally, 72 shows the fraction of EU27 animal-related CO2eq emissions (left) and the fraction of EU27 Agri-Food Supply Chain related CO2eq emissions (right). It shows that these evolutions leads to decreasing animal related GHG emissions in the EU27 (that is, even with the other emission sources being addressed), even in the case of the Great Decoupling, and decreasing relative Supply Chain contributions.

8.5 Simulated nitrogen: manure, synthetic fertilizer, NFB, wastewater

Provided that today's N Nutrient Balance inflows are much higher than the N Nutrient Balance outflows from crop removals, a decreasing N Nutrient Balance inflow would be desirable for nature (water quality, air quality, soil quality) in most EU27 countries.
The "budget" (which is the inflow minus the outflow due to crop removal) remains in the soil (affecting it), leaches into the water (adding nutrients to the water body or flow), or volatizes into the atmosphere, to be deposited elsewhere – possibly as excess nutrients in nature.
The number of animals kept in stables affects the N Nutrient Balance inflow as does application of synthetic N fertilizer, N Biological Fixation via crops (e.g., lupine), and nitrogen deposition. Animal stocks and the resulting application of manure to fields, as well as synthetic N fertilizers are decreasing in the pathways towards the imaginaries discussed above. This means that the N Nutrient Balance inflows (left-side graph in Figure 73) will drop, possibly even below N outflows due to crop removal (right-side graph in Figure 73). Most N outflows due to crop removals also decrease, but in case of in IMAG1 Great Decoupling (black), EU27 N crop removals increase (even beyond the base case).

Figure 73: EU27 N Nutrient Balance Inflow (left) versus main EU27 N Nutrient Balance Outflow (Crop Removal).



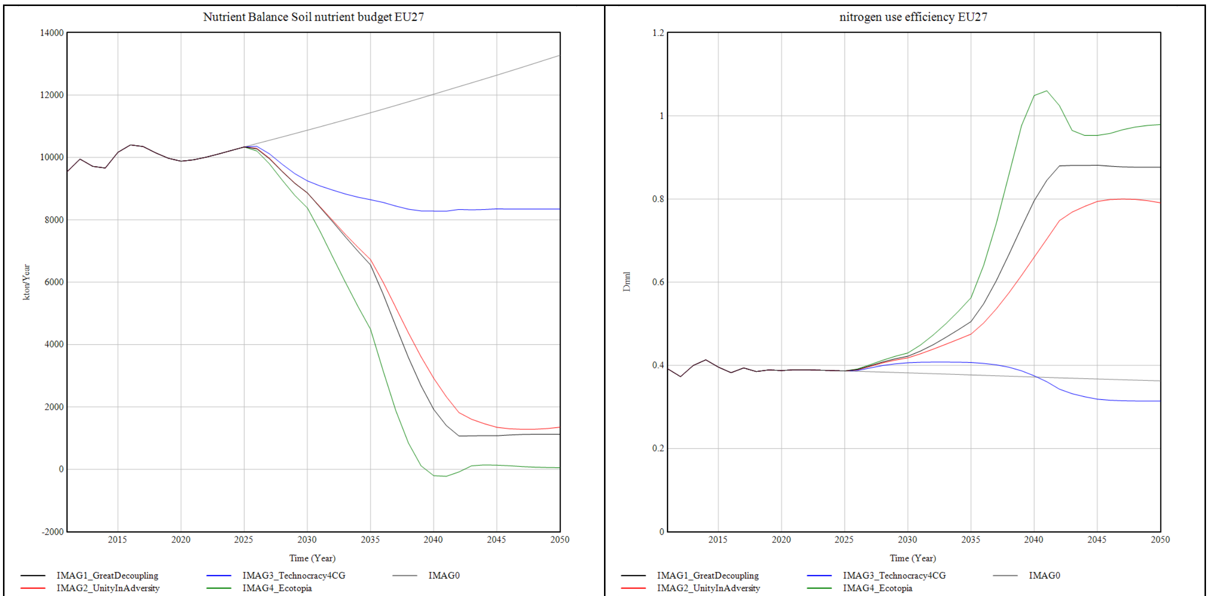
EU27 N Nutrient Balance Inflows for the pathways towards the imaginaries: IMAG1 Great Decoupling (black), IMAG2 Unity in Diversity (red), IMAG3 Technocracy for the Common Good (blue), IMAG4 Ecotopia (green), and IMAG0 base case (grey)	N Nutrient Balance Outflow (Crop Removal) for the pathways towards the imaginaries: IMAG1 Great Decoupling (black), IMAG2 Unity in Diversity (red), IMAG3 Technocracy for the Common Good (blue), IMAG4 Ecotopia (green), and IMAG0 base case (grey)

Source: Simulation results from Vensim Model. Erik Pruyt.

