Unpacking food system transitions across multiple scales

The Belgian livestock sector

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À Mam

Nulla dies sine linea

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Abstract

This PhD gathers a series of research outputs on the livestock transition in Belgium. It pursues a double objective. First, we aim to reflect on the concept of scale in the context of food system transitions. As food system transitions occur at different spatial scales, include a diversity of actors, and a succession of activities in supply chains, we try to discuss how different scales of analysis affect our perception of food system transitions. Second, we aim to ground these reflections by investigating one case study: the transition of the Belgian livestock sector, which we analyse at multiple scales, following the different steps of a transition cycle (assessing – envisioning – implementing). In the process, we pay particular attention to the diversity of farming systems, the multidimensional nature of sustainability, the design of transition tools (in particular foresight scenarios), and the challenges encountered in the implementation of transition pathways.

The research that is presented has first and foremost been developed in collaboration with a range of non-academic actors (civil society organisations, food system actors) through a number of research projects. Its primary purpose has been to produce practical knowledge that would be relevant for these actors and their activities. This PhD contains a mix of both empirical findings and more theoretical conceptualisations. As such, the work that follows should be seen as a retrospective and reflective exercise on the practical and shared knowledge produced initially.

Table of contents

List and status of publications

Chapter 2

Under revision in One Earth

Riera A, Baret PV. (2025). From micro to macro, local to global and farm to fork: a multi-scale framework for food system transitions.

Chapter 3

Published in Agronomy for Sustainable Development

Riera A, Duluins O, Schuster M, Baret PV. (2023). Accounting for diversity while assessing sustainability: insights from the Walloon bovine sectors. Agron Sustain Dev 43:30. https://doi.org/10.1007/s13593-023-00882-z

Chapter 4

Published in Agricultural Systems

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Chapter 5

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Additional publication

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Section 1

Setting the scene

It's all about scale my son, what looks like a sea to you is a river for me

R. Van de Velde

Chapter 1 General introduction

1.1 Foreword: a consolidation of action research experiences

This document gathers a series of research outputs with the objective of presenting a coherent and scientific piece of work on the livestock transition in Belgium. Before delving into the specifics of the content, we want to clarify the process that has guided this work. The research that is presented has first and foremost been developed in collaboration with a range of non-academic actors (civil society organisations, food system actors) through a number of transdisciplinary action research projects. Its primary purpose has been to produce practical knowledge that would be relevant for these actors and their activities.

In particular, this PhD has been shaped by three research projects taking place between 2017 and 2024. First, an investigation for Greenpeace Belgium led to the development of foresight scenarios for the Belgian livestock sector (2017-2019)[1]. Second, a study for WWF Belgium allowed to shed light on the diversity of beef and dairy systems in Wallonia (2020)[2]. Finally, a research project funded by the Flemish government supported the development of a local and organic soybean value chain (2022-2024)[3]. These research projects were developed in close interaction with food system actors. In the first two cases, research projects were commissioned by civil society organisations, which provided funding and defined the main research questions while we as researchers conducted the research independently. In the third case, the research was performed as a collaboration between research organisations and value chain actors.

The research projects introduced above provide the empirical base of this dissertation: chapter 3 presents the results of the WWF project on beef and dairy systems; chapter 5 builds on the scenario exercise for Greenpeace, and chapter 6 further expands the analysis of the soybean value chain. As this document aims to go beyond an aggregation of individual research project results, the work that follows contains a mix of both empirical findings (chapters 3, 5 and 6) and more theoretical conceptualisations (chapters 2, 4 and 7). Both aspects are of equal importance in the

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1 Riera A, Antier C, Baret PV. (2019). Study on Livestock Scenarios for Belgium in 2050. https://sytra.be/publication/scenarios-livestock-belgium/.

2 Riera A, Antier C, Baret PV. (2020). Analyse des performances environnementales et économiques de différents systèmes de production bovins en Région wallonne. https://sytra.be/publication/dual-challenge-livestock/.

3 Riera A, Deraeve S, Delanote L, Verzelen K, Pollet I, Dewaele K. (2024). LoCoSoy - Economisch model van de sojaketen. https://sytra.be/publication/locosoy/.

context of this work. Conceptual frameworks serve as analytical guides for empirical research while empirical results allow to test (attempts at) theorisation. As such, this dissertation should be seen as retrospective and reflective exercise on the practical and shared knowledge produced initially. From a personal point of view, this was the main motivation and objective behind this PhD.

A double guiding thread allows to consolidate the empirical cases into a single body of research. First, they share a common object of investigation: the livestock transition in Belgium. While it is analysed from different entry points, for instance in terms of spatial scope or even expanding from the livestock sector to protein crops and the wider protein transition, this topic provides a relevant case study that traverses the dissertation. Second, the empirical cases, although they each have their dedicated methods, are grounded in a set of shared methodological roots. These include an anchoring in food and farming systems research, a multidimensional consideration of sustainability, a contribution to sustainability transitions, and a transdisciplinary approach to research. Our research largely benefits from existing frameworks and related research communities on these principles, while also trying to contribute to them. In particular, to apprehend the different entry points taken to the case study, we propose a reflection on the concept of scale in the context of food system transitions.

In the following paragraphs, we further introduce these key methodological principles and frameworks (1.2). We then provide a short presentation of the case study (1.3), before presenting the main research questions (1.4).

1.2 Methodological principles and frameworks

1.2.1 Defining food and farming systems

What are food and farming systems? A potential entry point to discuss this contrasts two analytical approaches: farming systems research and food systems research.

Farming systems research departs from two main elements: (1) the recognition of the diversity of structures, practices and values in the farming activity, and the fact that specific ways of farming exist, and are shared by large groups of farmers (Van der Ploeg 2010; Darnhofer et al. 2015); (2) the recognition of the multifunctional character of farming (Darnhofer et al. 2012). Importantly, farming systems are embedded in specific spatial contexts. Both the geographical location and the local bio-physical conditions have an influence on the farming practices, and also on the transitions that may or may not be possible (Darnhofer et al. 2015). Farming systems have to be understood as *open* (in relation with an external environment and context), *dynamic* (the state of the system may change over time as a result of one or more structural changes) and *purposeful* (there are multiple ways to achieving the same outcome, thus recognising the diversity of farming systems) (Darnhofer et al. 2012). To address these characteristics, farming systems research importantly relies on systems thinking, interdisciplinarity and participatory approaches (Darnhofer et al. 2012). While farming systems research recognises that farming systems are in constant connexion with external structures and processes, it remains centred on the farm level and the productive stage.

Food systems widen this scope by including all food system actors, from upstream activities (input production) to downstream activities (processing) and consumption. The concept has been discussed for a long time but has regained prominence with the realisation of the multiple roles of food production (Béné et al. 2019). A common definition is proposed by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security (HLPE): *'a food system gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes'* (HLPE 2017). Food systems lay at the interplay between social and ecological systems, and are as such considered as social-ecological systems (Ericksen 2008; Gordon et al. 2017)[4]. Components of food systems include food system activities, food system outcomes, drivers (environmental, socio-economic and their interactions) and feedbacks (environmental and socio-economic) (Ericksen 2008). Food systems are seen as complex, heterogenous over space and time and replete with non-linear feedbacks, the outcomes of which are the result of interactions between *structure* (the broader macro-level institutions and structures which govern people's actions) and *agency* (the micro-level individual actions and decisions) (Ericksen 2008). Six features are attributed to them (Leeuwis et al. 2021): (1) emergent properties, which may lead to positive and negative synergies; (2) interactions between actors, with actions and changes of one actor affecting the others (at same level or different levels); (3) food systems are diverse, throughout the value chain and/or geographical space; (4) diversity also exists between actors, leading to different narratives (also among researchers); (5) self-organizational dynamics, with no single actor that has sufficient

[4] Farming systems too can be considered as social-ecological systems. Without being explicitly centred exclusively on farming systems, Duru et al. (2015a) structure their analysis of local agriculture around three types of systems which are in constant relation: farming systems, social-ecological systems and socio-technical systems. Each of these systems help to manage different types of resources: respectively farm resources, natural resources and technologies.

power and control to steer the system in a particular direction; (6) dynamic stability and resilience: food systems are continuously dynamic, but at the same time relatively stable, except when external shocks occur.

Both farming systems research and food systems research are strongly embedded in systems thinking, recognising the complexity of these systems and their components and acknowledging that the practices and activities within are diverse, influenced by external factors and lead to a variety of outcomes (Ericksen 2008; HLPE 2017). Importantly, both approaches recognise the existing diversity within farming and food systems. The management of this diversity and its effects on the functioning of the system as a whole are referred to as the *coexistence of systems* (Gasselin et al. 2021a). Besides a coexistence of systems, a *coexistence of visions* can also be observed (Gasselin et al. 2021a; Penvern et al. 2023). These visions reflect diverging views, priorities and objectives regarding food and farming systems, held by parties with different power and agency (Dendoncker et al. 2018; Béné et al. 2019) and often linked to different disciplines and communities of practice (Brunori et al. 2024).

1.2.2 A multidimensional approach to sustainability

It is commonly acknowledged that the currently prevailing industrial and productivist model of agriculture and food production, which started to expand since the early 20th century and mainly after World War II, faces multiple challenges (Foley et al. 2011; IPES-Food 2016). Agriculture has played an active role in the world entering the 'Anthropocence', i.e. an era in which human activity significantly impacts the functioning of the Earth system (Steffen et al. 2015), or in exceeding the planetary boundaries, i.e. a safe operating space for our society within the Earth system (Rockström et al. 2009; Campbell et al. 2017).

As a response to the realisation of the negative impacts of food production, several concepts and frameworks have emerged since the 1970s to acknowledge that agriculture plays multiple roles in our society, beyond the sole production of food. For instance, multifunctional agriculture (MFA) stresses the fact that beyond producing food and fibre, agriculture has multiple functions, including the management of renewable natural resources and landscape, conservation of biodiversity and contribution to the socio-economic viability of rural areas (Renting et al. 2009). Alternatively, ecosystem services (ES) refer to the *'benefits human populations derive directly or indirectly from ecosystem functions'* (Costanza et al. 1997). While the concept is not specific to agriculture, it applies to it as agriculture is both a provider and a receiver of ecosystem services (Duru et al. 2015b; Therond and Duru 2019). Although the two approaches take different entry points (either agriculture-centred or ecosystems-centred), both are anthropocentric concepts which stress human dependency on natural processes and interactions of agricultural activities with nature, society and economy (Huang et al. 2015; Dendoncker et al. 2018). The two concepts are rooted in sustainability thinking (which developed at the same time as MFA and ES), and the general idea of sustainable agriculture. They particularly relate to the multidimensionality aspect of sustainability, i.e. the three dimensions lying at its core: environment, society and economy.

Realising the multiple roles and functions of agriculture led to a need to measure these multiple outcomes, and in general the sustainability of agricultural activities. As a result there has been a multiplication of assessment frameworks and tools (de Olde et al. 2016; Latruffe et al. 2016), which rely on a wide range of multidimensional quantitative and/or qualitative indicators, leading to what has been considered as an *'indicator explosion'* (Riley 2001; Bergez et al. 2022). Indicator-based sustainability assessments can be structured following three hierarchical levels: sustainability dimensions – themes within those dimensions – indicators to measure those themes (de Olde et al. 2016). Such assessments have multiple purposes and can benefit a wide range of actors, including decision-makers, farmers (and their advisors), value chain actors and consumers (Van Passel and Meul 2012; de Olde et al. 2016; Kelly et al. 2018). Beyond benefitting different actors, the scope and boundaries of sustainability assessments can extend to different levels of food systems, including the farm level, the sector level, the regional level, or more recently the whole food system level (Van Passel and Meul 2012; Schneider et al. 2023). As different assessment approaches coexist, several methodological constraints and considerations emerge when performing sustainability assessments and using sustainability indicators.

Multidimensionality. One of the core principles of sustainability (and its assessment) resides in covering the three dimensions of sustainability. In practice, it has been noticed that this principle is not always applied, with the environmental dimension often receiving more attention (Lebacq et al. 2013; de Olde et al. 2016).

Choice of indicators. In essence, the choice of indicators can be related to two parameters: its ease of measurement and its relevance, i.e. its capacity to accurately predict an environmental outcome. With this in mind, three types of indicators can be distinguished (Bockstaller et al. 2015). Two are obtained through direct measurements, with means-based indicators on one end and impact-based indicators on the other end. The former reflect practices. They are easy to measure but have a low power of prediction on impacts. The latter have a closer link to impact but are difficult and expensive to measure. As an alternative to those two types, we find modelled, or predictive indicators. They present an intermediate solution, with increased environmental relevance compared to means-based indicators, and easier feasibility compared to measured impact-based indicators (depending on the complexity of the models they rely on).

Boundaries. As mentioned above, sustainability assessment can target different levels of food systems, at different spatial and temporal scales. Bergez et al. (2022) distinguish three main approaches: agri-environmental indicators, usually implemented at field, farm or country level; life cycle assessments (LCA), which adopt a product (or service) lifecycle perspective with clearly established calculation boundaries; and ES assessments, classically performed at the landscape level (Bergez et al. 2022).

Functional units. Indicators can either be expressed in relative terms, with the help of a functional unit (e.g. per kg product, or per ha), or in absolute terms (e.g. at a national or global level)[5]. Relative assessments are useful to compare different products, or production systems over one same functional unit, i.e. they give an indication of the efficiency of products and production system to deliver a certain outcome. The choice of the functional unit is not insignificant as it impacts the conclusions of an assessment. Product-based functional units, most common in LCAs, tend to favour intensive systems while area-based functional units tend to favour extensive systems (Bergez et al. 2022). When relying on efficiency-based assessments and indicators, attention must also be paid to potential rebound effects, where increases in efficiency lead to increased activity, which on the whole lead to increased impacts in absolute terms. It is therefore useful to combine both relative and absolute indicators (de Olde et al. 2025).

Thresholds and aggregation. For both absolute and relative indicators, reference values or thresholds allow to set an upper or lower limit and thereby define a sustainable space of operation (e.g. the planetary boundaries framework sets nine absolute boundaries that define a safe operating space for humanity). In the case of relative assessments, setting thresholds may also avoid rebound effects. Finally, assessments comprising sets of multiple indicators may resort to aggregating these indicators into unique composite indicators for simplification and clarification purposes (Van Passel and Meul 2012).

[5] The question of *boundaries* and *functional units* can also be related to the level of reporting. Deconinck et al. (2023) identify four main levels of reporting: product, project, firm, country. Other levels could be used to report assessments, such as financial assets or portfolios.

1.2.3 A contribution to sustainability transitions

Besides the need for assessments, realising the multiple roles and outcomes of food production also highlights the need for our food systems to undergo a transition (or transformation) towards more sustainability (Béné 2022). This need is widely acknowledged and calls for such a transformation abound both within and outside of the scientific community (Juri et al. 2024). Sustainability transitions refer to non-linear and large-scale shifts in societal systems that emerge over long periods of time (Loorbach et al. 2017). Transitions of societal systems can be considered as a particular case of complex system dynamics and can thus be particularly challenging (Loorbach 2010).

In practice, the transition of our food system has been rather slow and stalling, with a missing link between designing transitions and implementing them (Dendoncker et al. 2018; Leeuwis et al. 2021). A contributing factor to this complexity resides in the coexistence of visions (Gasselin et al. 2021b; Penvern et al. 2023), and more particularly in the tensions and possible incompatibilities between different visions (Dendoncker et al. 2018; Béné et al. 2019). With regards to the (un)sustainability of food systems, Béné et al. (2019a) identify four main narratives (food security, nutritional quality and health, social justice, environmental (un)sustainability), which although they agree on the general unsustainability of our food system, they disagree on the nature of the failure and what should be prioritised (Brunori et al. 2024). These narratives emerge from different conceptualisations of the sustainability concept by different communities of practices, related to agriculture and agronomy, nutrition, (social-)ecology, agroecology or nutrition-sensitive value chains (Béné et al. 2019). To try to overcome the challenges of engaging in transitions, several frameworks have emerged, either to explain past or on-going transitions, or to help guide new ones. Below we introduce three frames: the multi-level perspective (MLP), transition governance and agroecological transitions.

The MLP has been developed to understand and analyse socio-technical transitions (Geels and Schot 2007). It conceptualises transitions as an emerging process resulting from the interactions between three levels: the *niche level*, where radical innovations and experimentations happen; the *regime level*, which groups the main practices and structures, relative to several domains (policy, culture, science, technology, market, etc.), that provide the deep structure for the current functioning of the system; and the *landscape level*, which corresponds to exogenous factors which are beyond influence of niche and regime actors, but which exert an influence on them by applying potential pressures on the current regime and thereby creating opportunities for change.

Transitions are the result of reconfigurations of the main socio-technical regime, influenced by niche-level innovations and landscape-level pressure. The MLP has been widely mobilised to analyse past and on-going sustainability transitions, including those of food and agriculture systems, with a focus on farm-level innovations and bottom-up initiatives (Geels 2011; Bui et al. 2016; Dumont et al. 2020; Leeuwis et al. 2021; Elsner et al. 2023). While the MLP framework is particularly useful to explain *how* transitions may or may not happen, it has been argued that it does not sufficiently question *what* transition is desired, i.e. the direction of transition, or the *sustainability* part of sustainability transitions (Elsner et al. 2023).

Transition governance focuses on how actors can influence and steer transition processes (Loorbach et al. 2017). It takes a more process-oriented and goal-seeking approach designed to deal with complexity and uncertainty by focussing on the gradual nature of transitions over time (Duru et al. 2015a; Prost et al. 2023). More specifically, this is conceptualised within the transition management framework through transition cycles composed of four successive and iterative stages (Loorbach 2010): (1) a *strategic step*, aimed at structuring and envisioning the problem and the transition arena; (2) a *tactical step*, aimed at developing coalitions, images and transition agendas; (3) an *operational* step, aimed at mobilizing actors and executing projects; and (4) a *reflexive* step, aimed at evaluating, monitoring and learning (Loorbach 2010). Adopting a similar approach, several transition frameworks have been developed specifically for the transition of agriculture and food systems. Duru et al. (2015a) propose a five-step methodology to help design the agroecological transition and develop biodiversity-based agriculture at a territorial level; Dendoncker et al. (2018) develop a four-step, iterative framework to help steer agroecological transitions based on ES assessments at farm and landscape levels; Prost et al. (2023) consider transitions to agroecology at the farm level as an open-ended process of successive stages leading to the implementation of agroecology principles and practices; Gaupp et al. (2021) propose a four-step framework for food system transformation, which specifically integrates policy implementation barriers in a pathway modelling exercise. Despite some variations in terms of specific steps or targets within the food system (farm, territory, landscape, policy), all these frameworks share a step-by-step, often iterative, approach, which could be summarised by the following sequence (Figure 1): *assess (current/new situation) - envision (possible futures) - implement (transition pathways).* While transition governance takes a pro-active approach, it may be considered too "managerial", in particular transition management, creating the idea that transitions can be managed while they are complex and long-term processes (Kueffer et al. 2019).

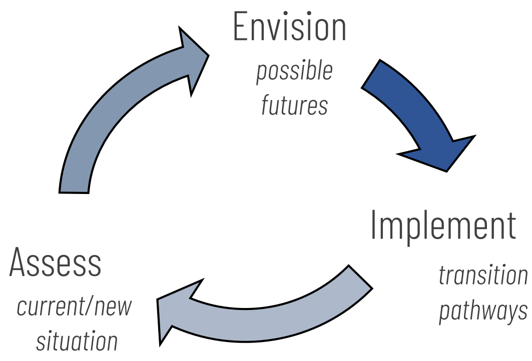

Figure 1. Three main stages of transition cycles, based on existing transition governance frameworks.

Finally, agroecology, understood as a science, a social movement and a practice, and consolidated around a set of principles (Wezel et al. 2009, 2020), is also strongly embedded in a transition perspective as it also pursues to transform food systems towards greater sustainability (Gliessman 2016). This is conceptualised through five levels of agroecological transitions, which vary in the level of ambition and scale of application, ranging from more incremental approaches aimed at improving practices at farm level (levels 1 and 2), to the redesign of agroecosystems at landscape level (level 3), and the transformation of food networks and food systems as a whole (levels 4 and 5) (Gliessman 2016; Wezel et al. 2020). Analysing the possible ecological intensification of agriculture, Tittonell (2014) notes that the transition toward sustainable food systems extends beyond the farm level to the landscape (and further). In turn, this implies that both individual and collective decision-making processes are involved, and calls for innovations not only in technology but also at the institutional and policy levels (Tittonell 2014, 2023). This also requires the involvement of a wide range of actors and activities across the entire food system, going well beyond the farm stage (Tittonell 2014; Duru et al. 2015a).

1.2.4 A transdisciplinary approach at the science-policy-society interface

Transition governance frameworks strive to assist transition processes. It is debated to which extent such transitions and societal change must originate from (individual) food system actors (*bottom-up*), or be pushed through institutions and policies (*top-down*), or from the interplay between both (Loorbach 2010; Geels 2011; Elsner et al. 2023). Whether coming from top-down or bottom-up initiatives, transition cycles present similarities with the policy cycle (Figure 2). The latter is conceived through a number of successive steps which can be summarized as follows: (1) problem definition and agenda setting; (2) policy design; (3) policy implementation; (4) policy evaluation (Connors 2016; Galli et al. 2020; Brunori 2023).

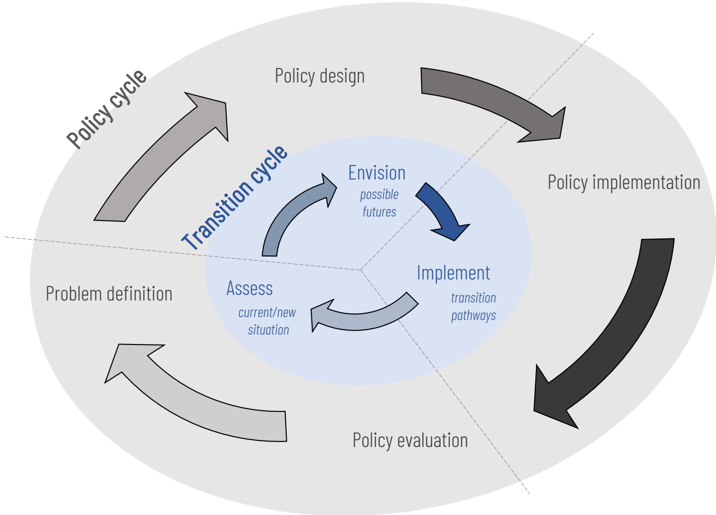

Figure 2. From the transition cycle to the policy cycle.

Given the similar sequence of their cycles, the field of transitions research seems to be closely linked to policymaking: Gaupp et al. (2021) directly integrate policymaking in their transition management framework, while Galli et al. (2020) propose a hybridised framework bringing together the policy cycle and the MLP. The interaction and possible alignment between both cycles could be an example of fostering the science-policy-society interface, which has been advocated in the context of food system transitions (Rivera-Ferre 2011; Singh et al. 2022, 2023; Benton 2023). The science-policy-society interface can provide multiple functions, some of which may be linked to different stages of the policy cycle. These include multi-stakeholder dialogues, capacity building, open access to food systems data, modelling and foresight exercises (policy agenda setting stage), independent assessments (policy formulation and evaluation stages) and diplomatic forums for setting policy targets (Connors 2016; Singh et al. 2023).

In a European context, there are several examples and analyses of how science has contributed to specific pieces of agriculture- and food-related policymaking, and how the position of science has evolved over time. The Common Agricultural Policy (CAP) constitutes an evident first case given its long-standing history. While there is evidence that research has supported the design and evolution of this policy in the past, the impact of research on the policy today is less clear (Guyomard 2025). The evidence produced by researchers on the unsustainability of the currently dominating intensive farming practices and systems may have contributed to a progressive greening of the CAP over the years. Yet, environmental sustainability has only marginally improved. While this failure may be attributed to policy in the first place (due to insufficient ambition and/or enforcement), Guyomard (2025) argues that research may also be responsible of this failure. The main reasons for this reside in the lack of a shared vision for the future of

European agriculture, both within society and within the scientific community, and the too unfrequent acknowledgement of trade-offs between conflicting goals. Moving the focus to parallel pieces of legislation, Pe'er et al. (2025) analyse the role of science in the cases of the Nature Restoration Regulation (NRR) and the Sustainable Use Regulation (SUR), which faced different outcomes as the former was adopted while the latter was rejected. The authors identify three factors that may have contributed to the different fates of both policies: the level of consensus within society (very high in the case of nature restoration and more uncertain in terms of reducing agrochemicals), the degree of voluntary participation (measures were less mandatory and restrictive in the NRR compared to SUR), and the role of industry and economic-driven interests (which are significant in the case of the agrochemical industry and more diluted in the case of sectors affected by the NRR). Finally, Van Zanten et al. (2025) analyse the evolution between the 2024 multi-stakeholder Strategic Dialogue on the future of EU Agriculture and its 2025 successor proposed by the European Commission, the Vision for Agriculture and Food. In their analysis, the authors highlight the noticeable mismatch between both documents. While the first gathered major actors from the European food and farming sectors, including scientists, the second showcases significant scientific shortcomings, resulting in a gap of ambition between both documents.

Based on these examples and perspectives from Benton (2023), a series of recommendations can be found for fostering science-policy-society interfaces in the context of food system transitions. We propose to group them into three main points.

1. **Acknowledging a diversity of visions and revealing trade-offs.** It has been mentioned earlier that a diversity of visions and narratives coexist with regards to the future of our food systems. It is believed that research should overcome disciplinary silos and foster system-wide overviews (despite their limitations in terms of limited boundaries, lack of view on displaced effects, etc.). To accurately inform policymakers, these systemic views should reveal the trade-offs involved and not shy away from reflecting and communicating complexity (Benton 2023; Guyomard 2025; Van Zanten et al. 2025). Inevitably, new policies will favour some stakeholders and penalise others. It is therefore necessary to know how to support those actors accordingly (Pe'er et al. 2025).
2. **Overcoming the failure of a 'knowledge deficit' model.** Researchers largely act as information providers, considering that what is done with the generated information is out

of scope, even though it is known that providing knowledge is rarely sufficient to spark change (Benton 2023). Different strategies for overcoming this challenge are proposed:

a. Co-creation and co-design of research questions and research agendas with non-academic actors (Benton 2023).
b. Generation of 'transition knowledge': beyond subject knowledge, we need to generate information about the costs of inaction, the benefits of action, a vision on the system's functioning after transformation, and a plan on how to get there (Benton 2023).
c. Proactive engagement of scientists in communicating scientific evidence and making it more accessible (e.g. through open letters) while remaining unbiased and transparent on the data and information (Pe'er et al. 2025).

3. **Questioning political ideologies.** Researchers do not often question the ideological divide between the vision of the world which they aim to pass onto policymakers (through the provision of knowledge), and the currently prevailing political ideology, which is largely immersed and driven by neo-liberal paradigms of free markets and economic growth (Benton 2023). Arguably, both sides are and consider each other ideological. From the academic side, it is believed that more research is needed on how to change political ideologies. Without change in the political space, systemic transformation is unlikely to occur (Benton 2023).

From a more theoretical perspective, a series of concepts related to different types of knowledge and research approaches allow to better apprehend the functioning of science-policy interfaces. Comparing the actors involved on both sides of the interface, scientists are usually considered as 'uncertainty creators', while policymakers seek to reduce uncertainty. This distinction should be nuanced as academics engaging in interfaces with policy and society may shift between a position of uncertainty creators and uncertainty reducers (Cleaver and Franks 2008). In these two positions, and in relation with the three recommendations provided above, we find two myths which need to be overcome: a 'rationality myth' assuming that all policy decisions are evidence-based (Cleaver and Franks 2008; Benton 2023), and a 'power of science myth' assuming that science is capable of providing the necessary data and knowledge to inform such decisions when necessary (Cleaver and Franks 2008; Pe'er et al. 2025). Going further, as research priorities may be set by policy (e.g. at EU level), some research results may be policy-driven, rather than policy being research-driven (Guyomard 2025).

In their conceptualisation of science-policy interfaces, Cleaver and Franks (2008) build on the different approaches to knowledge creation proposed by Burawoy (2005). Four approaches stand out based on the aim of knowledge production (either instrumental or reflexive) and the intended audience (either academic or extra-academic). In this framework, 'policy knowledge' is characterised by a concrete and pragmatic approach in the service of problems identified by clients, while 'critical knowledge' questions and discusses theoretical assumptions and tends to remain within the academic sphere. Policymaking thus often relies on instrumental approaches to knowledge, where empirical information is used to identify 'best practices' which in turn can guide policymaking (Cleaver and Franks 2008). The danger of such 'positivist' approaches resides in the generalisation of case-specific best practices to situations which do not meet the same conditions, with the risk of eventually leading to a theoretical fragmentation due to the incompatible nature of solutions retained. Contrary to this position, critical realism acknowledges that events take place within geo-historical contexts, and that according to context, outcomes are influenced by a variety of mechanisms. Going back to policymaking, an intermediate approach is advocated, where information on what works (best practices) is complemented with coherent conceptualisation seeking to develop a more general understanding of the system which transcends particular contexts (Cleaver and Franks 2008). From a transdisciplinary perspective[6], research can contribute to societal problems through three types of knowledge (Hirsch Hadorn et al. 2006; Kueffer et al. 2019): systems knowledge (asking why and how processes occur and where change is needed), target knowledge (asking what better practices we should aim for) and transformation knowledge (asking how can we get from the current to the desired situation).

Beyond the type of knowledge, the intended use of research can also be considered, with three main purposes being identified: research for knowledge (i.e. improving our general understanding of the world), research for policy (i.e. providing evidence of outcomes) and research for practice (i.e. generating location-specific data to inform practical actions). Unsurprisingly research for policy is the most characteristic of the science-policy-society interface, and is often undertaken for campaigning or advocacy (Cleaver and Franks 2008).

[6] Transdisciplinary research, or transdisciplinary action research is understood here as a *processes for cultivating and sustaining collaborations across multiple disciplines* (academic and non-academic), *all of which are working to achieve a broad array of shared community goals* (Stokols 2006). The idea is to focus more on the goals and the problems to solve rather than on disciplinary specificities (Hirsch Hadorn et al. 2006).

1.3 Case study: the Belgian livestock transition

A case study approach investigating the Belgian livestock transition was adopted to substantiate the more theoretical considerations presented in the previous paragraphs, and to derive practical elements of analysis in response to a series of research questions. Two elements make this case study particularly relevant for our research. First, as the livestock sector is well-established in the Belgian agricultural landscape, it exhibits multiple scales and levels of operation, including a diversity of actors, sub-sectors, value chains and geographical scales. Second, the transition of the livestock sector is a particularly pressing and complex (e.g. multidimensional) issue. In the context of the transition of food and farming systems, the role and share of livestock production are being increasingly debated due to the many pressures it exerts on the environment and on socio-economic aspects, both globally and in Belgium (Westhoek et al. 2014; Röös et al. 2017b; Willett et al. 2019).

Livestock production occupies an important place in the Belgian food system. The country is a net exporter of livestock products, with self-sufficiency ratios above 100% for the five main productions (beef, pork, poultry, milk and eggs). Close to half of Belgian farms are specialized in livestock productions, both in Flanders (46% of farms) and in Wallonia (48% of farms). There are however important differences in the sectors that developed in both regions, and the resulting challenges. Among other factors, easy access to imported animal feed (such as soy) via the port of Antwerp and a higher population density (and thus increased pressure on land) have led Flanders to adopt more intensive systems, in particular of monogastric productions (Flanders concentrates about 90% of Belgian pigs and poultry). As a result, the region faces important challenges in terms of nitrogen pollution. Wallonia on the other hand is characterized by more available land, and in particular an ample supply of grasslands. It is therefore more suited for extensive systems, particularly of cattle productions. Yet it is not exempt of challenges either as grassland areas have been decreasing over the past years (-14% over the 1990-2018 period) and cattle farmers face dire economic situations. These challenges on the production side are further exacerbated by pressures on other stages of the value chain, in particular on the consumption side, with the intake of animal products being increasingly put into question as several institutional and civil society voices call for a "protein transition", understood as *a shift from a diet rich in animal proteins to one richer in alternative protein intakes, including a reduction in total protein intake and a reduction in animal-based production* (Duluins and Baret 2024b).

In a context of increased societal expectations, the Belgian livestock is thus under significant pressure. It faces several sustainability challenges and needs to embark on alternative development pathways to meet future challenges. For these reasons, the livestock sector and the livestock transition (understood in a wide sense extending to the production and consumption of alternative protein sources), makes a particularly well-suited case study for this research.

1.4 Research positionality and research questions

1.4.1 Complementing existing frameworks

To situate our research, below we provide a summary of the key methodological principles and research assumptions that have been introduced above, and which guide the case study analysis (Figure 3, grey arrow):

1. **An anchoring in food and farming systems research.** Trying to clarify the objects of investigation, common conceptualisation of farming and food systems consider them as complex structures with a diversity of actors, components and activities, which are influenced by external factors and lead to a variety of outcomes.
2. **A multidimensional consideration of sustainability.** Realising the unsustainability of our food system has prompted the necessity to assess its multiple functions and outcomes. Several indicator and sustainability assessment frameworks have emerged for this purpose, targeting different levels and actors of food systems and entailing methodological choices.
3. **A contribution to sustainability transitions**. In parallel, it has become clear that we need to engage in a transition of our food system towards greater sustainability. Definitions of sustainability transitions highlight that they are complex and long-term processes involving a variety of actors and occurring at multiple scales. Transition frameworks have emerged to help analyse and guide such transitions, but their progress so far remains unsatisfactory.
4. **A transdisciplinary approach to research**. Situated at the science-policy-society interface, research can contribute with different types of knowledge. It must nevertheless consider a series of attention points to ensure effective integration in policymaking

As laid out initially, the empirical cases at the origin of this work take different entry points to analyse the question of the livestock transition in Belgium. The empirical chapters investigate different spatial scopes (Wallonia, Flanders, Belgium), different sectors (the livestock transition is understood widely, extending to the protein transition as two sides of the same coin), different value chain stages (from production alone, to the integration of consumption aspects and wider value chain perspectives). While the methodological principles introduced above provide a consolidating framework, we feel insufficiently well equipped to fully grasp the nuances and implications that these different analytical entry points entail. Hence, we aim to take the opportunity of this dissertation to further explore how analyses performed at different scales and levels may interact, be complementary and affect how the different methodological principles outlined earlier are applied in each case. To this end, the following chapter will investigate the concept of scale in food system transitions, providing a complementary research framework for the joint analysis of the investigated case studies.

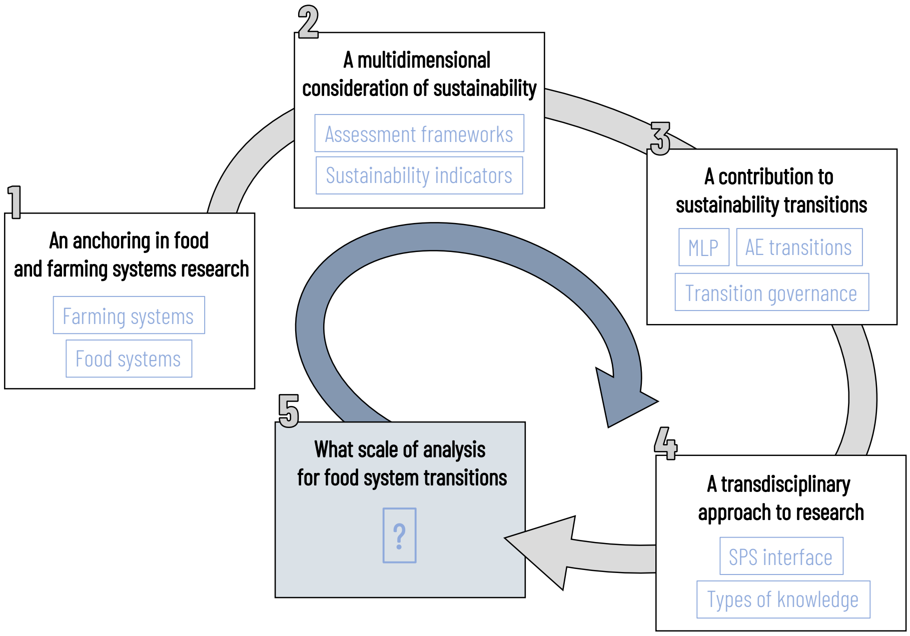

Figure 3. From methodological principles to the research proposal. The grey arrow represents the flow of concepts presented in the introduction. The blue arrow represents the proposed flow of research. Light blue and white boxes represent conceptual frameworks.

1.4.2 Research questions

In this research, we first seek to further investigate and consolidate the concept of scale, and then strive to analyse how this affects assessments of food system sustainability and food system transitions (Figure 3, blue arrow). As a result, this PhD addresses three transversal research questions (RQ), grounded in the multifunctional nature of food systems and adopting the multi-step approach of transition cycles:

1. **Research question 1:** Is it possible to conceive and adopt a framework of analysis which conciliates the fact that food system transitions are multi-scalar?
2. **Research question 2:** How to address the multifunctional nature of food systems while accounting for the multiplicity of scales?

3. **Research question 3:** How to navigate the different stages of the transition cycle while accounting for the multiplicity of scales?

1.4.3 PhD outline and document structure

This dissertation is structured into seven chapters, grouped into three main sections (Figure 4 and Table 1).

The first section aims at setting the scene of the PhD, with a double objective: (1) providing a general introduction resulting in the identification of the main and transversal research questions (chapter 1), and (2) defining a conceptual research framework (chapter 2), that will serve as a complementary research guide in the subsequent chapters.

The second section is an implementation of the methodological framework established in the first section throughout a research process, applying it to the livestock case study. The section is structured around the three stages of a transition cycle: the assessment step (chapter 3), the envisioning step (chapters 4 and 5) and the implementation step (chapter 6).

The final section pursues a reflective objective. Taking the form of a general discussion (chapter 7), it aims at taking a step back and retrospectively discussing the adopted approach and how it may or may not contribute to advancing food system transitions.

The PhD hinges on methodological questions (i.e. trying to answer questions surrounding the methods to research food system transitions) and topical questions (i.e. trying to answer questions surrounding the topic of the livestock transition). Besides contributing to the transversal research questions, each chapter seeks to answer its own specific research questions (Table 1), which are either methodological (chapters 2 and 4) or topical (chapter 6), or both (chapters 3 and 5).

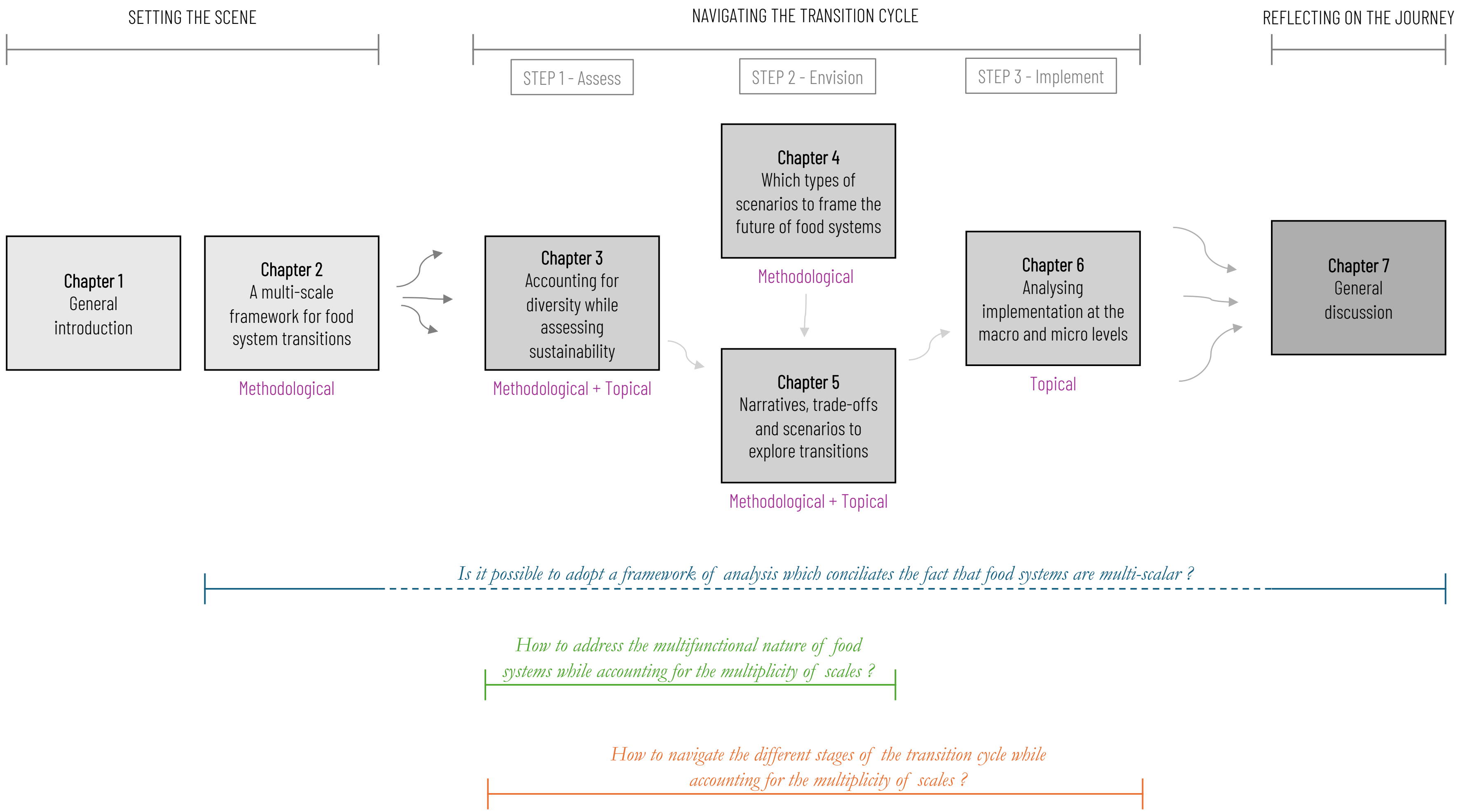

Figure 4. Overview and flow of PhD chapters and main research questions.

Table 1. Overview of PhD chapters (excluding introduction and discussion) in terms of content type, research questions and methods.

Research theme	Chapter 2 From micro to macro, local to global and farm to fork: a multi-scale framework for food system transitions	Chapter 3 Accounting for diversity while assessing sustainability: insights from the Walloon bovine sectors	Chapter 4 Which types of quantitative scenarios to frame the future of food systems? A review	Chapter 5 Narratives, trade-offs and scenarios to explore the livestock transition in Belgium	Chapter 6 Will the protein transition happen? An analysis of macro- and micro-level implementation in Flanders
Content type and focus	**Methodological:** Food system and transition studies **Topical:** /	**Methodological:** Sustainability assessments and diversity assessments **Topical:** Walloon bovine sectors	**Methodological:** Quantitative foresight scenarios **Topical:** /	**Methodological:** Foresight scenarios and transition cycles **Topical:** Belgian livestock sector	**Methodological:** / **Topical:** Flemish protein transition
Research questions	How can we conceptualise the multiplicity of scales and what are the implications for food system analysis? Transversal RQ 1	How to articulate diversity and sustainability when assessing the performances of a farming sector? Transversal RQ 2 (1-3)	What are different types of scenario exercises and what are the methodological implications laying behind? Transversal RQ 3 (1-2)	What are the implications of main livestock transition narratives and how can foresight scenarios advance food system transitions? Transversal RQ 2 & 3 (1)	How are transition pathways implemented at macro and micro level and how do these two levels interact? Transversal RQ 1 & 3
Methods	Literature review	Sustainability assessment Diversity assessment	Literature review	Scenario design	Policy analysis Narrative analysis Value chain mapping Barrier analysis

Chapter 2 From micro to macro, local to global and farm to fork: a multi-scale framework for food system transitions

This chapter is under revision in *One Earth*,
as a Perspective article co-authored by Anton Riera and Philippe V. Baret

Abstract

Food system transitions occur at multiple scales. Yet, this multiplicity is not always explicitly addressed in food system studies. Departing from different understanding of meso approaches, this paper aims to clarify the concept of scale. It proposes a framework that considers three interconnected scales: the spatial scale (from local to global), the supply chain scale (from production to consumption), and the scale of action and decision-making (from individual action to policymaking). The framework can be used for two main purposes: fostering transparency of research approaches on analytical scales, and providing a guide to unpack the functioning of food systems at multiple scales and levels. The paper investigates the challenges and trade-offs that appear from cross-level and cross-scale interactions. Through the proposed framework, the importance of adopting food system approaches and accounting for diversity becomes apparent. In this regard, greater attention to sectoral, territorial and meso-level approaches could be a promising avenue to support food system transitions, if certain attention points are not overlooked.

2.1 Introduction

The societal call for food system transitions is widespread given the many challenges faced by food systems in terms of environmental, nutrition and socio-economic outcomes (IPES-Food 2016; HLPE 2017; Béné 2022; Juri et al. 2024). On the one hand, food systems are commonly understood as complex socio-ecological systems encompassing all actors, activities and drivers affecting the production, processing and consumption of food, including the socio-economic and environmental outcomes of these activities (Ericksen 2008; HLPE 2017). On the other hand (sustainability) transitions refer to non-linear and large-scale shifts in societal systems that emerge over long periods of time (Loorbach et al. 2017). Joining both concepts, Juri et al. (2024) propose to define food system transitions as *"significant reconfigurations of the assemblage of food system activities, outcomes and relationships [..] to ensure sustainable, resilient and just models production and consumption"*. The authors highlight that food system transitions can be *"debated and enacted at multiple scales"* (Juri et al. 2024).

Discussions on the concepts of scale and multi-scale dynamics related to sustainability challenges and societal changes are not new. Scale can be understood as *"the spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon"* (Gibson et al. 2000). Related to scales, *levels* refer to units of analysis at different positions on a scale (Gibson et al. 2000). Levels can be ranked along a scale following hierarchical relations, which can be exclusive (lower levels are not contained in higher levels), or nested (inclusive hierarchy where lower levels are contained in higher levels; or constitutive hierarchy where different levels combine into new units with emergent properties) (Gibson et al. 2000). Accounting for cross-scale and cross-level interactions is important as scale challenges are considered to be part of why societies struggle to achieve sustainability (Cash et al. 2006).

Common frameworks used in the context of food system transitions, such as the multi-level perspective (MLP), transition governance, and agroecological transitions, indeed recognise that these processes occur at different scales and levels. The MLP conceptualises transitions as emerging from interactions between three levels: niches (sites of innovation), regimes (dominant practices and structures), and landscapes (exogenous factors). The framework has been widely applied to food and farming systems (e.g. Geels 2011; Bui et al. 2016; Dumont et al. 2020; Leeuwis et al. 2021; Elsner et al. 2023), though often with a focus on niche-level innovations at the farm level (Elsner et al. 2023). Alternatively, transition governance focuses on how actors can steer transitions, conceptualised within transition management through iterative cycles of assessment, envisioning, and implementation (Loorbach 2010; Loorbach et al. 2017). Frameworks sharing this step-by-step approach have been designed for agriculture and food systems but vary in scale and level of application, often targeting the farm level (Duru et al. 2015a; Dendoncker et al. 2018; Prost et al. 2023; Meynard et al. 2023), and in some cases integrating supply chain (Duru et al. 2015a), policy (Gaupp et al. 2021), and territorial perspectives (Duru et al. 2015a; Dendoncker et al. 2018). Finally, agroecology, is also strongly embedded in a transition perspective as it pursues to transform food systems towards greater sustainability (Gliessman 2016). This is conceptualised through five levels of agroecological transitions, which vary in the level of ambition and scale of application, ranging from incremental approaches targeting practices at farm level, to the redesign of agroecosystems at landscape level, and the transformation of food networks and food systems as a whole (Gliessman 2016; Wezel et al. 2020). Together, these perspectives highlight that transitions toward sustainable food systems extend beyond the farm level to landscapes and further, implying that both individual and collective decision-making processes are involved, calling for innovations not only in technology but also at the institutional and policy levels, and requiring the involvement of a wide range of actors and activities across the entire food system, going well beyond the farm stage (Tittonell 2014, 2023).

As phenomena can be analysed from different scales and levels along these scales, interactions occur across levels and scales (Cash et al. 2006). Accounting for cross-scale and cross-level interactions may pose a series of decision-making and sustainability challenges when analysing complex socio-ecological systems and human-environment relations. Cash et al. (2006) identify three main scale-related challenges, and three possible responses. Scale challenges include *ignorance* (the failure to recognise the existence of multiple scales, levels, and interactions), *mismatch* (between the scales and levels of analysis and that of action), and *plurality* (the assumption that the best way to frame a problem is from one single scale and level, often the point of one specific actor). Proposed responses to address these challenges include institutional interplay (coordinated interplay between different jurisdictional levels), co-management (coordinated interactions and responsibility sharing between governments and local communities) and bridging organisations (addressing the plurality challenge by bridging different levels) (Cash et al. 2006).

In the case of food system transitions, so-called *meso* approaches (Gibson et al. 2000; Schenk et al. 2007; Borman et al. 2022; Quattrini et al. 2024; De Herde and Dufays 2025) are put forward to overcome scale-related challenges as they allow to bridge across levels, between macro and micro. Yet, these terms are used in relation to different scales in the literature, with different coexisting conceptualisations of macro, meso- and micro-level approaches. For instance, the terms can be used the case of supply chains (Borman et al. 2022; De Herde and Dufays 2025), where food systems are presented as a macro-level concept while sectoral and value chain approaches constitute a meso level that facilitates practical implementation at the micro level. The micro-meso-macro can also be linked to spatial scales, referring to small-, medium- and large-scale phenomena (Gibson et al. 2000). Between local and global approaches (Quattrini et al. 2024), territorial, landscape or supply shed approaches (Duru et al. 2015a, b; Cammelli et al. 2025) can constitute and intermediate meso level. Finally, as described in public policy literature (Hooghe 1995; Roberts 2020; Quattrini et al. 2024), the terms can also refer to levels of decision-making, ranging from micro-level individual action to macro-level policymaking, and where meso actors play a bridging role between both.