This is the case for the pathway towards Ecotopia: The Nitrogen inflow drops substantially, even below the Nitrogen outflow due to crop removals, after which more N-binding crops are planted to increase N Biological Fixation. Consequently, the Nitrogen budgets significantly decrease, except for the IMAG3 Technocracy for the Common Good pathway (the blue curve in left-side graph of Figure 74). Nitrogen

Use Efficiency consequently increases substantially, except for the IMAG3 Technocracy for the Common Good pathway. Nitrogen Use Efficiency even increases for a while above 100% in the Ecotopia pathway. This is possible because of Nitrogen accumulation in soils.

Figure 74: Nitrogen Soil Nutrient Budget (left) and Nitrogen Use Efficiency (right) for pathways towards the imaginaries.

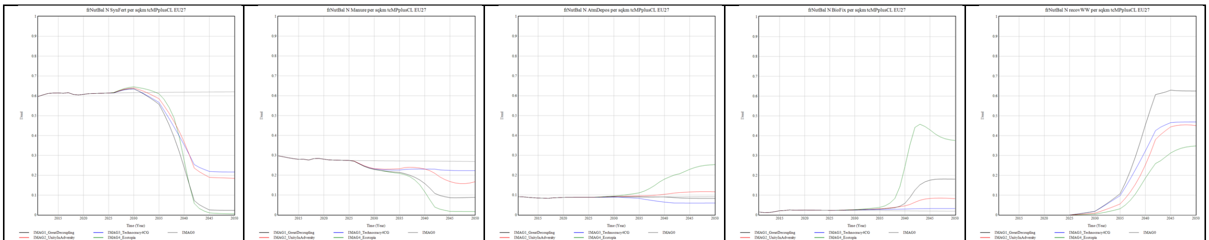


Nutrient Balance Soil Nutrient Budget for the pathways towards the imaginaries: IMAG1 Great Decoupling (black), IMAG2 Unity in Diversity (red), IMAG3 Technocracy for the Common Good (blue), IMAG4 Ecotopia (green), and IMAG0 base case (grey)	Nitrogen use efficiency for the pathways towards the imaginaries: IMAG1 Great Decoupling (black), IMAG2 Unity in Diversity (red), IMAG3 Technocracy for the Common Good (blue), IMAG4 Ecotopia (green), and IMAG0 base case (grey)

Source: Simulation results from Vensim Model. Erik Pruyt.

Moreover, there is a significant shift between Nitrogen Inflow contributors: Figure 75 shows the shift from Synthetic Fertilizers and (for most imaginaries) Manure towards N recovery from Wastewater (circularity) and N Biological Fixation (nature-based fertilizer). Note that the shift is much less pronounced in the pathways towards Unity in Diversity (red lines) and Technocracy for the Common Good (blue lines). The fraction of atmospheric deposition rises in the Ecotopia pathway due to the significant overall decrease in the Nitrogen inflow (which, consequently, inflates the contribution of atmospheric deposition which is decreasing but less profoundly than the Manure and Syn Fertilizer).

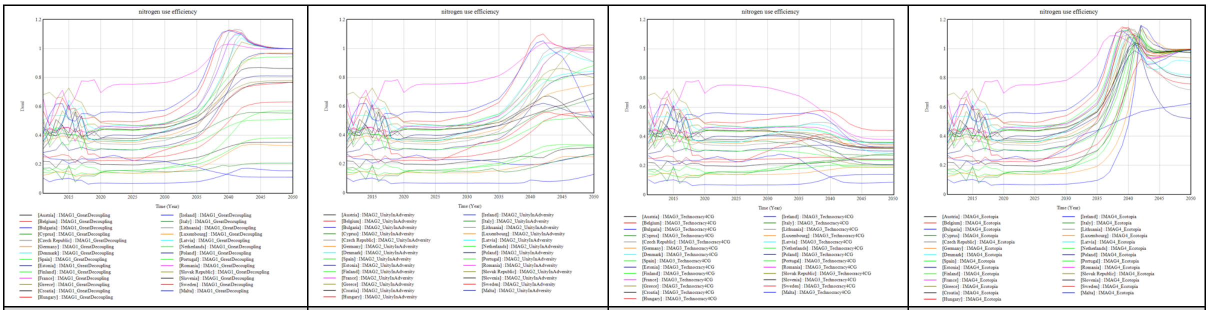
Figure 75: Shift between Nitrogen Inflow contributors, from Synthetic Fertilizer and Manure towards N recovery from Wastewater and N Biological Fixation.



Fr Synthetic Fertilizer	Fr Manure	Fr Atmos. deposition	Fr N Biological Fixation	Fr Wastewater recovery

Source: Simulation results from Vensim Model. Erik Pruyt.

Figure 76: N Efficiency dynamics resulting from the transitions towards the 4 imaginaries across EU27 Member States.



N efficiency, EU27 MSs, IMAG1	N efficiency, EU27 MSs, IMAG2	N efficiency, EU27 MSs, IMAG3	N efficiency, EU27 MSs, IMAG4

Source: Simulation results from Vensim Model. Erik Pruyt.

As with all data and simulated dynamics in this report, values and evolutions of EU27 Member States differ substantially. The same is true for the N balance, N budget (per sqkm), and N efficiency (Figure 76).

9 Discussion and Conclusions

9.1 Conclusions & recommendations based on the qualitative causal chain analysis

A multi-methods approach was followed in this project, both qualitative and quantitative. For the qualitative methods, Impact systems diagrams (Imodeler), Causal Loop Diagrams as well as Stock and Flow diagrams were used. Literature was researched to substantiate the connections of factors and conclusions of the qualitative analysis where it was appropriate. This approach has been used to analyse the main structure of the food and mobility systems, their cross-linkages, important feedback-loop mechanisms, and the impact on food value chain.

One of the central tasks was to connect F2F policy objectives to measurable targets through policy instruments. The project has demonstrated how this approach can be applied by utilizing a causal loop analysis of policy instruments to compare their effectiveness, identify complementarities, and assess trade-offs. As the F2F strategy represents a political framework that primarily offers suggestions regarding specific policies, it has not undergone testing, thereby making it challenging to consider trade-offs.

The qualitative modelling precedes the quantitative modelling and should therefore not be underestimated. Nevertheless, it is possible to integrate all different measures into one model and compare their potential effectiveness. This type of assessment has been successfully applied in prior instances (e.g., (Lorenz and Neumann, 2012), (Haraldsson and Ólafsdóttir 2018). Further research and dialogue would be necessary to systematically integrate more measures into the model. Engaging experts in the modelling exercises through interviews, focus groups, or full group-modelling sessions has proven to be crucial, e.g. ((Vennix, 1999), (Hovmand, 2014), (Eker et al., 2018), (Wright and Meadows, 2008)). Based on qualitative modelling and combined causal loop analysis, potential levers, synergies, trade-offs, and ambiguities can be identified. However, it is important to note that qualitative modelling serves as the initial step in defining system boundaries, framing the key questions to be addressed in a quantitative analysis. The subsequent paragraphs will highlight the key aspects resulting from this analysis.

Transport is an important component of the food value chain. The analysis conducted in this report clearly shows that the energy, transport and health systems are strongly linked with the food system. There are connections between the food system and freight transport, which involve a large, global freight transport activity and GHG emissions. Li et al. (2022) argue that the contribution of transport to food system emissions is much higher than previously estimated. The future change to digital, low-carbon logistics systems requires considering how these systems will change supply chain structures in the agricultural and food systems and how the associated GHG emissions may change.

Whether linked to the energy used for the production, processing and manufacturing of food products, the transport and distribution of food and food production inputs (including infrastructure and equipment) or the linkages in terms of diets and health, these systems have a strong influence on the food system. For example, in the food value chain, transport occurs in terms of transport of food products (internationally and regionally), transport of additives (e.g., fertilisers, pesticides, feed) and capital goods (e.g., infrastructure and equipment), and accessibility of consumers to sustainable food products (existence of transport to reach retail spaces and affordability of these means of transport). The environmental impacts of the food value chain are linked with the current structure of the energy and transport systems.