Thus, different scales have been recognised and proposals to deal with cross-level interactions have been put forth, e.g. through the concept of meso-level approaches. Yet, to our knowledge, the multiplicity of scales involved in food system transitions has not yet been explicitly brought together. Departing from the multiple understanding of macro, meso and micro levels, we propose a framework centred around three scales: a spatial scale (from local to global), a supply chain scale (from production to consumption), and a scale of action and decision-making (from individual actions and decision-making to policymaking). The purpose of this paper is threefold as it seeks to investigate three questions: (1) how can meso-level approaches be integrated and what does this imply regarding the multi-scale nature of food system ; (2) how can the resulting framework be used in the perspective of food system transitions; (3) does the framework, and in particular meso-level approaches, facilitate cross-level and cross-scale interactions, and what does it overlook ? In the following paragraphs, the paper proceeds by further introducing the proposed framework and its different scales (paragraph 2.2), before considering possible uses and discussing the possibility to address cross-scale and cross-level interactions through meso-type approaches (paragraph 2.3). Finally, concluding perspectives for policy and research are provided (paragraph 2.4).

2.2 A multi-scale framework for food system transitions

In the following paragraphs we first consider the three proposed scales individually, along with respective levels and challenges resulting from cross-level interactions. The last paragraph proposes to integrate these individual scales into a multi-scale framework.

2.2.1 Spatial scale: from local to global

A first perspective on scale focuses on the spatial extent at which food and farming systems operate, ranging from local to global, distinguishing food and agricultural products that are produced and traded locally versus internationally or globally. This topic has been extensively debated in recent years. Influenced by a diversity of values, perceptions and visions (Carlile and Garnett 2021), it has taken the form of a polarised local-global debate, or what has been coined by Wood et al. (2023) as a *dichotomy of scale*. Yet, the question should not necessarily be to know at which scale our food systems should operate, as both globalised and localised systems have arguments in their favour (Enthoven and Van den Broeck 2021) and maintaining a diversity of scales is seen as important (Carlile and Garnett 2021).

From a transition perspective, it seems important to elucidate at which level change should be triggered and implemented, for instance investigating the functioning of food systems at national level (Parajuá et al. 2025). In this sense, various voices advocate for intermediate approaches situated at landscape, supply shed or territorial action scale when designing transition pathways, to account for the local specificities of food systems, to increase relevance and facilitate implementation (Duru et al. 2015a; Caron et al. 2018; Padró et al. 2020; Carlile and Garnett 2021; Gasselin et al. 2021a; Duru and Thérond 2021; Béné 2022; Juri et al. 2024; Cammelli et al. 2025). Similarly to the level scale which may refer to several definitions and understandings (Liu 2025), these intermediate approaches does not necessarily refer to well-defined geographical or administrative scales. For instance, the territorial level can be understood as an *"adequate spatial distribution of agriculture and non-agricultural land use in the landscape fostering the ecosystem services"* (Duru et al. 2015a).

While smaller-scale and localized approaches may result in easier and more effective implementation (Liu 2025), they must pay attention to avoid falling into a so-called *local trap* where the single focus lies on the local dimension, implicitly dismissing possible interactions and impacts of larger scales (Landon and Rosol 2025), as well as spill-over effects and leakages (Balmford et al. 2025), with generalisation at higher levels also posing a challenge. Inversely, large-scale planning and analyses have the advantage of a greater coverage but require more efforts of implementation and risk overlooking local specificities, posing challenges in downscaling to locally relevant levels, e.g. national (Parajuá et al. 2025) or urban (FAO 2019). This resonates with possible scalar *mismatches* between the spatial level of analysis and that of governance (Cash et al. 2006). Leaving room for *cross-scalar* or *multi-scalar* approaches is also important (Liu 2025; Landon and Rosol 2025). Socio-spatial relations are considered to emerge from interactions between scales (relations between local, regional, national and global levels), places (as spaces of socio-ecological interactions), territories (as jurisdictional spaces) and networks (Jessop et al. 2008). Thus, the question of the spatial, scale is both analytical and operational: at which scale should food and farming systems be analysed to most effectively guide and implement their transition?

2.2.2 Supply chain scale: from production to consumption

A second perspective on scale focuses on the involved and targeted supply chain stages. From an operational point of view, the supply chain scale can be seen as a succession (rather a network) of the different stages between production and consumption: from input providers to plot to farm to middle chain actors and the consumer. On the research side, several approaches (and communities) coexist, each with different scopes and research boundaries.

Some approaches focus their attention on specific supply chain stages. For instance, commodity-oriented research mainly focuses on production objectives and agricultural practices at crop and animal levels (Darnhofer et al. 2012). Taking a more systemic stance, farming systems research shifts its attention from productivity objectives to the farm system, emphasising the importance of the external context (socio-political, cultural, bio-physical) on the choices of farmers, their practices and their outcomes (Darnhofer et al. 2012, 2015). At the other end of the supply chain, consumer behaviour studies focus on the consumption stage. In between, studies on upstream and downstream actors and activities (e.g. input manufacturing, transport, processing, retail, etc.) are less frequent, despite the determinant role of these actors in defining the functioning of food systems (Weituschat et al. 2023; Grabs et al. 2024; Fischer et al. 2024).

Other approaches may try to apprehend several supply chain stages jointly. Recently, the attention has increasingly shifted to food system approaches, both in political spheres (e.g. EU Farm to Fork strategy, UN Food Systems Summit) and academic spheres, emphasising the urgency of engaging in a transition of our food systems as a whole (Weber et al. 2020; Béné 2022; Juri et al. 2024). Similar to farming systems research, food systems research is strongly embedded in systems thinking, recognising the complexity of these systems and their components and acknowledging that the practices and activities within are diverse, influenced by external factors and lead to a variety of outcomes (Ericksen 2008; HLPE 2017). Compared to approaches focusing on specific supply chain stages, food systems widen the scope and include all stages (although they are larger in scope and go beyond the activities of supply chains). Arguably, the concept of food systems is not always easy to operationalise in practice (Brouwer et al. 2020; Juri et al. 2024).

Value chain and sectoral approaches are presented as intermediate and more operational conceptualisations of food systems (Borman et al. 2022; De Herde and Dufays 2025). Sectoral approaches focus one specific sector or "commodity", such as vegetables, cereals, dairy, etc. They are claimed to bring more tangible granularity by analysing how different actors of a specific sector (e.g. farmers, processors, consumers, etc.) operate and interact, highlighting possible blocking elements and identifying potential interventions (Borman et al. 2022).

2.2.3 Scale of action and decision-making: from micro to macro

A third perspective on scale relates to the level of action and decision-making. Actors within the food and farming systems operate at different levels (Borman et al. 2022). To frame this, we apply to food systems the micro, meso and macro levels, as described in public policy literature (Hooghe 1995; Roberts 2020; Quattrini et al. 2024). On one end, the micro level represents individual action and decision-making (Roberts 2020; Quattrini et al. 2024), corresponding to specific practices of individual farms, consumers or other supply chain actors. On the other end, macro-level policymaking aims to provide guidance on how the system should operate (Roberts 2020)[7]. In between, meso-level actors or institutions facilitate the implementation of macro-level policies and connect the policy level to individuals (Hooghe 1995; Quattrini et al. 2024), although direct feedback from the micro level is also possible (Roberts 2020). Presented as such, the meso level can be considered as an interface, with a bridging role between the micro level and the macro level, with also its own network of actors (farm counsellors, farmer unions, sectoral organizations, etc.), activities, properties and policy needs (Quattrini et al. 2024).

From an analytical perspective, the micro-, meso- and macro levels can be both objects and/or recipients of research. Analyses can either look at how things work at different levels (e.g. researching the functioning of farms, the role of farmer unions or the impact of policies), or they can aim to assist actors at those levels (e.g. by designing farm-level decision support tools, producing research that fosters dialogue between food system actors and local governments, or providing insights directly for the policy level). Translating the analysis of Schenk et al. (2007) on energy systems research to food systems, the micro-meso-macro levels embody different research approaches. Among other elements, micro-, meso-, and macro-level approaches deal differently with farming and food systems' inherent diversity (Box 1, Figure 5).

[7] The macro-level in itself can spread over multiple levels (multi-level governance). In the EU, this can for example be seen in the articulation from EU institutions to national and local administrations (López-García et al. 2024; Borniotto et al. 2025).

Micro-level analyses describe the individual functioning of isolated elements of the system at low aggregation levels (Schenk et al. 2007) (e.g. farm assessments, consumer behaviour studies, etc.). They are well-suited for specific problems requiring 'engineering solutions' but provide little information on interactions with the overall functioning of the system. Although some awareness of the macro level should always be incorporated (Roberts 2020), micro-level research may produce an 'optimistic bias' or 'engineering paradigm' leading to potentially too optimistic generalisation of micro-level results at higher levels (Schenk et al. 2007).

Macro-level analyses describe the overall functioning of a system at a high level of aggregation and often for policy purposes (Schenk et al. 2007) (e.g. agricultural outlooks, policy analyses, etc.). They are valuable for monitoring but are less flexible and less able to foresee trend-breaking events, known as the 'macro bias' or the 'economic paradigm' (Schenk et al. 2007).

In between, meso-level analyses describe the system from an intermediate level of aggregation. Meso-level research is associated with systems analysis, providing the possibility to acknowledge trade-offs and feedbacks and to account for the heterogeneity of actors (Schenk et al. 2007). Potentially targeting both micro-level and macro-level actors, meso-level research plays a bridging role between micro and macro (Roberts 2020). Compared to micro-level and macro-level approaches, research on the meso-level seems to be more seldomly pursued (Schenk et al. 2007; Quattrini et al. 2024).

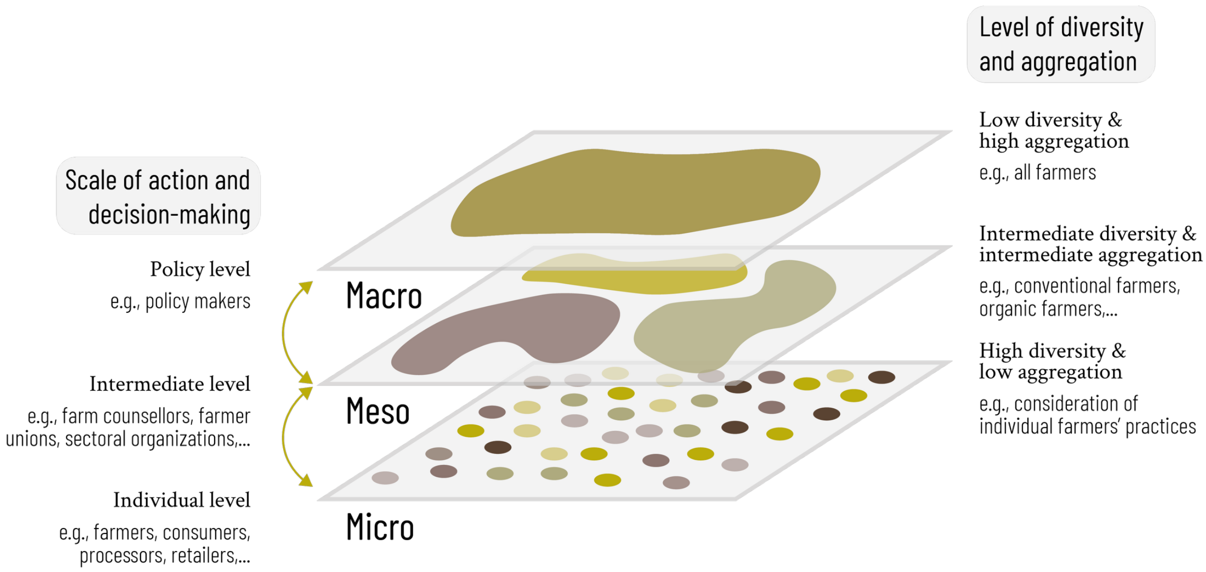

Figure 5. Linking the scale of action and decision-making to the level of diversity and aggregation considered.

Box 1. Micro, meso and macro-level approaches to apprehend diversity.

Usual conceptualisations and definitions of farming systems (Van der Ploeg 2010; Darnhofer et al. 2012, 2015) and food systems (Ericksen 2008; HLPE 2017) recognise a diversity of practices and configurations. The diversity of systems, its management, and its effects on the functioning of the system as a whole are referred to as the *coexistence of systems* (Gasselin et al. 2021a). From a transition perspective, accounting for a diversity of systems and actors is crucial for several reasons. First, it enables a better understanding of challenges and possible solutions (e.g. by identifying "promising" systems). Second, different actors have different needs at different moments and should thus be targeted differently to design adequate policies (Schenk et al. 2007). Finally, not every actor will evolve along the same pathway in transition processes. Societal transitions can be represented through an X-curve in which some systems or visions might "win" through experimentation, emergence and stabilisation phases, while others might "lose" and will eventually phase out after initial optimisation, destabilisation and breakdown phases (Loorbach et al. 2017). In this perspective, accounting for diversity allows putting every actor in the picture and thus better accompanying them in transition processes (Fesenfeld et al. 2023). In turn, this helps tailor solutions to actors and pathways (e.g. compensatory measures for "losing" actors) rather than oversimplifying solutions and deepening polarisations.

With regards to the scale of action and decision-making, macro-level analyses ambition to cover the entire system and all of its actors but often consider them as homogenous (e.g. homogenous farmers or consumers) as they rely on aggregated data. On the other end, the micro-level displays a high level of diversity and heterogeneity of actors and practices (in terms of farms, agricultural practices, consumer behaviours, value chains, etc.). Yet, micro-level analyses do not necessarily capture all of the existing diversity as focusing on subparts of a system possibly limits the representativeness of the analyses and overlooks challenges and emergence factors occurring during scale-up or scale-out (Schenk et al. 2007; Moore et al. 2015) (e.g extrapolating to a whole sector the implementation of a new technology after testing it in a limited number of farms). Meso-level analyses are situated in between and pay particular attention to reflecting the diversity of practices and actors within the system by relying on intermediate levels of aggregation (Schenk et al. 2007) (e.g. by considering typologies of production systems or consumption behaviours) (Figure 5).

2.2.4 Integrating across scales: operational continuity vs. analytical viewpoints

The previous paragraphs delineate different understandings of scale, detailing three dominant conceptualisations related to meso approaches. Each scale is confronted with a series of challenges and cross-level interactions, which meso-level approaches are meant to facilitate. In the context of this paper, we primarily apply the terms micro, meso and macro to the scale of action and decision-making where the macro level corresponds to the policy level and the micro level represents individual actions and decision-making. Yet, sectoral and value chain approaches on the supply chain scale, or territorial, landscape and supply shed approaches on the spatial scale can also be considered to fall under meso-type approaches. As such, the meso level can be considered as an interface (between micro and macro), an object (with its own actors, functioning and properties), and an approach (to research a system).

The three scales introduced provide a first base for stabilisation and frame the question of the multiplicity of scales. From the perspective of food system transitions, the challenge resides not only in addressing the cross-level interactions within each individual scale (e.g. articulation of local vs. global; production vs. mid-chain vs. consumption; individual action vs. policymaking), but also in integrating across scales to understand how the scale-specific challenges interact and how they can be articulated. The integration of the three scales can be conceptualised as a three-dimensional space comprising a spatial scale, a supply chain scale and a scale of action and decision-making (Figure 6). It provides a framework allowing us to apprehend food and farming systems both from an operational and analytical point of view. From an operational perspective, the three scales provide a continuous space in which activities from the food system take place at different spatial scales and different stages of the supply chain, ranging from individual actions at the micro level to policymaking at the macro level. From an analytical perspective, the space created by the three scales and their different levels can be considered as possible viewpoints to analyse a certain product, activity, or food system component. The spatial scale allows us to define the spatial boundaries of an analysis, the supply chain scale determines which activities of the food system are assessed, and the scale of action and decision-making shapes the research approach with regard to the level of action and the diversity of actors that are being targeted.

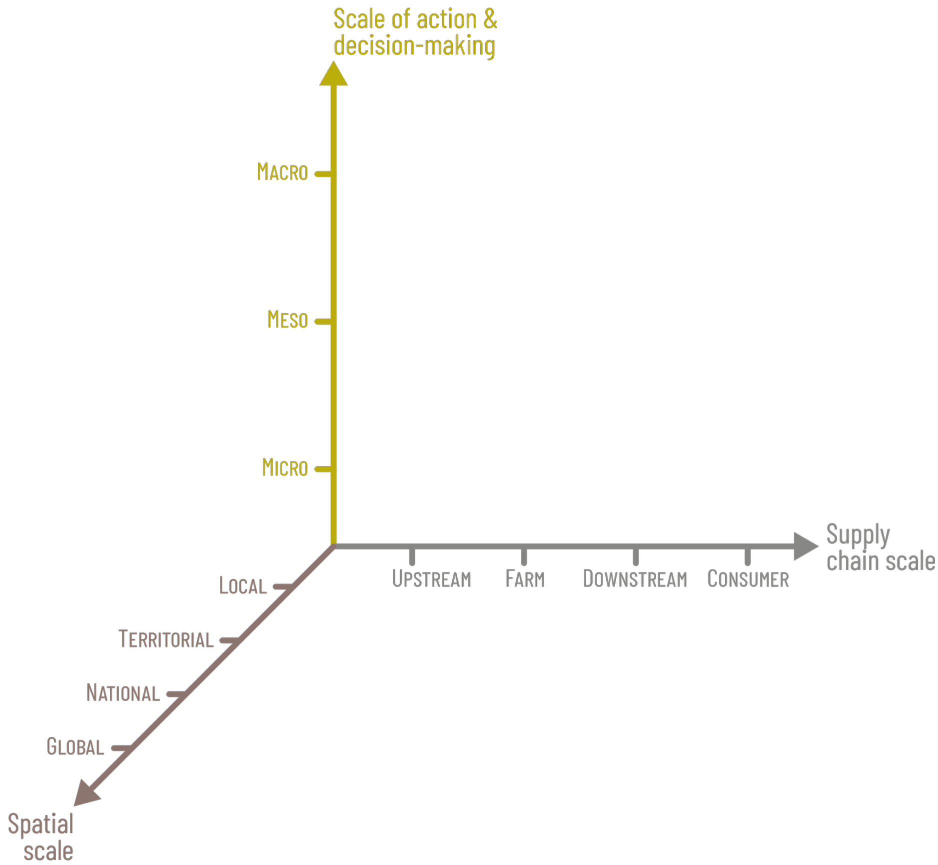

Figure 6. Integrating the multiplicity of scales in the context of food system transitions: the spatial scale, the supply chain scale and the scale of action and decision-making.

Note: The figure present possible levels associated with the spatial scale and the supply chain scale, but additional levels could be added (e.g. landscape, supply shed), while the boundaries of certain levels are not always clearly defined (e.g. local, territorial) and may overlap with others.

2.3 Addressing scale challenges

The main purpose of this framework is to visibilise the multi-scale nature of food systems to avoid overlooking scale interactions and scale challenges (e.g. ignorance, mismatch and plurality) in the perspective of food system transitions. Resulting from the combined analytical and operational purpose of the framework, the following paragraphs illustrate two possible uses of the framework: fostering transparency of analytical approaches and explaining (part of) the functioning of food systems. We then turn our attention to the potential of so-called meso approaches to address scale challenges. Finally, we consider a series of limitations that are overlooked by the framework, particularly in the perspective of its contribution to food system transitions.

2.3.1 Foster transparency and awareness of multi-scale food systems

In line with recent calls for more transparency on the analytical choices made by research (Fischer et al. 2024), the proposed framework can constitute a contribution in this regard. The levels described above can serve as a viewpoint to analyse the functioning of (parts of) the food system from different perspectives. For instance, each stage of the supply chain can be researched at the different levels of action and decision-making and at different spatial scales. Micro-level approaches will focus on specific farming practices, the functioning of (a group of) individual farms, the role of certain supply chain actors in a specific sector, the behaviour of consumers towards certain products, etc. Taking a more aggregated view, macro-level approaches will assess the impact of policies along the different stages of the supply chain. Outlook assessments on prices or productions also fall under the macro level as they are mainly directed towards the policy level. In between, meso-level approaches either focus on the role of meso-level actors in the supply chain (e.g. the role of farmer unions and sectoral organisations in policymaking) or in the process of linking the micro and macro operational levels (e.g. classifying farms with similar characteristics in EU specialisation farming type typologies to facilitate the monitoring of European farms and inform policymaking).

To illustrate this, we take the example of considering different entry points and possible scales of analysis to study the livestock transition (Figure 7), considered a key component in the transition towards more sustainable food systems (Röös et al. 2017b; Herzon et al. 2024; Jaisli and Brunori 2024). As the literature on this topic is abundant, we take a few examples of seminal publications that have shaped the debate over the past years, along with other publications which illustrate the diversity of approaches and scales of analysis adopted.

Starting on the production side, publications by the FAO on the climate change impacts of livestock (Steinfeld et al. 2006; Gerber et al. 2013) provide a macro- and global-level analysis on the potential extent of livestock globally (Duluins et al. 2025). Taking a consumption-side entry point, the EAT-Lancet planetary diet (Willett et al. 2019) provides a macro- and global-level assessment on what a sustainable and nutritional diet would look like. Challenges in such global approaches reside in zooming in and downscaling to locally relevant levels, as shown in the case of the EAT-Lancet diet (van Selm et al. 2022). While they may lack potential for practical and lower-level implementation, such global assessments are nevertheless essential to provide a general framing to the issue. Failing to acknowledge them risks overlooking the scope of the issue. For instance, the analysis by the 'Dublin Declaration of Scientists on the Societal Role of Livestock', hinting that maintaining or increasing livestock may be necessary, partly results from considering the problem at a more localised and micro level (e.g. Global South perspective), while overlooking that, although livestock systems may indeed play an important local role, the issue is global in scope (Bryant et al. 2024). Zooming out may thus be a challenge too (plurality challenge). In between, there are examples of analyses working at intermediate spatial scales and trying to cover several supply chain stages. For instance, the TYFA foresight scenario exercise outlines what an agroecological European food system might look like (Poux and Aubert 2018), including considerations on both production and consumption (among which livestock). At a more localised level, national-level scenarios for the livestock transition (Billen et al. 2018; van Selm et al. 2023; Karlsson et al. 2025a; Riera et al. 2026) provide more room to reflect local specificities, but come with concerns of boundary and spill-over effects (e.g. displaced impacts in other territories). Such assessments link consumption-side considerations (e.g. diets) and production-side assessments, but risk overlooking stages and activities (e.g. middle-chain actors, policy) or simplifying their interactions (e.g. implementation costs and barriers of adopting alternative diets) (Saujot and Waisman 2020; Riera et al. 2025).

Mapping out these different approaches allows to uncover the specific scales of analysis of each assessment (Figure 7), thus fostering transparency of research approaches, in this case related to the livestock transition. Additionally, the diversity of analyses illustrates a series of scale challenges. For instance, how can global-level approaches be downsized to be locally relevant (mismatch challenge); how to avoid focussing on isolated scales and overlooking the big picture (plurality and ignorance challenge); how to make locally relevant approaches actionable while accounting for higher level constraints (ignorance and mismatch challenges)?

2.3.2 Explain functioning of food systems

Switching to a more operational purpose, the framework can be used to describe the functioning of food systems. It can for instance help track the path followed by agricultural products, roughly summarised as follows. Starting at the micro-level, an agricultural product originates on a farm, with potential interactions with upstream actors (e.g. input providers). By passing through several potential supply chain actors and undergoing several potential activities, the product will eventually reach a consumer, at different possible spatial scales depending on the supply chain (from on-farm retail to international trade). This micro-level flow of a particular product will operate under the constraints of macro-level policies, including farm subsidies, production quotas, trade agreements, strategic orientations, etc., and with possible interactions with meso-level actors (e.g. farm counsellors, farmer unions, sectoral organisations, public health authorities providing dietary recommendations, etc.).

The framework can also serve as a guide to analyse how food systems are organised on more specific aspects. For instance, a recent analysis of agri-environmental governance at EU level focusses on the interactions between different levels of decision-making (from farm to policy and the role meso-level actors), but also across spatial scales (from the EU to Member States) (Borniotto et al. 2025). Expanding the scope, the framework can be used to provide a general overview of the EU food policy landscape, which serves as a good example to illustrate the challenge of articulating food system approaches across scales (Figure 8).

Currently, policy competences in the EU follow a siloed approach spread over individual stages of the supply chain and different domains (Galli et al. 2020). The separation of the common agricultural policy from trade policies, health policies and sustainability policies targeting middle-chain actors (e.g. CSRD) highlights the need for effective and well-articulated governance infrastructures (Fesenfeld et al. 2023). While a distribution of responsibilities over different competent authorities may indeed be necessary in the case of complex environmental problems, a key challenge resides in ensuring the different pieces of policy remain coherent and do not enter into conflict (Schenk et al. 2007). Spreading over different EU Commissioners, the EU farm to fork strategy was meant to provide an overarching framework ensuring coherence by adopting a food system approach. This poses challenges at both the micro and macro levels. As food systems thinking tends to happen mainly in policymaking or research settings at a rather high and more conceptual level with few entry points for practical application by food system actors (Brouwer et al. 2020; Borman et al. 2022), implementation at the micro level requires to translate and disaggregate that thinking for each stage of the supply chain, i.e. that of an individual farm, supply chain or consumer (Borman et al. 2022). The fact that recent protests by the farming sector have contributed (among other factors) to abandoning the introduction of a food system policy at the EU level could be an illustration of the difficulty of implementing food systems thinking at micro level (besides other challenges such as the perceived level of ambition of the policy, etc.) (Matthews 2024; Hulot 2025). Additionally, changing the governance model of the farming policy and expanding it from a single to multiple governing bodies may have contributed to exacerbating farmer protests (Matthews 2024).

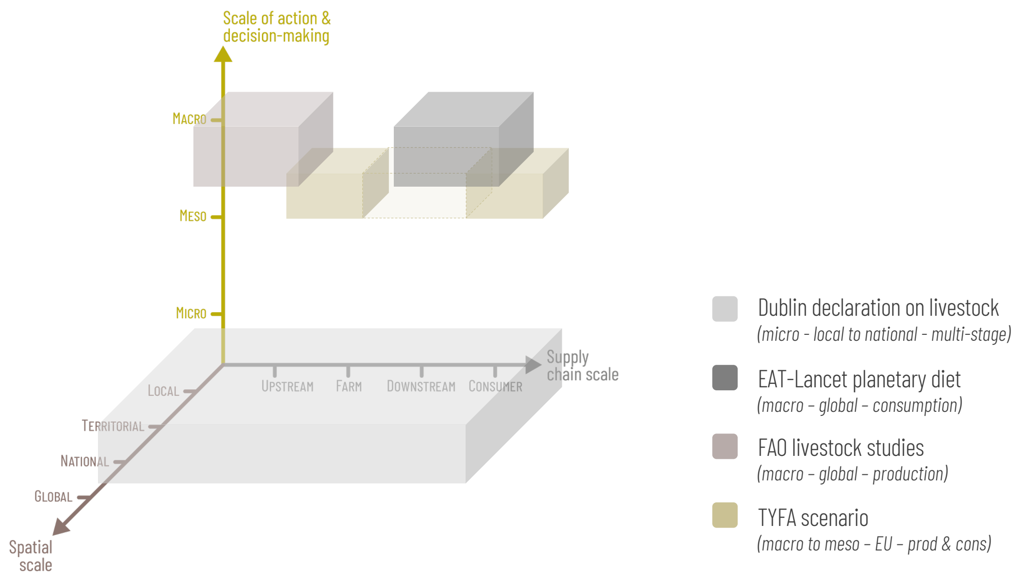

Figure 7. Illustrating different analytical approaches to research the livestock transition at different scales and different levels.

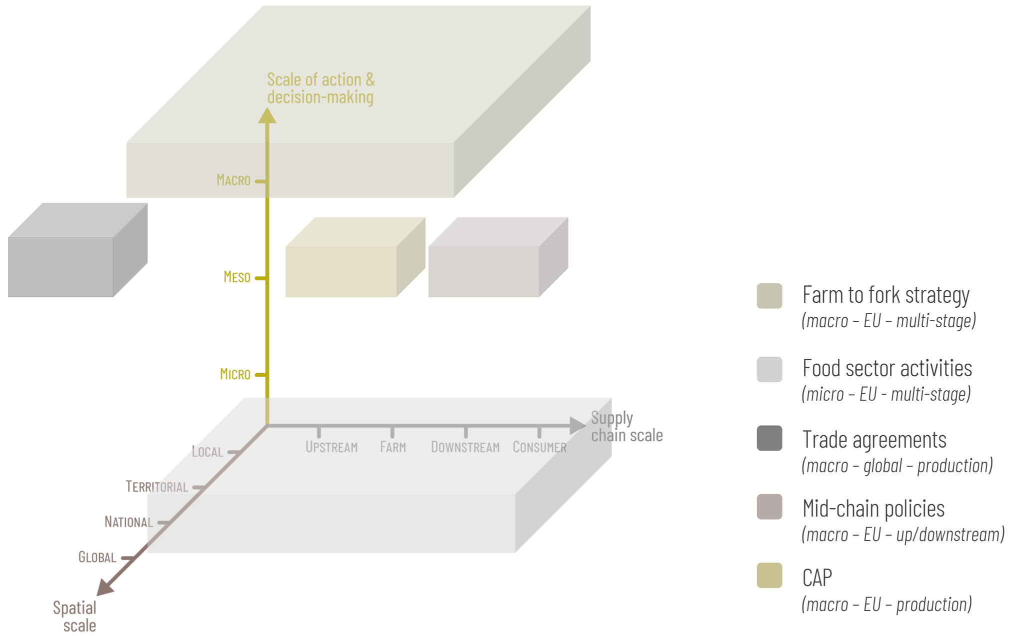

Figure 8. Mapping the EU food policy landscape. The current fragmented approach targets individual supply chain stages and poses challenges of policy coherence, while working at EU level requires articulation across spatial scales and multi-level governance. The tentative for an integrated system-wide policy (Farm to fork strategy) clashed (among others) with micro-level implementation.

2.3.3 Meso-level approaches to account for cross-scale interactions

The preceding paragraphs illustrate the diversity of scale-related changes in the case of two examples: the livestock transition and the EU food policy landscape. In this context, the proposed multi-scale framework helps to visibilise and uncover the multi-scale nature of these issues and related challenges, but gives little indication as to how these scale challenges can be overcome. In this regard, it is worth reflecting on the potential of so-called meso approaches (*sectoral*, *territorial* and *meso-level*) given their intended objective to overcome a series of cross-level challenges. Building on the examples above, it is worth reflecting on the joint application of such approaches and consider cross-scale interactions and possible resulting challenges (Table 2).

Table 2. Cross-level and cross-sector interactions that are addressed (+) or need to be accounted for (-) through meso type approaches (sectoral, meso-level and territorial).

Meso-type approach	Supply chain scale	Scale of action	Spatial scale
Sectoral approaches	**+ :** Account for all supply chain stages **- :** Acknowledge cross-sector interactions	**+ :** Facilitate micro-level implementation	**+ :** Assist in defining relevant spatial scale
Meso-level of action	**- :** How to account for diversity at each stage, or through the food system as a whole ?	**+ :** Bridge individual and collective decision-making **+ :** Ensure e.o is situated in transition pathway (X-curve) **- :** Might be an 'unidentified messy middle'?	**+ :** Account for local specificities **- :** Balance level of local diversity and extent of coverage
Territorial	**+ :** Facilitate participation for locally embedded actors	**+ :** Facilitate micro-level implementation **- :** Avoid mismatch between level of action and level of governance	**+ :** Avoid local trap and globalism **- :** Overlook potential spill-over effects

Notes: '+' indicates how a certain meso-type approach helps addressing cross-level and cross-scale interactions, while a '-' indicates the challenges and attention points to consider when adopting certain approaches.

Sectoral approaches fall under food systems thinking as they integrate all stages of the supply chain but focus on one specific sector and its actors (e.g. dairy, cereals, cocoa). By zooming in on the specificities of a single sector, they aim to facilitate the translation of food systems thinking at the micro level on the scale of action, resolving the tension between the two levels (Borman et al. 2022). Sectoral approaches may also facilitate the integration of frequently overlooked midstream actors, as illustrated in the case of the dairy sector by Ceppatelli et al. (2024) or De Herde et al. (2020). By doing so, sectoral approaches may contribute to overcoming the challenge of micro-level implementation of food system approaches, highlighted in the case of the Farm to fork strategy. Yet, value chains can be double-edged, as they have the potential to both amplify and accelerate sustainability practices, or restrain them (De Herde and Dufays 2025). Furthermore, such approaches require to be complemented with zoomed-out perspectives to avoid missing system-wide effects, feedbacks, and interactions with other sectors (e.g. crop-livestock interactions), possibly even outside food systems (e.g. interactions with energy domain).

Moving to the spatial scale, sectoral approaches can be considered and managed at different scales, including local or territorial conceptualisation of food systems (Liu 2025) and the possibility of traversing multiple spatial scales (Landon and Rosol 2025). Thus, a balance must be struck between local and global analyses, with territorial, landscape and supply shed approaches being advocated as they acknowledge local specificities of food systems to increase relevance and facilitate implementation, even though they do not correspond to well-defined spatial scales. The adoption of sectoral approaches may assist in elucidating the most appropriate spatial scale of analysis depending on the scale of operation of the considered sectors. For instance, while market gardening usually remains restricted to localized and territorial contexts (Enthoven et al. 2023; Enthoven and Van den Broeck 2023), other sectors such as wheat production are particularly meaningful to analyse at larger scales, as was recently made clear in the events of the Russian-Ukrainian conflict (Lin et al. 2023; Bertassello et al. 2023). Multiple spatial scales might be relevant to consider simultaneously as territorially embedded productions, e.g. a dairy product, might be both consumed locally or traded internationally, e.g. as skimmed milk powder. Supply sheds further exemplify the link between supply chains and spatial scale as they shift the focus from purely sectoral approaches (e.g. cocoa) to greater embeddedness with the local supply area and landscape (Cammelli et al. 2025).

Finally, meso-level approaches (as related to the scale of action and decision-making), while allowing to pay attention to diversity, bridge the link between individual practices and policymaking and ensure everyone has a place in the transition picture. When integrated with other scales, diversity introduces additional complexities that must be carefully considered. With regard to the spatial scale, an inverse relation tends to appear between the spatial extent of an analysis and the degree of diversity that can be accounted for. Working at a local or territorial level permits taking in a higher degree of diversity and better reflecting local conditions, but complicates generalisation. Inversely, working at a global level necessarily requires a greater level of aggregation and generalisation, constraining the level of diversity. For instance, Riera et al. (2023) and Díaz de Otálora et al. (2022) propose typology classifications of cattle systems at different spatial scales. The former, carried out at a sub-national level (Wallonia, Southern Belgium), is rather limited in scope but has more room to integrate local specificities such as locally relevant breeds to delineate production systems. The latter, carried out at a supra-national level (EU), presents broader and less specific typology groups but has the advantage of covering a greater spatial scope. Both approaches are compatible and there is certain space for overlap: as one provides a comprehensive framework particularly useful for EU-level policymaking, the other presents more detailed insights that can help tailor local policies or inform local farmers. Many more applications beyond this example account for the local specificities in the characterisation of diversity, e.g. in the pig sector (Bartlett et al. 2024) or in the case of conservation agriculture (Ferdinand and Baret 2024) to name a few recent examples. With regard to the supply chain scale, diversity can either be accounted for at specific stages or across the supply chain. On the production-side, farming systems research often analyses diversity through the characterisation of production systems, as in the examples above by Riera et al. (2023) and Díaz de Otálora et al. (2022). On the consumption side, accounting for diversity may consist in considering a multiplicity of diets (e.g. surveys aiming to estimate the prevalence of different diets). Covering multiple stages of the supply chain, some studies may combine a diversity of practices both at the production stage and at the consumption stage (e.g. modelling the effects of incremental adoption levels of organic agriculture and alternative diets). Finally, some studies characterise diversity at the level of the whole food system, as in Gaitán-Cremaschi et al. (2019), who provide an analysis of the vegetable sector in Chile (thus adopting a sectoral approach to food systems). The authors combine a typology of vegetable production systems to a typology of distribution channels and refer to the MLP to position the different identified systems with regard to transition processes. A key challenge of such mid-aggregated approaches, which remain relatively uncommon (Schenk et al. 2007; Quattrini et al. 2024), is ensuring that they are actionable for food system actors, rather than producing abstract theoretical representations that place the level of analysis in a "messy middle" (between practices and policies) that may be difficult for actors to perceive as concrete or relevant.

The combination of sectoral, territorial and meso-level approaches thus provides some opportunities to bridge across scales and are aligned with proposed responses to scale-related challenges, such as resorting to co-management, institutional interplay and bridging organisations (Cash et al. 2006). Yet, their joint application also brings to the fore a series of cross-scale and cross-level challenges (e.g. participation of supply chain actors and inclusion of diversity at different spatial scales, consideration of sectoral interactions, etc.).

2.3.4 Towards food system transitions and limitations

Starting from multiple understanding of meso approaches, the proposed framework aims to facilitate the comprehension of multi-scale food systems and make it more apparent. Acknowledging this multi-scale nature is important in a transitions perspective to avoid a series of scale-related challenges (e.g. ignorance, mismatch and plurality). By proposing three interconnected scales, the framework aims to contribute to visibilising the inherent complexity of food systems and associated transitions. Yet, as these processes are complex, it is important to remain cautious of adopting approaches which may be too reductionist, as transition processes unfold in spaces which go beyond those outlined by the proposed framework. For instance, the framework and the considered examples are focussed on terrestrial food systems but do not address the role of blue food systems. While some of the considerations might be applicable, it would be interesting to integrate the specificities of these systems in the framework.

One key aspect and scale overlooked by the paper is time. Transitions are non-linear processes which can occur over long time periods. Taking the perspective of transition processes, one can wonder how the multi-scale framework relates with the three-step cycle *assessing* – *envisioning* – *implementing*, or the five levels of agroecological transitions. In this regard, we might see evolving scales and levels of attention at different steps of the cycle: while the farm level has concentrated a lot of attention in terms of assessment (Bockstaller et al. 2008; de Olde et al. 2016), the micro (individual) and farm level is more seldomly involved in envisioning phases (Prost et al. 2023), which gather more examples at the macro or meso levels, and larger spatial scales than that of a farm. In turn, this might ask how different levels interact and contribute to the implementation step, as discussed in the case of micro-macro interactions within the Farm to fork strategy and farmer protests. Given the complex and emergent nature of food system transition, such managerial approaches considering that transition processes can be guided in successive steps must be put in perspective (Kueffer et al. 2019). In this regard, the MLP provides a useful and complementary view reminding us of the importance of external landscape elements in transition processes. Furthermore, tensions across scales are in some cases intrinsic and cannot be avoided, especially since societal transitions inevitably imply the breakdown and phase out of certain systems.

2.4 Conclusions

In this paper, we aim to contribute to discussions surrounding the multiplicity of scales involved in food system transitions. Starting with multiple understandings of meso-level approaches, we strive to clarify this concept by conceptualising it through three interconnected scales that we consider from an operational and analytical perspective: the spatial scale, the supply chain scale and the scale of action and decision-making.

The framework can particularly be used for two purposes: fostering transparency of research approaches and analytical scales, and providing a guide to unpack and visibilise the functioning of food systems at multiple scales and levels. In the perspective of addressing cross-level and cross-scale interactions, meso-type approaches are identified as possible solutions. While they indeed provide some capacity to address these interactions, certain attention points must be taken into account (Table 2). To guide further research, a possible four-step sequence would be the following:

1. Engaging in *food systems* thinking ensures attention to the multi-scalar nature of food systems. A disaggregation in *sectoral approaches* may facilitate implementation by actors but cross-sectoral interactions must not be overlooked.
2. Adopting a *meso-level* of analysis allows communicating with all levels of action and decision-making, and accounting for a certain degree of *diversity*, while paying attention to remaining actionable for all actors.
3. Accounting for a *diversity of practices* ensures that everyone has a clear view of where they stand with regard to the transition process.
4. Working at a *relevant spatial scale* (e.g. territorial) maximises chances for operationalisation and implementation, while remaining aware of boundary effects, and the challenges of zooming in and out.

Through this analysis, we hope to contribute to existing frameworks on food system transitions, such as the multi-level perspective, transition governance or agroecological transitions. Such frameworks can be mutually reinforcing to assist research in guiding the transition of our food systems. In the process of moving towards actual implementation, a diverse set of practical research tools will need to be mobilised, including participatory processes, sustainability assessments, foresight scenarios, lock-in and barrier analyses, etc.

Section 2

Navigating the transition cycle

Caminante no hay camino, se hace camino al andar

A. Machado

Chapter 3 Accounting for diversity while assessing sustainability: insights from the Walloon bovine sectors

This chapter has been published in *Agronomy for Sustainable Development*.

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Abstract

Livestock production is confronted with significant challenges across all dimensions of sustainability. There is an urgent need to identify sustainable livestock systems that are environmentally friendly, economically viable for farmers and socially acceptable. To this end, diversity assessments and data-driven indicator-based sustainability assessments can be helpful tools. These two mutually reinforcing approaches each have their own dilemmas and strengths, however their combination is not straightforward. In this paper we propose a method that simultaneously assesses the diversity and sustainability of production systems within one agricultural sector, while overcoming the dilemmas of diversity and sustainability assessments. We test our method on the Walloon dairy and beef sectors (Belgium) and base our assessment on data from the European Farm Accountancy Data Network (FADN).

Our results confirm the importance of complementing sustainability assessments with diversity assessments. Our case study results show that a diversity of livestock systems coexist and that it is possible to overcome trade-offs between economic and environmental performances. Extensive grass-based systems present the best combination of economic and environmental results, which highlights the importance of preserving grassland resources at the regional level. The proposed method proves effective to improve the relevance of FADN data and supports the ongoing call to transform the FADN into a more comprehensive database that satisfactorily covers all dimensions of sustainability.

3.1 Introduction

3.1.1 A necessary transition

The need to operate a transition towards sustainable agriculture and food systems is widely acknowledged (Foley et al. 2011; IPES-Food 2016; Campbell et al. 2017). In this context, the role and share of livestock production in our food system are being increasingly debated (Westhoek et al. 2014; Röös et al. 2017b; Willett et al. 2019). Over the past years, the pressure of livestock production on the environment has been extensively documented. The main impacts are contributions to global anthropogenic greenhouse gas emissions (Weiss and Leip 2012; Vermeulen et al. 2012; Gerber et al. 2013; Notarnicola et al. 2017); pollution of water resources through overuse of manure (Velthof et al. 2014; Notarnicola et al. 2017); significant requirements in terms of land use, and the reliance on feed crops entering in direct competition with human consumption, and potentially representing high impacts in terms of habitat and biodiversity loss (Steinfeld et al. 2006; Vermeulen et al. 2012; Karlsson et al. 2020).

However, livestock systems also have the potential to provide key ecosystem services. Important benefits include contributions to soil fertility in well-balanced crop-livestock systems; in the case of ruminants, the conversion of non-human-edible biomass into nutrient-dense food; in the case of pasture-based systems, the potential to help mitigate climate change through the storage of carbon in pastures; and contributions to grassland biodiversity (Steinfeld et al. 2006; Garnett et al. 2017; Mottet et al. 2017).

Combined with the economic precarity faced by some livestock farmers in Europe (Havet et al. 2014) and growing societal concerns regarding issues such as animal welfare (Boogaard et al. 2011), these contrasting attributes of livestock systems highlight the need to identify sustainable livestock systems which are both environmentally friendly, and also economically viable for farmers and socially acceptable.

More sustainable livestock systems will emerge from the most relevant systems in the diversity of extant and upcoming propositions. To identify these options for a more sustainable future, two types of tools are key: diversity assessments and indicator-based sustainability assessments.

3.1.2 Diversity assessments

Diversity assessments aim to acknowledge the diversity of practices and systems within an agricultural sector. Combined with sustainability assessments, they allow to better understand the studied agricultural sector and thereby favour a transition towards greater sustainability (de

Snoo 2006; Lebacq 2015; Stylianou et al. 2020a, b). Diversity assessments rely on quantitative or qualitative typology classifications to identify and capture the diversity of production systems (Kuivanen et al. 2016; Stylianou et al. 2020a).

Performing diversity assessments is important for three main reasons. First, in order to ensure the adoption of sustainability assessments, the developed tool or assessment must be perceived as relevant by farmers (de Olde et al. 2016). Farms are the decision-making units that will decide whether to implement sustainability practices (Diazabakana et al. 2014; Latruffe et al. 2016; Kelly et al. 2018). As such, farmers need to be able to relate to the practices which are outlined and analysed in a sustainability assessment. This will be enhanced if, rather than considering a homogenous set of farms and their average practices, farm-level diversity is taken into account. Farmers may then refer to a group of peers sharing the same practices. Second, understanding and highlighting the diversity of farms is key for the development of adequate interventions and policies aimed at addressing the challenges faced by farmers (Kamau et al. 2018). Third, grouping farms that present similar practices into production systems situates the scale of analysis at a meso-level, above the highly diverse plot and farm levels (micro-level) and below the very uniform regional or national levels (macro-scale). This is necessary to create constructive links between farmers and higher-level actors and develop a mutual understanding of respective objectives and constraints. In short, this approach accounts for farm-level diversity without being overwhelmed by it. As noted by Lynch et al. (2018), aggregating similar practices into production systems allows identifying trends which can be extrapolated at a higher level (e.g., regional or national) while still accounting for the existing diversity of models. Diversity assessments tend to have three main dilemmas, related to a lack of diversity, a lack of representativeness and a lack of multidimensionality.

Dilemma 1: A focus on extreme systems is not sufficient to capture diversity. Many assessments focus on the dichotomies between two opposite systems, such as organic and conventional or extensive and intensive (Escribano et al. 2015; van Wagenberg et al. 2016). While such studies are necessary to characterize these contrasting systems, it is important to go beyond this dualization and, to acknowledge a greater level of diversity so that all farmers can relate to the analyses. Moreover, other studies compare different farm types (e.g., arable, livestock or mixed) without accounting for the diversity of systems within farm types (Westbury et al. 2011; Slijper et al. 2022).

Dilemma 2: The representativeness of assessments is constrained by the number of sampled farms. Assessments are often focused on a small number of sample farms (less than 20) (Batalla et al. 2014; Reinsch et al. 2021; Resare Sahlin et al. 2022). Collecting data *in loco* is important to better apprehend farmers' realities and priorities. Yet, such assessments generally lack the necessary representativeness to extrapolate and generalize results at a wider scale. In this sense, using farm accountancy databases, such as the European Farm Accountancy Data Network (FADN) is highly relevant as, by construction, their aim is to be representative of different farming sectors at regional or national level. While some limitations have been identified with regards to the representativeness of FADN, such as the overrepresentation of "commercial" farms and underrepresentation of smaller farms, it is still considered as the most reliable sample survey (Diazabakana et al. 2014; Mari 2020; Masi et al. 2021).

Dilemma 3: Diversity assessments fall short of accounting for the multidimensionality of sustainability. The combination of diversity and sustainability assessments is not always straightforward. For instance, some diversity assessments focus on one single dimension of sustainability (Reinsch et al. 2021; Froldi et al. 2022), or do not complement core accountancy data with additional and more relevant sustainability indicators (Gonzalez-Mejia et al. 2018; Stylianou et al. 2020b; Masi et al. 2021). As such, while some papers manage to combine farm typologies with multidimensional assessments (Haileslassie et al. 2016; Micha et al. 2017; Díaz de Otálora et al. 2022), diversity assessments remain often affected by the dilemmas of indicator-based sustainability assessments identified below.

3.1.3 Indicator-based sustainability assessments

Indicator-based assessments in the context of agricultural sustainability are relevant since their results are ready-to-use by a multiplicity of actors, including decision makers, farmers (and advisors) and consumers (Boogaard et al. 2011; Diazabakana et al. 2014; Schader et al. 2014; de Olde et al. 2016; Kelly et al. 2018). Through a set of multidimensional indicators, they provide a better understanding of the sustainability performances of agricultural systems (Sadok et al. 2008; Binder et al. 2010; Van Passel and Meul 2012; de Olde et al. 2016). Yet, performing indicator-based sustainability assessments comes with several challenges in the context of data-driven approaches (i.e., which rely on farm accountancy databases, such as FADN). We identify four main dilemmas (see Figure S1).

Dilemma 1: Current sustainability assessments mainly focus on the environment. In order to perform a satisfying sustainability assessment, the selected set of indicators should be multidimensional, i.e., cover all three dimensions of sustainability, namely environmental, economic and social. In practice, however, there is an imbalance in the dimensions of sustainability which receive more attention, both in the public and scientific debate, as the main focus currently lies on the environment (Binder et al. 2010; Lebacq et al. 2013; Diazabakana et al. 2014; Schader et al. 2014; de Olde et al. 2016; Stylianou et al. 2020b). The literature on economic and social sustainability is less abundant (Diazabakana et al. 2014) and the social dimension seems to be the least studied of all three (Boogaard et al. 2011).

Kelly et al. (2018) carried out a non-exhaustive review of FADN-based sustainability assessments. Of the twenty-seven studies included in the review, the social dimension was considered in ten studies, as part of a global sustainability assessment but never on its own. In contrast, the environmental and economic dimensions were studied in respectively twenty and eighteen studies, either individually or as part of a comprehensive sustainability assessment. Regarding the need for combined assessments, the review shows that fifteen of the twenty-seven studies focus on one sole sustainability dimension, whereas the other twelve consider at least two or all three dimensions (Kelly et al. 2018). Although not based on a statistically representative sample, this shows that an important number of current assessments do not yet cover all three dimensions of sustainability.

Dilemma 2: The focus on the environment clashes with low availability of data. The availability of indicators in farm databases varies greatly between sustainability dimensions. At the European level, none of the available databases were explicitly developed to assess farm-level sustainability (Kelly et al. 2018). Economic indicators are generally quantitative and monetary. As such, they can be easily measured and recorded in farm accountancy databases (Lebacq et al. 2013; Kelly et al. 2018). In contrast, the assessment of social sustainability is less straightforward. Except for some indicators such as the workforce or the workload, the required data for many social indicators are insufficiently available (Jan et al. 2012; Lebacq et al. 2013). The subjective character of some of these indicators (e.g., self-evaluation of a farmer's quality of life) complicates their measurability and hence availability (Lebacq et al. 2013). Consequently, social indicators generally require additional data collection (Kelly et al. 2018). Despite receiving much attention, the environmental dimension is poorly covered in farm accountancy databases, with a general lack of precise and comprehensive environmental data (Jan et al. 2012).