From the production and processing side of the food value chain, the analysis provided in this report highlighted some aspects that need to be considered when modelling food systems or thinking about food policy. These are:

- Different systems have different productivities. Ecological modes of production have lower productivity (product per unit of area) than intensive and super-intensive modes of production. This means that more area would be required from ecological modes of production (if existent and with all the environmental impacts associated with this area increases) to fully be seen as a substitution for intensive and super-intensive modes of production. Sustainable food systems need to tackle food security (satisfying food demand) and the environmental impacts of production at the same time. This may require increasing the productivity of ecological modes of production (where research is required) and reducing the environmental impacts of intensive and super-intensive modes of production.
- The whole food system efficiency should be analysed. Food losses throughout the system and the production of energy-intensive but nutrient-poor foods can increase food demand. These inefficiencies of the system need to be tackled.

Policy and modelling exercises need to tackle the demand side of the food value chain. The factors that affect consumer choices are manifold. The way these factors influence food choices is also not linear, forming a web of interactions and resulting in complex dynamic causal chains (see figure 24). Dealing with the factors that affect consumer choices will inevitably bring many other systems, namely, the planning system, the transport and mobility system, labour and social policy, education policy, and public procurement policies.

Recommendations for policies for tackling food waste:

- The competition for the resource "food waste/biomass" should be further assessed in the quantitative assessments. Data sources and information can be found on the EU Platform on Food Losses and Food Waste4.
- Food waste reduction will affect transport.
- Packaging and cooling (during transport) must be balanced carefully in the quantitative models.

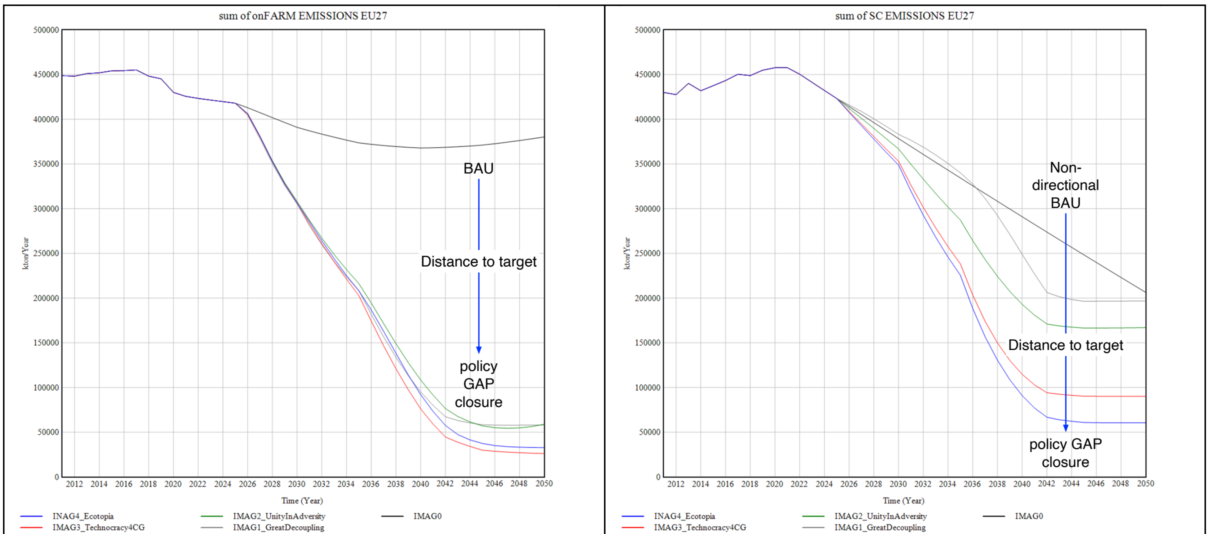
New trends are growing in the food system. Some of these are the future change to digital and low-carbon logistics systems and the increasing trend in ultra-processed foods. First, it will bring about changes in supply chain structures in the agricultural and food systems and affect associated GHG emissions. Second, processed and ultra-processed food products have impacts in terms of GHG emissions (from increased energy usage for processing, but also, in terms of fugitive emissions from f-gases in refrigeration). It can be expected that the processing stages of the food value chain and refrigerated transport will gain weight in terms of relative GHG emissions in the future.
More systematic research on new trends in food and mobility systems is recommended.

9.2 Conclusions & recommendations based on the quantitative modelling

Integrated dynamic assessments of the effects of policy levers on the agri-food system are essential. Primary agricultural production and the agri-food supply chain significantly impact GHG emissions and contribute to other environmental issues, such as water quality degradation, biodiversity loss, and potential human health risks. Transformative changes are necessary to shift the current agri-food system toward sustainable production and consumption practices.