Dilemma 3: Environmentally relevant indicators are hard to measure and less available. With regard to environmental sustainability, indicators are often classified along what is referred to as the cause-effect chain (Diazabakana et al. 2014; Latruffe et al. 2016). On one end, means-based indicators reflect agricultural and farmers' practices (e.g., pesticide costs). On the other end impact-based indicators reflect the actual impact related to a specific environmental theme (e.g., pesticide concentrations in soil and water resources) (Lebacq et al. 2013; Diazabakana et al. 2014). Environmental indicators tend to present an inverse relation between their relevance (i.e., their ability to effectively reflect an environmental impact) and their availability or measurability (i.e., their ease of access or measurement). In terms of relevance, means-based indicators have a low quality of prediction of environmental impacts given that they reflect agricultural practices, whereas impact-based indicators have a high environmental relevance given their direct link with the environmental theme to be assessed (Lebacq et al. 2013). In terms of availability and measurability, means-based indicators are easier to collect given their close link to technical means and inputs used on the farm. As such, they are readily available in farm databases. In contrast, the collection of impact-based indicators is more complex, time-consuming and expensive, and their availability is therefore more limited (Diazabakana et al. 2014).

Dilemma 4: Attempts to address sustainability dilemmas do not account for diversity. Previous research has addressed the three previous dilemmas, mainly by complementing core data from farm databases through the mechanistic modeling of additional environmental indicators. For example, Jan et al. (2012) complemented Swiss FADN data with Life Cycle Assessments. Lynch et al. (2018) complemented British FADN data with the Farmscoper tool, developed for the United Kingdom Department for Environment, Food and Rural Affairs (Defra). Westbury et al. (2011) applied the Agri-Environmental Footprint Index (AFI) methodology to British FADN data to assess the environmental performance of three different farm types (arable, lowland livestock and upland livestock). Slijper et al. (2022) relied on FADN data to assess which farm characteristics affect resilience among different farm types (arable, livestock and mixed). All these studies capitalized on FADN data to produce comprehensive assessments of farm resilience or multidimensional sustainability (with the social dimensions nevertheless still remaining understudied). However, such approaches tend to overlook the diversity of practices and systems within farm types.

3.1.4 Research objectives

The seven dilemmas presented above show that the combination of diversity and sustainability assessments is not straightforward. Yet, both tools are complementary and mutually reinforcing: diversity assessments are essential to enhance the relevance of sustainability assessments; while multidimensional sustainability assessments constitute a precondition to ensuring the usefulness of a diversity assessment. In this paper, we contribute to the literature by proposing an *ad hoc* method that simultaneously assesses the diversity and sustainability of production systems within one agricultural sector, while concurrently overcoming the dilemmas of both diversity and sustainability assessments. First, we start with an identification of multiple production systems to account for the diversity of practices within one farming sector, at regional level. Second, we combine the diversity assessment with a multidimensional indicator-based sustainability assessment to identify the livestock systems with the greatest potential to contribute to the transition towards a more sustainable food system (Table 3). We show that it is possible to perform a comprehensive assessment which addresses the several dilemmas: it accounts for a high level of diversity (*diversity dilemma 1*); it is representative of the regional diversity, as it relies on a comprehensive farm accountancy dataset (*diversity dilemma 2*); it proposes a combined assessment of diversity and multidimensional sustainability (*diversity dilemma 3* and *sustainability dilemma 4*), spanning over both the socio-economic and environmental dimensions (*sustainability dilemma 1*); it complements the set of available indicators to enhance the relevance of the assessment (*sustainability dilemmas 2 and 3*).

We applied the proposed method to the dairy and beef sectors in Wallonia (Southern Belgium). These two sectors constitute relevant case studies as they dominate the Walloon agricultural landscape. In 2018, about 50% of Walloon farms were specialized in bovine production, with a clear distinction between specialized beef farms, on the one hand, and specialized dairy farms, on the other (SPW 2020). The Walloon landscape is particularly well suited for these productions given its ample supply of grasslands, and in particular permanent grasslands, which represented 43% of the region's utilized agricultural area (UAA) in 2018 (SPW 2020). This is much higher than Flanders (Northern Belgium), where permanent grasslands only represent 27% of the region's UAA (Statbel 2019), or even the EU average, as permanent grasslands represented 34% of the EU's UAA in 2016 (EU Commission 2018). This particularity is of high interest from an environmental perspective given the associated benefits fostered by permanent grasslands, such as biodiversity conservation (Peeters 2009) or carbon storage (Gourlez de la Motte et al. 2016, 2018). However, both sectors have undergone significant changes in recent decades in terms of concentration and intensification, posing challenges to their social, economic and environmental sustainability (Peeters 2009; SPW 2020). There has been a decrease in the share of permanent grasslands (-14% over the 1990-2018 period), replaced by an increase in arable crops. In particular, forage maize, which is often associated with a quest for productivity and high input use (Lebacq et al. 2015), has gradually gained in importance in bovine systems in Belgium and all over Europe (Peeters 2009; Natagora 2020; Reinsch et al. 2021). Finally, current studies in Wallonia have primarily focused on the dairy sector (Lebacq et al. 2013, 2015; Lessire et al. 2019; De Herde et al. 2019, 2020; Dalcq et al. 2020), with a lack of studies on the sustainability of the beef sector.

This paper is organized as follows: In paragraph 3.2, we outline the data sources and develop the proposed method. Paragraph 3.3 provides an overview of the results, including a description of the identified systems and their sustainability performances. In paragraph 3.4, broader considerations on the proposed method are provided. The Walloon case study results are further discussed and put in the perspective of the literature. Finally, paragraph 3.5 delivers general conclusions and recommendations.

3.2 Data & methods

3.2.1 Data

We base the assessment on FADN data to ensure representativeness of the studied region. The database comprises a wide range of farm-level indicators reflecting the diversity of practices in European farms. Farm household data was provided by the DAEA (*Direction de l'Analyse Economique Agricole*), the regional office in charge of collecting the data at local level and providing it to the FADN. Throughout this paper, we refer to the analysed dataset as DAEA.

The analysed sample covers a four-year reference period (2014-2017). It initially included 359 observations of specialized Walloon dairy farms (corresponding to 108 different farms), and 419 observations of specialized Walloon beef farms (corresponding to 128 different farms). A farm is considered as specialized and classified into a specific farm type (dairy, beef, arable, etc.) by the FADN if at least two thirds of its standard gross product (SGP) come from that particular activity. One observation corresponds to an individual farm for a given year. For some farms of our sample, there are multiple observations over the four-year period. A two-step data cleaning process was performed. First, all non-specialized farms were excluded from the sample. For the dairy sector, all observations presenting a significant number of suckler cows (more than 10% of total cows on the farm) were excluded from the sample in order to focus the assessment on specialized dairy farms. For the beef sector, it was chosen to put the focus on breeding farms and to exclude all farms performing a fattening step (see supplementary material for more detail). Indeed, the Belgian beef sector presents a clear distinction between breeding and fattening activities, with a clear regional specialization: Wallonia tends to focus on the breeding stage while the fattening of calves and young bulls is more strongly concentrated in Flanders (Calay et al. 2020). Second, after the classification of farms into production systems (see below), farms situated below the 10th percentile in terms of farm income per family work unit were trimmed from the sample in order to exclude the majority of non-profitable farms from the sample (see supplementary material for more detail). The final analysed sample included 290 observations of specialized dairy farms and 216 observations of specialized beef-breeding farms.

3.2.2 Cost-effective method for production system classification and comprehensive sustainability assessments

The cost-effective method we propose for a multidimensional sustainability assessment accounting for the diversity of practices follows three main steps (Figure S2): (1) a classification step, which groups farms in typologies of production systems; (2) an indicator selection step, which consists in constructing a comprehensive set of structural, environmental and socio-economic indicators, based on both core DAEA and calculated data; and (3) an analysis step, which consists in assessing and benchmarking the identified systems through the multidimensional set of indicators.

Step 1: Classification

For each sector, three classification criteria were used to cluster similar farms into production systems (Figure S3). Two classification criteria are common to the dairy and beef-breeding sectors (share of pasture and stocking rate), while the third criterion is specific to each sector (herd size for the dairy sector and breed for the beef-breeding sector). The classification criteria were selected based on their capability to reflect important differences in farming structures and entail environmental benefits. The share of pasture can be associated with positive effects on the environmental impacts of dairy farms, such as biodiversity, global warming potential, acidification and energy use (Guerci et al. 2013). Stocking rate, among other farming characteristics, can be negatively related to the environmental impact of dairy farms (Bava et al. 2014). Herd size was selected as a classification criterion based on the concentration of the dairy sector which has occurred over the last decades, leading to differences in strategies and practices between smaller and bigger farms (Lebacq 2015). Finally, we included a criterion related to breed given the historical importance of the highly specialized Belgian Blue breed in the Belgian beef sector (Stassart and Jamar 2008; Calay et al. 2020).

The percentage of pasture on the forage area distinguishes grass-based farms from diversified farms (in terms of forage, i.e., with a significant share of arable forage crops). We use a threshold corresponding to the sample median (92% in the case of dairy farms and 89% in the case of beef-breeding farms).

The stocking rate was used as a proxy for the intensification level of farms (the intensification level constitutes a more complex phenomenon resulting from a series of farm management practices and could also be measured by looking at the productivity level per unit of labour or per animal). A threshold of 1.8 LSU (Livestock Units)/ha on-farm forage area was used to separate extensive farms from intensive farms, in line with the Walloon Agri-Environment-Climate Measure, which aims at developing forage self-sufficiency (Natagriwal).

For the dairy sector, a distinction between small-scale and large-scale farms was made based on the herd size. The sample median (69 dairy cows) was used as a threshold.

For the beef sector, farms are classified into two possible groups of breeds: the *Belgian Blue* breed or French breeds (such as *Limousin*, *Blonde d'Aquitaine*, etc.). Farms for which the share of the dominant breed was less than 50% (68 observations) were excluded from the sample as they were considered as mixed (*Other breeds*).

Step 2: Indicator selection

We use a set of structural, environmental, and socio-economic indicators (summarized in Table 3) to carry out the sustainability assessment. The choice of the indicators was based on the research objectives, i.e., comparing a diversity of dairy and beef-breeding production systems in terms of their socio-economic and environmental performances. We aligned our indicators to the three criteria of indicator selection identified by Lebacq et al. (2013): parsimony (non-redundancy of indicators), consistency (necessary indicators for the interpretations) and sufficiency (the indicators are sufficient to cover the three dimensions of sustainability). The structural and socio-economic dimensions were mainly analysed through core data readily available in the DAEA dataset. For the environmental dimension, additional calculations were necessary.

Structural indicators. Besides the indicators used for the classification step (percentage of grassland; stocking rate; herd size and beef breed), a series of additional structural indicators were used to analyse the dairy and beef-breeding systems: land use (on-farm and off-farm areas of crops which are dedicated to the bovine herds; see supplementary material for included crops); share of forage maize in on-farm forage area; total (on-farm and bought) annual consumption of concentrates (expressed per cow and progeny); self-sufficiency of concentrates (share of on-farm concentrates on total concentrates); dairy yields in the case of dairy farms (annual production of milk per dairy cow); and herd size in the case of beef farms (number of suckler cows per farm). All these data were readily available in the original DAEA dataset. Some additional calculations and hypotheses were nevertheless needed to calculate the land use (see supplementary material), which as such is considered as a 'calculated' indicator (Table 3).

Socio-economic indicators. Social sustainability was assessed using two indicators readily available in the dataset (Table 3): level of workforce, expressed in work units (one work unit corresponds to an annual working time of 1800 hours) and level of workload, expressed in number of cows per work unit. The number of cows per work unit merely gives an indication of the workload level (e.g., farms with milking robots might have more cows per work unit without necessarily enduring a greater workload). Nevertheless, in the absence of more accurate data, this was considered as a satisfying proxy, as a greater number of cows entails more work for certain tasks (feeding, birth-giving, etc.). Ideally, additional indicators related to aspects such as education, quality of life, multifunctionality or animal welfare would be included in such assessments.

The analysis of the economic dimension relies on one main indicator: farm income. This indicator is based on the cost and product structure of a farm. It corresponds to the difference between total farm products (including milk products, beef products, other products and subsidies) and total costs (operational, structural and financial). This indicator thus also includes farm income generated by other activities than dairy or beef products. Farm income was mainly expressed in euros per family work unit (FWU), but was also analysed per working hour, per litre of milk (dairy systems) and per suckler cow and progeny (beef systems). Two additional indicators are derived from the cost and product structure: the share of subsidies (on total products) and the economic efficiency (ratio between the gross margin and the total products without subsidies; see supplementary material for more detail). These economic data were readily available in the original DAEA dataset (Table 3).

Environmental indicators. Five environmental indicators were assessed (Table 3). Unlike the other dimensions, none of the environmental indicators were directly available in the dataset. They were therefore calculated on the basis of available data and emission factors provided in the literature (see supplementary material for detailed methodologies).

Habitat degradation was assessed through the consumption of soy. Soy was considered to be bought by farms. As per ERM & UGent (2011), it was estimated that 22% of bought concentrates corresponded to soy in the case of dairy farms, and 5% in the case of beef-breeding farms. The pollution of water and soil resources was assessed through two indicators: pesticide use and nutrient management. The use of pesticides associated with the production of feed ingredients was estimated based on the land use of farms and the average pesticide use of associated crops in Wallonia (Comité Régional Phyto 2015, 2017) (Table S1). Nutrient management was assessed through nitrogen emissions, which were estimated based on fixed nitrogen emission factors per animal category (VMM et al. 2020) (Table S2). The impact on biodiversity was assessed through the *Damage Score* indicator, which estimates the impact of different management practices (intensive – less intensive – organic) on different land uses (arable land – fertile grassland) through impact factors established by De Schryver et al. (2010) (Table S3). A higher Damage Score value represents a greater negative impact on biodiversity. Finally, climate change was assessed through the greenhouse gas (GHG) emissions associated with the dairy and beef productions. Unlike previous environmental indicators, which were assessed at farm-level, GHG emissions could not be assessed specifically for each farm of the analysed samples. Estimations were made based on the results of carbon footprints calculated for similar bovine typologies in Wallonia (Petel et al. 2018a, b; Riera et al. 2019).

As recommended in the literature (Lebacq et al. 2013), both area-based (per ha) and output-based (per litre of milk in the case of dairy systems, and per suckler cow and progeny in the case of beef systems) functional units were used for four indicators: pesticide use, nitrogen emissions, biodiversity impact and greenhouse gas emissions. In this way, results are neither favourable to very productive systems, nor to extensive systems. For beef-breeding farms, the number of animals per farm was used as a proxy for productivity as the available data does not provide a satisfying indicator. For the consumption of soy, only one functional unit was considered: per animal. As a result, the environmental dimension was assessed through nine indicators in each sector.

Finally, as suggested by Bockstaller et al. (2008), the individual indicators were complemented with an aggregated environmental indicator based on the relative performance of each system against the performances of the entire dataset. For each environmental indicator, every system received a score ranging between one and four depending on the corresponding quartile of the average score of that system. Summing the scores for all nine indicators provided an environmental impact score (ranging between 9 and 36) which allowed comparing and classifying systems based on their environmental performances. A similar approach was adopted by Bijttebier et al. (2017).

Step 3: Multidimensional analysis

The combination of structural, socio-economic and environmental indicators outlined above allows for a comprehensive and multidimensional assessment of the identified dairy and beef-breeding systems. Apart from analysing each indicator individually, the farm income (as it is one of the main economic indicators at farm-level) and the environmental impact score (as it provides an overview of the environmental impact across several themes) were used as the two main indicators to perform a combined assessment and benchmarking of the global sustainability performance of the identified systems.

Table 3. Set of indicators used to perform a sustainability assessment of bovine production systems in Wallonia. All environmental indicators were expressed per hectare, per litre of milk (dairy systems) or per suckler cow and progeny (beef systems). Soy consumption was only expressed per cow and progeny. Abbreviations: C(&P): Cow (& Progeny); DC: Dairy Cow; SC: Suckler Cow; cc: concentrates; (F)WU: (Family) Work Unit; a.i.: active ingredient; N: Nitrogen; DS: Damage Score.

Indicators	Unit	Availability	Comments
Structural indicators			
Land use	ha/C&P	Calculated	Information was available but additional hypotheses were needed
Share of forage maize	% forage area	Calculated	Information was available but additional hypotheses were needed
Concentrate use	kg cc/C&P/year	Core DAEA	Sum of on-farm and bought concentrates
Conc. self-sufficiency	%	Core DAEA	Share of on-farm concentrates on total use
Productivity	L/DC/year	Core DAEA	Assessed only for dairy systems
Herd size	SC/farm	Core DAEA	Assessed only for beef-breeding systems (used as classification criterion for dairy systems)
Social indicators			
Workforce	WU	Core DAEA	Total work units (family and hired)
Workload	C/WU	Core DAEA	Number of cows per work unit
Economic indicators			
Farm income	€/FWU	Core DAEA	Based on the cost and product structure. Was also assessed per hour, litre of milk (dairy systems) and suckler cow (beef systems)
Share of subsidies	%	Core DAEA	Share of subsidies on total products
Economic efficiency	%	Core DAEA	Ratio of gross margin on total products, without subsidies
Environmental indicators			
Soy consumption	kg soy/C&P	Calculated	Fixed share of bought concentrates (22% for dairy systems and 5% for beef systems)
Pesticide use	kg a.i.	Calculated	Based on land use and average pesticide use on different crops
Nitrogen emissions	kg N	Calculated	Based on fixed nitrogen emission factors per animal category
Biodiversity impact	DS	Calculated	Based on land use and estimated impact factors of different land uses
Carbon footprint	kg CO_2e	Calculated	Based on results from similar typology

3.3 Results

3.3.1 Description of identified production systems

Dairy systems

Eight dairy systems were identified as a result of the classification step (Table 4). They are divided in large-scale systems (D1-D4) and small-scale systems (D5-D8). These two groups are in turn subdivided in either grass-based or diversified systems, which can be intensive or extensive.

Extensive systems present higher land use values than intensive systems. Diversified systems, and particularly the two intensive diversified systems (D2 & D6) present higher shares of forage maize, which is almost absent in grass-based systems. The diversified system D5 relies on other forage crops than maize (e.g., alfalfa) to pursue its diversification. The different strategies in terms of land use appear clearly on Figure 9(a). The use of concentrates is systematically higher in intensive systems compared to their extensive counterparts. Furthermore, large-scale systems (D1-D4) tend to present higher concentrate consumption levels than small-scale systems (except D8 which presents the highest concentrate use). The two small-scale extensive systems (D5 & D7) present the lowest use of concentrates. The self-sufficiency of concentrates is higher in diversified systems compared to grass-based systems, which present a nearly null self-sufficiency. The small-scale diversified extensive system (D5) presents the lowest overall use of concentrates and the highest self-sufficiency of concentrates. In terms of milk yields, large-scale systems tend to present high production levels compared to small-scale systems. Furthermore, intensive systems tend to present higher yields than extensive systems. The large-scale diversified intensive system (D2) has the highest milk yield whereas the small-scale diversified extensive system (D5) has the lowest yield.

Beef-breeding systems

Six beef-breeding systems were identified as a result of the classification step (Table 5). Based on the main breed, they are divided in Belgian Blue systems (B1-B4) and French breed systems (B5 & B6). These two groups are in turn subdivided in either grass-based or diversified systems, which can be intensive or extensive. Intensive French breed systems were not analysed as these only included six observations.

Extensive systems, and in particular those working with French breeds (B5 & B6), present higher land use values than intensive systems working with the Belgian Blue breed. Within extensive Belgian Blue systems, the grass-based system (B3) occupies more land than the diversified one (B1). The share of forage maize is highest in the Belgian Blue diversified intensive system (B2).

Unlike the Belgian Blue diversified systems (B1 & B2), the French breed diversified system (B5) relies on other forage crops than maize (e.g alfalfa) to pursue its diversification (similarly to the dairy system D5). The different strategies in terms of land use appear clearly on Figure 9(b). The use of concentrates is higher in the intensive and/or diversified Belgian Blue systems (B1, B2 & B4). The extensive grass-based Belgian Blue system (B3) and the two French breed systems (B5 & B6) present lower concentrate uses. The self-sufficiency of concentrates is significantly higher for the three diversified systems (B1, B2 & B5) compared to the three grass-based systems (B3, B4 & B6). Compared to dairy systems, beef-breeding systems present lower concentrate consumptions and higher concentrate self-sufficiencies. As no specific productivity indicator was available, the output levels of the systems were estimated through their herd size. The two grass-based extensive systems (both Belgian Blue and French breeds; B3 & B6) present the smallest herd sizes whereas the Belgian Blue diversified intensive (B2) and the French breed diversified extensive (B5) systems present the largest herd sizes.

Table 4. Summary statistics (mean ± standard deviation) of structural, socio-economic and environmental indicators for eight dairy systems in Wallonia. Within rows, different superscript letters indicate significantly different means between systems at P<0.05, or P<0.1 for indicators marked with an *. Abbreviations: DC(&P): Dairy Cow (& Progeny); cc: concentrates; (F)WU: (Family) Work Unit; a.i.: active ingredient; N: Nitrogen; DS: Damage Score.

		Large-scale				Small-scale			
		Diversified		Grass-based		Diversified		Grass-based	
Indicator	**Unit**	**Extensive**	**Intensive**	**Extensive**	**Intensive**	**Extensive**	**Intensive**	**Extensive**	**Intensive**
		D1	D2	D3	D4	D5	D6	D7	D8
Number of observations	-	24	63	15	44	27	31	49	37
of which organic	-	2	0	1	0	9	0	17	0
Structural									
Land use	ha/DC&P	1.2 ± 0.2^{ab}	0.8 ± 0.2^{c}	1.1 ± 0.1^{a}	0.8 ± 0.1^{c}	1.2 ± 0.2^{b}	0.8 ± 0.2^{c}	1.3 ± 0.3^{d}	0.8 ± 0.1^{c}
Share of forage maize	% Forage area	15% ± 12%^{a}	23% ± 13%^{b}	0% ± 1%^{c}	1% ± 2%^{c}	11% ± 11%^{a}	28% ± 10%^{d}	1% ± 2%^{c}	1% ± 2%^{c}
Concentrate use	kg cc/DC&P	1579 ± 937^{abc}	1756 ± 529^{ab}	1312 ± 556^{acde}	1656 ± 778^{abc}	793 ± 621^{d}	1345 ± 965^{ce}	1030 ± 483de	1889 ± 851^{b}
Concentrate self-sufficiency	%	13% ± 18%^{a}	7% ± 14%^{ab}	0% ± 0%^{b}	0% ± 0%^{b}	32% ± 41%^{c}	4% ± 9%^{ab}	2% ± 0%^{b}	0% ± 0%^{b}
Productivity	L/DC/year	6683 ± 2007^{ab}	6983 ± 1293^{a}	6660 ± 704^{abc}	6572 ± 1032^{ab}	5309 ± 1778^{d}	5957 ± 1794^{bcd}	5660 ± 1399^{cd}	6476 ± 1625^{ab}
Social									
Workforce	WU	2.3 ± 0.5^{a}	2.0 ± 0.6^{bc}	2.3 ± 0.6^{ab}	2.0 ± 0.5^{bc}	1.9 ± 0.7^{c}	2.0 ± 0.7^{bc}	1.5 ± 0.4^{d}	1.4 ± 0.4^{d}
Workload	DC/WU	44 ± 10^{a}	59 ± 19^{b}	39 ± 11^{acd}	56 ± 14^{b}	30 ± 16^{ce}	28 ± 11^{e}	33 ± 13^{cde}	39 ± 11^{ad}
Economic									
Farm income	€/FWU	31601 ± 22805^{a}	25522 ± 28080^{ab}	25830 ± 18486^{ab}	35696 ± 23599^{a}	16369 ± 14901^{b}	15235 ± 11217^{b}	31498 ± 17267^{a}	31646 ± 21837^{a}
	€/hour	12.3 ± 10.3^{a}	10.0 ± 11.1^{ab}	9.7 ± 6.7^{ab}	12.1 ± 8.4^{a}	6.4 ± 5.3^{b}	6.2 ± 4.7^{b}	11.2 ± 5.4^{a}	11.9 ± 6.6^{a}
	€/L milk	0.10 ± 0.07^{ab}	0.07 ± 0.08^{a}	0.10 ± 0.06^{ab}	0.10 ± 0.06^{ab}	0.12 ± 0.10^{b}	0.10 ± 0.07^{ab}	0.18 ± 0.07^{c}	0.12 ± 0.05^{b}
Share of subsidies	%	13% ± 7%^{ab}	10% ± 3%^{ac}	12% ± 3%^{abc}	9% ± 3%^{c}	21% ± 10%^{d}	13% ± 4%^{b}	20% ± 10%^{d}	11% ± 4%^{abc}
Economic efficiency	%	52% ± 7%^{a}	52% ± 10%^{a}	64% ± 8%^{bc}	59% ± 11%^{b}	61% ± 10%^{bc}	53% ± 12%^{a}	63% ± 8%^{c}	60% ± 8%^{bc}
Environmental									
Soy consumption	kg soy/DC&P	281 ± 143^{ab}	360 ± 110^{acd}	293 ± 124^{abc}	369 ± 174^{cd}	135 ± 134^{e}	288 ± 214^{ab}	227 ± 111^{b}	421 ± 190^{d}
Pesticide use	kg a.i./1000L	0.09 ± 0.05^{a}	0.07 ± 0.02^{b}	0.03 ± 0.01^{cd}	0.04 ± 0.01^{ce}	0.05 ± 0.05^{e}	0.08 ± 0.02^{a}	0.03 ± 0.02^{d}	0.04 ± 0.01^{ce}
	kg a.i./ha	0.5 ± 0.2^{a}	0.6 ± 0.2^{b}	0.2 ± 0.1^{cd}	0.3 ± 0.1^{e}	0.3 ± 0.2^{ce}	0.6 ± 0.2^{b}	0.1 ± 0.1^{d}	0.3 ± 0.1^{e}
Nitrogen emissions	kg N/1000L	29 ± 16^{abc}	25 ± 6^{ad}	24 ± 2^{ad}	24 ± 4^{d}	33 ± 11^{b}	32 ±11^{bc}	31 ± 8^{bc}	27 ± 8^{acd}
	kg N/ha	156 ± 21^{a}	246 ± 53^{b}	161 ± 18^{a}	225 ± 30^{c}	139 ± 20^{ad}	240 ± 51^{bc}	136 ± 26^{d}	226 ± 19^{c}
Biodiversity impact*	DS/1000L	791 ± 501^{a}	489 ± 163^{b}	562 ± 165^{b}	472 ± 76^{b}	607 ± 376^{ab}	592 ± 183^{b}	531 ± 493^{b}	522 ± 143^{b}
	DS/ha	3838 ± 1045^{ab}	4110 ± 308^{a}	3497 ± 946^{b}	3842 ± 105^{ab}	2783 ± 1623^{c}	4102 ± 289^{ab}	2436 ± 1813^{c}	3857 ± 110^{ab}
Carbon footprint	kg CO_2e/L	1.03 – 1.34	1.13 – 1.14	1.29 – 1.55	1.17 – 1.38	1.27 – 1.73	1.12 – 1.65	1.14 – 1.40	1.16 – 1.37
	kg CO_2e/ha	7219 – 10596	10751 – 11627	6768 – 7192	6890 – 8982	7205 – 9235	9470 – 10817	6723 – 7147	6883 – 8975
Env. Impact score	-	19 ± 4^{a}	21 ± 2^{b}	13 ± 3^{cd}	17 ± 2^{e}	15 ± 4^{c}	22 ± 2^{b}	13 ± 4^{d}	18 ± 3^{ae}

Table 5. Summary statistics (mean ± standard deviation) of structural, socio-economic and environmental indicators for six beef-breeding systems in Wallonia. Within rows, different superscript letters indicate significantly different means between systems at $P<0.05$, or $P<0.1$ for indicators marked with an *. SC(&P): Suckler Cow (& Progeny); cc: concentrates; (F)WU: (Family) Work Unit; a.i.: active ingredient; N: Nitrogen; DS: Damage Score.

Indicator	Unit	Belgian Blue (BB)				French breeds (FR)	
		Diversified		Grass-based		Diversified	Grass-based
		Extensive	Intensive	Extensive	Intensive	Extensive	Extensive
		B1	B2	B3	B4	B5	B6
Number of observations	-	11	77	42	55	15	16
of which organic	-	0	0	4	0	14	11
Structural							
Land use	ha/DC&P	1.4 ± 0.1^{a}	0.9 ± 0.2^{b}	1.7 ± 0.4^{c}	0.9 ± 0.1^{b}	1.6 ± 0.4^{c}	1.7 ± 0.4^{c}
Share of forage maize	% Forage area	7% ± 3%^{a}	12% ± 9%^{b}	1% ± 3%^{c}	3% ± 4%^{ac}	2% ± 6%^{ac}	0% ± 2%^{c}
Herd size	Nb suckler cows	66 ± 21^{abcd}	93 ± 48^{a}	43 ± 24^{b}	72 ± 34^{cd}	86 ± 45^{ac}	49 ± 17^{bd}
Stocking rate	LSU/ha forage	1.7 ± 0.1^{a}	2.6 ± 0.6^{b}	1.3 ± 0.3^{c}	2.5 ± 0.4^{b}	1.4 ± 0.3^{ac}	1.3 ± 0.3^{ac}
Concentrate use	kg cc/SC&P	828 ± 310^{abc}	1156 ± 643^{a}	486 ± 320^{bd}	884 ± 483^{c}	403 ± 277^{bd}	319 ± 252^{d}
Concentrate self-sufficiency	%	43% ± 28%^{a}	31% ± 31%^{a}	7% ± 18%^{b}	9% ± 16%^{b}	45% ± 31%^{a}	13% ± 21%^{b}
Social indicators							
Workforce	WU	1.6 ± 0.4^{ab}	1.8 ± 0.6^{a}	1.4 ± 0.5^{b}	1.6 ± 0.5^{ab}	1.9 ± 1.0^{ab}	1.4 ± 0.6^{ab}
Workload	DC/WU	46 ± 24^{ab}	52 ± 19^{a}	34 ± 21^{b}	45 ± 17^{a}	46 ± 8^{ab}	40 ± 18^{ab}
Economic indicators							
Farm income	€/FWU	3016 ± 12751^{a}	10098 ± 13284^{a}	9436 ± 12421^{a}	6382 ± 12249^{a}	14044 ± 15731^{a}	11719 ± 18995^{a}
	€/hour	0.8 ± 4.3^{a}	3.5 ± 4.4^{a}	4.0 ± 5.2^{a}	2.4 ± 5.2^{a}	4.7 ± 5.2^{a}	5.8 ± 8.5^{a}
	€/SC&P	38 ± 326^{a}	184 ± 244^{a}	389 ± 638^{b}	126 ± 328^{a}	340 ± 347^{ab}	312 ± 378^{ab}
Share of subsidies	%	30% ± 7%^{a}	22% ± 5%^{b}	41% ± 11%^{c}	24% ± 6%^{b}	46% ± 8%^{d}	42% ± 10%^{cd}
Economic efficiency	%	39% ± 19%^{a}	41% ± 13%^{a}	52% ± 16%^{b}	44% ± 13%^{a}	50% ± 12%^{ab}	59% ± 15%^{b}
Environmental indicators							
Soy consumption	kg soy/SC&P	33 ± 26^{ab}	55 ± 42^{a}	31 ± 22^{b}	55 ± 34^{a}	11 ± 9^{b}	17 ± 14^{b}
Pesticide use	kg a.i./SC&P	0.44 ± 0.14^{a}	0.43 ± 0.14^{a}	0.19 ± 0.10^{b}	0.22 ± 0.08^{b}	0.05 ± 0.20^{c}	0.06 ± 0.09^{c}
	kg a.i./ha	0.32 ± 0.08^{a}	0.48 ± 0.14^{b}	0.12 ± 0.07^{c}	0.25 ± 0.09^{a}	0.03 ± 0.13^{d}	0.04 ± 0.06^{d}
Nitrogen emissions	kg N/SC&P	174 ± 15^{a}	171 ± 16^{a}	174 ± 17^{a}	171 ± 15^{a}	171 ± 13^{a}	170 ± 13^{a}
	Kg N/ha	132 ± 9^{a}	208 ± 53^{b}	108 ± 25^{a}	210 ± 32^{b}	112 ± 22^{a}	107 ± 20^{a}
Biodiversity impact	DS/SC&P	5334 ± 613^{a}	3804 ± 1015^{b}	6066 ± 2538^{a}	3578 ± 641^{b}	773 ± 1527^{c}	1683 ± 2891^{c}
	DS/ha	3936 ± 175^{ab}	4179 ± 388^{a}	3555 ± 1237^{b}	4091 ± 397^{a}	500 ± 1010^{c}	1146 ± 1809^{d}
GHG emissions	kg CO_2e/SC&P	4902	5455	3945	4871	4083	4315
	kg CO_2e/ha	4791	7249	3235	6467	5085	2688
Environmental impact score	-	19 ± 2^{ab}	21 ± 3^{a}	16 ± 4^{c}	19 ± 3^{b}	10 ± 3^{d}	11 ± 4^{d}

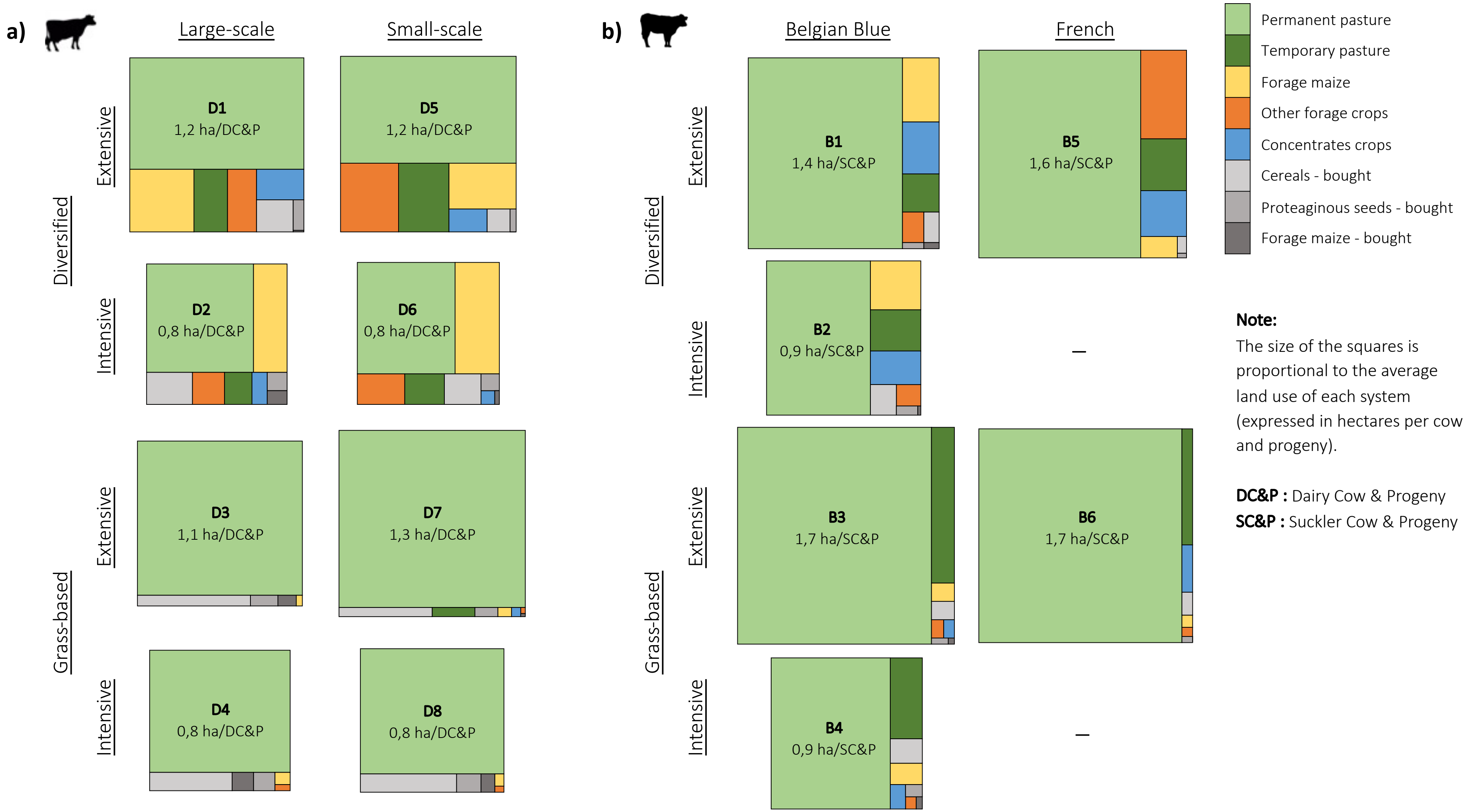

Figure 9. Average land use (ha per cow and progeny) of eight dairy systems (a) and six beef-breeding systems (b) in Wallonia.

3.3.2 Sustainability assessment of identified production systems

Socio-economic sustainability

Dairy systems (Table 4)

In large-scale systems, the two intensive systems (D2 & D4) present lower workforce levels and higher workloads compared to the two extensive systems (D1 & D3). In small-scale systems, the workload is lower than in large-scale systems. Small-scale grass-based systems (both intensive and extensive; D7 & D8) present the lowest workforce levels (which are not necessarily associated with highest workloads).

The average farm income across all systems is 27424€/FWU, i.e., 10.2 €/family working hour or 0.11 €/L milk. In all systems, intra-system variability is very high for farm income (high standard deviations). Only the two small-scale diversified systems (D5 & D6) present statistically significant lower farm income levels compared to the six other systems. These similar farm income levels hide very different product and cost structures, as illustrated in Figure 10.

Regarding the share of subsidies, it is particularly high for small-scale extensive systems (D5 & D7), which is where the majority of organic farms from the sample are found. In terms of economic efficiency, small-scale extensive and/or grass-based systems (D5, D7 & D8), as well as the large-scale grass-based extensive system (D3) present higher performances than the other systems (D1, D2, D4 & D6).

Beef-breeding systems (Table 5)

The Belgian Blue grass-based extensive system (B3) presents the lowest workforce and workload levels whereas Belgian Blue diversified intensive (B2) presents the highest workforce and workload levels. The other systems present intermediate situations.

The average farm income for beef-breeding farms across all systems is 9057€/FWU, i.e., 3.4 €/family working hour, which is significantly lower than for dairy farms. Here too, intra-group variability is very high, resulting in an absence of statistically significant differences between group means. As for the dairy sector, Figure 10 illustrates that beef-breeding systems present different product and cost structures despite similar farm income levels.

Regarding the share of subsidies, it is extremely high (over 40% of total products) for the two French breed systems (B5 & B6, which are composed almost exclusively of organic farms) as well as for the extensive grass-based Belgian Blue system (B3). The share of subsidies is the lowest (around 20%) for the diversified intensive Belgian Blue system (B2). In general, the share of subsidies is significantly higher for beef-breeding farms than for dairy farms (around 10-20% of total products). Finally, in terms of economic efficiency, similar groups appear as for the share of subsidies (as well as for the farm income per suckler cow): the two French breed systems and the extensive grass-based Belgian Blue system (B3, B5 & B6) present better performances than the remaining three Belgian Blue system (B1, B2 & B4).

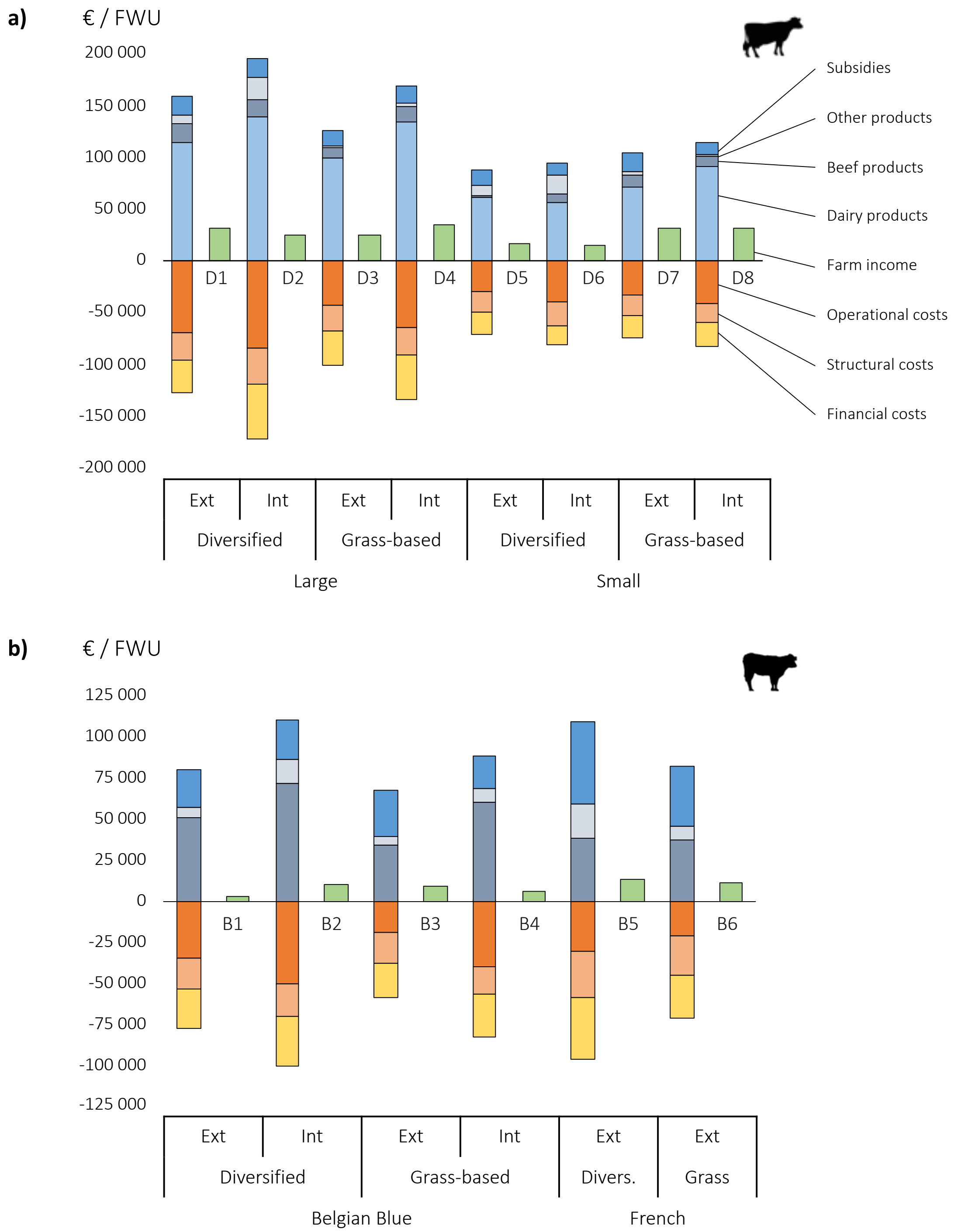

Figure 10. Product & cost structure and resulting farm income (€/FWU) of eight dairy systems (a) and six beef-breeding systems (b) in Wallonia.

Environmental sustainability

Dairy systems (Table 4)

Regarding soy consumption, the intensive systems present the highest consumption levels whereas the small-scale extensive systems (D5 & D7) present the lowest values.

Regarding pesticides, results show that grass-based systems, and in particular the extensive ones (D3 & D7) use lower amounts of pesticides, both per ha and per litre of milk. This is partly because these systems benefit from the presence of organic farms (for which a null use of pesticides is assumed), although the trend holds true when organic farms are excluded from the sample.

Regarding nitrogen emissions, small-scale extensive systems (D5 & D7) present the lowest emission levels when results are expressed per hectare. On the contrary, the more productive systems (in particular D2, D3 & D4) present the lowest emission levels when results are expressed per litre of milk.

Regarding biodiversity, small-scale extensive systems (both diversified and grass-based; D5 & D7) present the lowest impact levels per hectare across all systems. They benefit from the presence of organic farms in their groups which present lower impact scores. Per unit of output, the more productive systems (in particular D2 & D1) present lower impact levels compared to less productive, and in general more extensive systems.

Regarding GHG emissions, grass-based systems (in particular the extensive ones; D3 & D7) present lower emissions levels when results are expressed per hectare whereas intensive systems (in particular the diversified ones; D2 & D6) present lower emission levels when results are expressed per unit of output.

Overall, when aggregating all nine environmental indicators into an environmental impact score, the two extensive grass-based systems (D3 & D7) present the lowest environmental impacts, followed by the small-scale diversified extensive systems (D5). Diversified intensive systems (D2 & D6) present the highest overall impacts. The remaining systems (D1, D4 & D8) present intermediate situations.

Beef-breeding systems (Table 5)

Regarding soy consumption, the two French breed systems (B5 & B6) show much lower soy consumptions compared the two intensive Belgian Blue systems (B2 & B4), which present the highest values of soy consumption. The two extensive Belgian Blue systems (B1 & B3) present intermediate situations (Table 5). In general, beef-breeding systems present much lower soy and concentrate consumptions than dairy systems.

Regarding pesticides, the two French breed systems (B5 & B6) present the lowest values of pesticide use, both per hectare and per animal. This can be explained by the fact that these systems are composed almost exclusively of organic farms, for which the pesticide use was assumed to be inexistent. Within Belgian Blue systems, extensive grass-based (B3) presents the lowest value.

Regarding nitrogen emissions, when results are expressed per hectare, extensive, and in particular grass-based systems (B3 & B6) lead to lower emissions levels. On the contrary, intensive Belgian Blue systems (B2 & B4) lead to higher emissions, almost twice as high. Analysing the results per suckler cow is not particularly relevant given that the nitrogen emission factor per animal was considered the same across all farms and systems.

Regarding biodiversity, the two French breed systems (B5 & B6), and in particular the diversified one (B5) present the lowest impact levels, both per hectare and per animal. Within Belgian Blue systems, the two intensive systems (B2 & B4) present lower impact levels when results are expressed per animal whereas the two extensive systems (B1 & B3), and in particular the grass-based one (B3) tend to present lower impact levels when results are expressed per hectare.

Regarding GHG emissions, grass-based systems (B3, B4 & B5), and particularly the extensive ones (B3 & B5), as well as the French breed diversified system (B6) present the lowest impact level. The Belgian Blue diversified intensive system (B2) presents the highest impact level, both per hectare and per animal.

Overall, when aggregating all environmental indicators, the two French breed systems (B5 & B6) present the lowest environmental impact score, followed by the Belgian Blue grass-based extensive system (B3). On the contrary, the Belgian Blue diversified intensive system (B2) presents the highest environmental impact score. The two remaining Belgian Blue systems (diversified extensive and grass-based intensive; B1 & B4) present intermediate situations.

Combined results: multidimensional sustainability

A combined assessment of the socio-economic and environmental performances of the dairy and beef-breeding sectors is based on the farm income and the environmental impact score of the different farms and systems (Figure 11). Farms and systems should aim for the top-left corner of the figure as this is where lower environmental impacts meet higher farm incomes. In both sectors, there are examples of systems reaching this goal.

Within dairy systems, two ways towards the top-left corner can be identified: an economic way and an environmental way. The former is composed of the four intensive systems (D2, D4, D6 & D8) as well as the large-scale diversified extensive system (D1). The latter is composed of the two grass-based extensive systems (D3 & D7) as well as the small-scale diversified extensive system (D5). Five systems can be considered as close to the top-left corner: D1, D4 & D8 have followed the economic way whereas D3 and D7 have followed the environmental way. The remaining three systems are further away from the top-left corner and present either poor economic performances (D5), poor environmental performances (D2) or both (D6).

Within beef systems, three systems can be considered as close to the top-left corner: the two French breed systems (B5 & B6) as well as the extensive grass-based Belgian Blue system (B3). The remaining three Belgian Blue systems are further away, either in terms of environmental performances (B2) or both environmental and economic performances (B1 & B4).

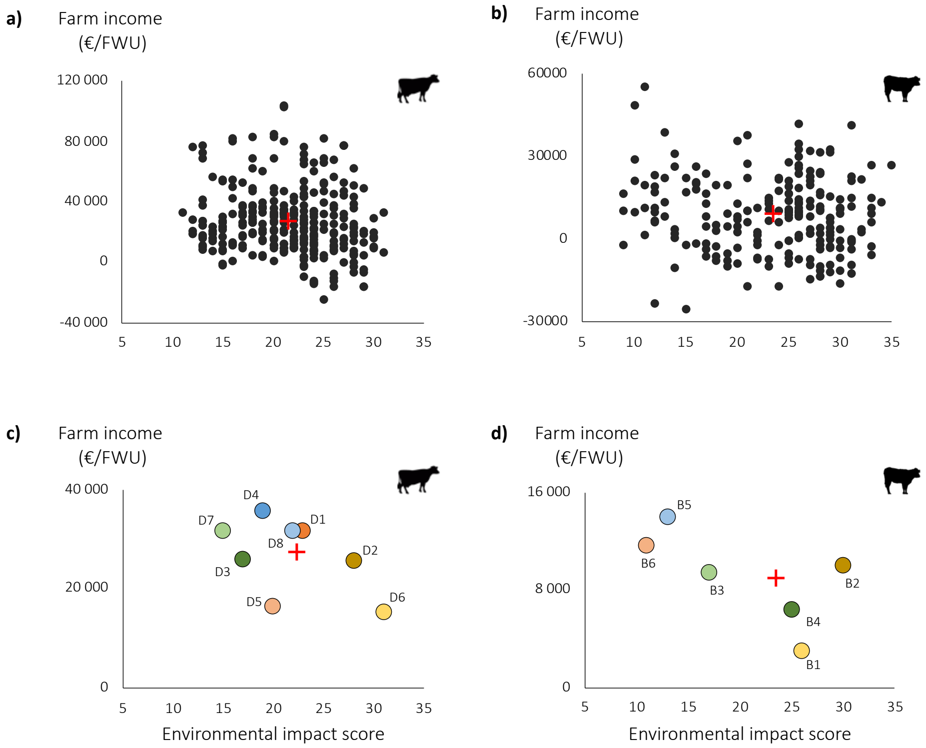

Figure 11. Combined economic and environmental performances of bovine systems in Wallonia: dairy sample observations (a); beef-breeding sample observations (b); dairy systems (c); beef-breeding systems (d). Greenhouse gas emissions were estimated at the production system level and were considered similar for all farms within a system. Red crosses indicate sample averages. FWU: Family Work Unit. The top left corner indicates the best performance of economic and environmental results (high farm income and low environmental impact score).

3.4 Discussion

3.4.1 Considerations on diversity assessments and implications for the sustainability of dairy and beef-breeding sectors

The first step, and key assumption of our method, was that a prior assessment of the diversity of systems and practices is necessary to enhance the relevance of sustainability assessments. A diversity of dairy and beef-breeding production systems coexist in Wallonia, showcasing different practices and strategies to pursue production and sustainability principles, as has recently been shown for Flanders (Tessier et al. 2021). Our typologies result from a representative sample of Walloon bovine farms and a set of qualitative criteria which are embedded in the local context. For instance, grouping farms based on the share of on-farm pasture results from the relative importance of grasslands in Wallonia (SPW 2020). Similarly, accounting for the breed was considered necessary given the historical importance of the highly specialized Belgian Blue breed in the Belgian beef sector (Stassart and Jamar 2008; Calay et al. 2020). Six main production systems were identified for the beef-breeding sector while eight systems were identified for the dairy sector. Our typology of the dairy sector is in line with the one proposed by Lebacq (2015).

The usefulness of the diversity assessment becomes evident when analysing the combined economic and environmental performances of the dairy and beef-breeding farms. Drawing conclusions on the environmental and socio-economic sustainability of both sectors is difficult when a diversity of production systems is not taken into account and only an undifferentiated set of farms is considered (top of Figure 11; sub-figures a and b). On the contrary, the analysis gains in clarity and relevance when done through the lens of the identified production systems (bottom of Figure 11; sub-figures c and d), thereby allowing to better grasp the challenges at stake in terms of sustainability within the dairy and beef-breeding sectors. It is necessary to identify the specific practices or biophysical features which make farms more or less environmentally efficient (Lynch et al. 2018). Our diversity assessment approach sets a first step in this direction as it shows that extensive grass-based systems present better combined results.

In terms of economic sustainability, our results have confirmed that the Walloon dairy and beef sectors face important challenges. The situation is particularly dire for beef farms. With structurally low farm incomes and a high dependence on subsidies, the economic viability of this sector can be put into question, as noted by Calay et al. (2020) and SPW (2020), and confirmed by Duluins et al. (2022). Average farm income values did not show significant intergroup differences, but they do hide different strategies to secure their farm income, resulting from different product and cost structures (Figure 10). On one side, more large-scale, intensive and generally maize-based systems (e.g., dairy systems D2 & D4 and beef-breeding systems B2 & B5) tend to aim for a product- and productivity-maximization strategy, which allows compensating higher costs. On the other side, more extensive grass-based systems (e.g., dairy systems D3 & D7 and beef-breeding systems B3 & B6) tend to aim for a cost-reducing strategy, to compensate lower output levels. Fostering the economic viability of bovine farms thus constitutes a necessity, for example through the implementation of fair prices and fair relationships in value chains, or adequate policy instruments rewarding systems with better environmental performances.

Regarding the environmental sustainability, more extensive and grass-based systems present the lowest environmental impacts as opposed to more intensive and diversified systems which rely more importantly on forage maize. This confirms the higher impacts attributed to forage maize in comparison to grasslands (Peeters 2009; Lebacq 2015), and the potential of grass-based systems in terms of environmental conservation (Meul et al. 2012; Reinsch et al. 2021). Yet, the freedom to engage in practices and production systems (e.g., implementing extensive, grass-based practices) is not always guaranteed as farmers might be constrained by external factors such as pedo-climatic conditions or access to land (Lebacq 2015; Lynch et al. 2018).

In terms of combined environmental and socio-economic performances, environmentally friendly systems (mainly grass-based and extensive) present a better compromise between environmental impact score and farm income (bottom of Figure 11). Although we cannot assert that environmentally friendly systems perform better economically than the more environmentally harmful systems, we can conclude that the environmentally friendly systems are not burdened by poorer economic results, as also concluded by Duluins et al. (2022). This is crucial as farmers need to perceive that taking up sustainable practices does not imply any economic disadvantage (Lynch et al. 2018). Our results show that there is not necessarily a trade-off between environmental and economic performances.

3.4.2 Considerations on data-driven indicator-based sustainability assessments

The second step and objective of this paper was to adopt a method allowing for comprehensive sustainability assessments based on farm accountancy data, and to overcome the dilemmas of indicator-based sustainability assessments. For our case study, the available DAEA data mainly included structural and socio-economic indicators. We were able to complement this core data and to produce relevant environmental indicators. Two options can be pursued to collect additional data for a comprehensive assessment: complementary on-farm enquiries and measurements, or the modelling of additional data with the help of some assumptions and estimations, as applied in our method.

In comparison with the collection of on-farm information, the main advantage of our method resides in its cost effectiveness for a large-scale implementation. As suggested by Lebacq et al. (2013), in the context of indicator-based sustainability assessments, data should be collected at a reasonable cost. From this perspective, the modelling approach constitutes an interesting alternative to the collection of on-farm information as the latter may be costly and time-consuming, as well as representing a potential challenge in terms of ensuring that a representative number of sample farms are surveyed (e.g., it might not be possible to measure GHG emissions for all FADN sample farms) (Lynch et al. 2018). On the downside, modelled data will always remain estimations, which are by definition less accurate than real measurements. Furthermore, the complexity of mechanistic models may in some cases limit their use (Halberg et al. 2005; Bockstaller et al. 2008), and the relevance of modelling is highly dependent on the quality of the models it relies on. Yet, a more systematic use of modelling within assessment processes may nurture a virtuous loop: the need for more accurate models will reinforce the motivation of modelers to develop research on models. Increased interactions between modelling specialists and assessment actors should lead to a better understanding of respective expectations. Moreover, data collected in the assessment may help to better fit models and check their relevance in real-life situations.

Choosing for the modelling approach also implies considerations on the cost of the additional calculations. In the case of farm accountancy databases, environmental indicators that are readily available (e.g., pesticide costs) present low environmental relevance (third dilemma of sustainability assessments). Modelling complex impact-based indicators (e.g., pesticide concentrations in soil) increases the accuracy of the assessment, but also its cost (Lebacq et al. 2013). Hence, for the sake of cost-effectiveness, we argue there is an optimum to find when calculating additional indicators. As illustrated in Figure 12, intermediate indicators (e.g., quantities of pesticides) might be more suitable, as they allow a gain in relevance while being relatively easy to estimate (i.e., with a limited cost). This does not question the usefulness of highly specific models, which focus on one particular environmental issue and seek to model it without having to rely on costly primary measurements. Rather, it suggests a complementary approach, which can be useful to overcome potential time and budget constraints while taking advantage of the structure of farm accountancy databases.

As long as FADN and other farm accountancy databases remain focused on the economic dimension, our approach provides a hybrid cost-effective way to perform comprehensive sustainability assessments. In the context of its Farm to Fork strategy, the European Commission plans to transform the Farm *Accountancy* Data Network (FADN) into a Farm *Sustainability* Data Network (FSDN). Broadening the scope of FADN by giving a greater attention to social and environmental themes would allow meeting the evolving information needs of a variety of actors (farmers, policymakers, consumers, etc.) (Kelly et al. 2018; Lynch et al. 2018). Yet, this transformation represents a significant task that will require supplementing the existing dataset with new indicators, with an estimated increase in the data collection costs of up to 40% (Vrolijk and Poppe 2021). It will be necessary to strike a balance between providing the necessary information and minimizing the additional burden for farmers and data collectors. Our method has the advantage of being FSDN-ready, as a more comprehensive set of core sustainability indicators would only increase the quality of the assessments, without having to rely on estimated indicators.

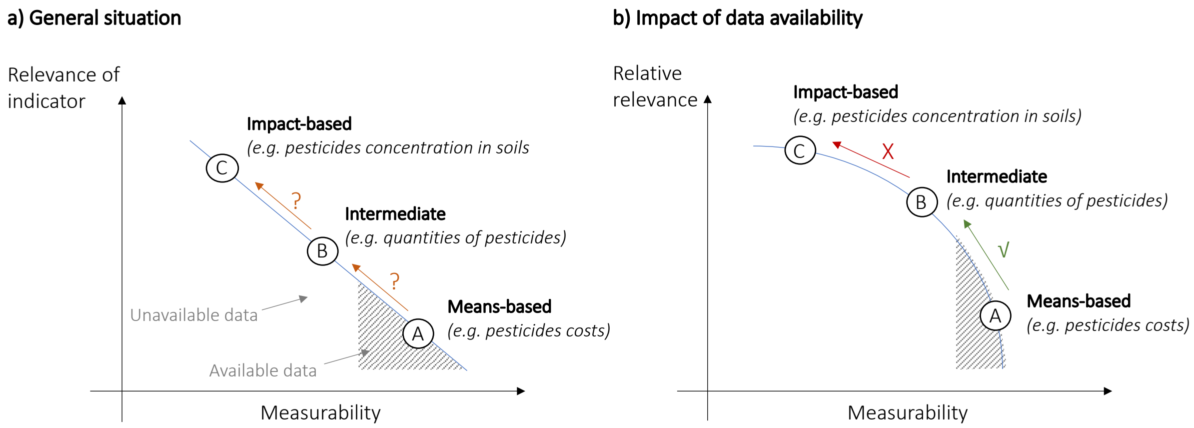

Figure 12. Relation between the relevance and measurability of environmental indicators. Hatched areas represent available data (i.e., core dataset data, or measurements); white areas represent unavailable data (i.e., calculated data, or approximations). General situation (a): Environmental indicators which are available in farm accountancy databases have a low relevance, but it is possible to calculate additional indicators to improve the accuracy of the assessment. Impact of data availability (b): For the sake of cost-effectiveness, it might be more pertinent to rely on intermediate indicators which are easy to estimate rather than on complex impact-based indicators.

3.4.3 Further considerations on the representativeness and replicability of our method

In terms of representativeness, it is important to keep in mind that results are only representative of the Walloon bovine sector (and only of the breeding step in the case of the beef sector, the fattening step being excluded). Such a regional approach is highly complementary to wider-scale analyses, comparing, for instance, trends across European countries or regions, based on country or region averages (e.g., Díaz de Otálora et al., 2022). Working upwards from the farm-level, regional FADN data allows us to account for specificities at the farm level and leaves more room for regional diversity (identification of eight dairy systems and six beef-breeding systems in our case or highlighting the importance of the Belgian Blue breed). These region-specific assessments might be valuable to assist in the design and implementation of adequate local policies, such as the CAP strategic plans.

Despite being of regional relevance, our approach is highly replicable as it builds on EU-wide standardized FADN data. Our methodology can thus be applied in other Member States, or with other farm data surveys, as long as it can rely on locally relevant classification criteria.

3.5 Conclusions

In this paper, we present an *ad hoc* method, which allows performing comprehensive and multidimensional sustainability assessments based on farm accountancy data, while acknowledging the diversity of practices and production systems. Our combined approach seeks the best compromise between specificity (i.e. accounting for diversity), relevance, and cost-effectiveness. We tested this method on the Walloon dairy and beef-breeding sectors by analysing FADN data. Five conclusions and key messages can be drawn from our results:

1. The results of our case study confirmed that complementing sustainability assessments with diversity assessments is key to fully grasp the challenges at stake in different farming sectors.
2. A diversity of systems coexists (large-scale or small-scale; grass-based or diversified; intensive or extensive; etc.). Although they showcase different practices and strategies, the results prove that it is possible to overcome trade-offs between economic and environmental performances.
3. Results show that extensive grass-based systems present the best combination of economic and environmental results. This highlights the importance of preserving grassland resources at the regional level.
4. The results confirm that Walloon bovine farms face challenging economic situations, stressing the need to ensure their economic viability.
5. While our method proved effective to complement FADN data, it also suggests that the planned transformation of the Farm *Accountancy* Data Network into a Farm *Sustainability* Data Network is strongly needed.

Our results should be corroborated by further evidence able to overcome the identified methodological limitations of the study (e.g., include the beef fattening step in the analyses, or improve the assessment of GHG emissions). Further research on strategic ways to implement a transition to more sustainable livestock systems in Europe is also needed (e.g., via the adoption of sustainable practices in different systems and geographical regions while dealing with year-to-year economic fluctuations, or tools to foster the economic sustainability of bovine farms).

3.6 Supplementary material

Supplementary material for this chapter can be found at the end of the document (Appendix to chapter 3). It includes the following elements:

- Additional figure on the three dilemmas of indicator-based sustainability assessments
- Additional detail on the data cleaning process
- Additional figure on the methodological steps of the study
- Additional figure illustrating the classification steps
- Description of on- and off-farm areas considered for the land use calculations
- Description of structural indicators
- Description of economic indicators
- Description of environmental indicators
- Additional figure illustrating the economic and environmental performances of sample farms

Chapter 4 Which types of quantitative foresight scenarios to frame the future of food systems? A review

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Abstract

Quantitative scenarios have become common tools to explore the evolution of agricultural and food systems. Despite the diversity in methods and questions explored, a notable gap remains in methodically categorizing such scenarios. Through reviewing a broad range of studies, this paper aims to address this gap. It pursues two main objectives: (1) proposing a comprehensive typology classification of distinctive scenario types; (2) delving into the practical implications that diverse scenario designs bring to the forefront. Based on a snowball sampling method, 36 quantitative food system scenario studies were reviewed. Each study was characterised based on a set of variables focused on the scenarios' design process (e.g. purpose of the scenarios, number of scenarios tested, scale of analysis, considered sustainability dimensions, etc.).

The paper proposes four scenario types of quantitative food system scenarios, centred on the scenarios' purpose and design process. Scenario types A and B are more normative as they seek to demonstrate the feasibility of a specific scenario or frame the conditions for its feasibility, differing in the number of scenarios tested (respectively one and many). Scenario types C and D are more exploratory as they aim to assess the consequences of different scenarios, differing in the number of scenario variables being explored (respectively one and many). Besides the proposed classification, the paper discusses important methodological considerations related to scenario design (e.g. the consideration of multiple sustainability dimensions, the adoption of participatory approaches, etc.). This paper contributes to enhancing coherence across food system foresight studies.

4.1 Introduction

4.1.1 Foresight as a valuable discipline for food system transitions

Agriculture and food systems stand as significant contributors to the global and local environmental challenges faced by societies. Across the nine planetary boundaries related to Earth-system processes as defined by Rockström et al. (2009), agriculture & food systems are concerned with at least five: biodiversity loss, nitrogen and phosphorus cycles, climate change, chemical pollution and land use change (Foley et al. 2011; Campbell et al. 2017; Bowles et al. 2019). As these challenges escalate, questioning the governance and future visions of these systems becomes imperative.

The need for a fundamental transformation in global food systems is clear, calling for a re-evaluation of evolution pathways. Foresight studies constitute a valuable discipline in this perspective. Foresight is understood here as the broad discipline which gathers several sub-schools of thought and terminologies, including future studies, strategic foresight and the French *prospective* approach (Coates et al. 2010). Besides lexicographical differences, each school has its specificities (e.g. in terms of relation with decision-making, or the level of participation and actor engagement) but shares the overarching goal of facilitating the creation of new visions of the future (Coates et al. 2010; McEldowney 2017). Contrary to forecasting which exclusively relies on the extrapolation of past trajectories to predict insights into the future, foresight adopts a broader perspective, including possible ruptures and critical uncertainties to explore mid- to long-term future situations (McEldowney 2017; de Lattre-Gasquet et al. 2023; Woodhill et al. 2024). Foresight is embedded into systemic thinking (de Lattre-Gasquet et al. 2023). As such, foresight studies can play an essential role in addressing the uncertainty of potential futures, particularly in the dynamic landscape of agriculture and food systems. Foresight studies can contribute to empowering organisations to anticipate and prepare for forthcoming challenges or opportunities.

4.1.2 Quantitative scenarios as useful tools in the context of foresight studies

Scenarios, either qualitative or quantitative, emerge as central tools in foresight studies and associated frameworks such as transition management (Loorbach 2010; Duru et al. 2015a; Dendoncker et al. 2018). In particular, quantitative scenarios do so by presenting numerical data through tables and graphs. They consist of simulations that test a set of assumptions with the help of a model (see Box 2 for more detailed definitions of scenario-related terms). Quantitative scenarios offer a robust method to scrutinise the evolution of agricultural and food systems, as exemplified by numerous publications in recent years, particularly in a European context (Röös et al. 2017b; Poux and Aubert 2018; Riera et al. 2019; Couturier et al. 2022; Rieger et al. 2023; van Selm et al. 2023). This paper positions itself at the forefront of exploring quantitative foresight scenarios within the agriculture and food systems. Our focus extends to the intricacies of quantitative scenario design, unravelling how these scenarios are constructed. We contribute a comprehensive typology categorisation to identify distinctive groups of scenario exercises. Moreover, we engage in a discussion shedding light and insights on the practical implications that diverse scenario designs bring to the fore, marking a significant contribution in the discipline of agricultural and food system foresight.

Box 2. Definition of scenario-related terms

Scenarios are defined by the European Environment Agency as *'a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Scenarios are neither predictions nor forecasts but provide a view of the implications of developments and actions'* (European Environment Agency 2017).

Qualitative scenarios employ language or visual symbols, often presented as narrative storylines, to describe existing or potential drivers and strategic future directions (European Environment Agency 2017).

Quantitative scenarios correspond to simulations derived from models following a comprehensive set of assumptions (European Environment Agency 2017). They represent a possible trajectory in time resulting from a set of variables simulated under parameter and input combinations.

Models are mathematical or physical representations of a system that account for all or some of its known properties. They allow computing quantitative scenarios by testing the effect of changes in system components on the overall performance of the system (European Environment Agency 2017).

Scenario variables are the variables (system components) that are affected by scenario assumptions and which, by changing their default value, affect the outcomes of the model.

Scenario exercises consist of individual studies that model one or more quantitative scenarios. Thus, a scenario corresponds to one single simulation whereas as a scenario exercise corresponds to the set or family of scenarios tested by authors within one scenario study.

4.1.3 Comparative analyses of food system scenarios

The growing interest in foresight and quantitative scenario modelling for scrutinising the inherent uncertainty of food systems and their potential development pathways has spurred several analyses seeking to compare and classify scenario studies. Here we synthetise the findings of four seminal studies that analyse the design and implementation of quantitative foresight approaches within the context of food systems. We focus on existing proposals to classify scenario studies and on methodological considerations regarding scenario design, including elements of scale, sustainability dimensions and themes, production systems and participatory approaches.

Reilly & Willenbockel (2010) employ a classification derived from Börjeson et al. (2006), categorising scenarios based on their purpose. They distinguish between three categories of scenarios, each offering unique insights into the potential evolution of food systems: *predictive* scenarios aim at finding out what will happen, *exploratory* scenarios investigate what might happen, and *normative* scenarios aim to uncover how to reach a certain predefined state. This classification is underpinned by analysing five case studies, representative of the three proposed categories. Regarding sustainability, the authors conclude from their analysis that the concept has been insufficiently explored in its multidimensionality, with overemphasis on 'narratives of growth' (and thus the economic dimension of sustainability) and too little attention to integrated assessments of the economic, biophysical, political and institutional dimensions of the food system (Reilly and Willenbockel 2010).

Prost et al. (2023) shift their focus to exploring and defining desired futures, particularly supporting agroecological transitions at the farm level. They draw connections between the scale of analysis and the actors leading the foresight exercise, distinguishing between farmer-led scenarios focussed on the farm level, and expert-based scenarios often operating at broader levels (regional, national, European and global). In this regard, they stress the difficulty to integrate such different approaches and scales of operation, with a particular focus on the integration of the farm level. Similarly to Reilly & Willenbockel (2010), Prost et al. (2023) identify that the exploration of desired futures and targets ranges from being based on pre-identified solutions to more open and exploratory answers. Looking at farm-level assessments, the authors also note imbalances in the sustainability dimensions addressed, with a lower level of attention and detail for social sustainability.

Duru et al. (2021) contribute by reviewing six scenarios that quantify greenhouse gas emissions for achieving net-zero emissions by 2050 and shifts in dietary patterns, particularly reductions in meat consumption. Their analysis evaluates scenarios based on two key considerations: whether the climate challenge is primarily addressed through technological improvements or socio-technical behavioural changes, and whether the scenarios exclusively focus on climate objectives or adopt a more systemic approach. By doing so, they bring important considerations on the link between diverse production systems (e.g. extensive or intensive) and the choice of sustainability indicators being assessed (e.g. climate change or biodiversity). They conclude that scenarios focused on technological solutions are mostly climate-centred and tend to overlook biodiversity and health. On the other hand, scenarios considering multiple sustainability objectives (including for example biodiversity and health) are based on more systemic innovations, requiring behavioural and societal changes (e.g. regarding the consumption of animal products) which are more challenging to implement as a greater number of socio-technical barriers need to be removed (Duru et al. 2021).

Finally, de Lattre-Gasquet et al. (2023) scrutinise thirteen foresight studies, including both qualitative and quantitative approaches, with a specific focus on agroecology. Through their analysis, they provide important insights on how food system foresight approaches are currently being implemented. While not proposing an explicit classification, this research sheds light on the main characteristics of foresight approaches. Among other elements, the authors distinguish four (non-exclusive) aims of scenario exercises, including advocacy; structuring debates and navigating diverse futures; analysing and assisting political decision-making; empowerment and capability development. Further, they analyse the geographical scales of analysis and note the potential challenges related to the 'translation of scales'. They also note that the type of participation in foresight is related to scale, with global exercises mostly involving experts and researchers while more local exercises are more likely to engage with a greater diversity of actors. Looking at the sustainability dimensions and themes included and the drivers of change considered, they note high occurrences for land use issues, biodiversity and climate change (the latter being mainly considered as a driver rather than as an outcome) while water resources are not much considered. On the socio-economic side, general food security, wages, profits and trade appear well-researched whereas social sustainability is not frequent.

These comparative analyses collectively underscore the diversity of methods and questions explored in quantitative food systems scenario exercises. However, a notable gap exists in a more systematic classification and analysis of such scenarios. With the burgeoning number of quantitative scenario studies, this paper aims to fill this void. Building on the findings from the four studies presented above, this analysis aims to complement and consolidate them by pursuing two main objectives: (1) propose and/or confirm a stabilising framework to classify quantitative foresight food system studies, and (2) discuss methodological considerations and their implications with regards to elements of scenario design, such as the boundaries of scenario exercises, the inclusion of sustainability dimensions or the consideration of a variety of production systems. Importantly, we aim to base our analysis on a broader and sufficiently diverse set of studies to provide a robust framework which can support further discussions on the design and relevance of food system scenarios.

4.2 Methodology

4.2.1 Overview

A four-step methodology was rolled out in the research process: (1) a study selection step allowed to build up the set of studies that would be reviewed; (2) a coding step consisted in reviewing and characterising the selected studies with the help of a set of variables; (3) a typology identification step led to discerning main categories of scenario studies in the sample; (4) an analysis step investigated methodological considerations regarding quantitative food system scenarios.

4.2.2 Study selection

Initiating the literature review, the identification of studies (Figure 13) began with two rounds of expert meetings, organised in March and April 2020, which gathered sixteen experts from across Europe. All members had a proven expertise in the subject as they had all previously co-authored or participated in food system scenario studies. Experts were tasked with compiling a list of food system scenarios, while also discussing the nuances of scenario design, encompassing research intentions and outcomes. These expert sessions yielded an initial list of eleven reference studies constituting the basis of our analysis (Table 6). This process led to the writing of a draft working paper based on the eleven reference studies. Building on this work, a more in-depth literature review was carried out in 2022-2023, consisting in an iterative process systematically exploring all studies citing these eleven reference studies, starting with the oldest one (Agrimonde scenarios; Chaumet et al., 2009). This chronological snow-ball sampling process led to the identification of additional studies (6243 citations), which were tested against inclusion/exclusion criteria. The criteria ensured focus on studies proposing new scenario exercises featuring the modelling of one or more quantitative scenario with a specific focus on the food system (Table 7). The analysis in this paper focuses on the scenario exercises as a whole (i.e. the reviewed studies), looking at how individual scenarios are constructed within those exercises. To be noted that reference studies mentioned during the expert sessions were not automatically included in the final list if they did not comply with the inclusion criteria. For instance, Van Zanten et al. (2018) was excluded as it does not actually model a new scenario. In first instance, 37 studies were selected based on title and abstract reading. After reading these studies in full, one additional study was excluded as it adopted a qualitative scenario approach (Mitter et al. 2020). As a result, a total of 36 articles were eventually included (Table S4).

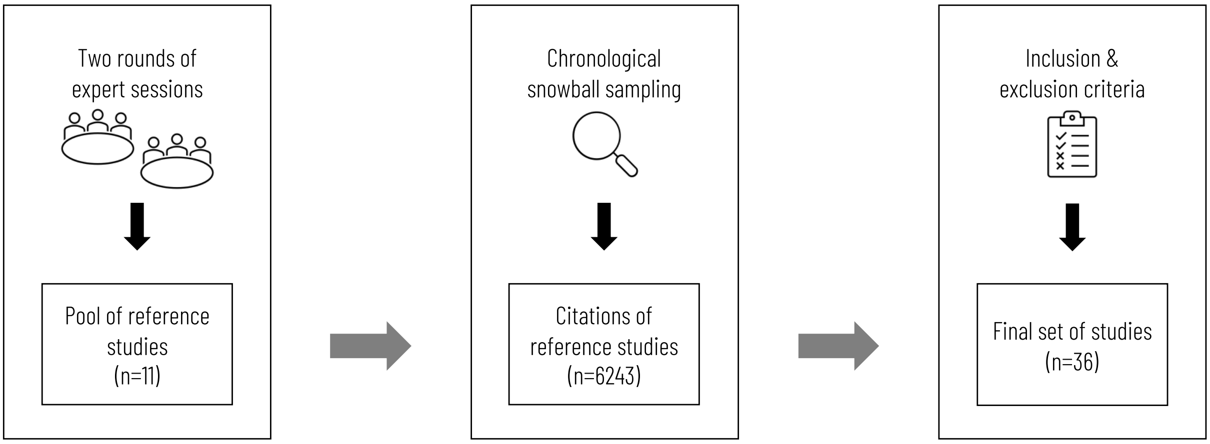

Figure 13. Methodological approach followed for the selection of analysed studies.

Table 6. Initial compilation of reference studies identified by experts and number of associated citations that were explored as part of the snowball sampling process.

Name of the study	Reference	Cited by
1. Agrimonde: Scenarios and Challenges for Feeding the World in 2050	(Chaumet et al. 2009)	86
2. Afterres 2050 – Un scénario soutenable pour l'agriculture et l'utilisation des terres en France à l'horizon 2050	(Couturier et al. 2016)	8
3. Limiting livestock production to pasture and by-products in a search for sustainable diets	(Röös et al. 2016)	126
4. Agrimonde-Terra: Foresight land use and food security in 2050.	(de Lattre-Gasquet et al. 2016)	41
5. Protein futures for Western Europe: potential land use and climate impacts in 2050	(Röös et al. 2017a)	78
6. Strategies for Feeding the World More Sustainably with Organic Agriculture	(Muller et al. 2017)	495
7. Une Europe agroécologique en 2050: une agriculture multifonctionnelle pour une alimentation saine (TYFA)	(Poux and Aubert 2018)	55
8. Less is more: Reducing meat and dairy for a healthier life and planet	(Tirado et al. 2018)	21
9. Defining a land boundary for sustainable livestock consumption	(Van Zanten et al. 2018)	208
10. Pathways to Sustainable Land-Use and Food Systems	(FABLE 2019)	3
11. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems	(Willett et al. 2019)	5122

Table 7. Inclusion/exclusion criteria applied for the selection of studies following the snowball sampling process.

Inclusion	Exclusion
The study focuses on food systems (targeting activities from agricultural production to food consumption)	The study does not focus on food systems (e.g. energy sector; health sciences; etc.)
The study includes a quantitative scenario	The study includes a qualitative scenario approach (e.g. through the development of narratives and storylines)[1]
The study proposes a scenario exercise and models one or more scenarios	The study: - compares different scenarios or models but does not propose a new one[2], - defines targets allowing scenario development[3], - describes the participatory approach that leads to the modelling exercise[4], - describes the software/model used to perform the scenarios[5],
Available online text	Unavailable resources such as books
The study is a scientific report or article	The study is a master's thesis

[1] E.g. Mitter et al. (2020)
[2] E.g. Van Zanten et al. (2018)
[3] E.g. van Vuuren et al. (2022)
[4] E.g. Karlsson et al. (2018)
[5] E.g. Kalt et al. (2021)

4.2.3 Coding

Moving to the coding process, a set of coding variables was established to characterise the selected articles, and the scenario exercises they propose (Table S5). Coding variables were initially proposed based on authors' knowledge of scenario design. Five test articles were coded in first instance to calibrate and refine the coding process. Subsequent coding of articles was conducted independently by the authors. The main focus of the coding process resided on elements including the purpose of the scenario exercises, the number of scenarios tested and the number of scenario variables, the adoption of participatory approaches, the time horizon, the scenario boundaries (in terms of geographical scale and analysed sectors), the number of production systems considered and the inclusion of sustainability dimensions.

4.2.4 Typology identification and classification of studies

Building a typology consists in the '*classification of objects, structures, or specimens by subdividing observed populations into a theoretical sequence or series of groups (types) and subgroups (subtypes) according to consideration of their qualitative, quantitative, morphological, formal, technological, and functional attributes*' (Oxford Reference Dictionary 2008). The process of delineating a typology involved two iterative rounds of discussion among the authors. Initially, each author submitted two or three variables they deemed pivotal for distinguishing scenario types. As a reminder, the focus of the typology lies on the scenario exercise as a whole, i.e. the set of scenarios tested by authors within one study. The first meeting was dedicated to scrutinising and deliberating these initial proposals. Upon achieving a consensus, the authors were divided in two groups. The first group contributed to formulating descriptions of the identified scenario types and classifying the articles. Subsequently, the remaining authors rigorously tested and scrutinised the classification. Instances of disagreement were carefully discussed, fostering a refinement of both the typology descriptions and the classification of articles. This collaborative process ensured a comprehensive and robust framework for distinguishing scenario types, fostering clarity and coherence in the subsequent analysis.

The selection of variables to categorise studies and identify scenario types centred on two aspects: the purpose or intention of the research and the intricacies of scenario design. On the one hand, purpose delineates whether the desired future is distinctly identified and aligns with a singular more *normative* vision or whether a more open-ended and *exploratory* approach is adopted. On the other hand, scenario design encapsulates both the number of scenarios examined and the variables explored within each scenario (number of variables involved in scenario design and how they influence scenario design). It is pertinent to note that our classification hinges on the methodological approaches to scenario design rather than on the narratives of the scenarios (i.e. the content or storytelling that is being emphasised in the scenarios).

4.2.5 Analysis of scenario characteristics

Once the scenario types were identified, subsequent analyses delved further into the analysis of the coding variables, describing scenario characteristics and thus enriching contextual understanding. Specific attention was paid to the depth of actors' involvement, the scale of analysis, the consideration of production systems, the considered time horizons, the sectors of interest and the incorporation of sustainability dimensions (social, economic, environmental) within the scenarios. This multi-faceted analytical approach, performed through the lens of the identified typology when possible, facilitated a comprehensive exploration, going beyond the mere classification of scenario types.

4.3 Results

4.3.1 Identification of four methodological scenario types

Departing from a set of 36 studies, this review set out to identify different types of food system scenarios. Based on the purpose of the research and the scenario design, a typology composed of four scenario types is proposed (see Figure 14 and Table 8).

Purpose refers to the normative or exploratory character of the modelling exercise and what is predetermined. One coding variable allows to distinguish two groups in terms of purpose. A first group composed of 15 studies aims to demonstrate the feasibility of a specific scenario or to frame the conditions for its feasibility. A second group, composed of 21 studies, aims to assess the consequences of different scenarios or trajectories. As such, the first group can be considered as more normative whereas the other group can be considered as more exploratory.

Scenario design refers to specific modelling choices. Three coding variables were used to further subdivide the two groups obtained previously: the number of scenarios, the number and set of scenario variables. Within the ‘normative group’, one subgroup (scenario type A) composed of six studies tests one single scenario based on a unique set of scenario variables. A second subgroup (scenario type B), composed of nine studies, tests multiple combinations of scenario variables, often resulting in many scenarios. Within the ‘exploratory group’, one subgroup (scenario type C) composed of seven studies explores several scenarios by testing one scenario variable in a 'gradient' perspective. The second subgroup (scenario type D) explores several scenarios by testing multiple sets of scenario variables from one scenario to another.

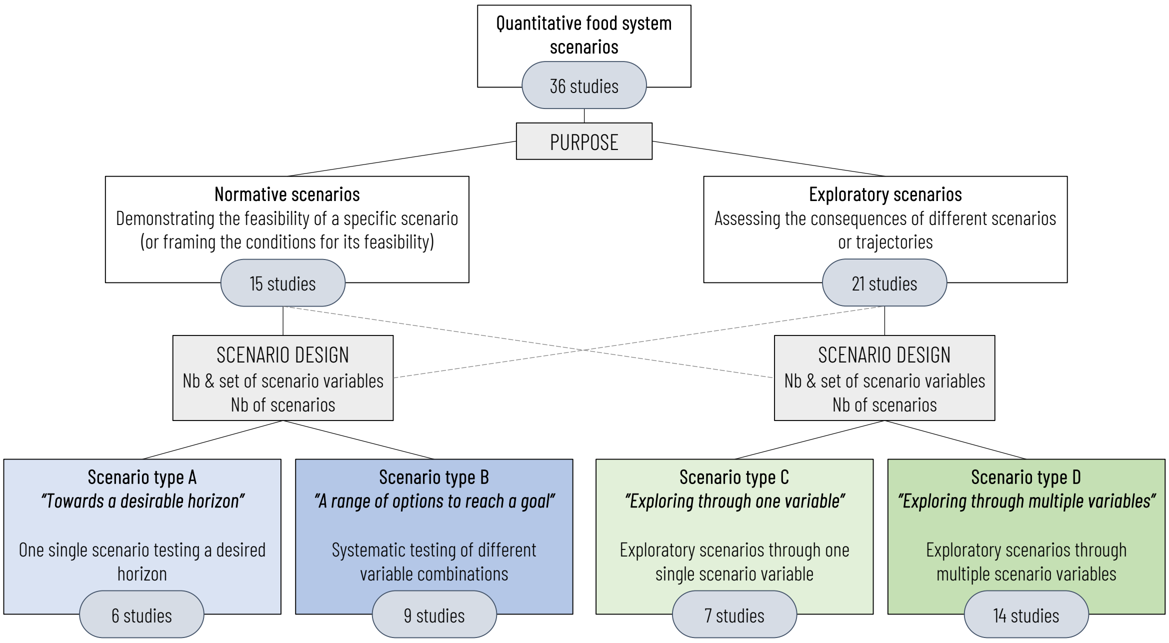

Figure 14. Construction of a typology of four methodological groups of food system scenarios based on purpose and scenario design.

Scenario type A – Towards a desirable option

Scenario type A delves into the feasibility and outcomes of a specific pre-identified scenario corresponding to a desirable future (Table 8). One single scenario is tested, based on a fixed set of scenario variables. Scenarios within scenario type A can be considered as normative. These studies often focus on a single production system, such as organic or agroecological farming, adopting a *hard sustainability* approach which prioritizes non-negotiable environmental objectives over socio-economic objectives.

Scenario type B – A range of options to reach a goal

Scenario type B studies aim to compare the effects of various scenario variables and identify their optimal combinations to attain predetermined goals, leading to many scenarios (Table 8). The focus is on defining an option space within boundaries, possibly representing the desirable future as a space rather than a specific point. As such, scenario type B can be considered as less normative compared to scenario type A. Scenario type B studies may resort to optimization models (Barbieri et al. 2021; Frehner et al. 2022)[8].

Scenario type C – Exploring through one variable

Scenario type C involves comparing the consequences of different scenarios without predefining a desirable trajectory nor an ideal endpoint. Only the starting point is pre-identified. Scenario type C evaluates scenarios based on a single specific variable (Table 8), such as the share of organic and local food consumed (Billen et al. 2012) or the utilisation of different leftover streams for livestock feeding (van Selm et al. 2022). The goal is to understand how changes in this variable can affect food production, land use, GHG emissions, nutrient flows, and more.

Scenario type D – Exploring through multiple variables

Scenario type D also explores different scenarios without predefining a desirable trajectory nor an ideal endpoint. It does so by examining the effects of multiple variables, which may be different from one scenario to another. As a result, a diversity of scenarios can emerge and new variables can be considered to develop scenarios, making this group the most exploratory (Table 8). Typically, studies in scenario type D group a business-as-usual scenario based on recent trends with one or several alternative scenario(s).

[8] Regarding the use of optimisation models, as the classification was not built around this, it could be that scenario exercises resorting to optimisation models would fall under other categories. For instance, Mosnier et al. 2017 uses an optimization model to simulate typical French bovine farms but is classified in category D as the purpose and construction of the scenarios is exploratory.

Table 8. Characteristics of four quantitative food system scenario types, based on purpose and scenario design.

Differentiating factor	**Scenario type A** *« Towards a desirable horizon »* *(6 studies)*	**Scenario type B** *« A range of options to reach a goal »* *(9 studies)*	**Scenario type C** *« Exploring through one variable »* *(7 studies)*	**Scenario type D** *« Exploring through multiple variables »* *(14 studies)*
Purpose				
Modelling purpose	The modelling aims to assess the consequences or demonstrate the feasibility of a specific, pre-identified scenario	The modelling compares and optimises the effects of various combinations of variables to reach specific goals	The modelling explores multiple scenarios by assessing the consequences of the change in one variable along a gradient	The modelling serves to explore contrasted scenarios, assessing and comparing their consequences
What is predetermined	The scenario being tested	The endpoint (space)	The starting point	The starting point
Scenario design				
Number of scenarios	1	Many	Generally, between 2 and 6	Generally, between 2 and 6
Number of scenario variables	Variable	Variable	One variable – Gradient perspective	At least two variables
Set of scenario variables	Fixed (as only one scenario is tested)	Fixed (multiple combinations are tested)	Fixed (as only one variable is considered)	Flexible (the set of scenario variables may change from one scenario to another)

4.3.2 Characteristics of included studies

Upon identification of scenario types and classification of the sample studies in said categories, the review aimed at enriching the contextual understanding of quantitative food system scenarios through the analysis of several variables. In this paragraph, our sample is presented and disaggregated in quantitative terms for transparency and clarity purposes. While we acknowledge that our sample is not fully representative of all quantitative models, we consider it important to discuss the figures observed within this set of studies. We do so with caution, refraining from generalizing these results to the broader field. These findings and their validity are further discussed and put in the perspective of the existing literature in the discussion and conclusion.

Purpose (classification variable)

Out of the 36 reviewed studies, 15 studies aim at demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility (Table S6). As per typology construction, these studies are concentrated in scenario types A and B (except for Billen et al. (2012), classified in scenario type C). The remaining 21 studies adopt a more exploratory stance and aim at assessing the consequences of different scenarios or trajectories. These studies are thus concentrated in scenario types C and D (except for Röös, Bajzelj, et al. (2017), classified in scenario type B).

Number of scenarios (classification variable)

The number of scenarios in each study varies considerably, ranging from a single scenario to as many as 56 scenarios. Six studies explore a single scenario, 18 test between two and four scenarios, and 12 test more than four scenarios, showcasing the diverse approaches employed in the reviewed foresight studies (Table S6).

Regarding scenario types, all studies with one single scenario belong to scenario type A by construction. Studies with two to four scenarios are predominantly in scenario types C and D, and studies with more than four scenarios are often in scenario type B. This group habitually leads to many scenarios, with the exception of one study that only tests two scenarios (Padró and Tello 2022), which is explained by the fact that only two extreme situations are tested although the scenario design could allow a wide spectrum to be tested.

Research process and participatory approach

The extent of participation in scenario development, either through experts or through operational actors, greatly varies from one study to another. Out of the 36 reviewed studies, 24 did not rely on participatory approaches, while six relied on expert consultations and six engaged with operational actors (Table S6). Participatory approaches served different purposes, such as creating the narrative framework for scenarios, discussing the evolution of critical variables in the coming years, translating qualitative hypotheses into quantitative model inputs, or refining the story post-scenario analysis. With regards to the typology, all approaches engaging with operational actors except one were classified in the exploratory groups C and D, seemingly reflecting a greater participatory approach to scenario development in those categories.

Time horizon

In terms of time horizon, 2050 is the most common target year within our sample (21 studies). Shorter time horizons (2030, 2035 or 2040) or studies specifying no temporal horizon are less frequent (six studies and nine studies respectively; Table S6). This highlights that, within our sample, foresight scenarios seem to be predominantly used for long-term planning.

Scenario boundaries: geographical scale and sectors

Scenario studies can adopt either horizontal approaches (by geographical scope) or vertical approaches (by farming sector) or a combination of both. Horizontal approaches seem to be much more frequent as they are adopted by 21 out of the 36 studies, while only four adopt a vertical approach and nine adopt a combined approach. Territorial approaches thus seem to predominate over sector-specific approaches.

Geographical scale. The studies included in the review cover a broad range of scales, from farm-level to global. Of the 36 studies, seven are global in scope, six focus on Europe, eight studies are conducted at the national scale, and six at the regional scale (understood as a sub-national level). Hence, the majority of studies (28) seem to focus on one single scale. In complement, nine studies adopt a multi-scale approach, combining different geographical scales such as regional-to-global, regional-to-national, farm-to-national or farm-to-regional. Additionally, two studies do so by examining multiple countries. Focus within the reviewed studies is on high-income countries and regions. There does not seem to be any effect of the typology on the question of geographical scale as all approaches can be found in all four scenario types (Table S6).

Sectors. In terms of studied sectors, livestock productions are the more investigated within our sample, either on their own (six studies) or in combination with crop sectors (29 studies) (Table S6). Crop productions on their own are only studied in one study (Antier et al. 2020a). Here too, the four scenario types do not seem to influence the choice of the studied sectors.

Accounting for diversity in scenarios: number of production systems considered

Beyond the inclusion of various sectors, studies showcase a range of approaches in the consideration of different production systems within those sectors. Production systems refer to different methods of producing a specific crop or animal product.

Out of the 36 reviewed studies, only 15 studies account for the diversity of production systems (i.e. more than one production system considered) while 21 studies do not account for it (i.e. either only one production system is considered or none, or no information) (Table S6). All studies in scenario type A consider one single production system (or none). As mentioned in the description of the group, these studies often focus on a single production system which they seek to assess (and/or promote), such as organic or agroecological farming. Studies in scenario type B pay less attention to the diversity of production systems (only one third). In scenario types C and D, about half of the studies account for a diversity of production systems.

Sustainability and productivity-related dimensions

The analysed publications approach the different dimensions of sustainability in a diversity of ways through their scenarios. Beyond the three dimensions of sustainability (environment, economy and society), three variable categories are considered for the purpose of this analysis: environmental variables, socio-economic variables and productivity-related variables.

Regarding sustainability, only seven studies cover all three dimensions of sustainability. The environmental dimension (including biophysical factors) is the most considered as it is included in all 36 studies, either on its own (13 studies), or in combination with other dimensions. Eleven studies combine the environment and the economic dimensions while five studies combine the environment and social dimensions. The economic dimension appears in 18 studies, but never on its own. The social dimension is the least studied within the sample as it only appears in 12 studies, and never on its own (Table S7). The occurrence of sustainability dimensions is not influenced by the typology.

Looking more specifically at the three variable categories, we find that within the environmental dimension, land use, climate and the nitrogen cycle are the three most common themes considered (24 studies each). Biodiversity, water and the phosphorus cycle show an intermediate occurrence (about 10 studies each). Finally, elements related to acidification, eutrophication, erosion, afforestation and deforestation, soil carbon sequestration, potassium, the use of energy, or the use of pesticides are considered less frequently within the reviewed sample (ranging from two to six studies). Regarding socio-economic variables, trade is the most common variable included in scenario studies (19 appearances). It is followed by economic results (eight appearances, including farmer income and profit), population (six appearances), labour demand and use (four appearances) and health (four appearances). Other element such as food sovereignty, policy implications, prices, animal welfare, etc. all represent two appearances or less. Economic variables are more present compared to social variables. Finally, within productivity-related variables, general production indicators are widespread in all studies (more than 40 appearances, sometimes through several themes in one study). They are followed by food demand (13 appearances), food waste (ten appearances), productivity and yield (ten appearances) and feed production and demand (nine appearances). Other elements such as food balance, technology, the size of the livestock herd and livestock density appear less than five times each. Demand-side variables and dietary shifts are well represented in the sample as only five studies do not analyse them as part of their scenarios.

These variables can either be used as input variables (constraints) or as output variables (results) in the scenario design process, or both. In the majority of reviewed studies, environmental variables are considered as outputs of scenarios. Within our sample, scenarios seem to be more commonly constrained by socio-economic variables, and even more so by productivity-related variables.

4.4 Discussion

4.4.1 Relevance of the proposed typology

The proposed typology, resulting from analysing a set of 36 articles, offers a stabilising framework for classifying quantitative food system scenarios into four major scenario types. Previous research, exemplified by that of Börjeson et al. (2006) and mobilised by Reilly & Willenbockel (2010), predominantly constructed typologies from theoretical standpoints, with classifications rooted in the key questions the authors deemed relevant for exploring future scenarios. This paper distinguishes itself by contributing to the literature with a systematic typology based on an existing body of literature. The categories within this typology are defined according to the scenarios' purpose and design (number of scenarios and scenario variables). Compared to existing classifications, the four scenario types proposed show similarities in the distinction between normative and exploratory approaches, as proposed by Börjeson et al. (2006) and Prost et al. (2023), with further fine-tuning related to the choices of scenario design in terms of numbers of scenarios and scenario variables.

In the context of this study, the proposed classification explains the diversity of scenario studies. Within the 36 reviewed studies, only two (Billen et al. 2012; Röös et al. 2017b) presented a conflict between the 'purpose group' and their 'scenario design group' (both were classified according to their 'scenario design group' rather than to their 'purpose group'). This indicates that porous relations between 'purpose groups' and 'scenario design groups' may occur (Figure 14). Similarly, the three groups mentioned by Reilly & Willenbockel (2010) were not exclusive as some of the example studies belonged to two different groups.

This typology serves as a comprehensive framework for deliberating the choices made during scenario design and publication. On the one hand, these choices may be influenced by diverse factors, such as the goals pursued by scenario commissioners and scenario designers, their focal points of interest, and their alignment with specific development paradigms or world views (Lumbroso 2019). The availability and ease of use of data, along with the historical and scientific context in which scenarios are designed are additional factors that influence these choices. On the other hand, these choices have a direct impact on the outcomes of the scenarios. Providing a framework that identifies and clarifies the main possible configurations in which scenario design can take place seems crucial to improve their analysis and understanding. Thus, the proposed framework not only aids in discussing the choices made during scenario design but also provides a basis for assessing the relevance of different types of scenario exercises for different scientific and political objectives. For instance, by examining the potential benefits of pursuing a predetermined scenario, studies within scenario type A may contribute to shaping specific visions for a sustainable and desirable agricultural future. In other instances, with the objective of reaching a specific goal, studies within scenario type B open up avenues for understanding the trade-offs and synergies between different variables and their combinations. Similarly, although more exploratory in the sense that they do not seek to reach a specific goal, studies within scenario type C also allow to explore the incremental effects of a specific variable. Finally, studies within scenario type D provide the flexibility to draw a vast range of exploratory scenarios, based on multiple variables.

In considering impact evaluation, various quantitative and qualitative approaches can be employed to gauge the reach and influence of specific scenarios. The framework facilitates a comparative analysis of scenarios, elucidating how they contribute to shaping representations of the future of food systems and potentially influencing or excluding specific development pathways. By showcasing diverse ways to construct scenarios using quantitative modelling and proposing a typology of scenario types, this paper encourages reflection on the strategic aspects of discourse production about the future, actively participating in the transitions of socio-technical systems. Consequently, this research lays the groundwork for assessing scenarios' contributions and impacts on the transformative processes toward more sustainable food systems.

4.4.2 Exploring methodological considerations of quantitative foresight scenarios

Within this review, an array of challenges and opportunities for scenarios to contribute effectively to transition dynamics emerge. They encompass the consistency and relevance of sustainability dimensions, the role of actor participation, the definition of boundaries, the consideration of diversity and the adoption of food system approaches (including interconnexions between geographical scales, sectors, food system approaches and production systems).

Choice of sustainability dimensions

Of the 36 studies reviewed, all included environmental considerations in their scenarios, predominantly as output variables (e.g. modelling the environmental impacts of a specific scenario) and sometimes as input variables (e.g. modelling the impacts of climate change on the food system). Within the environmental impact categories considered, there appears to be an important imbalance. On the side of the most common themes, the focus on land use, climate and nitrogen can be related respectively to the agronomic and physical feasibilities of certain scenarios, the important attention that has been given to climate change in the last decades (both in the scientific sphere for example through the work of the IPCC, and the contribution of agriculture and food systems to global GHG emissions, but also in the political sphere, for example through international agreements and COP negotiations), and to lasting concerns around nitrogen pollution and local pollution episodes (e.g. in Brittany and in the Netherlands). On the side of the less studied themes, the limited number of studies on the intensive application of pesticides in modern agricultural systems stands out in particular, although this has been the object of recent foresight exercises not included in this review (Mora et al. 2023). This discrepancy gains resonance when contextualized within the broader perspective of global pollution associated with novel entities (in a geological sense), an assessment that has only recently been undertaken (Persson et al. 2022). Overall, the occurrence of environmental themes as mentioned above is in line with that observed in previous analyses (Duru et al. 2021; de Lattre-Gasquet et al. 2023).

With regards to the multidimensional character of sustainability, the findings reveal that about two thirds of the reviewed studies (23 studies) consider socio-economic sustainability dimensions, always in conjunction with the environmental dimension. Only seven studies consider all three dimensions of sustainability. This underscores the current scientific and societal preoccupation with environmental aspects, thereby emphasizing and confirming the need for a multidimensional approach that encompasses all three sustainability dimensions (Binder et al. 2010; Reilly and Willenbockel 2010; Lebacq et al. 2013; Diazabakana et al. 2014; Schader et al. 2014; de Olde et al. 2016; Prost et al. 2023; Riera et al. 2023).