GHG emissions from food production and the food supply chain in the EU decrease across all imaginaries. As previously discussed (Figure 70), the total EU27 on-farm and agri-food supply chain CO_2-equivalent emissions are influenced by policy-driven levers. These policies represent a shift from the current 'business as usual' (BAU) scenario toward targets defined by policy gap closures. Figure 77 demonstrates that if the policy gap is set based on the current BAU with existing policies (i.e., today's baseline), the policy gap closure and distance target, shown on the left side of the graph, differ slightly from a **non-directional BAU scenario**. In this alternative BAU, no specific imaginary pathway is followed; instead, it represents self-regulating policies without a predefined vision or strategy. In this base case, emissions from the supply chain are expected to decline, while on-farm emissions initially decrease but later rise slightly. Furthermore, a decrease in GHG emissions may occur due to land use change (LULUC emissions), potentially resulting in net negative emissions by 2050. However, this outcome remains highly uncertain due to possible double-counting of land use effects across other sectors. Overall, the scenarios in Figure 77 illustrate that all transitions toward the imaginaries result in significant reductions in agricultural emissions, albeit with varying gap closure policies.

Figure 77: Sum of all EU27 on-farm CO2eq emissions and sum of all EU27 in relation to BAU and non-directional BAU.



In all transitions towards the imaginaries, agricultural emissions significantly drop.	More so than the emissions from the supply chain, which would already drop in the base case.

Source: Simulation results from Vensim Model. Erik Pruyt.

General conclusions that apply to all (EU27) countries are limited in a sense that primary agricultural production is very different in different countries – within European and even more outside of Europe – in terms of products, practices, inputs, and (side)effects.

Even though there are differences for individual member states, there is hardly any difference on the EU27 level in terms of total amount of food between three out of four imaginaries (Great Decoupling, Technocracy for the Common Good, Unity in Adversity). An initial analysis for the four EEA imaginaries shows that the overall quantity of food remains approximately constant in the EU. Only the Ecotopia imaginary shows any significant change, with a decrease from 700 kg food per capita per year in 2010 to 490 kg food per capita per year in 2050. In terms of the distribution of the diet, the proportion of vegetables increases with meat substitutes (e.g. insect burgers) also reducing meat consumption across the EU.

However, this does not mean that there are no major shifts in these scenarios in terms of per capita consumption in individual Member States. Overall per capita demand in Croatia increases in the Great Decoupling and Technocracy for the Common Good scenarios, whereas they decrease in the Netherlands, while the opposite happens in the Unity in Adversity Scenario. The Ecotopia scenario is different, due to its settings for the DM01 Lever. Because of its settings for the DM01 Lever, it is the only scenario with dietary restrictions on the Member State level if domestic production does not cover the needs (possibly down to 10% of 2019 per capita consumption). The Great Decoupling and Technocracy for the Common Good have no restrictions, and Unity in Diversity still allows for intra-EU production and trade (up to 75% of domestic supply) and restricts to a maximum of 50% of 2019 per capita consumption.

Agricultural primary production needs to change drastically to become climate neutral and sustainable on other criteria. The negative environmental impact of agriculture comes especially from intensive animal husbandry. Total meat production displayed in Figure 56 will have to be drastically reduced. This is possible through a combination of meat, milk and egg substitution as well as a reduction in demand for animal-based products. This is the effect of a two-step calculation of substitution starting with diets (without making a difference between meat/milk/eggs and their substitutes) and the subsequent calculation of meat/milk/eggs and the substitutes for meat/milk/eggs. Assessment of levers to attain different imaginaries shows that there are different ways in which these emissions can be mitigated though.

While enteric fermentation emissions were already decreasing, each of the transitions towards the imaginaries does so faster. Manure management emissions are not decreasing yet. The levers activated for the different imaginaries pull CO2eq emissions related to manure management down. The importance of emissions due to enteric fermentation, means that, given the goal to substantially reduce GHG emissions, either the number of ruminants (esp. cattle) needs to be reduced significantly (either by reducing meat and dairy consumption or by shifting meat from ruminants to poultry), or ruminants need to be kept in stables that capture enteric fermentation emissions (CH4) which are then used (e.g., green gas, after which the resulting CO2 is used to accelerate plant growth).

GHG emissions from different tiers in the remainder of agri-food supply chain have about the same size. This means that actions are needed across the entire supply chain. Many can be tackled by transitions in cross systems, more specifically the energy sector (e.g., by means of a transition towards emission free electricity generation and after sufficient reduction of the GHG intensity of electricity, a shift to electricity) and the transportation sector. Electrifying farm energy would require an increase in total EU27 electricity generation in the order of 12%.