Actors and their involvement

Scenarios can be developed and used in the context of participatory approaches, providing the opportunity for fostering dialogue and empowering stakeholders. Despite emphasis on such approaches (Prost et al. 2023; Fiala and Jacob 2024), only a third of studies reviewed in our sample seem to resort to participatory processes, either with experts or with operational actors. According to Fiala & Jacob (2024), participation can be encountered in all kinds of scenario exercises and should thus not be constrained to certain scenario types. This appears to be in contradiction with our results which tend to show that exploratory scenario types C and D are more incline to participation. An explanation to this could reside in the more normative character of scenario types A and B. As studies in these groups pre-establish either the scenarios or their outcomes, participatory approaches may be less needed to explore the possible range of options. Reviewing additional studies would allow to get a better understanding of such a hypothesis given the partial representativity of the sample (see below) and the limited number of studies resorting to participation within the sample.

Setting the boundaries of scenario exercises

Designing scenarios entails questions on the boundaries of the exercise, including the geographical scales and the included sectors. The scenarios under review span various geographical scales, from local to global, each possibly serving different interests and audiences. Interactions among these scales are crucial, though challenging (de Lattre-Gasquet et al. 2023; Prost et al. 2023). While some scenarios can be viewed as viable at a regional or national level, their contextualisation at a larger scale (European or a global) may reveal additional constraints that could question the degree of plausibility of regional and national scenarios. A similar challenge can appear between regional and national scales (Riera et al. 2019; Antier et al. 2020b). Expanding a scenario at higher scale may thus be challenging. A possible solution is to account for boundaries defined at a global scale when designing national or regional scenarios. Nonetheless, downscaling global scenarios to the national or regional levels may be challenging too (van Selm et al. 2022). Beyond geographical scales, the boundaries of scenario exercises are also defined by the production sectors included. The sample of studies reviewed illustrates that a diversity of sectors are included in scenario studies, with an apparent greater focus on livestock sectors. Analysing different sectors allows to examine their interdependencies. In particular, crop-livestock interactions and the associated feed-food debate are crucial to consider when designing sustainable food systems (Mottet et al. 2017) but cannot be satisfyingly studied if only plant-based or livestock sectors are considered.

Accounting for diversity in scenarios: the case of production systems

The spectrum of scenario designs unveils distinct scenario types, each possessing unique attributes that dictate their applicability based on specific objectives and contextual intricacies. A pivotal determinant of this relevance lies in the capacity of a model to embrace diverse production systems, allowing to traverse across analytical scales, bridging the micro-level such as that of the farm and the macro-level such as that of policymaking (Lynch et al. 2018; Riera et al. 2023). As observed by de Lattre-Gasquet et al. (2023), the majority of studies reviewed here depart from a shared concern that conventional, input-intensive production systems are not desirable anymore. In response, alternatives must emerge (e.g. under the wide banner of agroecology in de Lattre-Gasquet et al. (2023)). This can be through the consideration of a diversity of production systems, but not necessarily. Our review showcases different approaches in that respect. Overall, less than half of the reviewed studies consider a diversity of production systems (i.e. at least two different production systems). The remaining studies either do not consider any production system but average practices instead, with possible evolutions of certain variables in the scenarios (e.g. Agrimonde scenarios) or focus on one single production system, such as agroecology (Poux and Aubert 2018) or organic (Smith et al. 2019). This is typically the case of studies in scenario type A.

The question of diversity poses further questions regarding the boundary-defining elements introduced in the previous paragraph: the interconnectedness across sectors and scales. On the one hand, scenarios that incorporate a mix of agricultural or livestock farming systems facilitate discussions on both practices and the systems themselves. This approach can be likened to studies and strategies in the energy sector, where various energy sources are combined. It nevertheless adds a supplementary layer as besides changing the mix of agricultural products, it makes it possible to adapt the mix of production systems. This proves particularly valuable for debating agri-food visions based on "intensive" versus "extensive" systems and assessing their relevance in production and environmental, social, and economic impacts, as in Duru et al. (2021). On the other hand, interconnectedness across scales introduces challenges in meaningful integration. A noteworthy trade-off emerges when contemplating the diversity of production systems while crafting a scenario tailored for Europe compared to a regional-level scenario. The extent of focus, whether local or global, significantly shapes the production systems that can be considered (i.e. to what extent they can represent regional specificities) and thus scenario outcomes. This prompts a critical reflection on the overarching purpose of the model and scenarios, seeking clarity on their underlying intentions and goals. In this sense, the selection of appropriate variables is a critical step in conducting high-quality studies. With relation to scale, constraints, such as data availability, scenario design or scope, can influence this selection. When examining various production systems, regional or national studies may possess the necessary information to differentiate between systems, while international or European studies may rely on an average production system due to data limitations. This constraint significantly impacts the generalizability of findings and the ability to capture the nuances of complex systems at larger scales.

Moving towards food systems: the case of diets

The inclusion of demand-side solutions in scenarios (through alternative diets and a decreased consumption of animal products, mainly in Global North countries) serves as an insightful example to discuss the adoption of food system approaches (as opposed to farming system approaches) and illustrate the diverse challenges related to scenario boundaries and diversity.

By considering dietary shifts, the majority of reviewed scenarios take a first step towards food system approaches. While foresight work focusing on the farming systems is useful, farming systems do not operate separately from the food value chains and related actor networks. Rather, farming systems are embedded in food systems (HLPE 2017), which themselves are multi-dimensional (Ericksen 2008). The inclusion of dietary shifts in scenarios is one form of acknowledging this. Additional efforts must be made to complement current scenarios with an assessment of the related changes and necessary efforts by midstream actors, in food processing infrastructures and value chains' strategies (Grabs et al. 2024).

Although the assessment of how much meat and dairy product per capita should be consumed varies among calculations (based on four reference scenarios included the review, target levels range between 16 kg/cap/year of meat and 33 kg/cap/year of dairy products in Tirado et al. (2018); 31 kg/cap/year of meat and 91 kg/cap/year of dairy products in Willett et al. (2019); 41 kg/cap/year of meat and 45 kg/cap/year of dairy products in Couturier et al. (2016) and 41 kg/cap/year of meat and 100 kg/cap/year of dairy products in Poux & Aubert (2018)), all global scenarios show that significant dietary shifts are required, going beyond simple adaptations. First, with regards to sector interactions, studying dietary shits requires to consider both livestock and plant-based sectors as both are impacted by those shifts. Second, with regards to geographical scales, while targets defined at a global level offer a certain flexibility to account for local specificities, those globally defined boundaries are not always taken into account or may be difficult to downscale in scenarios designed at a lower level, as exemplified by van Selm et al. (2022) for the EAT-Lancet diet (Willett et al. 2019).

In the perspective of moving towards food system approaches (approximated here through dietary shifts), the consideration of different production systems also pays a role. As noted by Duru et al. (2021), existing food diets act as a constraint when transitioning from intensive, input-dependent systems to extensive ones. Conversely, a shift towards low-meat diets may facilitate the development of extensive systems. Going further, the selection of environmental themes holds significance in interpreting scenario outcomes. As noted by Duru et al. (2021), climate change indicators tend to be central in technology-oriented scenarios which favour resource-efficient systems, while biodiversity and pesticide use indicators tend to be included in 'multifunctional' scenarios which more frequently lean towards extensive, low-input systems. Such scenarios, which entail higher levels of complexity, are generally harder to implement as they need to overcome more barriers and require greater changes, e.g. in terms of meat consumption. This intricate dance of variables underscores the complexity of scenario design and its implications for sustainable agricultural and food systems.

4.5 Conclusions, limitations and perspectives

This paper set out to shed light on the intricacies of quantitative food system scenarios. Based on the review of 36 studies, it presents a framework composed of four scenario type groups, corresponding to distinctive ways in which quantitative food system scenarios are being approached, based on the purpose of the scenario exercise and the scenario design process. Besides the identification of a typology of scenario types, this work also delved into the methodological considerations related to scenario design. In particular, it provides insights on how sustainability is being approached in scenario studies, the extent of participation in scenario design and the methodological choices and challenges related to setting boundaries and accounting for a diversity of production systems.

Drawing conclusions on our analysis requires to reflect on its limitations and to identify possible future perspectives. In particular, the snowball sampling methodology comes with limitations in terms of exhaustivity and representativeness as it does not allow to cover the entire literature and systematically capture all relevant studies. As a result, the quantitative considerations presented in the results paragraph should not be extrapolated to all scenario studies without putting them in the perspective of the existing literature, as done in the discussion paragraph. The aim of this study is not to extract precise numerical conclusions from our analyses but rather to identify broader trends and assess whether these are corroborated by the existing literature. For instance, elements on the general occurrence of sustainability dimensions and indicators are confirmed by de Lattre-Gasquet et al. (2023). On the contrary, on the question of participatory approaches, our findings are not aligned with information from Fiala & Jacob (2024), possibly due to our sample being too small. As a next step, applying this framework in a more systematic review would allow to further test, validate and fine-tune the framework. Some additional references have already been identified outside of the snowball sampling method and could constitute a starting point for such an expanded and more comprehensive analysis (Busch 2006; van Meijl et al. 2006; Westhoek et al. 2006; Hasegawa et al. 2015; Erb et al. 2016; Popp et al. 2017; Barbier et al. 2019; Aguilera and Rivera-Ferre 2022; Marin et al. 2022; Mora et al. 2023; Le Noë et al. 2023; Billen et al. 2024a, b). Another avenue to further expand and validate the proposed framework would consist in testing the compatibility and validity of the proposed typology in the case of qualitative food system scenarios. While this analysis was limited to quantitative scenarios, there is reason to believe it could fit more qualitative approaches too given the similarity with existing classifications such as that of Börjeson et al. (2006) and mobilised by Reilly & Willenbockel (2010), which seem to accommodate both quantitative and qualitative approaches. Finally, expanding the sector of application beyond the food system and testing the framework in the context of scenario exercises applied to other sectors (e.g. energy, biodiversity) would also constitute an interesting addition. The well-known millennium ecosystem assessment scenarios (Carpenter et al. 2005) and the more recent shared socio-economic pathways (Riahi et al. 2017) could be interesting points of comparison in this regard.

Certain elements of scenario planning and design were not researched, such as the influence of the study commissioners or of the discipline in which scenarios are developed on scenario development. de Lattre-Gasquet et al. (2023) provide elements on this in the case of agroecology. With regards to participation, it is expected that multidisciplinary research settings are more likely to lead to participatory approaches (Fiala and Jacob 2024). Besides participation in scenario design, a better understanding of how scenarios are taken up by different scenario actors to drive change appears crucial. This retrospective analysis on the impact of quantitative scenarios does not seem to be frequently implemented based on the studies included in this review, as also suggested by Prost et al. (2023) for farm-level transitions. Integrating elements from the French *prospective* approach (although it not systematically relies on quantitative scenarios), may be interesting to this end. With regards to the purpose of scenario exercises, it is important to keep in mind that in the process of scenario design, a choice must be made either to start as close as possible from reality, limiting the level of ambition of the desired horizon, or to propose a very ambitious scenario even if it differs quite significantly from the initial reality and may be perceived as less feasible. Keeping these limitations and perspectives in mind, we believe the proposed classification and analysis provides a useful framework to better grasp the specificities that lie behind different scenarios, thus improving their understanding and the underlying assumptions.

4.6 Supplementary material

Supplementary material for this chapter can be found at the end of the document (Appendix to chapter 4). It includes the following elements:

- Table of reviewed studies
- Coding variables used for analysis
- Overview of descriptive indicators of reviewed scenarios
- Occurrence of sustainability dimensions in reviewed scenarios
- Visual representation of four scenario types
- Visual representations of sample characteristics

Chapter 5 Narratives, trade-offs and scenarios to explore the livestock transition in Belgium

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Abstract

The need for a livestock transition is widely acknowledged, entailing both production- and consumption-side adaptations. Yet the direction of this transition remains uncertain as a diversity of narratives and visions coexist. In this paper, we test the outcomes of dominant narratives and recurring elements of debates surrounding the livestock transition. We adopt a quantitative foresight scenario approach and apply it to the case of the Belgian livestock sector, testing four possible scenarios towards 2050 (Business as usual; Land sparing; Land sharing; Radical). Paying particular attention to the diversity of livestock farming systems and the inclusion of a multidimensional set of sustainability indicators, the results reveal the trade-offs that dominating visions entail. As no perfect scenario stands out, the exercise opens a space of options rather than singling out a unique vision. Beyond providing quantitative scenario results, we also take the opportunity to reflect on methodological choices and the usefulness of foresight approaches to advance sustainability transitions.

5.1 Introduction

There is no question that current animal production and livestock sectors face important tensions and need to undergo a transition. Within each sustainability dimension, livestock may contribute to both positive and negative impacts (Steinfeld et al. 2006; Gerber et al. 2013; Erb et al. 2016; Notarnicola et al. 2017; Willett et al. 2019; Jordon et al. 2024; Kortleve et al. 2024). At present, it has become clear that costs generally outweigh benefits and that the current extent of animal production has become unsustainable (Torpman and Röös 2024). To relieve those tensions, two main approaches can be pursued, seeking to resolve two distinct questions (Antier et al. 2020b): (1) a quantitative question asks *how many livestock* should be produced and consumed to answer nutritional needs, meet societal expectations and remain within planetary boundaries; (2) a qualitative question asks *which livestock* should be produced, i.e. through which practices and farming systems can we produce animal products in a sustainable way.

Trying to solve these questions is no easy feat as food system transitions have to deal with the coexistence of several visions and narratives, and a multitude of potentially conflictual answers emerge (Freibauer et al. 2011; Béné et al. 2019; Gasselin et al. 2021a; Penvern et al. 2023). In the case of the livestock sector, Jaisli and Brunori (2024) identify three main narratives: an *efficiency* path, pursuing sustainability through increased efficiency of production (sustainable intensification); a *consistency* path, aiming for circularity of livestock production and grassland preservation; and a *sufficiency* path, aiming to pursue a protein transition (i.e. the rebalancing of animal versus plant based protein in both production and consumption). Additional narrative debates can be found in the case of *agroecology* vs. *sustainable intensification* (Fischer et al. 2024), or in the case of *land sparing* vs. *land sharing*, i.e. either separating high-productivity farming from nature conservation, or pursuing both productive and conservation objectives on the same land (Green et al. 2005; Phalan 2018). A variation of the land sparing/sharing framework advocates for a three-compartment model, adding intermediate extensively managed farmland between the productive and conservation areas (Finch et al. 2019, 2020). The sourcing of animal feed is another recurring element of discussion, trying to resolve a *feed/food competition* by deliberating on the use of agricultural land to produce human food or animal feed (or for other purposes). In this effort, alternative visions focus on decreasing the reliance on high-impacting feed ingredients such as soybean meal (Jennings and Schweizer 2019; Karlsson et al. 2020), or developing low-cost livestock that valorises coproducts rather than primary agricultural products (Van Zanten et al. 2018; van Selm et al. 2022; Frehner et al. 2022). These coexisting visions are often linked to different disciplines and communities of practice which, although they agree on the general unsustainability of our food system, disagree on its causes and what food and farming systems should be prioritised as a result (Brunori et al. 2024; Fischer et al. 2024). From a transition perspective, the compatibility and complementary of this diversity of visions remain an open question (Levidow et al. 2012; Levidow and Papaioannou 2016; Kueffer et al. 2019). Thus, a third question emerges besides aiming to relieve the tensions faced by the livestock sector, asking whether we can progress *towards a shared* vision on the first two questions.

Two theoretical frameworks can be useful to ground these three questions and help to operationalise them. First, from a transdisciplinary perspective, research can contribute to societal problems through three types of knowledge (Hirsch Hadorn et al. 2006; Kueffer et al. 2019): systems knowledge (asking why and how processes occur and where change is needed), target knowledge (asking what better practices we should aim for) and transformation knowledge (asking how can we get from the current to the desired situation). Second, rooted in transition governance and transition management, several transition frameworks have been developed for the transition of agriculture and food systems (Duru et al. 2015a; Dendoncker et al. 2018; Gaupp et al. 2021; Prost et al. 2023; Meynard et al. 2023). Despite some variations in terms of specific steps or targets within the food system (farm-level, territorial-level, policy-level), all these frameworks share a step-by-step, often iterative, and goal-seeking approach, which could be summarised by the following sequence: *assess* (current/new situation) – *envision* (possible and desired futures) – *implement* (transition pathways). These steps largely align with the three types of transdisciplinary knowledge: systems knowledge is created during the assessment step, target knowledge is generated during the envisioning step and transformational knowledge fosters the implementation step (Figure 15).

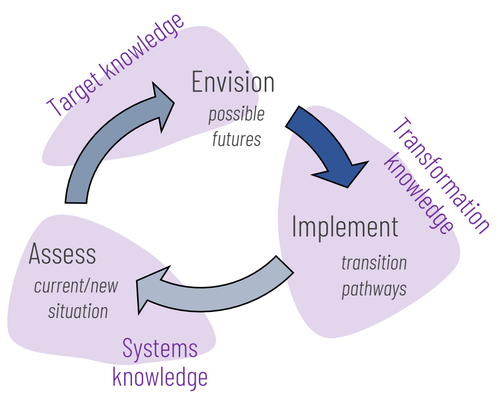


Figure 15. Three main stages of a transition cycle based on existing transition management frameworks, and three main types of transdisciplinary knowledge.

Foresight scenarios are commonly used tools in transition governance frameworks (Loorbach et al. 2017). Through the use of scenarios, it is possible to discuss future developments and define long-term goals for which short-term targets can be set as well (Loorbach 2010). While quantitative scenarios provide quantified insights on the outcomes of alternative futures, qualitative scenarios develop narratives and storylines providing an opportunity to better capture contextual insights, uncertainties and challenges which cannot always be modelled (Gupta et al. 2025). In the case of quantitative scenarios, a diversity of approaches and methods can be found and a few attention points stand out (Riera et al. 2025). With regards to the scope of scenario exercises, adopting food system perspectives ranging from production to consumption is important to gain a system-wide overview of challenges. Sectoral approaches targeting specific commodities and sectors (e.g. dairy, vegetables, cereals, etc.) are promising as they are more operational and closer to food system actors, thus facilitating possible implementation (Borman et al. 2022). On the downside, by overemphasising the challenges of one particular sector, they risk overlooking sectoral interactions (e.g. crop-livestock) and system-wide perspectives. The spatial scale of analysis adds further complexity to the question of implementation, as large-scale exercises are broader in scope but harder to translate locally, while more localised exercises are easier to operationalise but risk missing interactions and constraints at higher levels (Riera et al. 2025). These considerations apply both to the spatial extent (i.e. considered territory), and the spatial resolution (unit of analysis) (Gibson et al. 2000), with implications either for spill-over effects (trade-offs with other territories), or in terms of governance (defining the relevant governance levels). With regards to the diversity of visions and systems, scenario studies adopt different approaches depending on the purpose of the exercise, either assessing the feasibility of pre-identified visions (normative scenarios) or exploring a range of possibilities (exploratory scenarios). The diversity of systems and practices (e.g. farming systems) is not always considered in scenario studies, particularly in normative approaches. From a transitions perspective, accounting for diversity is important for two main reasons. First, as farming practices and systems are highly diverse within one sector, so are their sustainability outcomes. Highlighting diversity thus enables a better understanding of challenges and possible solutions (e.g. by identifying "promising" systems). Second, it allows to overcome polarising oppositions and better tailor the proposed solutions across different levels of action, thus bridging between practices and policies (Gasselin et al. 2021b; Penvern et al. 2023). With regards to sustainability, while accounting for its multidimensional nature is largely promoted, few assessments effectively cover all sustainability dimensions (Riera et al. 2025; de

Olde et al. 2025). Finally, the impact and contribution of scenarios studies to long-term transition processes remain uncertain and understudied (Dernat et al. 2022; Riera et al. 2025).

In this paper, we seek to contribute to the three questions surrounding the livestock transition through the use of foresight approaches, specifically focussing on the case of the Belgian livestock sector. Belgium is no stranger to the debates and tensions surrounding the livestock sector. Animal production occupies an important place in the Belgian food and farming system. The country is a net exporter of livestock products, with self-sufficiency ratios above 100% for the five main productions (dairy, beef, pork, poultry and eggs), and over 200% for pork, poultry or skimmed milk powder, reaching respectively 214%, 216% and 203% in 2023 (BCZ-CBL 2024; Statistics Belgium 2024a). While close to half of farms are specialized in livestock productions in the country's two main regions (Flanders in the North and Wallonia in the South) (Agentschap Landbouw en Zeevisserij 2024; Direction de l'analyse économique agricole 2024), there are important differences in the sectors that developed in both regions and the resulting challenges. In Flanders, a higher population density (and thus increased pressure on land) and easy access to imported animal feed have led to adopting more intensive systems, in particular of monogastric animals. Flanders concentrates the vast majority of Belgian pigs and poultry (respectively 94% and 85% in 2023 (Statistics Belgium 2024b)). This poses questions with regard to the dependence on imported feed, in particular soy, and its associated impacts in terms of land use change (Jennings and Schweizer 2019; Karlsson et al. 2020). As other European countries and regions relying on intensive animal farming and high feed imports (De Pue and Buysse 2020; Papangelou and Mathijs 2021; Leip et al. 2022), the region faces important challenges in terms of nitrogen pollution due to manure surpluses. This leads to pollution by air through the deposition of ammonia (NH_3) and nitrogen oxides (NOx) causing eutrophication of natural areas, and to pollution of groundwater and surface water bodies through the leaching of nitrates. Aiming to tackle this issue and to comply with European legislation, the Flemish government has introduced two main policies, with recent updates in 2024. A manure decree is designed to tackle nitrogen and phosphate leaching into surface and groundwater bodies, while a nitrogen decree seeks to decrease ammonia and nitrogen oxide emissions in Flanders. The latter aims to reduce the region's NH_3 emissions by 40% by 2030 compared to 2015 levels, with sector-specific targets for ammonia emissions in stables (-60% for pigs and poultry, -15% for dairy and beef). It also includes a 30% reduction target for the pig population by 2030. Wallonia on the other side is characterized by more available land and, in particular, an ample supply of permanent grasslands (42% of the region's agricultural land in 2023, compared to 26% in Flanders or 30% at EU level

(Statistics Belgium 2024b)). It is therefore more suited for extensive systems, particularly of cattle production (Riera et al. 2023; Battheu-Noirfalise et al. 2024). Yet it is not exempt of challenges either. As observed in other European regions, grassland areas have been decreasing over the past years and grass-based cattle systems are being replaced by maize-based systems which tend to be more input-intensive (pesticides and fertiliser) and linked to negative environmental outcomes (e.g. nutrient leaching and erosion) (Peeters 2009; Lebacq et al. 2015; Reinsch et al. 2021). In parallel, cattle farmers face dire economic situations, with beef farmers in particular facing structurally low income levels and a high dependence on income support subsidies (Duluins et al. 2022; Riera et al. 2023). On the consumption-side, current dietary patterns in Belgium have been shown to cause significant environmental impacts, particularly in terms of climate change and land use associated to ultra-processed food and animal products (Dénos et al. 2024). The resulting call for a protein transition in Belgium is being echoed at policy level, for example through a Green Deal Protein shift in Flanders. Thus, the Belgian livestock sector is under significant pressure on both the production and the consumption side. It faces several sustainability challenges and needs to embark on alternative development pathways to meet its future challenges. For these reasons, it makes a particularly well-suited case study for this research.

In summary, this paper pursues a double objective: first, we seek to contribute contextual and objectivation elements regarding the Belgian livestock sector and possible transition scenarios. Four scenarios are tested. They simulate prevailing narratives or recurring elements of discussion in the debates surrounding the future of the livestock sector (Table 11). By adopting a territorial (all agricultural production and food consumption activities on the Belgian territory) and sectoral (five main livestock sectors: dairy, beef, pork, poultry and eggs) approach, we aim to conduct our research at a level of analysis which, from a research perspective, is believed to be actionable and operational for food system actors to facilitate potential implementation (Duru et al. 2015a; Borman et al. 2022). We strive to display the existing diversity of visions (by considering multiple scenarios) and of systems (by considering multiple farming systems and consumer diets) to remain open to multiple possible transition pathways (exploratory approach) and allow actors to situate themselves in the possible future scenarios. We include a variety of sustainability indicators in the assessment to pay attention to the multidimensional nature of the issue and reveal potential trade-offs. Second, by reflecting on the adopted process, we hope to improve our collective understanding on the complexity of such transition processes and the usefulness of foresight approaches. To do so, this research adopts an iterative and incremental approach building on a previous foresight exercise that was carried out on the Belgian livestock sector in a transdisciplinary research context in collaboration with civil society and sectoral actors (Riera et al. 2019; Antier et al. 2020b). By discussing methodological choices and looking at the perception and evolution of foresight exercises over time, we seek to reflect on the usefulness of such approaches for transition processes. So doing, we strive to contribute to all three types of knowledge: systems knowledge (current status of the Belgian livestock sector), target knowledge (possible futures and their outcomes) and target knowledge (progress towards a more sustainable livestock sector).

5.2 Methods

5.2.1 Model construction

For the purpose of this research, a modelling tool was developed. It simulates the functioning of the Belgian food and farming system. Its general functioning and construction is detailed below.

Type of model.

The modelling tool is a biophysical process-based model. It follows a bookkeeping approach using agricultural land and animal populations as initial modelling units to assess a series of related biophysical flows (production of biomass, nutrient flows, gaseous emissions, etc.). As other biophysical models (Muller et al. 2017; Desmarez et al. 2025; Karlsson et al. 2025a), the developed modelling tool does not account for market effects resulting from production and price changes, which are better apprehended by specialised economic models. As the main purpose here lies on assessing the biophysical outcomes of certain scenarios, the inclusion of such economic effects would likely come at the expense of other modelling choices prioritised here (e.g. focus on a diversity of farming systems within each sector, inclusion of a diversity of environmental indicators, etc.).

Scope and boundaries of the model.

The scope of the model is the Belgian agriculture and food system. It accounts for all agricultural activities within both Belgian regions: Wallonia and Flanders. The model adopts a 'territorial LCA' approach in the sense that it accounts for all agricultural production and food consumption activities that occur on the Belgian territory (Loiseau et al. 2018), although the production side remains the main entry point. All agricultural production occurring in Belgium is included in the model and assessed through a series of indicators. This includes impacts occurring outside of Belgium, but which are necessary to allow production in Belgium (e.g. the production and imports of feed ingredients such as soybean meal to feed Belgian animals). On the consumption side, the demand for food is compared with local agricultural production, but impacts related to imported foods (e.g. tropical fruit) are not assessed. In short, the approach focuses on all agricultural productions taking place in Belgium (whether they are exported or not) and all the impacts related to those production activities (whether these are direct impacts occurring in Belgium or indirect impacts occurring abroad).

Input variables and sequence of calculation.

The model relies on three types of input variables: production factors, farming systems and control variables (Figure 16).

Two main categories of production factors are considered to estimate agricultural productions and outcomes: agricultural land (expressed in hectares) and animal populations (expressed in animal numbers). Human population can also be considered a production factor which is necessary to estimate food demand. The model encapsulates 56 different agricultural products, grouped into 16 sectors and two categories of agricultural production (Table S8). The model goes beyond animal sectors and also includes plant-based sectors to account for interactions between both. Yet, for the purpose of this study, the primary focus lies on the animal sectors (dairy, beef, pork, poultry and eggs). Production factor data comes from the Belgian statistical office. Other production factors such as farms and capital are not covered given the type and purpose of the model (biophysical process-based model).

A specificity of the approach resides in the consideration of a diversity of farming systems within agricultural sectors to represent the diversity of sustainability outcomes and better tailor the proposed scenarios to different types of actors. For each sector, a typology comprising two to six farming systems is proposed (e.g. enriched cage, indoor, free-range and organic in the case of the egg sector). Sector-specific farming systems are reclassified into generic categories (intensive, intermediate, extensive and organic) to facilitate comparison across sectors. Typologies are mainly built based on differences in practices. As no national statistical data is collected on farming systems, sources for farming system typologies include pre-existing results and expert consultations through an informed participatory process (Table S9).

Control variables are those that make the link between production factors, farming systems and the model outputs. They are generally expressed per production factor (per hectare; per animal; per capita). Control variables include elements such as agricultural yields, nitrogen and dry matter contents of crops, final uses of crops (food, feed, bioenergy, etc.), animal feeding practices (feed consumption and composition), input uses (e.g. N fertiliser and pesticides), human diets, etc. (Tables S3-S7). Data sources are diverse and have been compiled in 'sectoral fiches', which group all the information that is necessary to run the model. These fiches were sent to sectoral experts for validation and refinement of the typologies and their associated parameters. Depending on data availability, control variables are detailed at the farming system level or at higher levels (e.g. sectoral level).

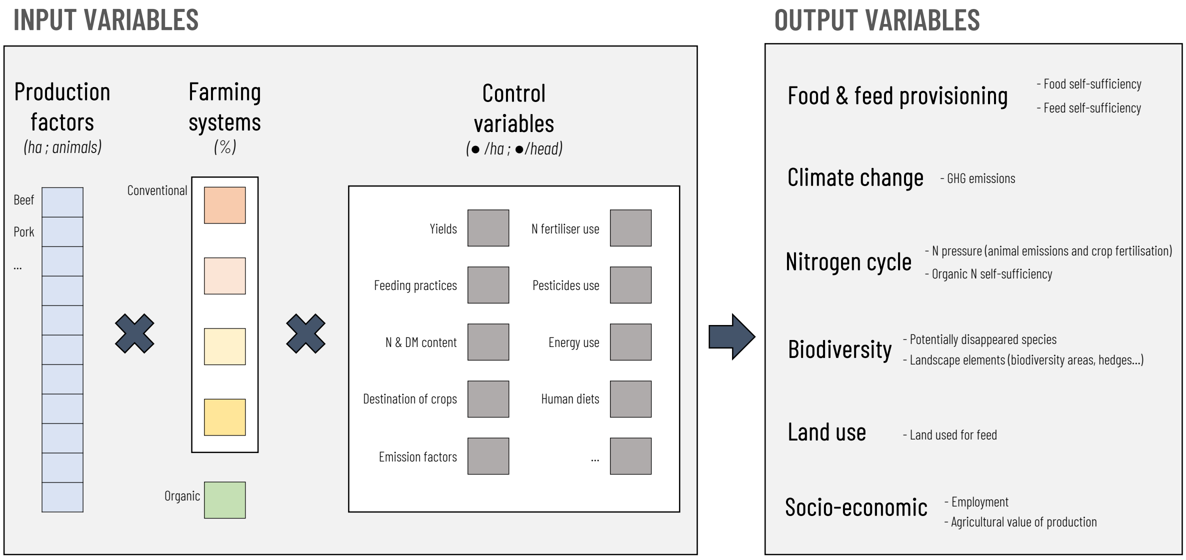


Figure 16. General structure of the model.

Model outcomes and output variables.

The combination of production factors, farming systems and control variables allows the calculation of a series of output variables and indicators (Figure 16 and Table 9). The choice of the indicators was guided by the three criteria of indicator selection (Lebacq et al. 2013): parsimony (non-redundancy of indicators), consistency (necessary indicators for interpretations, i.e. getting a comprehensive picture of the main challenges related to the Belgian livestock sector and comparing different scenarios) and sufficiency (indicators cover the three dimensions of sustainability). Included indicators are grouped in three main dimensions: production and consumption indicators; environmental indicators; socio-economic indicators. Additional indicators (e.g. antibiotic use, animal welfare, trade, health aspects) (Riera et al. 2025) and sustainability dimensions (e.g. time, permanence and people) (Seghezzo 2009) would be relevant to consider but were not included either due to a lack of available data (e.g antibiotic use, health aspects) or because not easily covered by the type of model (e.g. time, trade).

Production and consumption indicators allow to assess production, demand and self-sufficiency levels for both human food (with a focus on animal products) and animal feed. Results are expressed in absolute terms (kt/year) and relative terms (g/cap/day). Human food is analysed in terms of animal products and protein contents. Food losses and waste along the chain are taken into account, based on product-specific estimations (Income consulting - AK2C 2016). Departing from the total demand of legumes for human food consumption (considered in the different diets), the land use represented by this demand is calculated (based on average yields for legumes in each scenario). Similarly, the land use related to the demand of soybean meal for animal feed is calculated.

Environmental indicators cover three main themes. Climate change is assessed through the greenhouse gas (GHG) emissions associated to each farming system. Calculations include main emission sources from the IPCC guidelines (on-farm energy use, enteric fermentation, manure management, soil management, land use and land use change) and three additional sources (production of synthetic nitrogen, pesticides and imported feed, in particular soybean meal; see Table S11 for more detail). The nitrogen cycle is analysed by assessing animal nitrogen emissions through the production of animal manure and the self-sufficiency of organic nitrogen (animal manure) for crop fertilisation purposes. Nitrogen emissions are assessed based on animal feeding practices, nitrogen content of feed ingredients and nitrogen use efficiencies, following the method and data from Hou et al. (2016). Organic nitrogen needs of crops are based on grey literature (see Table S12 for more detail). Ammonia emissions from manure management in stables are calculated based on nitrogen emissions of animals (see above) and animal-, stable type- and region-specific emission factors which allow to estimate the fraction which is emitted as ammonia (see Table S12 for more detail). Finally, impact on biodiversity is assessed through damage score factors provided in Chaudhary and Brooks (2018), illustrating potentially disappeared species of a number of land use types (arable land, grasslands, forests, etc.) and land use intensities (intense use, light use, minimal use), including spatially-explicit data at country level (specific characterisation factors for Belgium; see Table S13 for more detail).

Finally, two socio-economic indicators are included in the assessment: employment level (expressed in full-time equivalents; FTE) and gross value of agricultural production (expressed in euros; €). Data is collected through an agricultural census carried out every five years by the national statistics office.

Calculation and analysis of output variables.

All output indicators are calculated via an R script. A few exceptions are calculated separately, in Microsoft Excel spreadsheets. This is the case of socio-economic indicators, biodiversity indicators, food demand indicators and food self-sufficiency indicators. All output variables are compiled and analysed in a dedicated Microsoft Excel spreadsheet.

Validation of results.

In order to verify the robustness of the model and ensure the validity of the scenario results, model outcomes for the current situation (reference year 2019) have been compared against external sources for certain output variables (Table S15). In certain cases, when differences appeared to be too significant, correction factors have been integrated in the model to ensure better calibration with external data. While some internal feedback loops are considered in the analysis (e.g. in terms of forage availability or organic nitrogen self-sufficiency), these are checked for scenario consistency but do not constrain the model (e.g. nitrogen deficit in scenario T3). Additional feedback loops and spillover effects expanding beyond the scope of the model are not included (e.g. on trade or production and impacts abroad).

Table 9. Set of output variables and indicators calculated by the model and included in the scenarios.

Dimension	Theme	Indicator	Unit
Production & Consumption	Production (offer)	Total crop production	kt/year
		Total animal production	kt/year
	Consumption (demand)	Human food	kt/year
		Animal feed	kt/year
	Self- sufficiency	Food self-sufficiency	Offer/Demand (%)
		Feed self-sufficiency	Offer/Demand (%)
	Land use	Land use for legume demand (human food)	ha/year
		Land use for soybean meal demand (animal feed)	ha/year
Environment	Climate	GHG emissions	kt CO_2e
	Nitrogen cycle	Animal manure production	kt N
		Organic N self-sufficiency	%
	Biodiversity	Non-productive biodiversity area	ha; % UAA
		Damage score (potentially disappeared species)	PDS
Socio-economy	Labour	Employment	FTE
	Value creation	Gross value of production	€

5.2.2 Scenario design

Building scenarios and scenario variables.

Scenarios are built by setting hypotheses on certain input variables, thus changing their default values and assessing how these changes affect the output variables. Five input variables are used to design scenarios (Table 10): evolution of livestock populations, shares of farming systems, reconfiguration of agricultural areas, optimisation of technical parameters, evolution of diets (Table S14). The last variable is exogenous to the model while the others are endogenous.

Process of identifying scenario narratives.

Scenarios were designed with the objective of simulating prevailing narratives and recurring elements of discussion in the debates surrounding the future of the livestock sector (Table 11). Scenario building relied on an iterative and mixed expert-based and participatory approach. A first set of scenarios for the Belgian livestock sector was built following a transdisciplinary research approach in collaboration with a civil society organisation and during which actors from the livestock sector had the opportunity to provide feedback on hypotheses and suggest additional scenarios (Riera et al. 2019; Antier et al. 2020b). The set of scenarios examined in this paper builds on the first scenario exercise. It was proposed by the authors with the aim of reflecting dominant visions for the future of the livestock sector while refining the first scenarios, taking certain comments into account.

Setting scenario hypotheses.

Elements of scenario narratives were proposed by sectoral actors (e.g. technological gains; no feed/food competition), based on Belgium-focused literature (e.g. three compartment vision (Honnay et al. 2021); no soybean meal (Jennings and Schweizer 2019)) or based on choices by authors (e.g. land sharing). Scenario narratives were translated into changes in scenario variables for the modelling exercise based on own expertise and the literature (Table 12). While the scenario exercise aims to adopt an exploratory approach, it inevitably involves some sort of normativity in the choice of tested narratives or in setting values for scenario variables. Alternative scenarios and narratives could have been investigated, e.g. focussing on 'agroecology' vs. 'sustainable intensification', testing a 'no-livestock/vegan' scenario, putting greater emphasis on technological gains, etc. All scenarios were tested with a 2050 time horizon to allow for sufficiently significant changes and reconfigurations of the system. A reference scenario representing the current situation (2018–2022) constitutes a baseline and is used as a point of comparison.

Table 10. Input variables used for scenario design (scenario variables).

Scenario variables	Explanation
1. Evolution of livestock populations	Evolution (% change against current situation) of animal population (per sector).
2. Shares of farming systems	Share (%) of animals and agricultural area within different farming systems (organic, extensive and others).
3. Reconfiguration of agricultural area	Share (%) of agricultural area set aside for non-productive biodiversity conservation.
4. Optimisation of technical parameters	Evolution (% change against current situation) of agronomic parameters (dairy yields, feed conversion ratios...).
5. Evolution of diets	Change to alternative diet, including four diets: current Belgian diet; Belgian food-based dietary guidelines (FBDG); TYFA diet; EAT-Lancet diet.

Table 11. Description of four scenarios for the Belgian livestock sector in 2050.

Scenario name	Scenario description
Business as usual scenario (*BAU*) 	The business as usual scenario simulates a continuation of trends from the past ten years (average evolution between 2008-2012 and 2018-2022). They are continued until 2030 and considered stable until 2050. Trends are adapted based on current policy measures and objectives (e.g. 30% reduction of animal populations in the pork sector in Flanders, regional objectives for organic agriculture, etc.). On the consumption side, this scenario assumes no change in consumption patterns compared to the current situation.
Transition scenario 1 ***Land Sparing (T1)*** 	The first transition scenario (T1) simulates a land sparing vision. It sets aside a significant share of agricultural land for biodiversity conservation (20%) and keeps highly productive systems for production objectives. Extensive systems make the link between productive zones and biodiversity areas. This three-compartment land sparing vision has been advocated for in the case of Belgium (particularly for Flanders (Honnay et al. 2021)). On the consumption side, this scenario is assessed against the TYFA diet, resulting from a scenario exercise modelling an agroecological food system for Europe (Poux and Aubert 2018).
Transition scenario 2 ***Land sharing - No Soy (T2)*** 	The second transition scenario (T2) is more aligned with a land sharing vision where extensive (and organic) systems dominate. It aims to tackle the dependence on soybean meal as a source of protein in animal feed. It seeks to replace it with locally (EU-origin) available protein sources, such as sunflower meal or rapeseed meal, which define the sizes of the livestock populations, in particular monogastric sectors. Ruminant sectors operate a shift to dual-purpose breeds, with the additional objective of preserving grasslands. A certain share of land is set aside for biodiversity conservation (10%). On the consumption side, this scenario is assessed against the Belgian food-based dietary guidelines (FBDG) (Conseil Supérieur de la Santé 2019).
Transition scenario 3 ***Radical - No food for feed (T3)*** 	The third transition scenario (T3) sets out a more radical vision. A low-cost livestock situation is simulated, in which only available coproducts (at EU-level) are used to feed animals. This significantly limits the sizes of the livestock populations, especially in monogastric sectors, but avoids feed-food competition (e.g. no cereal flour is used to feed animals). As in scenario T2, ruminant populations include dual-purpose breeds and the preservation of grasslands. Additionally, a full shift towards organic systems (100%) is operated and a certain share of land is set aside for biodiversity conservation (10%, as in T2). On the consumption side, this scenario is assessed against the EAT-Lancet diet (Willett et al. 2019), entailing ambitious reductions in the consumption of animal products.

Table 12. Scenario hypotheses and evolution of input variables in four possible scenarios for the Belgian livestock sector in 2050, in comparison with the current situation (2018-2022).

Scenario variables	BAU 2050	T1 2050 Land sharing	T2 2050 Land sparing - No Soy	T3 2050 Radical - No feed for food
Livestock populations[1]				
- Suckler cows	-26%	-50%	-100%	-100%
- Dairy cows	+7%	-30%	+22%	+14%
- Pigs	-30%	-30%	-74%	-91%
- Broilers	+55%	-30%	-75%	-89%
- Laying hens	+17%	-30%	-76%	-89%
Shares farming systems[2]				
Organic	5% FL & 30% WAL	25%	30%	100%
Extensive	Follows trends	Follows trends	70%	–
Others	Follows trends	Follows trends	–	–
Reconfiguration of agricultural area[3]				
Agricultural land set aside for biodiversity	0%	20%	10%	10%
Optimisation of technical parameters[4]				
Dairy yields	+10%	+10%	+10%	+10%
Feed conversion ratio - pigs and broilers	-10%	-10%	-10%	-10%
Enteric fermentation – cattle and pigs	-10%	-10%	-10%	-10%
Manure management	-15%	-15%	-15%	-15%
Diets and consumption patterns[5]				
Diets considered	Current Belgian diet	TYFA diet	Belgian FBDG	EAT-Lancet diet

Notes on scenario hypotheses

[1] **Livestock populations:** In scenario BAU, the pig population decreases by 30% as per the objectives set in the Flemish nitrogen decree for 2030. Other sectors decrease according to expected trends. In scenarios T2 and T3, the specialised dairy and suckler cow herds are replaced by a double-purpose herd. In scenarios T2 and T3, monogastric populations evolve according to available feed sources: EU-origin soybean meal alternatives in the case of T2 and EU-origin cereal-equivalent coproducts in the case of T3.

[2] **Shares of farming systems:** In scenario BAU, the shares of organic systems are aligned on the regional objectives for organic agriculture, which are set for 2030 (thus expecting a 20-year delay in the achievement in such objectives, as observed following current trends).

[3] **Reconfiguration of agricultural area:** As the scenarios focus on the livestock sector, no specific assumptions are set on the distribution of crops within the Belgian agricultural area. Nevertheless, the linkages and interactions between agricultural land and animal production are not overlooked. They are checked through a series of indicators (grassland and forage feed self-sufficiency, and availability of animal manure for organic crop fertilisation). While the distribution of crop areas remains constant, a scenario hypothesis allows to set aside a share of agricultural land for non-productive biodiversity conservation. This area is taken in priority from arable land, leaving grasslands unaffected. This hypothesis has implications not only in terms of biodiversity, but also in terms of GHG emissions. On this aspect, the hypothesis is that the freed land is considered to be transformed into forests, thus leading to a

null biodiversity damage score (Chaudhary and Brooks 2018) and to an additional storage of carbon (CELINE-IRCEL et al. 2023).

[4] **Optimisation of technical parameters:** Gains in productivity and efficiency (feed conversion ratios and yields) are based on expert consultations (Riera et al. 2019) and available literature (Vrints and Deuninck 2014, 2015; Van der Straeten 2015; Petel et al. 2018b). Gains in enteric fermentation and manure management emissions are based on IPCC estimations (IPCC 2014).

[5] **Diets and consumption patterns:** Four different diets are considered across the scenarios in the modelling exercise, with one reference diet for each scenario: (1) *current Belgian diet* in scenario BAU; (2) *TYFA diet* scenario T1; (3) *Belgian food-based dietary guidelines (FBDG)* in scenario T2; (4) *EAT-Lancet diet* in scenario T3.

5.3 Results

5.3.1 Livestock numbers

Livestock numbers decrease in all scenarios, with variations in affected sectors (Figure 17c). The BAU scenario shows little change. In ruminant sectors, the expected decrease in the beef sector (suckler cows) is compensated by a continued increase in the dairy sector (dairy cows). In monogastric populations, the planned decrease in the pork sector (–30% as per the nitrogen decree) is counterbalanced by an increasing trend in broiler populations (Table S16). In the transition scenarios, livestock reductions are increasingly bigger from T1 through T3. While the land sparing scenario strongly reduces ruminant populations (for climate purposes), monogastric sectors remain less affected compared to scenarios T2 and T3. In the latter, monogastric populations are strongly reduced due to available feed options (EU-origin protein sources in T2 and EU-origin coproducts in T3), while ruminant populations are slightly less affected given the choice to preserve grasslands (Table 13).

5.3.2 Farming systems

All scenarios see a progression of organic and extensive systems (Figure 17a and 17b). Organic livestock production remains limited in the BAU scenario (6% of animals) and increases incrementally in the transition scenarios, reaching 100% in scenario T3. Within non-organic systems, scenarios BAU and T1 remain dominated by productive systems (either as a result of current trends in scenario BAU or for productivity reasons in scenario T1), while scenario T2 engages in an extensification process (70% of animals in farming systems considered as extensive).

5.3.3 Agricultural land

Agricultural land (Figure 17a) is left untouched in the BAU scenario. In the transition scenarios, a share of land is set aside for biodiversity conservation. This share is higher in scenario T1 (20%) following a three-compartment land sparing approach advocated for Belgium (Honnay et al. 2021), which maintains productive farming systems and separates them from biodiversity conservation land. Scenarios T2 and T3 also set aside some land for biodiversity (10%) but this share is more limited compared to T1.

5.3.4 Animal feed

Demand for concentrate animal feed is strongly reduced in the scenarios, ranging between –14% in scenario BAU and –79% in scenario T3 (Table S16). With regards to protein sources, scenarios T2 and T3 are soybean-free. The soybean meal demand represents over 300 000 ha in the current situation and in scenario BAU (i.e. around 25% of Belgium's total agricultural area) and 200 000 ha in scenario T1 (Table S16). In scenario T3, the exclusive use of (EU-origin) coproducts to feed animals implies that no cereals are destined to animal feed. In terms of feed self-sufficiency (i.e. capacity of sourcing animal feed at Belgian or EU level), scenarios BAU and T1 entail little shifts compared to the current situation (except an increase in the self-sufficiency for protein-rich coproducts in scenario T1). Scenario T2 and T3 offer more perspectives in that regard. Both scenarios are self-sufficient in terms of protein-rich coproducts (i.e soybean meal alternatives) at EU level and cereal feed at Belgian level (scenario T3 does not require any). Additionally, scenario T3 is also self-sufficient in protein-rich coproducts at EU level (given the objective to rely exclusively on coproducts) while in scenario T2 available energy-rich coproducts cover nearly 50% of the demand for energy-rich feed (Table 13 and Figure 18).

5.3.5 Livestock production

The production of meat decreases in all scenarios compared to the current situation. Reductions in total meat production vary between -10% in scenario BAU and -84% in scenario T3. Milk production only decreases in scenario T1 (–25%) while it increases in scenario BAU (+18% as per current trends) and in scenarios T2 and T3 (+10 and +18% as a result of the shift to dual-purpose cattle systems). Overall, total production of animal protein decreases are comprised between – 10% in scenario BAU and –60% in scenario T3 (Table 13 and Figure 18).

5.3.6 Human food

In terms of human consumption, the production potentials of scenarios have varying capacities to cover the demands for meat and animal protein, which vary according to the considered diets (Table 13 and Figure 18). While scenario BAU maintains the current diet, scenarios T1, T2 and T3 are assessed under increasingly ambitious diets in terms of animal product consumption (respectively the TYFA diet, the Belgian FBDG and the EAT-Lancet diet). In scenarios BAU and T1, the production is largely sufficient to meet and even exceed meat demand (according to the current diet and the TYFA diet respectively). In scenarios T2 and T3, the lower production potentials would require greater efforts in terms of meat consumption. Scenario T2 falls just short with regards to the Belgian FBDG while scenario T3 is nearly aligned with the EAT-Lancet diet. Looking at total animal protein, all scenarios exceed the theoretical demand for animal protein intake, assuming that 50% of total protein intake (estimated at 0.8 g protein/kg bodyweight) should come from animal products in the perspective of rebalancing animal and plant-based protein sources. As the scenarios shift to less animal-based and more plant-based diets, they lead to a growing demand for protein-rich crops for human consumption. While the demand for legumes in the current diet (current situation and scenario BAU) represents about 5 000 ha (less than 1% of Belgium's agricultural area), this demand increases to around 50 000 ha in the TYFA diet (scenario T1), 90 000 ha in Belgian FBDG diet (scenario T2) and 200 000 ha in the EAT-Lancet diet (scenario T3), representing respectively 4%, 7% and 16% of Belgium's agricultural area (Table 13).

5.3.7 Export capacity

Assessing the self-sufficiency of meat and other animal products has implications for the potential exporting capacity of Belgium (Table 13 and Figure 18). Scenarios BAU and T1 maintain significant exporting capacities (meat self-sufficiency levels of 155% and 189% respectively, compared to 192% in the current situation). In scenarios T2 and T3, as production decreases are more important, the capacity to export becomes limited (with self-sufficiency levels of 97% and 95% respectively). Dietary shifts offer a certain flexibility to adjust the exporting capacity as ambitious reductions in animal product consumption increase the self-sufficiency levels and thus the export potential (e.g. adopting the EAT-Lancet diet in scenario T2 would raise the self-sufficiency for meat to 170%, thus leaving a surplus of production which could be exported; Figure 18).

5.3.8 Environmental impacts

The scenarios present contrasted situations with regards to environmental impacts (Table 13 and Figure 18). All scenarios lead to reductions in absolute GHG emissions, which are limited to –11% in the case of scenario BAU, while scenarios T1, T2 and T3 lead to increasing reductions of –38%, –46% and –54% respectively (Figure 18). While overall reductions for these three scenarios are close, the strategies are different (Table S16). Scenarios T2 and T3 show significant reductions in animal sector emissions (given the important decreases in animal populations). Scenario T1 exhibits smaller reductions for the animal sectors, and comparatively greater reductions in the plant-based sectors, as well as important negative emissions due to the conversion of agricultural land to biodiversity-rich land (considered to be forests). Reductions in this scenario reach -59% when accounting for the average sequestration of forests over the full scenario period (2022-205) rather than for the final annual emissions in 2050 (see Table S16). Decreases in relative GHG emission levels (per kg animal protein) are similar across scenarios, either resulting from the shift to more intensive and efficient systems in scenario T1, or from the decreased reliance on soybean meal in scenarios T2 and T3 (Figure S1). With regards to the nitrogen cycle, the decrease in animal populations allows to reduce the production of animal manure, N emissions and NH_3 emissions, thus decreasing the existing overproduction of animal manure with regards to cropping fertilisation needs and the resulting pressure on water and soil resources. Only scenario T2 seems to present a well-balanced situation when comparing manure production to organic nitrogen needs. Scenarios BAU (166%) and T1 (140%) remain in an excess situation, although improved compared with the current situation (193%), while scenario T3 results in a deficit of animal manure (73%). Finally, with regards to biodiversity impact, setting aside agricultural land for biodiversity conservation and shifting to organic systems decreases the potential impact on biodiversity. The greater reduction is achieved in scenario T1 (–20%), followed by scenario T3 (–15%) and scenario T2 (–10%), while scenario BAU shows little improvement compared to the current situation (–1%).

5.3.9 Socio-economic impacts

With regards to employment, the total number of FTEs remains similar in scenario BAU (-3%) but decreases by about 25% in the transition scenarios, mainly as a result of the reduced animal herd and agricultural area. Relative employment rates (per ha or per animal) show little variation for the plant-based sectors but show more variation for the animal sectors, with significant increases in scenarios T2 and T3 (Table 13). Gross value of agricultural production is increasingly reduced through the scenarios, reaching -45% in scenario T3, mainly due to the reduced sizes of the animal sectors. Relative value of production (per ha or per animal) shows signs of decrease in the case of plant-based sector in scenario T3 but, as in the case of employment, shows more variation for the animal sectors, with significant increases in scenarios T2 and T3 (Table 13).

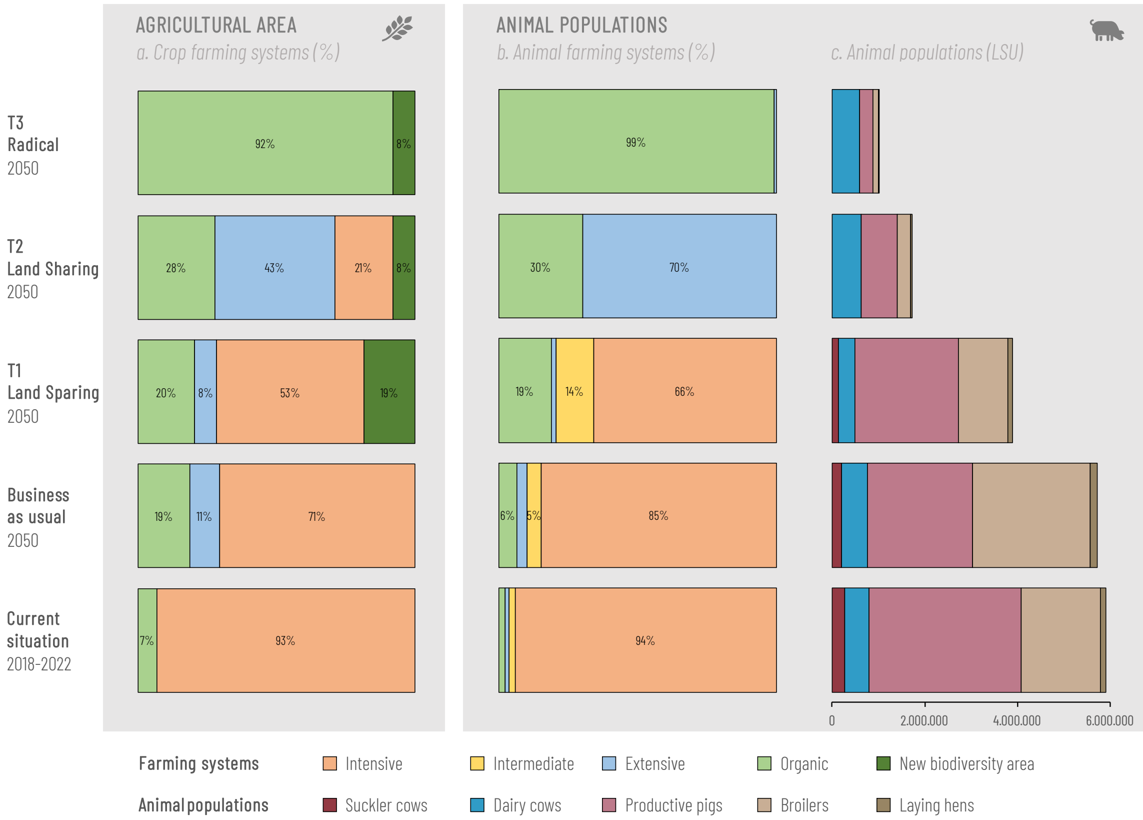


Figure 17. Evolution of agricultural production factors in four scenarios in 2050 compared to the current situation (2018–2022): a. evolution of crop farming systems (% of agricultural area); b. evolution of animal farming systems (% of animals); c. evolution of livestock populations (livestock units, LSU).

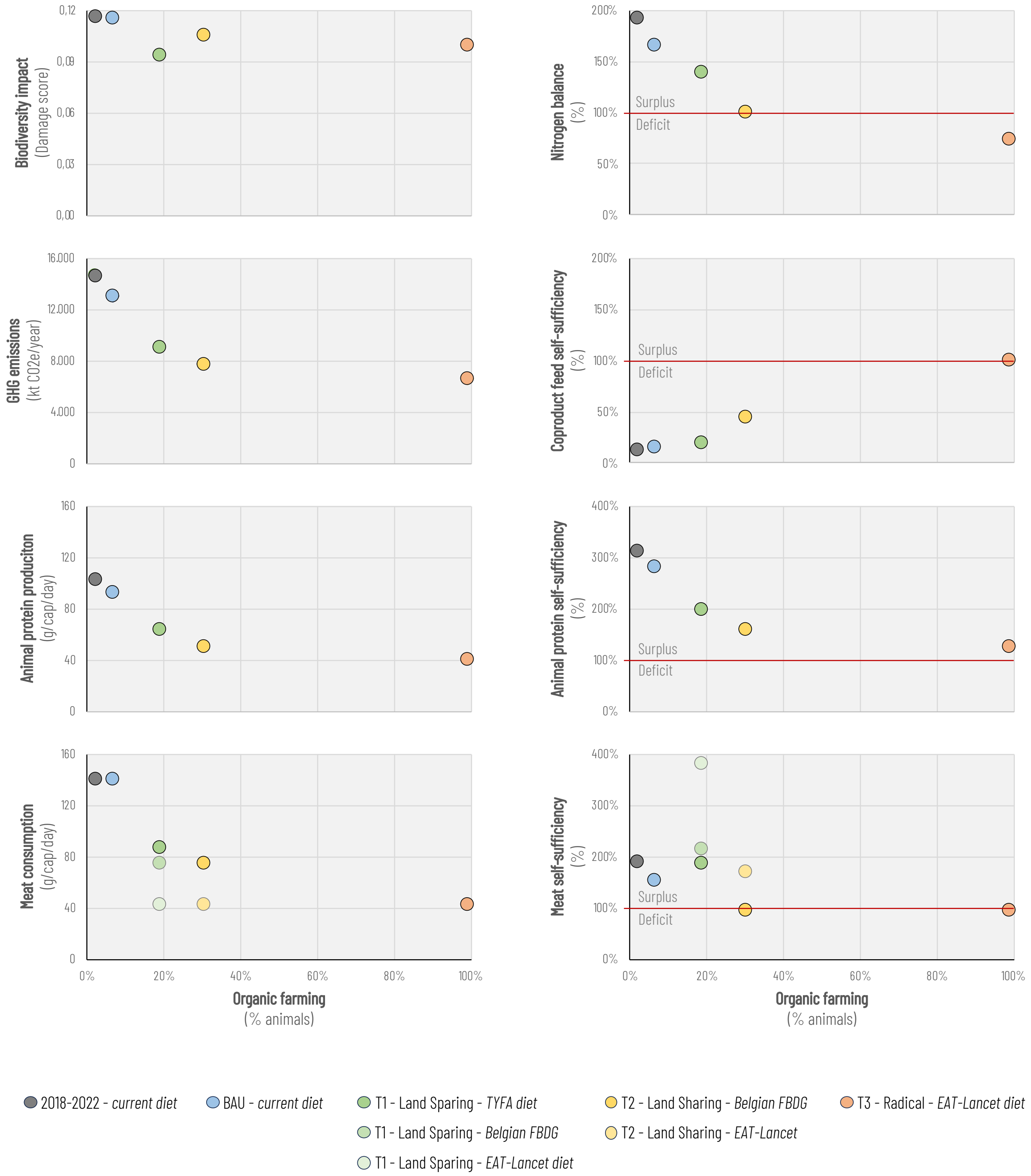


Figure 18. Visualisation of results for four scenarios for the Belgian livestock sector in 2050 and comparison against the current situation (2018–2022). All plots show the share of organic farming (% animals) on the x-axis. First row (top): biodiversity impact (Damage score) and nitrogen balance (% N from manure production/organic N demand for crop fertilisation). Second row: greenhouse gas emissions (kt CO_2e/year) and coproduct feed self-sufficiency (% coproduct feed offer/coproduct feed demand). Third row: animal protein production (g animal protein/cap/day) and animal protein self-sufficiency (% animal protein production/animal protein demand). Fourth row (bottom): meat consumption (g meat/cap/day) and meat self-sufficiency (% meat production/meat consumption).

Table 13. Overview of scenario outcomes (animal populations, production levels, feed and food self-sufficiency, environmental impacts and socio-economic indicators). Scenario results and evolutions (%) against current situation.

Indicator	Unit	Current situation 2018–2022	BAU 2050	T1 2050 Land sparing	T2 2050 Land sharing	T3 2050 Radical
Animal population[1]						
Ruminant population	Animals	863 574 –	808 383 -6%	535 102 -38%	632 697 -27%	590 702 -32%
Monogastric population	1000 animals	263 688 –	379 965 +44%	165 995 -37%	55 772 -79%	19 078 -93%
Production[2]						
Meat production	kt meat/year	1 315 –	1 179 -10%	867 -34%	372 -72%	209 -84%
Milk production	kt milk/year	4 087 –	4 806 +18%	3 077 -25%	4 813 +18%	4 484 +10%
Egg production	kt eggs/year	184 –	216 +17%	128 -31%	43 -76%	19 -90%
Animal protein production	kt protein/year	430 –	428 -1%	297 -31%	235 -45%	188 -56%
Animal feed self-sufficiency[3]						
Self-sufficiency for cereal feed (BE)	% (offer/demand)	46%	51%	46%	100%	NA
Self-sufficiency for protein-rich coproducts (EU)	% (offer/demand)	49%	55%	73%	114%	131%
Self-sufficiency for energy-rich coproducts (EU)	% (offer/demand)	13%	16%	20%	46%	101%
Human food self-sufficiency[4]						
Meat offer Meat demand Meat self-sufficiency	g meat/cap/day g meat/cap/day % (offer/demand)	271 141 192%	219 141 155%	164 87 189%	73 76 97%	41 43 95%
Animal protein offer Animal protein demand Animal protein self-sufficiency	g prot/cap/day g prot/cap/day % (offer/demand)	89 28.5 314%	81 28.5 283%	56 28.5 198%	45 28.5 159%	36 28.5 126%
Land use for legume demand (human food)	ha/year	4 824 –	5 428 +13%	47 953 +894%	89 429 +1 754%	201 965 +4 086%
Environment[5, 6]						
GHG emissions (all sectors) – total	kt CO_2e/year	15 040 –	13 443 -11%	9 280 -38%	8 061 -46%	6 914 -54%
GHG emissions (animal sectors) – relative	kg CO_2e/kg animal protein	25.8 –	22.7 -12%	22.9 -11%	22.3 -14%	24.4 -5%
Organic nitrogen self-sufficiency (manure)	% (available animal N/crop org N needs)	193%	166%	140%	101%	74%

NH3 emissions from stables	kt N-NH3/year	30 –	21 –29%	15 –48%	11 –65%	8 –74%
Biodiversity impact – Total	Damage score (potentially disappeared species)	0.117 –	0.116 –1%	0.094 –20%	0.105 –10%	0.099 –15%
Socio-economy						
Employment (all sectors) – total	FTE	49 463 –	48 045 –3%	37 087 –25%	38 495 –22%	36 666 –26%
Employment (animal sectors) – relative	FTE/1000 animals	0.5 –	0.3 –33%	0.5 –2%	1.2 +153%	2.4 +426%
Gross value of agricultural production (all sectors) - total	Mo €	8 019 –	7 839 –2%	5 585 –30%	5 271 –34%	4 386 –45%
Gross value of production (animal sectors) – relative	€/animal	103 –	71 –31%	95 –7%	217 +111%	390 +279%

Notes on results:

[1] **Animal populations:** In scenarios T2 and T3, the specialised suckler cow and dairy cow herds are replaced by a dual-purpose herd.

[2] **Production:** Production data is at farm gate, i.e. it does not account for losses and waste along the chain (except for slaughter and carcass yields in the case of meat).

[3] **Animal feed:** In scenarios T2 and T3, soybean meal is fully replaced by other protein-rich feed ingredients (rapeseed meal and sunflower meal). A replacement rate of 1.43 kg of rapeseed/sunflower meal for 1 kg of soybean meal is considered given the nutritional and protein profiles of respective feed ingredients. The self-sufficiency values indicate to what extent the available amounts of different feed sources (Belgian cereals, EU energy-rich coproducts or EU protein-rich coproducts) meet the corresponding demands for those feed categories (cereals, energy-rich feed or protein-rich feed).

[4] **Human consumption:** Consumption levels represent actually consumed amounts (i.e. accounting for losses and waste along the chain). Each scenario is attributed to an animal product demand (e.g. meat) or to a legume demand corresponding to a specific diet: *current Belgian diet* for current situation and scenario BAU; *TYFA diet* for scenario T1; *Belgian FBDG* for scenario T2; and *EAT-Lancet diet* for scenario T3. The animal protein demand corresponds to a daily protein demand of 0.8 g prot/kg body weight/person. In the perspective of operating a demand-side protein transition, we consider that 50% of this protein demand should come from animal sources, corresponding to 28,5 g animal protein/cap/day.

[5] **GHG emissions:** In scenarios T2 and T3 soybean meal is fully replaced by other protein-rich feed ingredients (rapeseed meal and sunflower meal). A replacement rate of 1.43 kg of rapeseed/sunflower meal for 1 kg of soybean meal is considered given the nutritional and protein profiles of respective feed ingredients. The GHG impacts of soybean meal production are replaced by those of sunflower meal. In scenarios T1, T2 and T3, the agricultural area that is freed for biodiversity conservation is considered to be transformed into forests, thus leading to an additional storage of carbon. This table reports annual emissions at the end of the scenario period (i.e. emissions in 2050), when these newly established forests are stabilised. See supplementary material (Table S16 - 'GHG emissions – average

22-50') for results considering the average annual emissions over the period, accounting for a 20-year transition period from cropland and grassland to forests, during which sequestration is assumed to be greater (CELINE-IRCEL et al. 2025).

[6] **Biodiversity:** The agricultural area that is freed for biodiversity conservation is considered to be transformed into forests, thus leading to a null biodiversity damage score (Chaudhary and Brooks 2018).

5.4 Discussion

Along with a baseline scenario representing the current situation (2018–2022), the scenario exercise comprises four scenarios for the Belgian livestock sector in 2050. A business as usual scenario (BAU) is complemented with three transition scenarios representing possible and increasingly greater shifts away from the current trends. Below we discuss what we can learn from the results and from the methodological approach. Points of discussion include the attention for diversity of systems and visions, the multidimensional nature of the issue and the involved trade-offs, the implications of adopting sectoral and territorial approaches, and the general usefulness of foresight approaches to advance the livestock transition.

5.4.1 Diversity of visions and systems

An objective of the study was to test a diversity of visions, i.e. currently prevailing narratives surrounding the future of livestock. The land sparing-land sharing continuum was tested by integrating both a three-compartment land sparing vision (Finch et al. 2019, 2020; Honnay et al. 2021) and a land sharing approach (scenarios T1 and T2 respectively). The three dominating livestock narratives identified by Jaisli and Brunori (2024) are reflected in our scenarios. Scenarios BAU and T1 are closer to an *efficiency* path, while scenarios T2 and T3 show similarities with the *consistency* and *sufficiency* visions. The scenario exercise also tackles a number of feed-related issues, such as the possibility of halting the use of soybean meal (Karlsson et al. 2020), tested in scenarios T2 and T3, or the implications of a low-cost livestock sector relying exclusively on coproduct feed and thus resolving the feed/food competition (Van Zanten et al. 2018; van Selm et al. 2022; Frehner et al. 2022), imagined in scenario T3.

Reflecting such a diversity of visions is facilitated by the integration of a diversity of farming systems (in this case livestock systems). For instance, the land sparing vision tested in scenario T1 is simulated by favouring highly productive systems while keeping organic and extensive systems more limited (as well as operating greater reductions in ruminant sectors compared to monogastric ones). Inversely, extensive systems, particularly grass-based ruminant systems, dominate in the land sharing vision tested in scenario T2, while intensive monogastric systems are strongly reduced (Figure 17). Scenario T3 embodies a more radical vision entailing a fully organic scenario tested in several studies (Muller et al. 2017; Smith et al. 2019; Barbieri et al. 2021; Borghino et al. 2024). Different visions thus favour different systems, confirming that systems and visions are to some extent connected (Darnhofer et al. 2012; Penvern et al. 2023). Systems can be seen as practical translations and implementations of visions, and conversely, visions can serve as argumentations in favour of certain systems. Besides the differences between animal products (inter-sectoral shifts), integrating this diversity adds additional nuance to sector-specific evolutions (intra-sectoral shifts) within each scenario. Discerning between different types of farming systems allows linking the exercise to the level of practices, thus facilitating identification to the scenarios for food system actors (e.g. farmers). Nevertheless, the practical implementation of a system is not limited to affinities with a certain vision, but might be constrained by external factors such as social, political, cultural or environmental contexts (Kazanski et al. 2025).

5.4.2 Assessing sustainability and defining an option space for the livestock sector

Trying to answer the first two question related to the livestock transition (*how many* livestock and *which* livestock) is not straightforward as no ideal scenario emerges from the results. Trade-offs appear when comparing scenarios in terms of production, nutrition, climate change, nitrogen cycle, biodiversity preservation and socio-economic outcomes (Figure 18). Yet, a few conclusions can still be drawn from the exercise.

Regarding the ambition of the scenarios, given the unsustainability of the current livestock sector, the results shows that a business as usual pathway is not enough (Figure 18). While maintaining high production levels, it shows little progress on all considered environmental aspects, leading to minor decreases of GHG impacts (–11%), insignificant improvements in terms of biodiversity impacts (–1%) and little improvements on the nitrogen balance (surplus of 166%), despite planned measures to reduce part of the livestock herd (30% reduction of the pig population), or expected technology and efficiency gains. Specifically for Flanders, the scenario fails to meet the NH_3 reduction objectives for all sectors except the beef sector (Table S 17). This confirms that a significant turn and a radical shift away from current trends must be undertaken if the Belgian livestock sector is to reduce its impacts locally and contribute to global efforts, as pointed out in previous examples (Röös et al. 2017b, 2022).

Turning to the transition scenarios, no silver-bullet scenario stands out but the results allow to draw certain conclusions. For instance, setting aside land for biodiversity brings significant benefits in terms of biodiversity conservation and climate goals. Yet, compartmentalisation with highly productive monogastric systems as in the land sparing approach does not solve nitrogen cycle balance issues or dependence on imported and high-impact animal feed such as soybean meal and would require greater reductions in livestock populations. On the contrary, a full shift to organic systems within a low-cost livestock scenario (T3) leads to a shortage in the nitrogen balance (74% self-sufficiency; Table 13), thus limiting the production potential of plant-based sectors, compromising the biophysical feasibility of such a scenario and confirming that nitrogen availability is a limiting factor for organic agriculture (Barbieri et al. 2021). An avenue to solve this issue and meet the nitrogen deficit would consist in raising the share of nitrogen-fixing legumes in the Belgian agricultural landscape and crop rotations, which was not considered by the current modelling but would make agronomic sense given the higher share of such crops in organic systems and the shift towards plant-based diets, as considered recently for Wallonia (Desmarez et al. 2025). Going further, scenario results confirm that both production-side and consumption-side measures are necessary. Lower-impact production requires shifts in dietary patterns, as previously shown in numerous scenario exercises (Röös et al. 2017b; Willett et al. 2019; Billen et al. 2021). The extent of the dietary shift is dependent on the ambition of the scenario. A fully organic and low-cost livestock scenario (T3) where animals feed exclusively on coproducts requires greater efforts on the consumption side. While it shows potential compatibility with the EAT-Lancet diet, as also found by van Selm et al. (2022), it does not with other diets such as the Belgian FBDG or the TYFA diet. The possibility to implement such changes, especially on the consumption side should be considered carefully (Saujot and Waisman 2020). Demand-side changes have been shown to be slow and challenging (Röös et al. 2017b), even with a specific policy framework targeting the protein transition in Flanders (Rubens et al. 2025).

In the light of such results, trying to single out one specific scenario or vision seems counterproductive given the trade-offs involved, as highlighted previously in the literature (Mahon et al. 2017, 2018; Auclair et al. 2024). Rather, the learnings of this analysis might point to considering a space of solutions rather than a single point (Figure 19). This option space is defined on the one hand by the considered scenarios (scenario option space) and on the other hand by established sustainability targets (sustainability option space). The crossing of both provides a new space in which scenario outcomes are compatible with sustainability objectives, thus delineating a possible sustainable space of operation. The extent of this space is flexible and can evolve depending on the scenarios considered and the acceptable sustainability boundaries.

In the case of Figure 19 (left), aiming for strict self-sufficiency of meat and nitrogen or allowing for import-export flows and complementation with synthetic nitrogen provides flexibility to expand the sustainability option space. Moving to ammonia emissions (here of the pork sector in Flanders; right of Figure 19) shows another option space defined by specific policy objectives. Thus, the purpose of accounting for a diversity of visions is not to identify precisely which future is the most desirable but to shed light on part of the available option space. This asks the question of whether the coexistence of visions could be a viable project of transition (Gasselin et al. 2021b), which is further discussed below. In any case, going back to the quantitative and qualitative questions of livestock transitions, the results confirm that both *downsizing* and *improving* livestock systems are needed (Herzon et al. 2024).

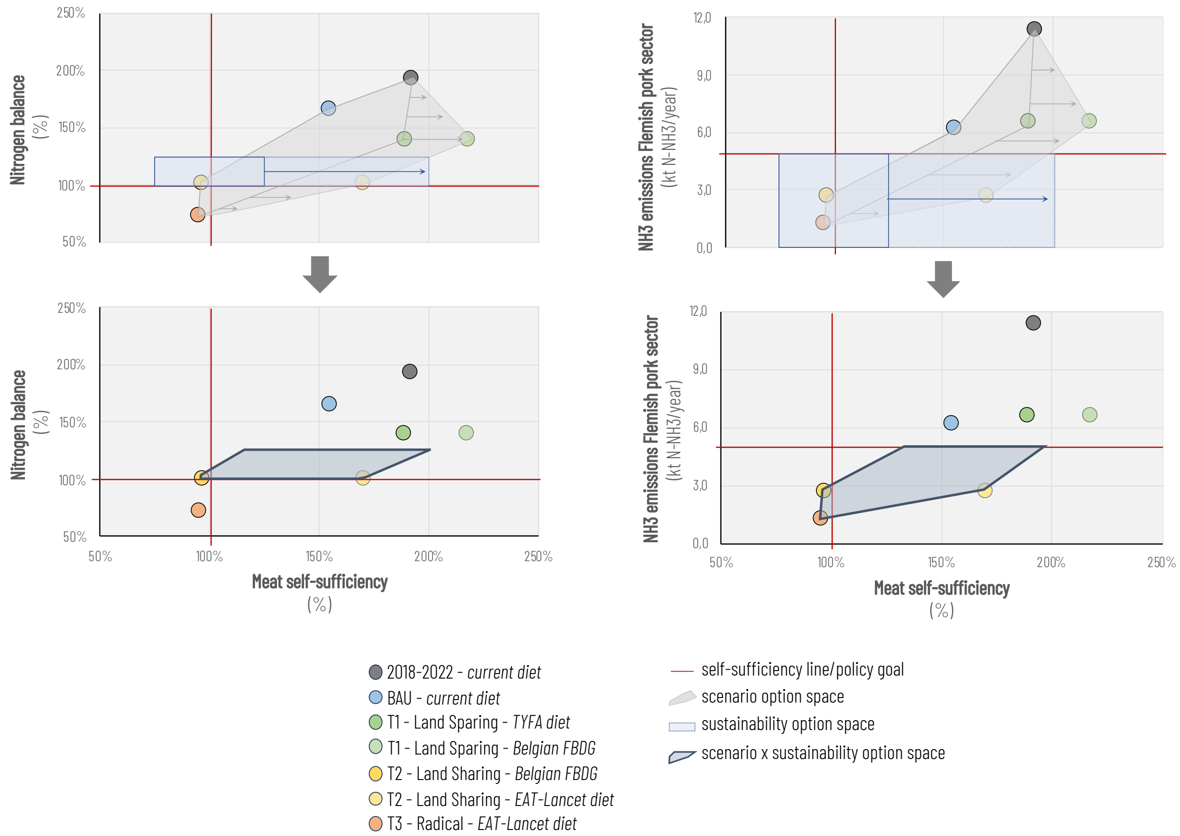


Figure 19. Defining option spaces for the livestock sector comparing meat self-sufficiency and nitrogen balance (left) or ammonia emissions from the Flemish pork sector (right). Top: a scenario option space is defined by the outcomes of the tested scenarios while a sustainability option space represents sustainability targets. The extent of both option spaces can be adapted (dotted lines and arrows), e.g. by designing new scenarios or considering scenario variants, or by adapting the sustainability boundaries. Bottom: The intersection of the scenario and sustainability option spaces provides a new space where scenario outcomes are compatible with sustainability objectives.

5.4.3 Boundaries and methodological considerations: a territorial, sectoral and multidimensional approach

The boundaries of the exercise are defined by three main methodological choices: the adoption of a territorial, sectoral and multidimensional approach. The scenario findings are constrained by their national (Belgian) scope and a theoretical assumption of self-sufficiency. In reality, the Belgian livestock sector, its actors and value chains largely operate in international markets with significant import-export flows and the flexibility to resort to a global food system. While scenario hypotheses might lead to hidden displaced effects due to disrupted trade flows (e.g. export flows in scenarios T2 and T3), efforts still need to occur at national level. Certain issues are inherently played out at the local territorial scales (e.g. nitrogen balance, biodiversity conservation). Other challenges are global in scope, e.g. reducing GHG emissions or shifting towards lower animal product consumption (Willett et al. 2019), but require local contributions. The adopted spatial scale also provides the flexibility to target more restrained territories (e.g. Flanders or Wallonia) and tailor the approaches to their specificities, challenges and levels of governance. The challenge resides in understanding livestock systems at regional scales to ensure local relevance while being broad enough to allow policy action (Kazanski et al. 2025).

The scenario exercise focuses on Belgium's five main animal sectors (dairy, beef, pork, poultry and eggs), also including plant-based sectors (although not the focus of the exercise), and considers both production-side and consumption-side activities. Such an approach allows to zoom in and out on parts of the system. On one hand, the aggregated zoomed-out system-wide approach adopted here ensures that interactions between sectors are not omitted (e.g. crop-livestock interactions). Although the exercise estimates the necessary area of legumes to meet the demand of alternative diets, and while the freed forage land resulting from lower animal feed demand is sufficient to cover this increase (in scenario T3), how and where shifts between crops and plant-based sectors would be implemented requires greater attention. On the other hand, while the approach makes the link between production and consumption, the role of mid-chain actors remains an important blind spot, as in many scenario exercises (Saujot and Waisman 2020; Riera et al. 2025). The capacity to progress on both the depicted production-side and consumption-side changes is greatly dependent on the adaptation of the system as a whole, including mid-chain actors which play a great role in steering the organisation of the livestock sector (Guthman et al. 2022; Baudish et al. 2024). In this sense, zooming in on a specific sector (e.g. dairy or beef) might be useful to gather food system actors, including mid-chain actors, and facilitate practical exchanges on disaggregated challenges at the sectoral level (Borman et al. 2022).

The set of output indicators provides a toolkit to characterize the outcomes of the Belgian farming and food system, spanning over multiple dimensions of sustainability. Additional indicators could be added to assess issues such as pesticide use, animal welfare or antibiotic use.

While pesticide use can be reduced through both extensive practices favouring diversification and ecosystem services, or intensive systems relying on genetic and technological solutions (Zimmermann et al. 2021; Mora et al. 2023), results show that more extensive systems tend to favour higher animal welfare and lower antibiotic use, generally at the expense of higher GHG emissions per unit of product (Bartlett et al. 2024; Karlsson et al. 2025b), although not systematically (Hashemi et al. 2024). Interestingly, while scenarios T2 and T3 operate an important shift to extensive systems, the average GHG emissions per kg of protein (Table 13) are not necessarily higher than those in scenarios BAU and T1, dominated by intensive high-productivity systems (due to a greater reduction in the GHG emissions related to soybean meal; see Figure S1). On the socio-economic dimension, while the included indicators provide some information, a greater number of indicators could be integrated (Lebacq et al. 2013; Riera et al. 2023). In this research, they remain limited to the agricultural production stage. The developed modelling tool fails to account for dynamic evolutions, better represented in economic models (e.g. partial and general equilibrium) generally centred on trade (Teeuwen et al. 2022). As a market dominated by organic and extensive productions would not look like the current one, and given the current economic precarity and subsidy-dependence faced by certain livestock farmers (Riera et al. 2023; Kortleve et al. 2024), further research is needed on the socio-economic impacts and the necessary changes in economic paradigms required by such transitions (e.g. through the instauration of taxation measures, healthy food access schemes, etc.). Such a two-step approach where socio-economic implications are researched after environmental framing has been applied in other foresight exercises, such as the TYFA modelling exercise (Poux and Aubert 2018; Schiavo et al. 2021). Importantly, while the study assesses the theoretical feasibility of certain scenarios and their expected outcomes, it does not demonstrate the political feasibility of the outlined scenarios.

5.4.4 On the use of foresight approaches in transition processes

Rooted in the three steps of transition cycles (*assess - envision - implement*), this paper seeks to contribute to the three types of knowledge on the topic of the livestock transition through quantitative scenarios, used as a tool to draw and objectify possible futures. Upon completion of the analysis, we take the opportunity to reflect on this double theoretical framework.

This study particularly takes on the *assessment* and *envisioning* steps, thus contributing systems and target knowledge. Regarding the former, while the study seeks to adopt a system-wide approach (from production to consumption, integrating all agricultural activities in Belgium and a comprehensive set of sustainability indicators), full system knowledge can in practice rarely be attained (Kueffer et al. 2019) as certain elements are out of scope (e.g. mid-chain actors, market-related consequences, spill-over effects on other territories, etc.) or would require more nuanced qualitative approaches (Gupta et al. 2025). Regarding target knowledge, the study aimed to consider and compare a diversity of narratives surrounding the livestock transition. In this sense, the adopted approach can be considered hybrid between exploratory and normative as it explores a range of preidentified visions (Riera et al. 2025). While it does not seek to demonstrate the feasibility of a particular vision, the specific (normative) choices of scenarios and scenario hypotheses risk favouring certain futures over others despite the initial exploratory purpose (Levidow and Papaioannou 2016). Still, the scenario outcomes point to the trade-offs between narratives rather than to a single future. In this sense, the idea to reach a consensual and shared vision might be both optimistic (in terms of reconciling different worldviews) and unfeasible (from a biophysical perspective), while overlooking issues such as power relationships, diversity and eventually delaying action (Kueffer et al. 2019). Rather, research should pursue and foster a shared sense of responsibility and environmental virtues (Kueffer et al. 2019), while striving for greater openness to alternative and radical futures and careful actor participation (Moallemi et al. 2025; Gupta et al. 2025).

Before moving to an implementation step, the objective of this paper is also to reflect on the usefulness of the approach, and how it can contribute transformation knowledge on the third question of livestock transitions: is it possible to progress towards a shared vision. Considering the results presented above with those of a previous scenario exercise performed on the Belgian livestock sector (Riera et al. 2019), including an analysis of the reactions of food system actors (in particular farmer unions) to this exercise (Antier et al. 2020b), provides an opportunity for medium- to long-term evaluation. The short-term reactions to the first scenario exercise showed imported tensions and little openness to the approach. In particular, paying attention to a diversity of visions and systems was largely overlooked by food system actors (Antier et al. 2020b). These challenges resonate with a critique of transition management approaches as being too managerial, creating a sense of controllability and putting too much emphasis on identifying solutions and generating transformation knowledge while there may be more potential in fostering empowerment, justice and agency (Kueffer et al. 2019; Kaljonen et al. 2025). Nonetheless, the study continued to live on in subsequent years, generating a "snowball effect". Study results were mobilised in civil society circles for advocacy purposes or in policymaking contexts, e.g. during a parliamentary session in June 2022. Among other factors, it contributed to establishing more interactions between civil society (environmental NGOs) and the farming sector (farmer unions), e.g. during negotiation rounds for the local implementation of the EU Common Agricultural Policy (CAP). The scenario exercise presented in this paper allowed to overcome a series (not all) of limitations and criticisms made: the set of indicators was expanded to include some socio-economic aspects and plant-based sectors were integrated to account for crop-livestock interactions. It remains to be seen how this new set of scenarios will be taken up and used by different food system actors. Yet, we do believe that such research can contribute to the cyclic and iterative processes that are transition cycles. The primary purpose, at least in exploratory approaches, resides in opening up debates and triggering new ways of thinking rather than pin-pointing specific pathways (Newell et al. 2025; Riera et al. 2025). The paradox for foresight approaches lies in a strong commitment to drive change, as per the objectives of transition governance frameworks (Loorbach 2010; Duru et al. 2015a; Dendoncker et al. 2018; Gaupp et al. 2021; Prost et al. 2023; Meynard et al. 2023), which conflicts with the difficulty of assessing its capacity to achieve such change (Dernat et al. 2022). Rather than willing to measure a potential impact of foresight approaches, we believe there is value in acknowledging a *slow* nature of foresight. Going further, the process must eventually feed into an *implementation* step to contribute to concrete transition pathways. As discussed above, the adopted territorial, sectoral and diversity approach may prove useful in this regard if certain attention points are taken into account (e.g. spill-over effects, sectoral interactions, etc.). Further building on the option space approach proposed here, actor participation and back casting approaches are put forward to foster concrete implementation of pathways (Moallemi et al. 2025; Duygan et al. 2025).

This paper set out to apply the use of foresight scenarios to the case of the Belgian livestock sector. The objective was to study both the object and the methodological process. While the presented foresight approach allows to draw important conclusions for the future of the Belgian livestock sector, limitations must be taken into account with regards to certain methodological choices (e.g. the boundaries of the exercise). The results confirm that designing foresight scenarios on the livestock sector is no easy task given the multiplicity of existing visions and the trade-offs involved. While measuring the impact of the approach is complicated, the long-term research process provides arguments in favour of a *slow foresight* approach as a valuable tool in the management of transition cycles.

5.5 Supplementary material

Supplementary material for this chapter can be found at the end of the document (Appendix to chapter 5). It includes the following elements:

- Details on model construction and validation
- Detailed scenario results

Chapter 6 Will the protein transition happen? Analysing implementation at the macro- and micro-levels in Flanders, Belgium

Abstract

As the conclusions of chapter 5 point to a reduction of both livestock production and consumption, this chapter shifts the focus from the livestock sector to the wider protein transition, understood as *a shift from a diet rich in animal proteins to one richer in alternative protein intake, including a reduction in total protein intake and a reduction in animal-based production*. The chapter, more exploratory in its current form, allows to explore the implementation step of transition cycles. The analysis originates in the development of an organic soybean value chain in Flanders, which is complemented with an examination of the regional policy landscape targeting the protein transition. This provides an opportunity to investigate how the protein transition, which is strongly pushed at the macro policy level, can be implemented in practice at the micro level by value chain actors. Inversely, it illustrates how the challenges faced by these actors are supported (or not) by the macro level policy framework. The chapter starts by analysing the macro-level policy context before introducing the micro-level value chain and looking at the interaction between both.

6.1 Introduction

In recent years, the importance of fostering a protein transition has gained significant attention in the research community (Aiking and De Boer 2020; IPES-Food 2022; Guthman et al. 2022; Jenkins et al. 2024). Despite many possible definitions, the protein transition, or protein shift can be understood as *a shift from a diet rich in animal proteins to one richer in alternative protein intakes, including a reduction in total protein intake and a reduction in animal-based production* (Duluins and Baret 2024b). Through this definition, it appears that the protein transition encompasses four main dimensions, as it covers the *production* and *consumption* of both *animal* and *alternative* protein sources. Seen as especially important in high-income countries (HIC), the justifications for engaging in a protein transition can be grouped in three main goals (Duluins and Baret 2024b): reducing the environmental impacts of protein production and consumption (Steinfeld et al. 2006; Herzon et al. 2024), providing healthy diets for a growing population (Willett et al. 2019), and addressing ethical problems related to animal welfare in industrial production systems (Bartlett et al. 2024; Karlsson et al. 2025b). The issue has also been taken up in policymaking. The European Commission mentions the need for sustainable protein production and consumption and healthy diets in several of its recent strategic documents, including the (now nearly left-behind) Farm to Fork strategy, its more recent successor Strategic Dialogue on the future of EU agriculture or the latest Vision for Agriculture and food (EU Commission 2020, 2024, 2025). Focussing on the European context, several countries have taken up the topic at national, sub-national or city level, such as in the Netherlands, Flanders (Belgium) or Amsterdam (Dagevos and Onwezen 2025; Drewnowski and Hooker 2025).

The ability to bring about and implement such a transition remains uncertain. Food system transitions are complex long-term processes occurring at multiple scales and played out at multiple levels (Juri et al. 2024). The multiplicity of scales can be conceptualised around three interconnected scales (Riera and Baret 2026): a spatial scales, from local to global; a supply chain scale involving various actors and activities beyond the farm stage, from production to processing, retail and consumption; and a scale of action and decision-making, ranging from micro-level individual actions and practices to macro-level policymaking, with meso-level actors (e.g. sectoral unions, research, counsellors, etc.) acting as an interface between macro and micro. The fact that sustainability transitions occur at multiple levels is also highlighted by the multi-level perspective (MLP) on socio-technical transitions (Geels and Schot 2007). It considers transitions to emerge from interactions between three levels: the *niche level* (radical innovations and experimentations), the *regime level* (main practices and structures), and the *landscape level* (exogenous factors beyond influence of niche and regime actors).

The body of work looking at the implementation of a protein transition spans across its four dimensions and addresses the multi-scale and multi-level nature of the issue, with nevertheless much research on the consumption side and only a few on the production side, in particular on the effects of a protein transition on animal farming (Duluins et al. 2022). Much research focusses on system-wide perspectives and macro-level policy options, putting the emphasis on policy coherence and the role of industry (IPES-Food 2022; Hundscheid et al. 2022, 2024; Guthman et al. 2022; Vallone and Lambin 2023; Pay and Gianoli 2024; Baudish et al. 2024; Dagevos and Onwezen 2025). To our knowledge, little research seems to confront such knowledge on the macro level with analyses of practical implementation at micro level by individual value chains and their actors. Yet, the interaction between the macro-level policy context and micro-level implementation has been shown to be key (Pay and Gianoli 2024). In this paper, we propose to contribute to recent research on the possible implementation of a protein transition by looking at this interface. Focussing on a HIC region, we aim to look at how a policy-induced protein transition can be implemented in practice by food system actors. Analysing both the macro-level policy context and a micro-level value chain example, we identify what challenges occur at both levels and at the interface between both.

We analyse the case of Flanders (Northern region of Belgium), which has recently equipped itself with several policy measures targeting different dimensions of the protein transition, including a *Flemish protein strategy* towards 2030 (Departement Landbouw en Visserij 2021a) or a *Green deal protein shift on our plates* (Departement Omgeving 2021). Besides a dedicated policy setting, Flanders makes a particularly relevant case study given its production-side and consumption-side context. Flanders is a densely populated region characterised by low land availability and intensive farming systems. Close to half of Flemish farms are specialised in livestock productions (45% of farms in 2023; Agentschap Landbouw en Zeevisserij 2024), in particular of monogastric animals. The region concentrates the vast majority of Belgian pigs and poultry (respectively 94% and 85% in 2023; Statistics Belgium 2024a), with a significant export orientation (self-sufficiency levels for pork and poultry reaching respectively 214% and 216% in 2023; Statistics Belgium 2024b). This poses serious challenges in terms of nitrogen pollution due to ammonia emissions and manure surpluses (De Pue and Buysse 2020; Papangelou and Mathijs 2021). On the consumption-side, current dietary patterns in Belgium have been shown to cause significant environmental impacts, in particular in the case of ultra-processed food and animal products (Dénos et al. 2024). Recent monitoring of protein consumption in the Flemish population shows little signs of an effective switch from animal to plant-based protein consumption (Rubens et al. 2025).

6.2 Methods

The research is rolled out in two main steps. First, we analyse the macro-level policy context by identifying and reviewing a series of Flemish policy measures that directly or indirectly tackle the protein transition. Second, we look at the case of a specific value chain wishing to contribute to the protein transition. Using tools such as value chain mapping and barrier analysis we identify the main challenges encountered in a micro-level setting. Crossing the information of both steps allows us to draw conclusions on the interaction between macro-level policy and micro-level implementation. Referring to a multi-scale framework for food system transitions (Riera and Baret 2026), this analysis is situated at both the macro and micro levels on the scale of action and decision making and spans over the multiple stages of the supply chain stage, while its spatial scale is set at regional level, covering the Flemish policy landscape and a Flemish supply chain.

6.2.1 Researching the macro-level: policy analysis

Identification of policy measures

Based on desk research, we perform a targeted review of the Flemish policy landscape. We include in the analysis all policy measures initiated by the Flemish government (including binding regulations, non-binding strategic documents or agreements, and the activities of organisations receiving public funding), and which target at least two dimensions of the protein transition (production and/or consumption of animal and/or alternative protein). In this research, policy delineation follows a bottom-up approach (Ossenbrink et al. 2019). This consists in identifying the relevant policies affecting a certain impact domain, in this case the protein transition (rather than a top-down approach starting the analysis from a mix of policies). We start by identifying key policy measures targeting the protein transition and complement this bottom-up identification through a recent analysis of the policy landscape targeting the food environment in Belgium (De Bauw et al. 2025), keeping specific policies which also target the protein transition. As a result, we identify twenty policy measures relevant for our analysis, which constitute the research sample (Table 14).

Table 14. Set of twenty Flemish policy measures related to the protein transition.

Policy measure	**Description**
1. Flemish food strategy *('Go4Food')*	Overarching food system-wide strategy
2. Flemish protein strategy *('Eiwitstrategie')*	Regional strategy comprising 6 strategic areas and objectives (part of the food strategy)
3. Research plan for implementation protein strategy (*'Realisatie eiwitstrategie')*	Funding of 19 projects related to the protein strategy
4. Green Deal protein shift on our plates *('Eiwitshift op ons bord')*	Public-private partnership aiming at fostering the consumption of plant-based protein
5. Energy and Climate plan and Covenant bovine enteric emissions	Agreement between public authorities and sectoral organisations to reduce enteric fermentation emissions
6. Circular Flanders – Circular food chain agenda (*'Vlaanderen Circulair - Werkagenda voedselketen'*)	Partnership between the Flemish government, businesses, civil society and research promoting the circular economy, among which in the food sector
7. Nitrogen decree *('PAS'; 'stikstofdecreet')*	Framework for limiting nitrogen pollution by air, in particular ammonia emissions from animals
8. Manure decree (*'MAP'; 'mestdecreet*)	Framework for limiting nitrogen pollution by water, defining the possible uses of animal manure (e.g. for crop fertilisation)
9. CAP Strategic Plan – Eco-scheme on protein crops	Eco-scheme of the Flemish CAP strategic plan providing support for growing protein crops.
10. CAP Strategic Plan – Coupled income support for bovine animals	Coupled income support provided to bovine farmers within the Flemish CAP strategic plan.
11. Public support and subsidies for Flemish Centre for Agricultural and Fisheries Marketing (*'VLAM'*)	Institute responsible of monitoring and promoting the products of Flemish agriculture (through consumption surveys, consumption campaigns...)
12. Public support and subsidies for Flanders institute for Healthy Living (*'Gezond Leven'*)	Institute producing and facilitating information on sustainable and healthy lifestyles, among other related to diets (nutritional recommendations, campaigns...).
13. Public support and subsidies for *Flanders Food*	Innovation platform aiming to foster innovation and research in the food industry.
14. Coordination of Flemish platform for Agrifood research (*'Platform voor Landbouw- en Voedingsonderzoek'*)	Research platform aiming to accelerate innovation in the food sector through a strong innovation and research policy
15. Public support and structural funding of *ILVO*	Regional research institute for agriculture and fisheries
16. Public support and subsidies for *Food Pilot* plant	Experimental food processing facility for developing innovative products or performing quality assessments
17. Public support and subsidies for *ProVeg Belgium*	Non-profit organisation advocating in favour of plant-based diets
18. Public support and subsidies for *GoodPlanet*	Non-profit organisation facilitating access to sustainability knowledge on schools and at work
19. Public support and subsidies for *MOS*	Non-profit organisation assisting schools in developing sustainability strategies
20. Development of sustainable public procurement criteria (*'MVOO tool'*)	Charter of critera for sustainable public procurement, including for food.

Policy analysis

Upon identification of relevant policy measures, the policy analysis was performed on two levels. First, a policy-specific analysis provides descriptive information on each policy measure. Elements of analysis include a general presentation of the measure, the targeted dimensions of the protein transition (production and/or consumption of animal and/or alternative protein), the nature of the policy measure (strategy, instrument – regulatory, instrument – economic, instrument – informational) and the competent authority or leading actor in charge of implementation.

Second, a policy-wide analysis describes how the twenty policy measures interact, thus gaining a more systemic perspective on the Flemish protein transition policy landscape. By revealing potential synergies and tensions between the analysed measures, this allows to assess general policy coherence. Policy coherence can be understood as follows: *policies designed to achieve food systems outcomes minimize trade-offs and conflicts, are implemented and governed such that policies are aligned and complementary, and promote mutually reinforcing actions at different levels of government, across borders, and across sectors* (Dewi et al. 2024). To facilitate such analysis, we look for the prevalence of the three main narratives and paradoxes that have been associated to the protein transition in high-income countries as proposed by Duluins and Baret (2024b, a) (Table 15).

Table 15. Three main narratives and paradoxes of the protein transition, as proposed by Duluins and Baret (2024b, a).

Name of narrative or paradox	Description
Consumer narrative	The consumer narrative focuses on consumption-based solutions targeting dietary changes.
Techno-centred narrative	The techno-centred narrative mainly aims at developing new, more resource-efficient protein production systems.
Socio-technical narrative	The socio-technical narrative intends to foster a transition in the agri-food system from an animal-dominated regime to an alternative protein regime.
Substitution paradox	The substitution paradox refers to the fact that focusing on increasing alternative protein sources without reducing total protein consumption might lead to an increase of total protein intake, thus displacing potential benefits. In short, the substitution of animal protein sources by alternative protein sources should not overlook the need to also target overall reduction.
Jevons paradox	The Jevons paradox, or rebound effect, refers to the fact that focusing on efficiency gains (i.e. reducing impacts per unit of output) might in fact lead to increased overall impacts if these efficiency gains lead to increases in consumption and/or production.
Productivism paradox	The productivism paradox resides in the pursue of a protein self-sufficiency for animal feed, which in turn contributes to maintaining the production of animal-based protein unaltered, while overconsumption of protein is already apparent.

6.2.2 Researching the micro-level: value chain analysis

Description of the value chain

To analyse micro-level implementation, we look at a specific value chain wishing to contribute to the protein transition. The value chain is composed of three farmers, one processor and one retailer wishing to set up an organic soybean value chain for human food. The value chain received financial support under one of the analysed policy measures (measure 3 in Table 14: *Research plan for the implementation of a protein strategy*) and contributed to a two-year research project called LoCoSoy[9], including partners from academia (among which the authors) besides the economic actors. Covering all value chain stages from production to consumption, a strong focus resided in adopting a value-chain approach, in which all economic partners collaboratively strive to implement a long-lasting relationship. In the rest of the paper, we refer to this value chain as the LoCoSoy value chain.

Analysis of the value chain

To grasp the specific challenges and opportunities faced by the value chain as a whole and throughout its different stages, we perform a combined barrier analysis and value chain mapping. Barrier analysis allows to analyse lock-in situations in which an accumulation of blocking elements (i.e. barriers) lock the system into specific trajectories that are hard to dislodge. In such situations, barriers are factors of a system that hinder a change of practices or strategies (Courtois and Baret 2024; Chevalier et al. 2026). In our case, barrier analysis is useful to understand which elements might hamper the development of the LoCoSoy value chain, and more broadly the implementation of the protein transition. For the analysis, nine categories of barriers are considered, as proposed by Chevalier et al. (2026) (Table S18). Value chain mapping applies to a value chain the logics of systems mapping, in particular value network maps (Dentoni et al. 2023). The aim of value network maps (and by extension value chain maps) resides in identifying actors related to a certain issue and how they interact. By doing so, they allow to visualise and understand how *systems of issues* interact with *systems of actors*, and how these interactions can or should be modified to steer the system into a desired way, allowing to address a certain issue (Dentoni et al. 2023). Barrier analysis and value chain mapping are highly complementary as the former allows a systematic identification of barriers while the latter allows for a visual representation of the issue highlighting relations between actors and other parts of the system.