Timing matters for these cross-systems transitions: in most (European) countries, the electricity mix needs to be greened first before shifting to electricity. Given transformation losses, power grid losses, and life cycle emissions of electricity generation technologies, electricity – especially when used for heating or engines – has, in many countries, a larger global warming impact than current technologies and energy carriers (including coal). The electricity sector therefore needs to accelerate its transition, before the agri-food supply chain shifts to electricity. Agri-food transportation emissions are related small compared to the emissions from primary production and the remainder of the supply chain. Although decarbonisation of the transport sector would further mitigate agri-food emissions from global trade, it does not solve all problems related to global agri-food trade.

In that relation, sustainability is more than climate neutrality alone. Sustainability is also about healthy food, healthy work, healthy ecosystems, a healthy environment, sustainable use of resources, dematerialisation, and an overall reduction of inputs. Where decarbonisation focusses mainly on CO2, it is also to a large extent about CH4 and N2O in the agri-food sector. Animal stocks and the resulting application of manure to fields, as well as synthetic N fertilizers are decreasing in the pathways towards the imaginaries discussed above. This means that the N Nutrient Balance will drop, possibly even below N outflows due to crop removal. Most N outflows due to crop removals also decrease, but in case of in IMAG1 Great Decoupling (black), EU27 N crop removals increase (even beyond the base case).

In relation to F2F and the analysis, different sustainable futures are, theoretically speaking, possible. However, only one future will eventually materialize. This future is very likely not the one anticipated and/or desired. The four EEA imaginaries constitute rather distinct visions of sustainable futures for Europe. Even though they are defined as sustainable destination, the worlds they represent are very different.

The transition towards these different imaginaries requires tackling different challenges along the way. For example, it is not trivial to transition from the current large-scale agri-food systems in many countries to an Ecotopia type of world, unless local communities explicitly break with the current agri-food system and persist in their choice. Successful transitions towards each of these different imaginaries requires solving issues that are not easily solved. For example, transitioning towards the Technocracy for Good Society and Sustainability world requires bringing down pesticide use while dealing with pests without losing efficiency of primary production. Transitioning towards a Green Growth world requires finding ways to bring down enteric fermentation emissions of grazing ruminants. Without explicit choices and policy actions directed towards a specific vision, the world will likely, in a BAU scenario, follow the path of least resistance or deviation from the current trajectory. This would result in the development of a more high-tech, efficient, large-scale agri-food system with controlled production, alongside small Ecotopia-like niches. Patchworks of these different systems are unlikely to develop alongside each other due to economies of scale, although they could be favorably reinforced by geographical location and climate.

9.3 The advantages of System dynamics modelling for the cross-systems analysis of the agri-food system in the EU and globally

Qualitative analysis- Causal loop analysis

The project delivered a qualitative analysis and a quantitative analysis of the F2F systems. The qualitative analysis framed the system boundaries for the F2F strategies into 9 policy objectives where levers and specific instruments related to these levers were identified. The analysis showed important insights into how the Farm to Fork (F2F) strategy aligns with policy goals, the role of policy mixes, and their impact on transition pathways toward the EEA Imaginaries 2050 (EEA, 2022). It specifically examined the causal relationships between policy objectives, the policy instruments used to achieve these objectives, and their interactions within various policy mixes to evaluate the feasibility of arriving at the different imaginaries (future scenarios) as outlined by the EEA.

The project used various systemic methods, such as system thinking and system dynamics, to effectively analyze and represent the F2F strategic objectives, their connection to broader policy goals, and how these relate to specific policy instruments. A key finding was that employing Causal Loop Diagrams (CLDs) allowed for a detailed visualization of the cause-and-effect relationships across the food value chain. By mapping these instruments, it was possible to identify how these support or contradict each other, highlighting the importance of strategic policy mix designs to achieve desired outcomes (see figures 9 and 11). It was illustrated that by adjusting the feedback loop structure between policy objectives and instruments, it is possible to test optimal policy mixes that align with the desired futures depicted in the EEAs imaginaries. This approach not only identifies potential supportive policy mixes for each EEA Imaginary but also illustrates the potential policy instruments on a more detailed level related to specific questions surrounding each policy objective of the F2F, leading to an aggregated mix of policy instruments needed to transition towards these envisioned futures. This lays a good foundation for continuing the work of mapping the different aspects of the value-chain items, and the actors and activities that are responsible for the evolution of the F2F.