[9] https://www.flandersfood.com/en/projecten/locosoy

6.3 Results and discussion

6.3.1 Analysing the macro-level policy landscape

Twenty policy measures were identified and analysed. Their main characteristics are summarised in Table 16, with a detailed analysis of each measure provided in the supplementary material (Table S19). To gain a systemic picture of the Flemish policy context related to the protein transition, below we discuss the actors involved, the targeted dimensions of the protein transition, the nature of the proposed policy measures, the dominating narratives and the prevalence of paradoxes.

Table 16. Summary and description of twenty Flemish policy measures related to the protein transition. Uppercase crosses in dark grey cells indicate coverage while lowercase crosses in light grey cells indicate partial coverage.

Policy measure	**Leading authority**	**Nature of policy**	**Production vs. Consumption**		**Animal-based vs. alternative protein**	
			P	C	Animal	Alter
1. Flemish food strategy *('Go4Food')*	Agency for agriculture & fisheries	Strategy	X	X	x	x
2. Flemish protein strategy *('Eiwitstrategie')*	Agency for agriculture & fisheries	Strategy	X	x	X	X
3. Research plan for implementation protein strategy (*'Realisatie eiwitstrategie'*)	Agency for agriculture & fisheries	Instrument – economic	X	x	x	X
4. Green Deal protein shift on our plates *('Eiwitshift op ons bord')*	Environment Department	Strategy		X	X	X
5. Energy and Climate plan and Covenant bovine enteric emissions	Energy & Climate Agency; Agency for agriculture & fisheries	Strategy	X		X	
6. Circular Flanders – Circular food chain agenda (*'Vlaanderen Circulair – Werkagenda voedselketen'*)	Agency for agriculture & fisheries – Fevia Flanders	Strategy	X	x	X	X
7. Nitrogen decree *('PAS'; 'stikstofdecreet')*	Flemish Land Agency	Instrument - regulatory	X		X	
8. Manure decree (*'MAP'; 'mestdecreet'*)	Flemish Land Agency	Instrument - regulatory	X			X
9. CAP Strategic Plan – Eco-scheme on protein crops	Agency for agriculture & fisheries	Instrument – economic	X			X
10. CAP Strategic Plan – Coupled income support for bovine animals	Agency for agriculture & fisheries	Instrument – economic	X		X	

11. Public support and subsidies for Flemish Centre for Agricultural and Fisheries Marketing (*'VLAM'*)	Flemish government	Instrument – informational	x	X	X	X
12. Public support and subsidies for Flanders institute for Healthy Living (*'Gezond Leven'*)	Flemish government	Instrument – informational		X	X	X
13. Public support and subsidies for *Flanders Food*	Agency for innovation & entrepreneurship	Instrument – economic	X		X	X
14. Coordination of Flemish platform for Agrifood research (*'Platform voor Landbouw- en Voedingsonderzoek'*)	Agency for agriculture & fisheries	Strategy	X		X	X
15. Public support and structural funding of *ILVO*	Flemish government	Instrument – informational	X		X	X
16. Public support and subsidies for *Food Pilot* plant	Flemish government	Instrument – informational	X			X
17. Public support and subsidies for *ProVeg Belgium*	Flemish government	Instrument – informational		X	X	X
18. Public support and subsidies for *GoodPlanet*	Flemish government	Instrument – informational		X	X	X
19. Public support and subsidies for *MOS*	Flemish government	Instrument – informational		X	X	X
20. Development of sustainable public procurement criteria (*'MVOO tool'*)	Flemish government	Instrument – informational		X	X	X

Multidimensional strategies and specific instruments

We start the analysis of the different policies by clustering them according to the targeted dimensions of the protein transition (production and/or consumption of animal and/or alternative protein sources). Out of the nine possible clusters, we find that the analysed policies cover five (Table 17).

Five policy measures cover all four dimensions of the protein transition (cluster 5). This is the case of the *Flemish food strategy Go4Food* which strives to adopt a systemic approach spanning through all stages of the value chain, although not focused exclusively on the protein transition. The *Flemish protein strategy* also aims for such a food systems approach and specifically targets the production and consumption of all types of protein sources, with six strategic objectives. In practice, 37 actions are directly attributed to the protein strategy (see dedicated entry in Table S19). Most actions (26 out of 37) are related to production-side actions, either of animal protein sources (10 actions) or of alternative protein sources (16 actions). Only five actions fall within the sustainable consumption objective, and six are related to other objectives such as increased product diversity. Through the 19 projects it funded (among which the LoCoSoy value chain), the *Research plan for the implementation of the protein strategy* also covers all dimensions of the protein transition, although each project focuses on specific objectives. The majority of funded projects (twelve) were aimed at the production of plant-based and alternative protein sources, while only three targeted sustainable consumption and four targeted animal production through sustainable feed. The *Circular food chain agenda* positions itself in support of the protein strategy and mentions improving the sustainability of protein consumption and production (both alternative and animal-based) and increasing the diversity of protein products. The *Flemish centre for agricultural and fisheries marketing (VLAM)* plays a dual role with regards to the protein transition, as on one hand it supports the production of innovative protein crops or surveys the consumption of plant-based and alternative proteins. On the other hand, it actively promotes the consumption of animal-based products, e.g. through communication campaigns such as the 'week of steak and fries'.

The remaining policy measures focus on more specific dimensions of the protein transition. On the production side, the *Nitrogen decree*, the *Energy and climate plan* (including the *Covenant for bovine enteric emissions*) and the *CAP coupled income support* all target the animal production dimension of the protein transition (cluster 1). The *CAP eco-scheme for protein crops* specifically targets the production of plant-based protein, which is also affected by the *Manure decree* and the activities of the *Food Pilot* plant (cluster 3). Finally, through its research projects, the activities of *Flanders Food,* the Flemish research institute for agriculture and fisheries (*ILVO*) and the *Flemish platform for agrifood research* cover the production of both animal and plant-based protein (cluster 2). On the consumption side, the *Green deal protein shift on our plates* undertakes several actions with the objective of rebalancing the shares of animal and alternative protein sources in our diets, with no apparent focus on the production side (cluster 8). Activities by the *Flemish Institute for Healthy Living (Gezond Leven)*, *ProVeg*, *GoodPlanet*, *MOS* and the *MVOO tool* target the same dimensions, mainly through information dissemination.

Table 17. Classification of policy measures into nine clusters following the targeted dimensions of the protein transition (policy numbers refer to order in Table 14).

	Production	Production & Consumption	Consumption
Animal protein	**Cluster 1** (3 measures) *5. Energy and climate plan and Covenant enteric emissions* *7. Nitrogen decree* *10. CAP coupled income support*	**Cluster 4** /	**Cluster 7** /
Animal & Alternative protein	**Cluster 2** (3 measures) *13. Flanders Food* *14. Platform for agrifood research* *15. ILVO*	**Cluster 5** (5 measures) *1. Flemish Food strategy* *2. Flemish protein strategy* *3. Realisatie eiwitstrategie* *6. Circular food chain agenda* *11. VLAM*	**Cluster 8** (6 measures) *4. GD protein shift* *12. Gezond Leven* *17. ProVeg* *18. Good Planet* *19. MOS* *20. MVOO tool*
Alternative protein	**Cluster 3** (3 measures) *8. Manure decree* *9. CAP eco-scheme protein crops* *16. Food Pilot*	**Cluster 6** /	**Cluster 9** /

A diversity of actors but agriculture leads the way

The current policy framework related to the protein transition in Flanders involves a diversity of actors and institutions. While all measures are being led by public institutions, there are cases of mixed policy measures involving actors from the private sector through public-private partnerships (*Green deal protein shift on our plates*, *Covenant bovine enteric emissions*, *Circular food chain agenda*, *Flanders Food*, *VLAM*), and/or actors from research through funding research programs and organisation (*Research plan for the implementation of the protein strategy*, *ILVO*, *Flanders Food*). Within the public domain, policies related to the protein transition are spread over several authorities and agencies showcasing a diversity of responsibilities, including agriculture (*Agency for agriculture & fisheries*), environment (*Environment Department*), land planning (*Flemish Land Agency*), energy and climate (*Energy & Climate Agency*) or the General Flemish government. As also noted by Candel & Mathijs (2024), agriculture-related authorities (*Agency for agriculture & fisheries*) appear as key leading actors in matters of protein transition as they oversee eight of the identified policy measures.

Diversity of policy measures

The analysed policy set showcases a diversity of policy measures, which can be analysed with regards to their level of legal constraint, resulting in structural or more isolated effects. The *Flemish food strategy* and the *Flemish protein strategy* are non-binding strategic documents aimed at providing a general direction for the Flemish food system. Although these strategic documents outline a certain vision or path forward, they do not set specific (quantified) targets or goals, apart for a few specific elements (e.g. the protein strategy sets specific objectives regarding animal feed, aiming to reach 100% certified soy in 2030 or 50% of feed ingredients coming from byproducts in 2030). The *Green deal protein shift on our plates*, the *Circular food chain agenda* and the *Covenant bovine enteric fermentation* can also be considered as general strategies. Their specificities reside in the partnerships and engagement with the private sector, seen as crucial given the important role of such actors (IPES-Food 2022; Vallone and Lambin 2023, 2024), and in the identification of specific goals (either for specific companies or for the sector/system as a whole), although these are non-binding.

The *Nitrogen decree*, the *Manure decree* and *CAP measures* provide a more constraining policy framework through regulatory or economic instruments, with mandatory actions for value chain actors through regulatory or economic instruments (although the eco-scheme for protein crops remains voluntary). Economic instruments can also support the protein transition through research and innovation, e.g. through the *Food Pilot* or the *Research plan for implementing the protein strategy,* with the latter being specifically targeted towards the protein transition but as a one-off research fund.

Finally, a series of informational instruments aim to assist the protein transition by fostering research (e.g. through *ILVO*, *Flanders Food* or the *Platform for agrifood research*), supporting the dissemination of information on the topic (e.g. through *VLAM, Gezond Leven, ProVeg, GoodPlanet, MOS)*, or assisting public procurement (*MVOO tool*).

Dominating narratives

With regard to the three main narratives surrounding the protein transition in high-income countries as defined by Duluins & Baret (2024a), we find that different visions coexist under the different policy measures. On one end, *techno-centric narratives* appear to dominate the Flemish policy landscape. They focus on improving the inefficiency of current protein production systems, either by developing alternative protein sources (plant-based or novel, including insects, algae, etc.) or by pursuing technological innovations, both for human food and animal feed. This narrative is present in nearly all policy measures considered and in particular in measures from clusters 1 to 3 such as the *Research plan for implementing the protein strategy*, the *Circular food chain agenda*, the *Nitrogen decree*, activities by *Flanders Food* or the *Food Pilot*.

On the other end, the *consumer narrative* focuses its attention on shifting dietary habits to an increased intake of plant-based and alternative protein sources. It is particularly embodied by the *Green Deal protein shift on our plates*, and can further be found in informational instruments from cluster 8 such as in the activities by *Gezond Leven*, *ProVeg*, *GoodPlanet*, and *MOS*.

In between, *socio-technical narratives* emphasise the importance of reconfiguring the protein regime as a whole, focusing on both the consumption side and the production side (including mentions of reduced livestock populations) and encouraging holistic policy framework approaches and coordinated action plans. The *Flemish protein strategy* (and the *Flemish food strategy*, although it is not focused exclusively on the protein transition) could be considered to fall under such a narrative. Yet, its practical implementation tends to be more aligned with production-side measures closer to the techno-centric narratives (see dedicated entries in Table S19). Calls for more systemic approaches are also found in the work of the *Flemish platform for agrifood research* as potential avenues for future research. This asks the question if and how the socio-technical narrative can effectively find its way into policy. Recommendations to overcoming policy silos and structurally implementing food system approaches at policy level (Benton 2023; Van Zanten et al. 2025) could go in the direction of the socio-technical narrative. The stated alignment of the *Protein strategy* with the objectives of the *Green deal protein shift on our plates* could be seen as a sign of efforts towards such a coordinated approach (e.g. the 'halve-halve' objective of the *Green deal protein shift on our plates* has also been adopted within the *Protein strategy*[10]). In this sense, the *Protein strategy* is presented as one of the domain-crossing areas of the Flemish food strategy.

6.3.2 Challenges of a micro-level value chain

A mapping of the LoCoSoy value chain, supported by the *Research plan for the implementation of the protein strategy* (measure 3 in Table 14), allowed to understand the functioning of each of the

[10] A specific objective of the *Green deal protein shift on our plates* is to reach a protein intake balance of 40:60 between animal-based and plant-based protein (instead of the current 60:40). To reach this objective, a 'halve-halve' strategy is pursued, meaning that halve of consumed meals should be vegetarian while the other halve could still contain animal products. Such a message should allow to reach the 40:60 objective and is seen as easier to vehiculate through communication campaigns.

value chain stages, how they interact and possible challenges and barriers to the development of the value chain. Although a small-scale value chain, several barriers emerge at each stage of the value chain and pose a challenge to its long-term establishment. These are summarised below along with a visual representation of the value chain's functioning (Figure 20). A detailed analysis of each value chain stage is provided in the supplementary material (Table S20).

Value chain description.

At the production stage, the LoCoSoy chain involved three organic farmers from the Biograno group, each growing 1 ha of soybean per year for two years (2022 and 2023). While yields were generally comparable to those in major producing countries, they remained variable and uncertain. As soy is a new crop in the Flemish context, farmers faced challenges related to limited adapted varieties, developing agronomic knowledge, wildlife pressure, and difficulties finding suitable contractors. Production costs were high and variable, especially when compared with international market prices, although looking beyond pure economic results, soybean contributed to diversifying crop rotations.

Post-harvest activities within the chain included drying the soybeans (at *ILVO*), sorting and dehulling by an external partner in Wallonia, and storing the beans, which was shared between farmers and *ILVO*. Small volumes, soy's allergen status, and reliance on external partners increased costs and logistical complexity. Key uncertainties remain regarding the optimal level of sorting and dehulling, as these affect both costs and yields. While buffer storage could improve flexibility, it would require additional logistical planning and investment.

The processing activities within the project were largely exploratory, with an intended focus on minimal processing. Soybeans were mainly used to produce soy flour for bread and pasta trials at the *Food Pilot* plant. Eventually, the soy was sold to an external cheese manufacturer for soy milk production. Limited processing capacity at SME scale, low feasible inclusion rates of soy flour, high costs for advanced processing techniques, and the absence of clear quality standards or supportive regulations all constrained further development of local soy processing.

At the retail stage, the involved partner identified several challenges to market entry, with an already significant offer of soy and plant-based products, making differentiation difficult. Retailers demanded clarity on final product specifications, soy content, pricing, and supply continuity before committing, which were not guaranteed in the context of the project. It was found that marketing strategies should emphasize taste and quality rather than local origin alone, while inconsistent supply posed risks once products are incorporated.

Finally, at the consumption stage, tasting tests showed mixed consumer responses, with soy bread performing better than soy pasta. From a consumer perspective, taste, price, and health benefits seemed to outweigh local sourcing, making effective product positioning and storytelling critical challenges for soy products.

Barrier analysis.

The LoCoSoy value chain is an example of a niche-level initiative, situating the project in a case of strategic niche management (Loorbach et al. 2017). Soybean, even more so organic soybean, is still very new and limited in the region's agricultural landscape (90 hectares of soybean were grown in 2020, out of 624.727 ha in total; VILT 2015; Statbel 2021). This small-scale, innovative-crop and niche-level status leads to several barriers that pose challenges to a long-term establishment of the value chain (Figure 20).

The novelty of the crop in the Flemish agricultural landscape leads to several *technical barriers,* mainly at the farming and processing stages. This includes limited availability of seeds and varieties that are adapted to the Flemish context, although research is ongoing. *Knowledge-related barriers* also play a role as technical know-how at local level is still in development, both on the agronomic side and on the processing side (e.g. quality requirements; post-harvest activities such as drying, dehulling, sorting and storing; final product processing, etc.). The difficulties encountered by the value chain to develop at mid-chain stages (e.g. few processing options, sufficient offer in retail) may confirm that there is little place for niche projects in the alternative protein sector, which is being dominated by bigger industry actors, with an important influence of international markets (IPES-Food 2022; Guthman et al. 2022; Vallone and Lambin 2023). The novelty of the crop also induces *financial barriers* related to necessary investments for post-harvest activities (e.g. on-farm storage) and *organizational barriers* as post-harvest activities need to be performed by external partners. The low production volumes lead to higher relative costs as they limit economies of scale. In turn, this contributes to *market-related barriers*, including limited competitiveness against international markets, but also little access to retail due to an already important offer of alternative protein products and to a low perceived demand of consumers for local soybean products. Thus, the consumption stage is also affected by *socio-cultur*al and *knowledge barriers* as a certain reluctance to move away from traditional diets and general lack of knowledge regarding a plant-based eating culture can still be found. All partners put a strong focus on adopting a collaborative value chain approach which improved collaboration and transparency but also brought a series of *relational* and *governance barriers* related to the greater need for communication and concertation, ultimately posing a risk for the long-term stability of the chain. In this regard, the fact that it could operate under a research setting for two years provided some stability and allowed it to guarantee medium-term perspectives to a certain extent (e.g. with the help of research partners and of the initial processing partner, the farmers engaged with a new processor, thus engaging in new collaborations).

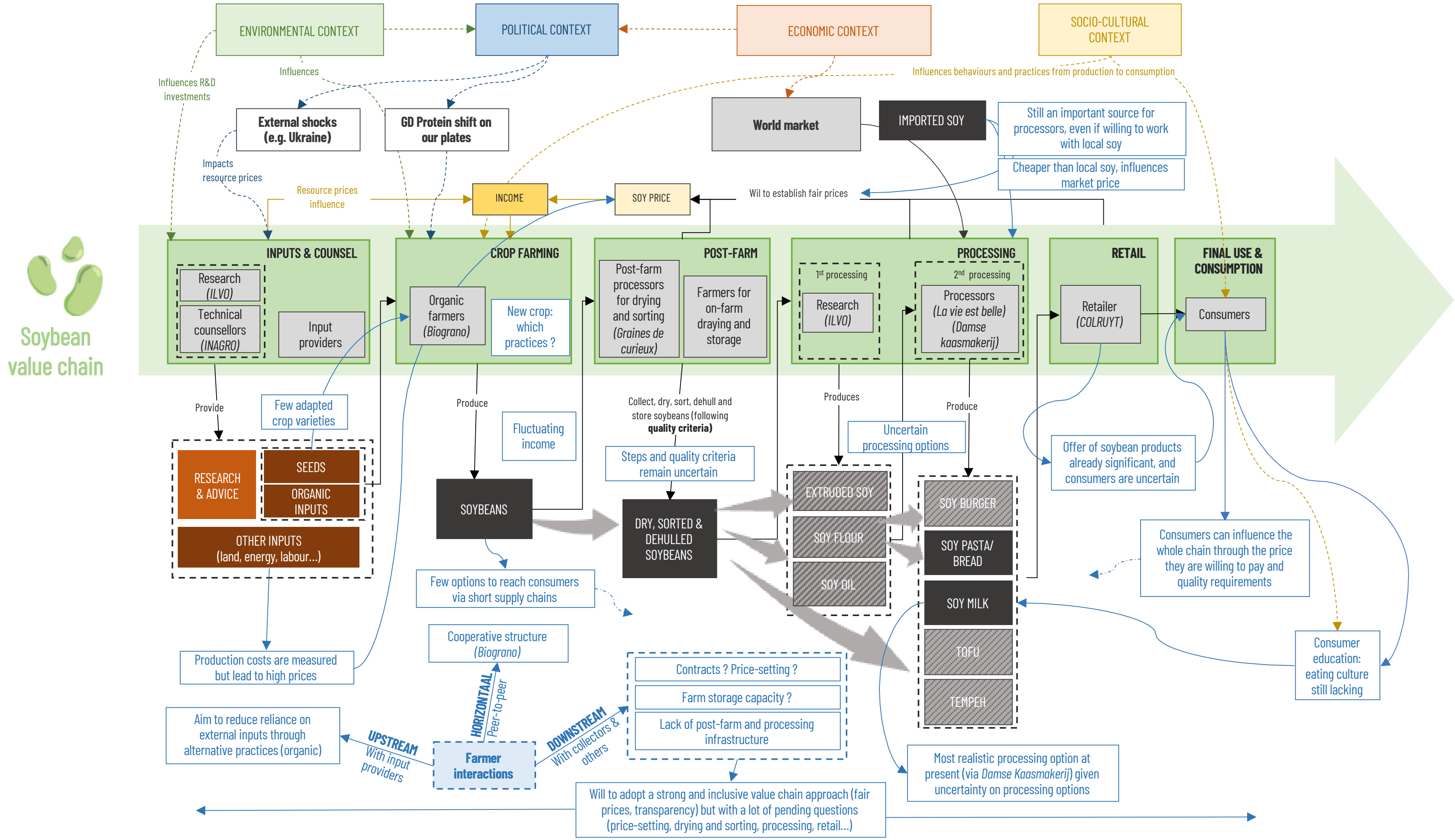


Figure 20. Mapping of the LoCoSoy value chain. Light grey boxes with black frames indicate actor types. Plain dark grey and orange boxes indicate material flows. White boxes with blue frames indicate challenges and open questions (barriers).

6.4 Implementing a protein transition from macro to micro

The analysis above situates this research in a multi-level setting (Riera and Baret 2026), combining policymaking at the macro level and value chain practices at the micro level. Analysing the case of the LoCoSoy value chain provides us an opportunity to derive information on the interactions between the macro and micro levels. Going beyond this case and looking for signs of paradoxes allows us to further discuss the state of the protein transition in Flanders and explore possible ways forward, considering for instance the role of meso-level actors.

6.4.1 Addressing micro-level barriers with macro-level policies

At micro level, the LoCoSoy value chain faces barriers at each stage, from production and post-production (technical and knowledge barriers) to retail (market-related barriers) and consumption (socio-cultural barriers), including also transversal challenges (relational and governance barriers). At the macro level, twenty policy measures are targeted at the protein transition and can help to address some of the barriers faced by the value chain (Figure 21).

On the production side, given the novelty of the soybean crop and of this type of value chain, the funding of research organisations and infrastructure such as *ILVO*, *Flanders Food*, *VLAM* and the *Food Pilot* can relieve technical and knowledge barriers related to agronomic know-how or processing possibilities. On the consumption side, several publicly supported initiatives and organisations, mainly from cluster 8 (*GD protein shift*, *Gezond Leven*, *ProVeg*, *GoodPlanet*, *MOS*, *MVOO tool*), may contribute to addressing socio-cultural barriers related to (slowly changing) eating habits. The work by *VLAM* plays a dual role in this regard as it also promotes animal-based products. In between production and consumption, there are few policy measures targeting barriers that emerge at the intermediate stages of the chain or transversally. The eco-scheme on protein crops partly relieves market-related barriers through financial support, although not sufficient to overcome competition with international market prices, nor to address the already significant offer at retail level. Finally, through its *Research plan for the implementation of the protein strategy*, the macro level has shown to provide support to micro-level alternative protein niches such as the LoCoSoy value chain. Providing funding through a research project allowed to explore the development of the value chain and alleviate certain transversal organisational, governance and relational barriers (e.g. roles and relations between different value chain actors). While support to niches is key, it is important to consider that the resulting gain in stability is only temporary, and that interactions with the predominant regime must not be overlooked (Pay and Gianoli 2024; Dagevos and Onwezen 2025). No policy measures (within the analysed set) seem to address these barriers in a more structural way. The transposition in Belgium of the European Directive on unfair trading practices could be a relevant policy measure to analyse in this regard.

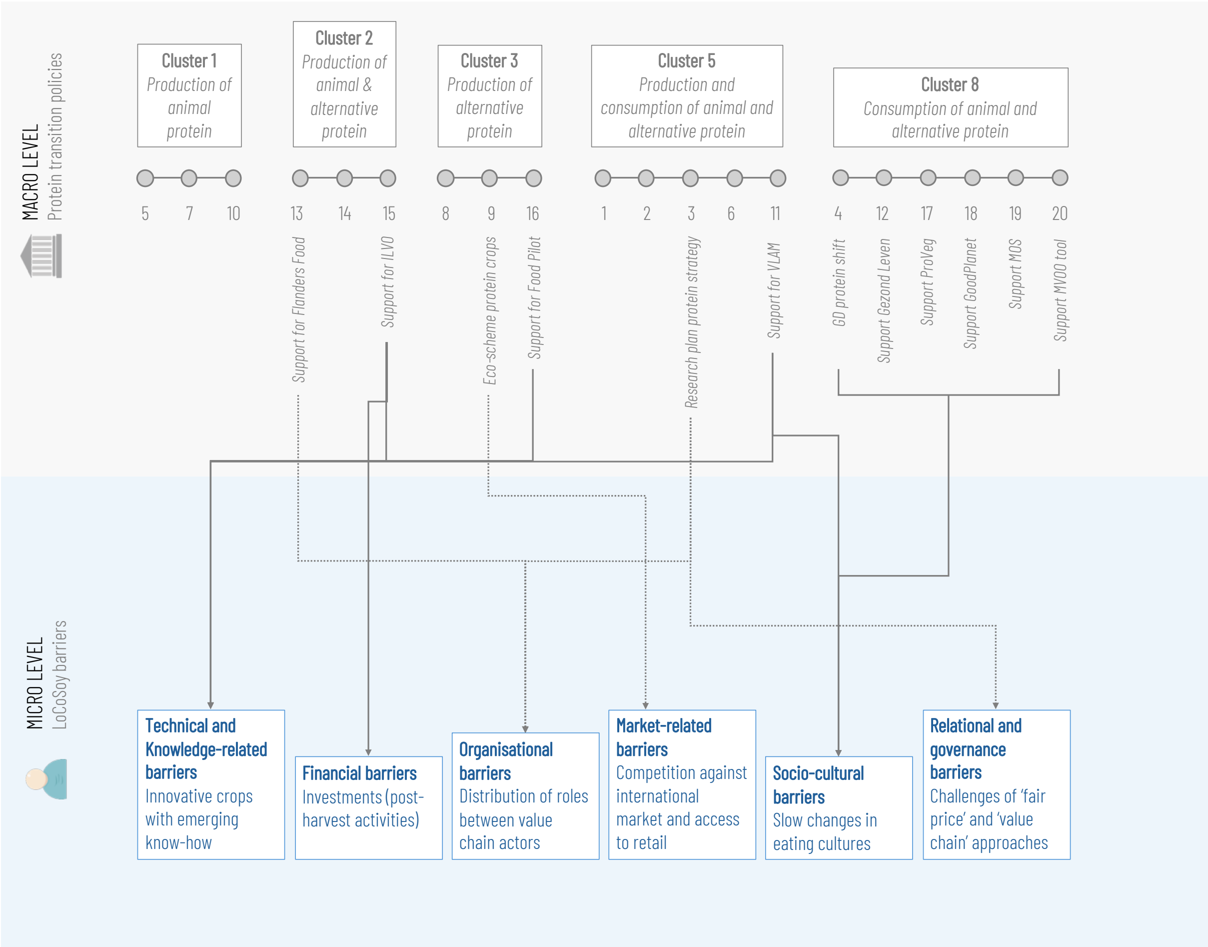


Figure 21. From micro to macro: identifying policy measures targeting the protein transition that could address the barriers encountered by the LoCoSoy value chain (policy numbers refer to order in Table 3). Dotted lines indicate that policy measures provide temporary or partial support.

6.4.2 A dual policy setting

Out of the twenty policy measures identified, twelve could contribute to addressing part of the barriers faced by the LoCoSoy chain. While this showcases the density of the Flemish policy landscape on this matter, it also illustrates its fragmentation. The analysis points to a dual policy setting, with two main policies that directly target and oversee the protein transition. On one side, the *Flemish protein strategy* officially addresses the four dimensions of the protein transition. In practice, however, it seems to be more importantly focused on the production of protein (e.g. through its *Research plan for the implementation of the protein strategy*). On the other side, the *Green deal protein shift on our plates* mainly covers the consumption dimension. While a certain alignment between policies is pursued, analysing the micro-level implementation of this dual production-consumption policy setting beyond the LoCoSoy case showcases signs of a series of paradoxes.

On the production side, the majority of measures favour new alternative protein (as in the case of the LoCoSoy value chain) or more efficient animal protein, thus mainly reflecting a techno-centric narrative (Duluins and Baret 2024b). While this is compatible with the objectives of the protein transition, the danger of such measures is to cause rebound effects (Jevons paradox) (Duluins and Baret 2024a). For instance, the *Nitrogen decree* requires either to add emission-reducing technologies in stalls or to reduce the size of animal herds. According to actors in the veal calf sector, the (theoretical) emission reductions from these technologies (up to -90%) exceed the macro-level reduction target for the sector (-28%). In turn, this could open opportunities for herd expansion at micro level to help offset technology investments (VILT 2024). As the emissions gains of such technologies remain uncertain and entail possible trade-offs between different types of nitrogen losses (e.g. NH_3, N_2O, NO_x) (Brownlie et al. 2024), increasing the size of the veal calf herd might lead to unintended consequences, also regarding other sustainability issues (e.g. animal welfare, impacts of feed production due to higher feed demand, etc.).

On the consumption side, the focus on dietary habits shown in the *Green deal protein shift on our plates* or in informational instruments such the activities by *Gezond Leven, ProVeg, GoodPlanet* and *MOS* strongly resonate with the consumer narrative (Duluins and Baret 2024b). While reducing total and animal protein intake is mentioned (e.g. in the Flemish food triangle), the focus of such initiatives is predominantly set on rebalancing the shares of animal and plant-based protein in our diets (from 60:40 to 40:60). The risk of focussing on the latter objective is to foster a *substitution paradox* in which an increase in alternative proteins (both on the production side and on the consumption side) is not accompanied by a decrease in animal protein, nor of total protein (Duluins and Baret 2024a). In practice, a monitoring of the protein intake of the Flemish population in 2023 and 2024 shows slow progress on the animal to plant-based protein ratio (59:41 in 2023 vs. 57:43 in 2024) (Rubens et al. 2025). On the contrary, total protein intake has slightly increased (73 g/cap/day in 2023 vs. 77 g/cap/day in 2024) and remains well above nutritional recommendations (Rubens et al. 2024, 2025), thus showing potential signs of the substitution paradox.

Besides the dual nature of this policy mix, a significant gap appears when looking at mid-chain actors (processors and retail), as highlighted in the LoCoSoy case. While these actors participate in the process, both through production-side measures (e.g. a retailer participated in the LoCoSoy project) or consumption-side measures (e.g. the *Green deal protein shift on our plates* grouped over 80 partners from the whole food system), their participation remains predominantly voluntary (e.g. voluntary agreements and targets) with few restrictive measures. The presence of *VLAM* and *Flanders Food* in the policy mix are important given that they originate and represent actors from the food industry. Yet, the duality and sometimes antagonistic nature of their activities with regards to the objectives of protein transition showcases the complexity of the matter.

Finally, an important aspect relates to the level of ambition and the nature of the policy measures. On the one hand, legally binding measures are restricted to the production side and may show a lack of ambition (e.g. it is questionable whether a 30% reduction in the pig population is sufficient to decrease impacts, as shown in chapter 5 (Riera et al. 2026), or have antagonistic objectives to the protein transition (e.g. CAP coupled income support, meat supporting campaigns), thus failing to tackle the overproduction of animals (Vallone and Lambin 2023). On the other hand, as in Austria, we find no restrictive measures targeting mid-chain stages or aimed at reducing meat consumption (Hundscheid et al. 2024).

6.4.3 The potential role of the meso level

Thus, the Flemish policy landscape surrounding the protein transition is complex. While it is dense and gathers several policy measures covering the different dimensions of the topic, it also appears as rather fragmented, showcasing a dual nature focusing on either production or consumption. Both dimensions predominantly fall under different competent authorities. This may put into question the effectiveness and synergies of such a dual policy setting, even though links between both are made. This situation, which can be found in other countries such as England (Benton 2023) or the EU (Van Zanten et al. 2025) is likely also at the origin of the presence of different narratives, mainly a techno-centric one and a consumer one, which in turn potentially exacerbate the lack of synergies. This situation is also exemplified in the case of the LoCoSoy chain, as the twelve measures that could contribute to addressing value chain barriers are led by almost as many different actors and organisations. This resonates with the call for greater horizontal integration, e.g. through food systems approaches at the policy level (Benton 2023; Van Zanten et al. 2025).

To further facilitate integration, meso-level actors have been shown to play a key role acting as an interface between the macro and micro levels (Borniotto et al. 2025), with potential for contributions to the protein transition landscape. The importance of meso-level actors such as research organisations has been illustrated in the case of LoCoSoy. Through research project settings, they can play a stabilising role in the development of innovative value chains. Similarly, organisations such as *ProVeg* or *Gezond Leven* may contribute to influencing consumption habits towards a better balance between animal and alternative protein sources. Yet, as they participate in operationalising the protein transition, meso-level actors also contribute to the emergence of narratives and paradoxes. The consumer narrative associated with the *Green deal protein shift on our plates* is also supported by other institutions, such as *Gezond Leven*, *ProVeg*, *GoodPlanet* or *MOS*. In parallel, actions promoting the consumption of (Belgian) meat (e.g. by *VLAM*) act in the opposite direction, possibly reinforcing the substitution paradox. Again, this points to the importance of integrated food system approaches to ensure policy coherence. In particular, sectoral approaches, e.g. through sectoral organisations, could be an avenue to pursue this. Sectors are perceived as more operational for food system actors (Borman et al. 2022). They fall under food system approaches but require that a series of attention points are taken into account (e.g. interaction of plant-based protein sectors with livestock sectors).

6.5 Conclusion

This paper set out to analyse the practical implementation of the protein transition in Flanders by looking at the interactions between the macro-level policy landscape and a micro-level value chain example. At the policy-level, the landscape is dense and includes a wide range of measures covering multiple dimensions of the protein transition. Yet, it also appears fragmented, with a big divide between production-side measures and consumption-side measures. Despite support from the macro and meso levels the analysis confirms the challenges of micro-level implementation at all stages of a value chain, from the niche production of a new crop to the challenges of finding processing options and partners and the slow changes in consumption.

The results presented must be taken cautiously as the analysed value chain constitutes a single example of implementation. Yet it allows to illustrate the challenges of a niche-level initiative wishing to engage in the protein transition. Similarly, while other policy initiatives and actors are involved in the macro-level policy context, the analysed set of policy measures is sufficient to showcase a series of challenges which need to be addressed. In conclusion, Flanders shows a strong will to move in the direction of a protein transition and has equipped itself with a substantial policy framework. Yet, the fragmented nature of the policy framework, the limited legal constraints of certain measures and their possible antagonistic objectives pose a series of challenges to effectively implementing the desired transition.

6.6 Supplementary material

Supplementary material for this chapter can be found at the end of the document (Appendix to chapter 6). It includes the following elements:

- Barrier categories
- Policy analysis
- Value chain analysis

Section 3

Reflecting on the journey

Fournir aux acteurs les clés pour une transition

Sytra

Chapter 7 General discussion

This final section takes a step back and discusses the main research findings from a wider perspective. Rather than deliberating further on the specific results of each chapter, here we propose a series of thoughts on the adopted methodological posture, from a more personal perspective as researcher, also discussing limitations of the approach. As a reminder, the approach adopted in this research has been guided by a triple methodological stance:

1. **Working at different scales:** as food system transitions occur at multiple scales, the research aimed to conceptualise and address this multiplicity of scales.
2. **Accounting for multidimensionality:** taking sustainability as a reference framework, we have strived to consider and assess its multiple dimensions (environmental and socio-economic).
3. **Contributing to food system transitions:** as an end goal, the objective of the research was to contribute to the different steps of a transition cycle.

In the introduction (paragraph 1.4) we identified three transversal research questions which resonate with these points (Figure 4). In this chapter, we go back to these three questions to structure our discussion.

7.1 A multi-scale framework for food system research

The first research question established in the introduction asked whether it is possible to *adopt a framework of analysis which conciliates the fact that food system transitions are multi-scalar?* This question was examined in particular in Chapter 2, leading us to propose a multi-scale framework of food system transitions, centred around three scales: the scale of action and decision making, the supply chain scale and the spatial scale. The main purpose of the framework is to bring to light the multi-scale nature of food system transitions to avoid scale-related challenges (e.g. ignorance, mismatch and plurality). In conclusion to the chapter, the adoption of a *meso-level*, *sectoral* and *territorial* scale of analysis emerged as a possible compromise to conciliate multiple scales. This has guided our research in subsequent chapters. Each of them aims to address the multiplicity of scales, although they occupy different spaces on the three-scale diagram (Table 18) [11].

[11] Here, we focus our discussion on chapters presenting empirical results on the Belgian livestock sector, i.e. chapters 3, 5 and 6. Elements of scale are also discussed in Chapter 4 but mainly reflect perspectives from the scientific literature (as the chapter is a literature review exercise).

Table 18. Positioning of research chapters on the three-scale diagram. Uppercase crosses in dark grey cells indicate coverage while lowercase crosses in light grey cells indicate partial coverage.

Scale	**Scale of action and decision-making**			**Supply chain scale**			**Spatial scale**		
Level	Micro	Meso	Macro	Production	Supply chain	Consumption	Local	Territorial	Global
Chapter 3 Micro-meso farm-level assessment of Walloon bovine systems	x	X		X			x	X	
Chapter 5 Macro-meso prod. & cons. scenarios of the Belgian livestock sector		X	x	X		X		X	
Chapter 6 Macro & micro value chain-wide analysis of the Flemish protein transition	X	x	X	x	X	X	x	X	

7.1.1 Covering three scales

With regards to the *scale of action and decision-making*, all chapters try to cross the divide between macro and micro. Starting with micro-level farm data, chapter 3 strives to identify dominant practices and farming systems to overcome micro-level heterogeneity and bring the scale of analysis to the meso level. The end-result provides a picture of the Walloon bovine sector which accounts for a certain degree of micro-level diversity, allowing to identify and differentiate most sustainable and promising farming systems. Chapter 5 also adopts a meso-level approach but relies on macro-level data (national animal number statistics) as the objective is to design scenarios for the Belgian livestock sector. Macro-level data is broken down into several farming systems within each sector to avoid oversimplification and increase actor identification to the scenario exercise, thus bridging to the meso level. While both chapters take different starting points (micro-level farm data vs. macro-level animal number statistics), they are good examples of how accounting for diversity offers an opportunity to link between micro and macro, i.e. between practices and policies. Chapter 6 takes a dual approach analysing how the macro-level policy context interacts with micro-level operations by value chain actors. While not situated at the meso-level per se, the chapter still aims to bridge between macro and micro, while also discussing the role of meso-level actors.

With regards to the *spatial scale*, all three chapters can be considered to cover a territorial scale, with chapter-specific settings. Chapters 3 and 6 investigate the regional level, focusing respectively on Wallonia and Flanders. This allows to focus on regional-specific issues and challenges, such as the preservation of grasslands in Wallonia through different types of bovine systems (chapter 3), or the practical implementation of a protein transition in Flanders, where important environmental pressures from the livestock sector (nitrogen pollution) coexist with an extensive (yet fragmented) policy framework in favour of such a transition. Making the link between the country's two regions, Chapter 5 takes a national perspective focussing on Belgium as a whole. While this leaves less room to focus on regional topics, it allows to better understand how the livestock system operates at a national and international level. Inter-regional flows of animals across value chain stages or the fact that Belgium is deeply embedded in EU and international markets are harder to assess at regional scale (mainly due to lack of data). As discussed in earlier chapters, whether the territorial level is the most appropriate scale of analysis remains an open question. As some degree of action and decision-making depends on this level, we would argue there is value in discerning what is happening at these scales, while keeping in mind that certain issues are played out a wider scales while others necessitate a localised approach.

With regards to the *supply chain scale*, a sectoral approach targeting the livestock sector is adopted throughout the research. Chapters 3 and 5 specifically focus on clearly identified sectors (dairy and beef in chapter 3, dairy, beef, pork, poultry and eggs in chapter 5). As discussed, this choice should lead to supposedly easier involvement of food system actors and their engagement with results (Brouwer et al. 2020). For instance, sector-specific focus groups were organised to the discuss the design and results of scenarios in Riera et al. (2019). Similarly, the micro-level organic soy value chain analysed in chapter 6 gathered actors throughout the chain. The macro-level analysis in chapter 6 adopts a somewhat broader approach as it takes the protein transition as an entry point rather than specific sectors. Although this does not impede from discussing sector-specific issues (e.g. planned 30% reduction of animals in the pork sector), putting the emphasis on protein inevitably shifts the focus away from individual sectors (despite a distinction between animal and alternative sources). While the sectoral approach is common to all chapters, the value chain stages in focus vary. Chapter 3 looks specifically at the farming stage, while chapter 5 tackles production and consumption and chapter 6 aims to take a value chain-wide perspective. A clear gap appears on mid-chain stages, which are only covered in chapter 6 at micro level.

7.1.2 A framework that reveals analytical choices and compromises

In conclusion, we believe that from an analytical perspective, the proposed framework indeed contributes to accounting for the multi-scale nature of food systems. It reveals what levels of food system transitions are being covered and, maybe more importantly, what levels are not, thus clarifying the scope of research and fostering transparency. Cleaver and Franks (2008) identify checklists as possible tools to communicate and facilitate engagement with concepts. In this regard, the conclusions proposed in chapter 2 (engaging in food systems thinking; adopting a meso-level of analysis; accounting for diversity; working at a relevant spatial scale) could be considered as a checklist favouring the acknowledgement of multiple scales.

Through the different chapters, we have strived to apply these conclusions by adopting a *meso-level*, *sectoral* and *territorial* scale of analysis. While Table 18 indicates that such approaches could indeed constitute a compromise to traverse across scales and levels, certain attentions points arise. First, a risk with the adoption of meso approaches resides in situating the analysis in a 'messy middle'. Positioned as an interface between macro and micro, meso-level approaches potentially become the target of both levels but might feel less actionable for food system actors, in particular for the micro level as hinted by the reactions to the first set of livestock scenarios (Antier et al. 2020b). Additionally, although the meso level has its own network of actors (farm counsellors, farmer unions, sectoral organizations, etc.), activities, properties and policy needs (Quattrini et al. 2024), it remains largely understudied compared to micro-level and macro-level approaches (Schenk et al. 2007; Quattrini et al. 2024). Second, all levels are not covered equally in our analysis (e.g. mid-chain actors or global scale). Compared to the scale of the investigated issue (i.e. the global livestock transition), the scope of our research covers a very limited space (i.e. the Belgian livestock sector), with many other actions and activities at stake at other levels and scales. Yet, through the adopted approach, we hope to account for some of the scale-related challenges introduced in chapter 2 (ignorance, mismatch and plurality), despite the compromises and trade-offs discussed throughout the manuscript. For instance, while our research does not cover the international and global levels (e.g. by considering displaced effects outside of Belgium), the approach seeks to introduce global considerations (e.g. necessity to reduce extent of livestock production and consumption) at the territorial level. Whether this approach of analysis effectively supports food system transitions in practice, or more generally how food system transitions are played out at multiple scales, is discussed in paragraph 7.3.

The framework proposes one way of conceptualising the multiplicity of scales, centred around three scales. This contribution is complementary to existing transition frameworks (Loorbach 2010; Duru et al. 2015a; Dendoncker et al. 2018; Gaupp et al. 2021; Prost et al. 2023; Meynard et al. 2023), which rarely acknowledge this issue explicitly. Other elements related to food system transitions, such as their timescale, are briefly discussed at the end of chapter 2 but not covered explicitly by the framework. Paying greater attention to the timeframes of transitions would be an interesting addition, especially since these elements seem to be rarely researched, as discussed in chapter 4 in the case of foresight studies.

7.2 Multidimensionality at multiple scales

The second research question asked *how to address the multifunctional nature of food systems while accounting for the multiplicity of scales?* The necessity to operate sustainability transitions and the resulting need to measure and monitor sustainability has undoubtedly led to an 'indicator explosion' (Riley 2001; Bergez et al. 2022), with sustainability indicators[12] being increasingly used as governance tools to improve the sustainability of food systems (de Olde et al. 2025).

The use of sustainability indicators triggers a series of methodological considerations and dilemmas, related to the multidimensionality of assessments, the nature of indicators and data, the use of functional units, etc. From an empirical perspective, in particular in chapters 3 and 5, we have tried to pay specific attention to integrating well-balanced and relevant sets of indicators. This has materialised by choices to include both environmental and socio-economic indicators, or to consider multiple functional units (per kg, per ha and total impacts). In this paragraph we take the opportunity of discussing our approach to sustainability assessments, how different levels and actors of food systems interact and depend on sustainability indicators, and to what extent indicators can contribute to drive change.

7.2.1 Multidimensional sustainability as a guide and a compromise

Among the methodological dilemmas of sustainability indicators (see paragraph 3.1.3 and Figure S1), we find that sustainability assessments are rarely multidimensional, and that different sustainability dimensions do not receive the same attention. Stated in the scientific literature (Binder et al. 2010; Lebacq et al. 2013; Schader et al. 2014; de Olde et al. 2016), this has been

[12] As a reminder, sustainability indicators (or metrics) can be understood as measurable variables which supply information on other variables and allow to reflect the sustainability performances of a process or system (Bockstaller et al. 2008; Lebacq et al. 2013; de Olde et al. 2016).

confirmed in the case of foresight scenarios in chapter 4. Imbalances occur not only between sustainability dimensions (environmental sustainability tends to be more assessed than socio-economic sustainability), but also within the environmental dimension (GHG measurements are more frequent than biodiversity impacts or food waste). Besides issues of imbalance, methodological uncertainties remain regarding the measurement of certain themes and indicators, not only when their assessments are less frequent and complex (e.g. biodiversity), but also when they are common (e.g. climate). This is illustrated in the case of climate goals and the ongoing discussions regarding the impact of short- vs. long-lived greenhouse emissions and the best global warming potential indicator to use accordingly (Lynch et al. 2020; Zionts et al. 2025).

While we have tried to pay attention to integrating a diverse set of indicators, these limitations can also be found in our research: certain themes are missing (e.g. there are no indicators regarding animal welfare or chemical pesticides in chapter 5), certain indicators are more 'robust' than others (e.g. the socio-economic indicators assessed in chapter 5 remain limited in scope), the aggregation of indicators in chapter 3 is not perfectly balanced between area-based and product-based functional units, etc. These limitations and the construction of indicator sets are important to take into account as indicators contribute to shaping practices (as further discussed below). In the end, as pointed out by De Olde et al. (2025), we should remember that indicators remain useful but imperfect tools with a tendency *'to measure the simple when the desired outcome is complex'*. As these measurement also have a cost, finding a balance between the added value of indicators and their measurement cost can be a way to guide indicator development (as proposed in Figure 12). As with covering multiple scales, multidimensional approaches may entail a compromise between getting a 'system-wide' overview and broader coverage of topics or gaining an in-depth understanding on specific issues.

7.2.2 Sustainability assessments and indicators at different levels and for different actors

Bergez et al. (2022) identified three main approaches to sustainability assessments: agri-environmental indicators, life-cycle assessments and ecosystem service assessments. To complement this analysis and further illustrate the diversity in scope and boundaries of sustainability assessments, we look at three examples taking different approaches at the intersection between scales and the resulting levels being targeted (Table 19).

Farming system assessments. As a first example, we take the case of farm-level assessment frameworks at local or national level, such as those developed to monitor the implementation of the European common agricultural policy. They often rely on agri-environmental indicators, which can be monitored through initiatives such as the farm accountancy data network (FADN), now turned into the farm sustainability data network (FSDN). This level of analysis falls under farming systems approaches and has concentrated significant efforts of indicator development (Bockstaller et al. 2008; de Olde et al. 2016).

Food system assessments. As a second example, recent developments of indicator frameworks are increasingly adopting food system approaches targeting all levels and scales of food system. The Food Systems Countdown Initiative (FSCI) is a prominent case of a global and food system-wide assessment framework, which emerged from the 2021 United Nations Food Systems Summit (UNFSS) (Schneider et al. 2023, 2025). The FSCI proposes a global assessment framework comprising 50 indicators which not only measure farm-level performances but also include consumption-side considerations; governance- and policy-related elements; and some indicators linked to market-related aspects, the role of the private sector and mid-chain actors. All indicators are assessed at national level and the main entry point of the framework remains a comparison across nations rather than one comparing global value chains and commodities.

Value chain assessments. Staying at the global level, in complement to frameworks centred on national perspectives, we consider value-chain centred (i.e. sectoral) approaches as a third example. An illustration of such approaches can for instance be found in the Transparency for sustainable economies platform (Trase), aiming to map and monitor specific value chains at global level (e.g. soy, cocoa, palm oil, beef, etc.), and assess their sustainability, for instance in terms of deforestation (Zu Ermgassen et al. 2020, 2022).

Table 19. Comparison of three sustainability assessment frameworks in terms of targeted stages of the value chain, targeted geographical scale and targeted actors.

Example of assessment framework	Value chain stages unit of analysis	Geographical unit of analysis	Target actors
EU CAP monitoring	Farming systems	EU member states	- EU institutions - National governments - Farmers
FSCI	Food systems	Global nations	- National governments - International organisations
Trase	Sectors (value chains)	Global value chains	- National governments - Value chain actors

The three approaches take different entry points to the food system and, as a result, target different actors (Table 19). The sustainability assessments carried out in this manuscript could to some extent be considered compatible with all three approaches. The analysis of Walloon bovine systems performed in chapter 3 clearly resonates with the first approach adopting a farming systems perspective to monitor farm-level sustainability. While it has value on its own, this analysis is also used to feed the national-level scenario exercise performed in chapter 5. Given the boundaries of the assessment, the latter chapter could be aligned with the second approach and initiatives such as the FSCI. Chapter 5 and particularly chapter 6 also strive to adopt a sectoral perspective and thus show some similarities with value-chain centred approaches such as Trase. In all three cases, the purpose of the assessment is to inform both the macro level (policy), and possibly the micro level (farmers and food system actors).