Quantitative analysis- system dynamic modelling

An experimental quantitative model of the agricultural system (CRAFT) has been developed, to show the potential for using the system dynamics methodology for scenario and policy analysis for F2F, applying data-driven approach. The model uses 'levers' to represent policy interventions, with each lever employing specific policy instruments that were partially developed as a result of the qualitative analysis. These levers were interpreted for the imaginaries to develop four scenarios in the model. The results obtained from this preliminary version of a SD model of the EU agri-food system demonstrate that simulation models offer the possibility to identify potential pathways towards imagined futures, but also to explore the development of what-if scenario pathway over time without a specific future in mind. Due to complexity with data-driven system dynamic models, the CRAFT model is not fully developed but shows potential for fully aggregated analysis. The purpose of system dynamic models is making all parts of the system being modelled visible, and flows and actions transparent. Thus, enabling testing and showing the effect of a policy pathway, from question to measured effect upon success parameters and subsequently performing a dynamic what-if policy robustness analysis. In this way, system dynamic model differs fundamentally from comparative static techno-economic optimisation models to the EU food system such as the CAPRI model.

Challenges of data-driven system dynamics modelling

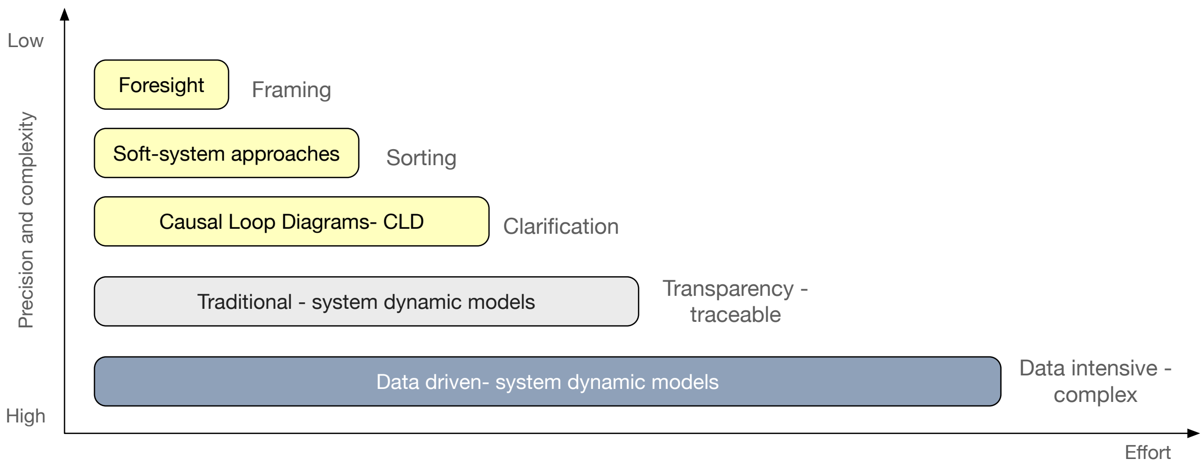
The modelling process begins with problem formulation and asking the right questions. Depending on the required accuracy of the answer (Figure 78), the steps toward providing the conditions to formulate the answer follow a top-down process (Vennix, 1999; Haraldsson and Sverdrup, 2021; Sverdrup et al., 2022). As depicted in Figure 78, foresight involves framing the issue, soft-system approaches involve sorting what is inside the framed boundaries, and causal loop diagramming helps clarify the structure and frame a complete conceptual model. As mentioned in the method chapter, traditional system dynamic models naturally progress toward analyzing the numbers defined in the conceptual model, creating a traceable, transparent link between the conceptual and numerical model. They also allow for simple policy sensitivity analysis and robustness what-if testing. On the other hand, data-driven system dynamics models are an extension of traditional system dynamic modelling and ultimately the most complex form of modelling (Pruyt, 2012; Sverdrup et al., 2022).

In this project, the goal was to assess the performance of quantifiable policy instruments, necessitating the use of a system dynamic model. The aim was to explore the feasibility of using a data-driven system dynamic model for policy assessment of the F2F. Due to time constraints, the focus on developing traditional "simpler" system dynamic models was reduced. The developed CLDs served as a bridge between conceptualization and structuring the F2F policy, and the building of the data-driven system dynamic model.

One challenge of a data-driven system dynamics model is organizing complexity, as these models tend to be structurally complicated, with detailed processes and feedback structures that are difficult to trace (Figure 78). Due to their large size, they lack clear transparency of the feedback structure and a clear representation through conceptual models (Sverdrup et al., 2022). These models are not structurally complex but are complicated with many detailed variables and associated data structures on multiple arrayed levels. They also tend to have multiple success parameters to showcase policy success, making it challenging to rank the importance of policy options in terms of overall impact and performance. In the case of the CRAFT model, the policy levers exceed 40 variables, making it cumbersome to perform a sensitivity analysis.

In hindsight, using a simpler system dynamic model would have made the transition from conceptual analysis to numerical analysis more transparent and built the bridge towards the data-driven approach. This is one of the methodological lessons from the project. Since this is an explorative approach for the EEA to develop useful in-house tools for policy analysis, the project is ahead of its time. However, the foundations have been laid and the reward potential very high.

Figure 78: The steps of system dynamic modelling, from a question to a fully data driven developed simulation.



Source: adapted from Haraldsson and Sverdrup, 2021.

In summary, the project has demonstrated the usefulness of applying CLD analysis and supporting qualitative methods to frame boundaries and questions related to the F2F. It has also been effective in formulating policy objectives concerning the food system/transport value-chain and subsequent levers and instruments. Furthermore, it provides an important foundation for further foresight activities to analyze systemic properties and policy mixes for transition pathways of large-scale changes in the agri-food system.

9.4 Possible directions for further analysis

The project can delve into several directions, both in development of the approach as well as applying the methodological approach tailored for the EEA in this project.

Short term:

- Utilize the CLD approach for existing and upcoming ETC work and EEA workstreams concerning further development of policy instruments and preparation for work on policy mixes for the transformation pathways related to the imaginaries.
- Utilize the CLD approach for sustainable finance analysis on fiscal, regulatory and finance levers.

Longer-term:

- Identification of intermediate policy steps along the pathways using a combination of CLD and simpler system dynamic modelling to support the data-driven approach. Intermediate policy actions can be interpreted as changes in the policy levers at intervals over time in the forward simulation.
- Further develop a system dynamic model for quantitative analysis of F2F and/or EEA-related nexus systems, beginning with traditional system dynamic modelling and then transitioning to data-rich system dynamic analysis.

Additional specific items to consider from modelling results

- The social acceptability of the policies as interpreted through the policy levers could be investigated. This would require the modelling of different social groups and impacts including changes in diet (as in the current pilot version), health effects of nitrogen and fertiliser use, changes in activities in farms for farming communities, changes in the demand for different foods etc.
- The requirements for sustainable finance, for investment in emissions mitigation technologies (e.g. CO2 capture from enteric fermentation, low carbon energy systems for agricultural production and transport) could be assessed using the projected changes in land use, technologies etc. Simulation of food waste and possible waste reduction measures. The data on food waste was found to be incomplete and very limited. Data collection over the EU member states could enable the representation of food waste and therefore the development of ideas for policies to reduce waste. The SD modelling approach could be developed for stakeholder based analysis. This could use the understanding of the agro-food system, and the data collated to develop a small scale SD model for use in stakeholder processes. A small model that can be relatively easily explained and in which the parameters of the model can be rapidly adjusted could be used in workshops with stakeholder to explore alternative policies, where the impacts of changes in the assumptions can be seen in 'real time'.

List of abbreviations

Abbreviation	Name
CO2eq (emission)	CO2 equivalent (emission)
Dmnl	Dimensionless (units = 1)
DS	Domestic Supply
EEA	European Environment Agency
EU27 (MSs)	EU27 (Member States)
fr	Fraction
GHGs	Greenhouse gases or Greenhouse gas emissions
KPIs	Key Performance Indicators
kton or kiloton	kiloton (= 1000 ton = 1000000 kg = 1 Gg)
Lux.	Luxembourg
Mton	Megaton (= 1000 kiloton = 1000 Gg)
NLD	The Netherlands
pa	per annum (= per year)
pc	Percentage
pppa	per person per annum (= per capita per year)
Prod	Production
RofEU27	The Rest of the EU27
RoW	Rest of the World (i.e., all non-EU27 countries)
TJ	Terajoule: 1 TJ = 10^{12} Joule = 0.000277 TWh
TWh	Terawatt hour: 1 TWh = 1000 GWh = 10^6 kWh

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