The perspective of food system transitions requires to define the relevance and potential for transformation of these different approaches at different scales. Van Passel and Meul (2012) argue in favour of multi-level and multi-user assessment frameworks as an efficient way of fostering food system sustainability. As sustainability improvements at one stage may benefit the value chain as a whole, we need a combined view on sustainability at different stages (multi-level). Furthermore, as different users have different needs, these sustainability assessments also need to be sufficiently tailored (multi-user). For instance, while farmers may benefit from a comprehensive set of individual indicators, policymakers are more likely to resort to unique composite indicators (Van Passel and Meul 2012).

Eventually, the potential for transformation also depends on the capacity of actors at different levels to steer the sustainability of food systems. This is discussed from a broader perspective in terms of power and agency in paragraph 7.3.2. With regards to metrics, one way of apprehending this is to distinguish between ‘metric setters’ and ‘metric takers’, i.e. whether or not actors contribute to the development of the metrics they use (de Olde et al. 2025), and for what purposes actors rely on sustainability indicators (Table 20):

- **Famers:** Farmers are typically considered to be metric takers. They rely on sustainability metrics to make sure they comply with policy and value chain requirements, or in a more voluntary perspective, to inform their practices and management choices.
- **Mid-chain actors:** Mid-chain actors can be both metric takers and setters. They rely on sustainability metrics to comply with both regulations and voluntary commitments, and may also use metrics to set sustainability requirements for upstream activities to gain credibility and facilitate access to markets.

- **Consumers:** Consumers can be seen as metric takers. Although their behaviours are not directly constrained by sustainability obligations, they may use sustainability metrics to guide and inform their choices in a voluntary way.
- **Macro-level actors:** Policymakers create sustainability requirements which apply to micro-level value chain actors. They are also bound to enforcing and meeting policy targets which have been set by themselves or at higher policy levels.
- **Meso-level actors:** Farmer unions, advisory services or research institutions are not usually bound by sustainability targets, but play a role in accompanying micro-level actors (voluntarily or through commercial schemes) and in informing macro-level policy.

Considering the elements above, a few conclusions and attention points can be raised with regards to the use of metrics and their capacity to drive change. First, measuring the sustainability of individual behaviours (e.g. farmers and consumers) is not sufficient to drive a change of practices since they are embedded in wider value chains and food systems. Beyond their position in the value chain, individual actions are also strongly influenced and constrained by other structuring elements, such as personal beliefs and norms. Relieving an information deficit through increased access to information alone is often insufficient to drive change (Benton 2023; de Olde et al. 2025). Second, we have seen that a gap often remains between metrics (proxies) and actual practices. As a result, in conceptualising leverages of systemic changes, metrics and standards are often considered as least effective leverage points. It is argued that the use of metrics tends to focus on optimization of systems rather than larger reconfigurations (de Olde et al. 2025).

Thus, we should remain cautious about putting too much emphasis on metrics as a theory of change and ensure that they are not too actor-centric or put excessive weight on individual behaviours. This resonates with the importance of considering jointly relative functional units (per kg or per ha) and absolute or total impacts, to inform both on the sustainability of a particular product or process and of the system as whole (de Olde et al. 2025). With regards to types of indicators, it may also be worth considering whether effective implementation of policies should rather strive to measure outcomes through impact-based indicators or fostering practices through means-based indicators. Depending on the level of the analysis (e.g. individual vs. societal), the most relevant types of indicators might not be the same.

Table 20. Sustainability requirements and uses of sustainability metrics of food system actors at different levels.

Levels of action and actors	Position to metrics	Compliance with sustainability requirements	Use of sustainability metrics	Examples
Micro level				
Farmers	Metric takers	**Yes** Policy requirements Value chain requirements	To comply with policy or value chain requirements To inform practices	Policy: EU CAP payments Value chain: organic label, milk carbon footprint[1]
Mid-chain	Metric takers and metric setters	**Yes** Policy requirements Voluntary value chain agreements	To comply with policy or value chain requirements To guide practices upstream To gain legitimacy downstream	Policy: EU CSR directive, EU Green claims directive, EU Deforestation regulation… Value chain: Green deal protein shift on our plates, sustainable soy and zero deforestation commitments[2]
Consumers	Metric takers	**No** Indirect nudges (taxes, food environments)	To inform consumption choices	Meat taxes Consumer guides Nutri- & eco-scores Nutritional recommendations
Macro level				
Policymakers	Metric takers and metric setters	**Yes** Higher-level policy requirements	To guide activities of micro-level actors To comply with higher-level policy requirements	EU Member States needing to enforce EU-level legislation.
Meso level				
Unions, Counsellors, Research	Metric takers and setters	**No?**	To accompany activities of micro-level actors To inform and help implement policy	Voluntary or commercial farm assessment tools to monitor farm performances[3]

Notes:

[1] Dairy cooperatives may put internal schemes in place that incentivise and reward farmers to reduce the carbon footprint of the milk they produce (example for Arla: https://www.arla.com/sustainability/the-farms/how-arla-farmers-reduce-dairys-carbon-footprint/).

[2] The Belgian feed association (BFA) has pledged that by 2030 all soy used by Belgian feed companies would comply with the European Feed Manufacturers' Federation (FEFAC) guidelines (https://www.bfa.be/Duurzamesoja).

[3] Farm assessment tools can be used to verify compliance with policy requirements, but also to generate new products such as carbon storage certificates or credits.

In conclusion, while metrics may be used to inform behaviour change at individual level, their primary purpose should be to drive systems change at societal level (Van Zanten et al. 2025). Comprehensive (e.g. multidimensional), multi-level and multi-actor sets of indicators may be valuable tools in this perspective.

7.3 Multi-scale transitions in practice

To conclude this chapter, we look at the third transversal research question, which asked *how to navigate the different stages of the transition cycle while accounting for the multiplicity of scales?* In this paragraph we first discuss how transitions can be conceptualised, and how the main framework used in this research relates to complementary frameworks. We conclude by discussing what we have learnt on how different levels and actors (including research) can actually drive transitions.

7.3.1 Conceptualising transitions through different frameworks

For the purpose of this research, and based on existing transition governance frameworks, we have proposed to conceive transition cycles as a succession of three iterative steps, including an assessment phase, an envisioning phase and an implementation phase (see paragraph 1.2.3 and Figure 1). The second section of this manuscript aimed at navigating this cycle, with chapters 3 to 6 each targeting one (or two) of these steps (Figure 4). While we conceive transitions as an iterative process with distinct and successive steps, whether transitions truly happen in such a coordinated way in practice can be questioned.

Throughout our research, the assessment and envisioning steps are indeed closely linked. Although restricted in scope to Walloon bovine systems, chapter 3 specifically focuses on assessing their diversity and sustainability. The results of this chapter directly feed into chapter 5, along with similar results from other sectors, which allow to perform a joint assessment of the Belgian food and farming system. In turn, this allows us to evaluate current challenges faced by the livestock sector (e.g. manure surpluses, decrease of grasslands and over-reliance on high-impacting animal feed, overconsumption of animal protein, etc.). Taking this as a starting point, we then move to an envisioning step through a scenario exercise (see Box 3) in which we devise possible alternative configurations of the system, and assess and compare their outcomes. Strictly speaking, the research process initiated in these two chapters did not move to the next step, i.e. the implementation of transition pathways. Nevertheless, this transition phase was investigated in chapter 6 in the case of the protein transition in Flanders. As such, the research carried out allowed to cover all three steps of a transition cycle, although all three steps neither follow each other, nor a sequential progression from a temporal perspective. This may question whether transition cycles are truly sequential or not. The implementation of the Flemish protein transition was already under way when performing the assessment and envisioning exercises of chapters 3 and 5 (which are not part of the coordinated Flemish protein transition movement). Rather than constituting an ex-ante contribution to the implementation of the Flemish protein transition (as presented in the sequence of chapters in this manuscript), the scenario exercise could provide valuable information for a second iteration of a protein transition cycle. This confirms the iterative nature of transitions, and the fact that, although the different steps do not necessarily follow a sequential order, they still have the potential to contribute to transition cycles, even if they are already underway.

Box 3. Foresight scenarios as a tool to discuss transitions.

Foresight scenarios are used as a central tool in the context of this work to apprehend possible transitions. Their use is discussed in chapters 4 and 5. Our analysis is mainly centred on strategic foresight scenarios rather than on external scenarios that focus on factors beyond the control of actors (Börjeson et al. 2006). This can be explained by the process-oriented nature of transition governance and transition management, which has guided this work and contributed to identifying the initial set of scenarios analysed in chapter 4. Keeping this in mind, one conclusion of chapter 4 highlights that different types of scenario exercises coexist as different purposes can be pursued. In our case, the objective of using foresight scenarios mainly resided in opening up a debate with food system actor on possible futures for the Belgian livestock sector, hence the choice to adopt a mixed exploratory/normative approach comparing a diverse (but limited) set of preidentified narratives. In other cases, single-scenario studies might be more relevant to demonstrate or push specific topics on the agenda. As such, scenario exercises should be considered in their wider context, according to their purpose and situated in time.

The policy analysis exercise performed in chapter 6 provides a good opportunity to link the transition cycle with other transition frameworks and cycles, first of which the policy cycle. While it may be more specific in scope (in the sense that it applies to the design and implementation of policies), it is also conceptualised as a succession of iterative steps, which are very much comparable and aligned with transition cycles (Connors 2016; Galli et al. 2020; Brunori 2023) (Figure 2). Chapter 6 is a good illustration of the possible alignment of both cycles as it analyses the implementation step of both a policy framework and of a wider transition process. As policy cycles also face temporal misalignments with regards to the succession of its steps (Borniotto et al. forthcoming), the overall (mis)alignment between policy cycles and transition cycles would be interesting to investigate further.

In general, both transition and policy cycle frameworks take strong 'management' perspectives, adopting a process-oriented and goal-seeking approach (Duru et al. 2015a; Prost et al. 2023). Yet, as transitions also have an unpredictable (e.g. accounting for climate change events or 'black swan events') or reversible (e.g. the reversal of the EU green deal) nature, such frameworks are complementary with more analytical frameworks, such as the MLP, which remind that reconfigurations result not only from the uptake of niche-level innovations and breakdown of established regimes, but also from the influence of external landscape elements (Loorbach et al. 2017). These processes are overlooked in the present research on the livestock transition and would merit further investigation. As introduced in the concluding remarks of chapter 5 and highlighted again in the previous paragraph, conceiving transitions through successive steps of transition management cycles is a simplification of these complex and non-linear shifts that emerge over long periods of time (Loorbach et al. 2017; Kueffer et al. 2019). In the context of this research, it helped provide an analytical framework. Yet, rather than falling in the trap of envisioning a desired and consensual future, which may lead to paralysis rather than action, research should also nurture a sense of shared responsibilities and environmental awareness. In this sense, it is argued that the term *transformation* may put too much emphasis on novelty, innovation and disruption, while overlooking elements such as empowerment, justice and agency (Kueffer et al. 2019).

7.3.2 Driving transitions: from transition cycles and scales to actors

To further discuss how transitions are actually played out in practice, we make the link between transition processes and the multi-scale framework and look at the power and agency of food system actors at different levels, i.e. the ability of each actor to define its own actions and to steer the organisation of food systems in a certain way (Figure 22).

Farmers and consumers. Starting at the micro level, we have already stressed that individual farmers and consumers are embedded in wider value chains. As a result, they do not have complete command on the actions they take (Van Zanten et al. 2025), e.g. because their farming practices need to comply with certain policy or value chain requirements, or because consumption choices are nudged and steered in certain ways (as discussed in paragraph 7.2.2). This does not mean that the farm stage is exempt of power and agency. Moving up to the meso-level, farmer voices, e.g. through farmer unions, can have significant impact on the policy context

(Germond 2013; Matthews 2024; Hulot 2025). The same could be said of the consumption stage, with civil society and consumer or health organisations having more power to activate system reconfigurations, although likely to a lesser extent than farming sector and food industry organisations (Carrad et al. 2023).

Mid-chain actors. In between the production and consumption stage, value chain actors (either micro-level private companies or meso-level sectoral organisations) have been shown to possess a great capacity to steer the system at all levels (Vallone and Lambin 2023; Baudish et al. 2024). Yet, the extent of this power may depend on the geographical level of operation of the actor and its belonging to the regime or niche level. As shown in chapter 6, a micro-level food processor willing to set up a local and organic soy value chain faces significant challenges of implementation due to is niche-level setting with regards to regime-level configurations (e.g. globalised market, competition with similar and better-established options within retail, etc.).

Policymakers. Finally, moving to the macro level, the agency and power of policymaking to influence micro-level operations at different stages remains a crucial point under consideration. Here too, power may depend on the geographical scale. In a European context, the EU level has historically been a significant steering force of European agriculture. As recent reforms focus on increased decentralisation and simplification of the EU farming policy (Guyomard 2025; Van Zanten et al. 2025), the level of agency and power may increase within lower geographical levels of governance. This resonates with debates regarding the best strategy for effective and efficient governance between centralised and decentralised models, but also how governance models are defined in the name of efficiency (e.g. as seen currently in the EU) (Hooghe and Marks 2009).

In sum, hot-spots of power and agency appear at different levels (Figure 22). Moving across levels, a question arises in the competition between these different levels: how does the power of private value chain actors, farmer unions or sectoral organisations compare to (and influence) that of national and international policymaking? On the one hand, Benton (2023) reminds us that regulators are the ones that set the rules of the game while market actors operate within those rules to maximise profit. On the other hand, analysing the abandonment of the proposed EU sustainable use of pesticides regulation, Pe'er et al. (2025) highlight the role of the agrochemical industry in obstructing initiatives favouring the reduction of pesticides. Resolving questions of power distribution and asymmetries is important to identify the levels that are most relevant in steering sustainability transitions. For instance, the usefulness of monitoring the state of food systems at a national scale (e.g. as in the SFCI framework) might be downplayed by the limited capacity of nations to steer the organisations of their food system compared to global corporations.

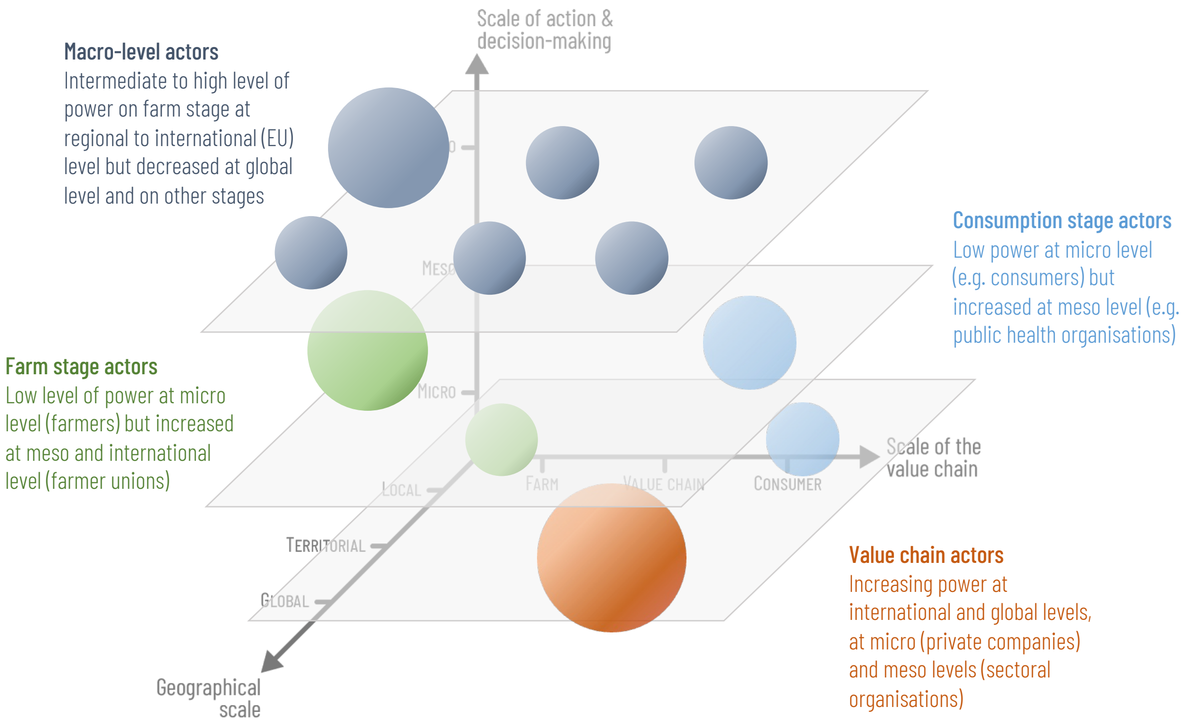


Figure 22. Visual representation of relation to power and agency to steer the organisation of food systems by food system actors at different levels. The size of spheres is proportional to the relative level of power and agency.

7.3.3 Food system transitions, what role for research

As a final paragraph, we analyse the position and role of a specific type of actor: researchers. Part of the research conducted in this PhD was done on behalf of/in collaboration with civil society organisations with the objective of contributing to their advocacy work. This was particularly the case of chapter 3 and a preliminary version of chapter 5 (Riera et al. 2019). In both cases, the distribution of responsibilities was clearly identified: environmental organisations defined the research questions, the scope of the research and the tested hypotheses (e.g. scenario assumptions), while we as researchers conducted the research independently. As such, part of the research can be considered to have been conducted at and in contribution to the science-policy-society interface.

Three main recommendations are put forward for research at this interface (paragraph 1.2.4): acknowledging a diversity of visions and revealing trade-offs; overcoming the failure of a 'knowledge deficit' model; questioning political ideologies. Our research meets several of these recommended good practices while falling short of others.

As discussed throughout the manuscript, we have paid particular attention to highlighting the diversity of visions and systems surrounding the livestock (and protein) transition, and their expected trade-offs. In doing so, we hope to contribute contextual and objectivation elements regarding a range of different possibilities and options on the question of the livestock transition in Belgium. How this attention to nuance and diversity is taken up in societal debates remains an open question, especially given the rather critical reception of a first scenario study on the Belgian livestock sector (Antier et al. 2020b).

On overcoming the failure of a 'knowledge deficit' model, three strategies are proposed (paragraph 1.2.4): co-creation and co-design; generation of transitions knowledge; proactive communication. All three strategies have to some extent been pursued in the context of this research. Part of the research has indeed been carried out in close relationship with extra-academic actors, either in a co-design process (civil society in the case of chapters 3 and 5), or in a co-creation process (with value chain actors in the case of chapter 6). Beyond system knowledge, transitions knowledge has been generated on the costs of inaction and the benefits of action (e.g. design of BAU and transition scenarios in chapter 5), or on a vision of the functioning of the system after transformation (e.g. development of a small-scale organic soybean value chain). The research did however not get to proposing a concrete plan for action (e.g. through a back casting exercise). Finally, some results can be considered to have been 'proactively communicated' to the wider society, not only by the partnering civil society organisations but also by the research side, for instance by participating in wide-audience debates or in a parliamentary session.

With regards to challenging political ideologies, we must acknowledge that though some of the research produced is likely to enter in conflict with prevailing paradigms and narratives (as shown to some extent in the policy analysis of chapter 6), we have not taken the opportunity to reflect on how to change current political ideologies. While this topic seems more likely to be addressed by research situated at the macro level, it would be interesting to explore how meso-level approaches could contribute to the question.

To conclude, we reflect on the types and intentions of the knowledge produced. Providing 'policy knowledge' for civil society and food system actors undoubtedly initiated the research process. The information contained in this manuscript is an attempt at complementing this initial 'policy knowledge' with a more 'critical' approach, resulting both in more theoretical conceptualisation exercises (chapters 2 and 4) and hybrid empirical content situated at the interface between the 'policy knowledge'/'critical knowledge' spectrum (chapters 3, 5 and 6).

As Cleaver and Franks (2008) argue in favour of coherent theorisation and conceptualisation to aid designing more adequate strategies and interventions, it would be a pleasing achievement if the conceptualisation effort pursued in this document not only showed (albeit modest) value for science, but also within wider society spheres (e.g. policy). In this case, the intended process of research would have gone from policy to science and back. With this in mind, we believe the following text by Benton (2023) to provide a satisfying closing statement:

> *'It does not require academics to be activists, but for the community to work together better to deliver the evidence needed that will drive change. This may include targeting evidence at civil society to politicise an issue to create an enabling political environment for change.'*

References

Agentschap Landbouw & Visserij (2024) Projecten realisatie eiwitstrategie

Agentschap Landbouw en Zeevisserij (2024) Landbouwcijfers. Agentschap Landbouw en Zeevisserij

Agentschap Landbouw en Zeevisserij (2025) Onderzoeksnoden Vlaamse land- en tuinbouw. Verslag workshops Platform voor Landbouw- en Voedingsonderzoek. Brussel

Aguilera E, Rivera-Ferre M (2022) La urgencia de una transicion agroecologica en Espana - Análisis de escenarios, estrategias e impactos ambientales de la transformación del sistema agroalimentario español. Amigos de la Tierra

Aiking H, De Boer J (2020) The next protein transition. Trends Food Sci Technol 105:515–522. https://doi.org/10.1016/j.tifs.2018.07.008

Antier C, Petel T, Baret P (2020a) Etat des lieux et scénarios à horizon 2050 de la filière céréales en Région wallonne. Sytra - Earth and Life Institute - UCLouvain

Antier C, Petel T, Baret P (2019) Etat des lieux et scénarios à horizon 2050 de la filière pommes de terre en Région wallonne. Sytra - Earth and Life Institute - UCLouvain

Antier C, Riera A, Baret P (2020b) A participatory prospective approach fails to ignite a debate on the future of the livestock sector in Belgium. Proc 14TH Eur IFSA Symp 576–589

Auclair O, Eustachio Colombo P, Milner J, Burgos SA (2024) Partial substitutions of animal with plant protein foods in Canadian diets have synergies and trade-offs among nutrition, health and climate outcomes. Nat Food 5:148–157. https://doi.org/10.1038/s43016-024-00925-y

Balmford A, Ball TS, Balmford B, et al (2025) Time to fix the biodiversity leak. Science 387:720–722. https://doi.org/10.1126/science.adv8264

Barbier C, Couturier C, Pourouchottamin P, et al (2019) L'empreinte énergétique et carbone de l'alimentation en France - de la production à la consommation. IDDRI

Barbieri P, Pellerin S, Seufert V, et al (2021) Global option space for organic agriculture is delimited by nitrogen availability. Nat Food 2:363–372. https://doi.org/10.1038/s43016-021-00276-y

Bartlett H, Zanella M, Kaori B, et al (2024) Trade-offs in the externalities of pig production are not inevitable. Nat Food 5:312–322. https://doi.org/10.1038/s43016-024-00921-2

Batalla I, Pinto M, del Hierro O (2014) Environmental, social and economic aptitudes for sustainable viability of sheep farming systems in northern Spain. 11th Eur IFSA Symp Farming Syst Facing Glob Chall Capacit Strateg Proc

Battheu-Noirfalise C, Mertens A, Faivre A, et al (2024) Classifying and explaining Walloon dairy farms in terms of sustainable food security using a multiple criteria decision making method. Agric Syst 221:104112. https://doi.org/10.1016/j.agsy.2024.104112

Baudish I, Sahlin KR, Béné C, et al (2024) Power & protein—closing the 'justice gap' for food system transformation. Environ Res Lett 19:084058. https://doi.org/10.1088/1748-9326/ad3d6f

Baufayt H (2022) Bilan énergétique du secteur agricole wallon : estimation pour 2019 et analyse prospective à l'horizon 2050. Master thesis (UCLouvain)

Bava L, Anna S, Zucali M, et al (2014) How can farming intensification affect the environmental impact of milk production? J Dairy Sci 97:. https://doi.org/10.3168/jds.2013-7530

BCZ-CBL (2024) Annual report - Reporting year 2023. Belgische Confederatie van de Zuivelindustrie - Confédération belge de l'industrie Laitière (BCZ-CBL)

Béné C (2022) Why the Great Food Transformation may not happen – A deep-dive into our food systems' political economy, controversies and politics of evidence. World Dev 154:105881. https://doi.org/10.1016/j.worlddev.2022.105881

Béné C, Oosterveer P, Lamotte L, et al (2019) When food systems meet sustainability – Current narratives and implications for actions. World Dev 113:116–130. https://doi.org/10.1016/j.worlddev.2018.08.011

Benton TG (2023) Academics can do more to disrupt and reframe the solution space for food system transformation. Nat Food 1–3. https://doi.org/10.1038/s43016-023-00876-w

Bergez J-E, Béthinger A, Bockstaller C, et al (2022) Integrating agri-environmental indicators, ecosystem services assessment, life cycle assessment and yield gap analysis to assess the environmental sustainability of agriculture. Ecol Indic 141:109107. https://doi.org/10.1016/j.ecolind.2022.109107

Bertassello L, Winters P, Müller MF (2023) Access to global wheat reserves determines country-level vulnerability to conflict-induced Ukrainian wheat supply disruption. Nat Food 4:673–676. https://doi.org/10.1038/s43016-023-00806-w

Bijttebier J, Hamerlinck J, Moakes S, et al (2017) Low-input dairy farming in Europe: Exploring a context-specific notion. Agric Syst 156:43–51. https://doi.org/10.1016/j.agsy.2017.05.016

Billen G, Aguilera E, Einarsson R, et al (2024a) Beyond the Farm to Fork Strategy: Methodology for designing a European agro-ecological future. Sci Total Environ 908:168160. https://doi.org/10.1016/j.scitotenv.2023.168160

Billen G, Aguilera E, Einarsson R, et al (2021) Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity. One Earth 4:839–850. https://doi.org/10.1016/j.oneear.2021.05.008

Billen G, Garnier J, Pomet A, Bonnet B (2024b) Is food self-sufficiency possible for Reunion Island? Reg Environ Change 24:58. https://doi.org/10.1007/s10113-024-02226-3

Billen G, Garnier J, Ramarson A, et al (2017a) Scénarios prospectifs du système agro-alimentaire du bassin de la Seine à l'horizon 2040

Billen G, Garnier J, Thieu V, et al (2012) Localising the nitrogen imprint of the Paris food supply: The potential of organic farming and changes in human diet. Biogeosciences 9:607–616. https://doi.org/10.5194/bgd-8-10979-2011

Billen G, Lassaletta L, Garnier J (2015) A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade. Environ Res Lett 10:025001. https://doi.org/10.1088/1748-9326/10/2/025001

Billen G, Le Noë J, Garnier J (2018) Two contrasted future scenarios for the French agro-food system. Sci Total Environ 637–638:695–705. https://doi.org/10.1016/j.scitotenv.2018.05.043

Billen G, Le Noe J, Lassaletta L, et al (2017b) Et si la France passait au régime "bio, local et demitarien" ? Un scénario radical de sobriété alimentaire et d'autonomie protéique et azotée pour l'agriculture et l'élevage. In: Le Déméter 2017

Binder CR, Feola G, Steinberger JK (2010) Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. Environ Impact Assess Rev 30:71–81. https://doi.org/10.1016/j.eiar.2009.06.002

Bockstaller C, Feschet P, Angevin F (2015) Issues in evaluating sustainability of farming systems with indicators. Oilseed Fats Crops Lipids 22:12. https://doi.org/10.1051/ocl/2014052

Bockstaller C, Guichard L, Makowski D, et al (2008) Agri-environmental indicators to assess cropping and farming systems. A review. Agron Sustain Dev 28:139–149. https://doi.org/10.1051/agro:2007052

Boogaard BK, Oosting SJ, Bock BB, Wiskerke JSC (2011) The sociocultural sustainability of livestock farming: an inquiry into social perceptions of dairy farming. Animal 5:1458–1466. https://doi.org/10.1017/S1751731111000371

Borghino N, Wissinger L, Erb K-H, et al (2024) Organic farming expansion and food security: A review of foresight modeling studies. Glob Food Secur 41:100765. https://doi.org/10.1016/j.gfs.2024.100765

Börjeson L, Höjer M, Dreborg K-H, et al (2006) Scenario types and techniques: Towards a user's guide. Futures 38:723–739. https://doi.org/10.1016/j.futures.2005.12.002

Borman GD, De Boef WS, Dirks F, et al (2022) Putting food systems thinking into practice: Integrating agricultural sectors into a multi-level analytical framework. Glob Food Secur 32:100591. https://doi.org/10.1016/j.gfs.2021.100591

Borniotto D, Antier C, Baret PV (2025) A governance perspective on agri-environmental schemes: Actors, roles, and barriers. Ambio. https://doi.org/10.1007/s13280-025-02182-0

Borniotto D, Duluins O, Polman D, Baret P (Forthcoming) Timeline misalignment in the CAP: why ex-post evaluations currently fall short of informing next policy cycles. Forthcoming

Bowles N, Alexander S, Hadjikakou M (2019) The livestock sector and planetary boundaries: A 'limits to growth' perspective with dietary implications. Ecol Econ 160:128–136. https://doi.org/10.1016/j.ecolecon.2019.01.033

Brouwer ID, McDermott J, Ruben R (2020) Food systems everywhere: Improving relevance in practice. Glob Food Secur 26:100398. https://doi.org/10.1016/j.gfs.2020.100398

Brownlie W, Aziz T, Sutton MA, et al (2024) Nitrogen Mitigation. INMS Guidance Document on Measures for Sustainable Nitrogen Management. UK Centre for Ecology & Hydrology, Edinburgh

Brunori G (2023) Towards a new generation of (agri-) food policies. Bio-Based Appl Econ. https://doi.org/10.36253/bae-14003

Brunori G, Carzedda M, Iliopoulos C, et al (2024) Has transformation of food systems reached an impasse? Considerations on the role of agri-food research. Agric Food Econ 12:26, s40100-024-00308–8. https://doi.org/10.1186/s40100-024-00308-8

Bryant C, Aiking H, Alessandrini R, et al (2024) The Dublin Declaration fails to recognize the need to reduce industrial animal agriculture. Nat Food 5:799–801. https://doi.org/10.1038/s43016-024-01054-2

Bui S, Cardona A, Lamine C, Cerf M (2016) Sustainability transitions: Insights on processes of niche-regime interaction and regime reconfiguration in agri-food systems. J Rural Stud 48:92–103. https://doi.org/10.1016/j.jrurstud.2016.10.003

Burawoy M (2005) For Public Sociology. Am Sociol Rev 70:4–28. https://doi.org/10.1177/000312240507000102

Busch G (2006) Future European agricultural landscapes—What can we learn from existing quantitative land use scenario studies? Agric Ecosyst Environ 114:121–140. https://doi.org/10.1016/j.agee.2005.11.007

Calay V, Burny P, Rondia P (2020) Les futurs incertains de l'élevage bovin en Wallonie. Inst Wallon Lévaluation Prospect Stat IWEPS. https://www.iweps.be/publication/futurs-incertains-de-lelevage-bovin-wallonie/

Cammelli F, Addoah T, Furrer NA, et al (2025) Scaling out agroforestry and forest conservation in West Africa requires more transformative policy interventions in cocoa supply chains. Environ Res Food Syst 2:033001. https://doi.org/10.1088/2976-601X/adf117

Campbell B, Beare D, Bennett E, et al (2017) Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecol Soc 22:. https://doi.org/10.5751/ES-09595-220408

Candel J, Mathijs E (2024) Wat shift de pod? Staat de eiwitshift op het beleidsmenu? De eiwitshifters Podcast - Kristof Rubens

Carlile R, Garnett T (2021) What scale for the food system? Moving beyond polarised debates. Table Rep TABLE Univ Oxf Swed Univ Agric Sci Wagening Univ Res

Caron P, Ferrero y de Loma-Osorio G, Nabarro D, et al (2018) Food systems for sustainable development: proposals for a profound four-part transformation. Agron Sustain Dev 38:41. https://doi.org/10.1007/s13593-018-0519-1

Carpenter SR, Pingali PL, Bennett EM, Zurek MB (2005) Millennium Ecosystem Assessment - Ecosystems and Human Well-being: Scenarios, Volume 2. Millenium Ecosystem Assessment

Carrad A, Smits R, Charlton K, et al (2023) The role of Australian civil society organisations in food system governance: Opportunities for collaboration in dietetics practice. J Hum Nutr Diet 36:2336–2350. https://doi.org/10.1111/jhn.13195

Cash DW, Adger WN, Berkes F, et al (2006) Scale and Cross-Scale Dynamics: Governance and Information in a Multilevel World. Ecol Soc 11:art8. https://doi.org/10.5751/ES-01759-110208

CELINE-IRCEL, Federal Public Service for Health, Food Chain Safety and the Environment, National Climate Commission, et al (2023) Belgium's greenhouse gas inventory (1990-2021) - National Inventory Report Submitted under the United Nations Framework Convention on Climate Change

CELINE-IRCEL, Federal Public Service for Health, Food Chain Safety and the Environment, National Climate Commission, et al (2025) Belgium's greenhouse gas inventory (1990-2023) - National Inventory Document Submitted under the United Nations Framework Convention on Climate Change

Ceppatelli A, Pozo CA, Bonnet CM, et al (2024) The benefits of the dairy value chain to inclusive sustainable development in European highlands: a systems thinking approach. Sustain Earth Rev 7:27. https://doi.org/10.1186/s42055-024-00099-2

Chaudhary A, Brooks TM (2018) Land Use Intensity-Specific Global Characterization Factors to Assess Product Biodiversity Footprints. Environ Sci Technol 52:5094–5104. https://doi.org/10.1021/acs.est.7b05570

Chaumet J-M, Delpeuch F, Dorin B, et al (2009) Agrimonde – Scenarios and Challenges for Feeding the World in 2050. Summary Report. Springer Netherlands, Dordrecht

Chevalier C, Courtois A-M, Borniotto D, Baret PV (2026) Lock-ins within sustainability transitions: a conceptual framework for a systemic perspective

Cleaver F, Franks T (2008) Distilling or Diluting? Negotiating the Water Research-Policy Interface. Water Altern 1:157–176

Climact (2024) GHG emission factors of energy sources in Belgium (communication with Climact). Climact

Coates J, Durance P, Godet M (2010) Strategic Foresight Issue: Introduction. Technol Forecast Soc Change 77:1423–1425. https://doi.org/10.1016/j.techfore.2010.08.001

Comité Régional Phyto (2015) Actualisation des données et des indicateurs pesticides en vue de la présentation dans les rapports sur l'état de l'environnement wallon. CORDER Asbl Earth Life Inst Univ Cathol Louvain. https://corder.be/fr/node/189

Comité Régional Phyto (2017) Estimation quantitative des utilisations de produits phytopharmaceutiques par les différents secteurs d'activité. CORDER Asbl Earth Life Inst Univ Cathol Louvain. https://corder.be/fr/node/189

Connors S (2016) GeoPolicy: Science and the policy cycle. Geol EGU Blogs

Conseil Supérieur de la Santé (2019) Recommandations alimentaires pour la population belge adulte. Conseil Supérieur de la Santé (CSS), Bruxelles

Costanza R, d'Arge R, de Groot R, et al (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260. https://doi.org/10.1038/387253a0

Courtois A-M, Baret P (2024) Mapping lock-ins to the internalization of externalities in agri-food systems. EU FOODCoST - Horizon Europe Project. Deliverable 3.2

Courtois A-M, Baret P (2022) Quelles agricultures en 2050 ? Une démarche prospective et participative pour explorer les trajectoires de transition vers moins d'intrants Le cas de la production de betteraves sucrières en Région wallonne. Sytra - Earth and Life Institute - UCLouvain

Couturier C, Charru M, Doublet S, Pointereau P (2016) Afterres 2050 - Un scénario soutenable pour l'agriculture et l'utilisation des terres en France à l'hroizon 2050. Solagro

Couturier C, Gibert C, Richard A (2022) Afterres2050 - Biodiversité: Un scénario fondé sur la nature & pour la nature. Solagro.

Crémer S (2015) La gestion des prairies. Fourrages Mieux

Dagevos H, Onwezen MC (2025) Toward consumer-focused food policies: a toolbox for encouraging the protein transition. Sustain Sci Pract Policy 21:2454060. https://doi.org/10.1080/15487733.2025.2454060

Dalcq A-C, Dogot T, Beckers Y, et al (2020) The Walloon farmers position differently their ideal dairy production system between a global-based intensive and a local-based extensive model of farm. Plos One 15:e0223346. https://doi.org/10.1371/journal.pone.0223346

Darnhofer I, Gibbon D, Dedieu B (2012) Farming Systems Research: an approach to inquiry. In: Farming Systems Research into the 21st Century: The New Dynamic. Springer, Dordrecht, pp 3–31

Darnhofer I, Sutherland LA, Pinto-Correia T (2015) Conceptual insights derived from case studies on "emerging transitions" in farming. In: Sutherland L, Darnhofer I, Wilson GA, Zagata L (eds) Transition pathways towards sustainability in agriculture: case studies from Europe, 1st edn. CABI, UK, pp 189–203

De Bauw M, Reybrouck K, Mathijs E, Vandevijvere S (2025) From Fragmentation to Transformation - Multi-Level Policy Mixes for Sustainable Healthy Food Environments in Belgium. Sciensano KULeuven

De Herde V, Baret PV, Maréchal K (2020) Coexistence of Cooperative Models as Structural Answer to Lock-Ins in Diversification Pathways: The Case of the Walloon Dairy Sector. Front Sustain Food Syst 4:584542. https://doi.org/10.3389/fsufs.2020.584542

De Herde V, Dufays F (2025) Amplifying Agri-Food Sustainability Pathways: A Configurational Model of Value Chain Organizing for Contextual Fit. Pre-Print Available SSRN. https://dx.doi.org/10.2139/ssrn.5736665

De Herde V, Maréchal K, Baret PV (2019) Lock-ins and Agency: Towards an Embedded Approach of Individual Pathways in the Walloon Dairy Sector. Sustainability 11:4405. https://doi.org/10.3390/su11164405

de Lattre-Gasquet M, Le Mouël C, Mora O, et al (2016) Agrimonde-Terra: Foresight land use and food security in 2050. Short report of the foresight. INRA CIRAD

de Lattre-Gasquet M, Rostom FZ, Hazoumé T (2023) Guidance Document on Foresight Processes for Food Systems Transformation through Agroecology. FAO, CIRAD, GIZ

de Olde E, Konefal J, Hatanaka M (2025) The role of farming by metrics in transforming food systems sustainably. Npj Sustain Agric 3:. https://doi.org/10.1038/s44264-025-00084-y

de Olde EM, Oudshoorn FW, Sørensen CAG, et al (2016) Assessing sustainability at farm-level: Lessons learned from a comparison of tools in practice. Ecol Indic 66:391–404. https://doi.org/10.1016/j.ecolind.2016.01.047

De Pue D, Buysse J (2020) Safeguarding Natura 2000 habitats from nitrogen deposition by tackling ammonia emissions from livestock facilities. Environ Sci Policy 111:74–82. https://doi.org/10.1016/j.envsci.2020.05.004

De Ridder K, Bel S, Brocatus L, et al (2016) Enquête de consommation alimentaire 2014-2015. WIV-ISP, Bruxelles

De Samber J (2019) Aardbeienteelt in Vlaanderen. Resultaten uit het landbouwmonitoringsnetwerk. Departement Landbouw en Visserij, Brussel

De Samber J (2021) Tomatenteelt in Vlaanderen. Resultaten uit het Landbouwmonitoringsnetwerk (LMN) 2014-2018. Departement Landbouw en Visserij, Brussel

De Schryver AM, Goedkoop MJ, Leuven RSEW, Huijbregts MAJ (2010) Uncertainties in the application of the species area relationship for characterisation factors of land occupation in life cycle assessment. Int J Life Cycle Assess 15:682–691. https://doi.org/10.1007/s11367-010-0205-2

de Snoo G (2006) Benchmarking the Environmental Performances of Farms (4 pp). Int J Life Cycle Assess 11:22–25. https://doi.org/10.1065/lca2006.01.235

Deconinck K, Jansen M, Barisone C (2023) Fast and furious: the rise of environmental impact reporting in food systems. Eur Rev Agric Econ jbad018. https://doi.org/10.1093/erae/jbad018

Delebecq A, Jamar L, Lateur M, et al (2016) Transbiofruit. Verger Bio: la diversité transfrontalière.

Dendoncker N, Boeraeve F, Crouzat E, et al (2018) How can integrated valuation of ecosystem services help understanding and steering agroecological transitions? Ecol Soc 23:art12. https://doi.org/10.5751/ES-09843-230112

Dénos C, Vandevijvere S, Boone L, et al (2024) Contribution of ultra-processed food and animal-plant protein intake ratio to the environmental impact of Belgian diets. Sustain Prod Consum 51:584–598. https://doi.org/10.1016/j.spc.2024.10.008

Dentoni D, Cucchi C, Roglic M, et al (2023) Systems Thinking, Mapping and Change in Food and Agriculture. Bio-Based Appl Econ 11:277–301. https://doi.org/10.36253/bae-13930

Departement Landbouw en Visserij (2021a) Vlaamse Eiwitstrategie 2021-2030. Brussel

Departement Landbouw en Visserij (2022) Go4Food, Een Vlaamse voedselstrategie voor morgen. Achtergrondrapport. Brussel

Departement Landbouw en Visserij (2019) Convenant Enterische emissies rundvee 2021-2030. Brussel

Departement Landbouw en Visserij (2021b) CAP Strategic Plan 2023-2027 - Flanders (Belgium)

Departement Landbouw en Visserij, FEVIA (2022) Vlaanderen Circulair - Werkagenda voedselketen - startcharter

Departement Omgeving (2021) Green Deal Eiwitshift op ons bord. Brussel

Departement Omgeving (2025) Voortgangsrapport PAS 2024. Brussel

Dernat S, Etienne R, Hostiou N, et al (2022) Ex-post consequences of participatory foresight processes in agriculture. How to help dairy farmers to face outcomes of collective decisions planning? Front Sustain Food Syst 6:776959. https://doi.org/10.3389/fsufs.2022.776959

Desmarez T, Bindelle J, Dumont B (2025) Towards sustainable diets and farming systems through land use optimisation. Npj Sustain Agric 3:49. https://doi.org/10.1038/s44264-025-00092-y

Deuninck J, Vervloet D (2016) Rentabiliteits- en kostprijsanalyse groenten in openlucht op basis van het Landbouwmonitoringsnetwerk. Departement Landbouw en Visserij, Brussel

Dewi D, Aytekin D, Schneider KR, et al (2024) Defining and measuring policy coherence for food system transformation: A scoping review. Glob Food Secur 43:100803. https://doi.org/10.1016/j.gfs.2024.100803

Díaz de Otálora X, Dragoni F, Del Prado A, et al (2022) Identification of representative dairy cattle and fodder crop production typologies at regional scale in Europe. Agron Sustain Dev 42:94. https://doi.org/10.1007/s13593-022-00830-3

Diazabakana A, Latruffe L, Bockstaller C, et al (2014) A review of farm level indicators of sustainability with a focus on CAP and FADN. FLINT Proj Deliv 12. https://hal.archives-ouvertes.fr/hal-01209046

Direction de l'analyse économique agricole (2024) Etat de l'Agriculture Wallonne. Direction de l'analyse économique agricole (DAEA)

Drewnowski A, Hooker K (2025) The protein transition: what determines the animal-to-plant (A:P) protein ratios in global diets. Front Nutr 12:1518793. https://doi.org/10.3389/fnut.2025.1518793

Duluins O, Baret PV (2024a) The paradoxes of the protein transition maintain existing animal production and consumption systems. Nat Food 5:725–730. https://doi.org/10.1038/s43016-024-01036-4

Duluins O, Baret PV (2024b) A systematic review of the definitions, narratives and paths forwards for a protein transition in high-income countries. Nat Food 5:28–36. https://doi.org/10.1038/s43016-023-00906-7

Duluins O, Goutsmedt A, Vandevoorde N, Baret PV (2025) A scientometric retrospective of the Livestock Long Shadow Report. Front Sustain Food Syst 9:. https://doi.org/10.3389/fsufs.2025.1656562

Duluins O, Riera A, Schuster M, et al (2022) Economic Implications of a Protein Transition: Evidence From Walloon Beef and Dairy Farms. Front Sustain Food Syst 6:803872. https://doi.org/10.3389/fsufs.2022.803872

Dumont AM, Gasselin P, Baret PV (2020) Transitions in agriculture: Three frameworks highlighting coexistence between a new agroecological configuration and an old, organic and conventional configuration of vegetable production in Wallonia (Belgium). Geoforum 108:98–109. https://doi.org/10.1016/j.geoforum.2019.11.018

Duru M, Aubert P-M, Couturier C, Doublet S (2021) Scénarios de systèmes alimentaires à l'horizon 2050 au niveau européen et français : quels éclairages pour les politiques publiques ? Agron Environ Sociétés 11:. https://doi.org/10.54800/ssa050

Duru M, Thérond O (2021) L'évaluation des systèmes agricoles à l'aune des services écosystémiques et de l'économie circulaire. Agron Environ Sociétés 11:. https://doi.org/10.54800/ccg203

Duru M, Therond O, Fares M (2015a) Designing agroecological transitions: A review. Agron Sustain Dev 35:1237–1257. https://doi.org/10.1007/s13593-015-0318-x

Duru M, Therond O, Martin G, et al (2015b) How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron Sustain Dev 35:1259–1281. https://doi.org/10.1007/s13593-015-0306-1

Duygan M, Binder CR, Meylan G, Fischer M (2025) Carving the transformation pathways to sustainable futures: A novel analytical framework for backcasting in sustainability transitions. Sustain Futur 9:100553. https://doi.org/10.1016/j.sftr.2025.100553

Elsner F, Herzig C, Strassner C (2023) Agri-food systems in sustainability transition: a systematic literature review on recent developments on the use of the multi-level perspective. Front Sustain Food Syst 7:1207476. https://doi.org/10.3389/fsufs.2023.1207476

Enthoven L, Skambracks M, Van den Broeck G (2023) Improving the design of local short food supply chains: Farmers' views in Wallonia, Belgium. J Rural Stud 97:573–582. https://doi.org/10.1016/j.jrurstud.2023.01.016

Enthoven L, Van den Broeck G (2021) Local food systems: Reviewing two decades of research. Agric Syst 193:103226. https://doi.org/10.1016/j.agsy.2021.103226

Enthoven L, Van den Broeck G (2023) How to boost the local trade of participatory guarantee system (PGS)-certified produce? A value chain perspective in Huánuco, Peru. Ecol Econ 212:107929. https://doi.org/10.1016/j.ecolecon.2023.107929

Erb K-H, Lauk C, Kastner T, et al (2016) Exploring the biophysical option space for feeding the world without deforestation. Nat Commun 7:11382. https://doi.org/10.1038/ncomms11382

Ericksen PJ (2008) Conceptualizing food systems for global environmental change research. Glob Environ Change 18:234–245. https://doi.org/10.1016/j.gloenvcha.2007.09.002

ERM, UGent (2011) Toepassen van de Carbon Footprint methodologie op Vlaamse veehouderijproducten. Environ Resour Manag ERM Univ Gent UGent. https://publicaties.vlaanderen.be/view-file/9992

Escribano AJ, Gaspar P, Mesías FJ, et al (2015) Comparative sustainability assessment of extensive beef cattle farms in a high nature value agroforestry system. In: Rangeland Ecology, Management and Conservation Benefits. Nova Publishers, p 27

EU Commission (2018) Land cover and land use. European Commission, DG Agriculture and Rural Development, Unit Farm Economics

EU Commission (2020) Farm to fork strategy For a fair, healthy and environmentally-friendly food system. European Commission

EU Commission (2024) Strategic Dialogue on the Future of EU Agriculture. European Commission

EU Commission (2025) A Vision for Agriculture and Food Shaping together an attractive farming and agri-food sector for future generations. European Commission

European Environment Agency (2017) EEA Glossary. In: EEA Glossaey. https://www.eea.europa.eu/help/glossary/eea-glossary. Accessed 21 Jan 2024

FABLE (2019) Pathways to Sustainable Land-Use and Food Systems. 2019 Report of the FABLE Consortium. International Institute for Applied Systems Analysis (IIASA) and Sustainable Development Solutions Network (SDSN), Laxenburg and Paris

FAO (2019) City region food systems programme. Reinforcing rural-urban linkages for climate resilient food systems. FAO, Rome

Ferdinand MS, Baret PV (2024) A method to account for diversity of practices in Conservation Agriculture. Agron Sustain Dev 44:31. https://doi.org/10.1007/s13593-024-00961-9

Fesenfeld LP, Candel J, Gaupp F (2023) Governance principles for accelerating food systems transformation in the European Union. Nat Food 4:826–829. https://doi.org/10.1038/s43016-023-00850-6

Fiala V, Jacob K (2024) Combining the multi-level perspective framework with participatory scenario development to explore the many facets of food system transitions in Germany. Sustain Sci. https://doi.org/10.1007/s11625-024-01505-6

Finch T, Gillings S, Green RE, et al (2019) Bird conservation and the land sharing-sparing continuum in farmland-dominated landscapes of lowland England. Conserv Biol 33:1045–1055. https://doi.org/10.1111/cobi.13316

Finch T, Green RE, Massimino D, et al (2020) Optimising nature conservation outcomes for a given region-wide level of food production. J Appl Ecol 57:985–994. https://doi.org/10.1111/1365-2664.13594

Fischer K, Vico G, Röcklinsberg H, et al (2024) Progress towards sustainable agriculture hampered by siloed scientific discourses. Nat Sustain. https://doi.org/10.1038/s41893-024-01474-9

Flanders Food (2025a) A strategic research and innovation plan to accelerate the protein shift in Flanders. https://www.flandersfood.com/en/new-and-shifting-resources/protein-shift

Flanders Food (2025b) Flanders Food - About us. https://www.flandersfood.com/en/about-us

Foley JA, Ramankutty N, Brauman KA, et al (2011) Solutions for a cultivated planet. Nature 478:337–342. https://doi.org/10.1038/nature10452

Food Pilot (2025) Over Food Pilot. https://www.foodpilot.be/nl/over

Frehner A, Cardinaals RPM, Boer IJM de, et al (2022) The compatibility of circularity and national dietary recommendations for animal products in five European countries: a modelling analysis on nutritional feasibility, climate impact, and land use. Lancet Planet Health 6:e475–e483. https://doi.org/10.1016/S2542-5196(22)00119-X

Freibauer A, Mathijs E, Brunori G, et al (2011) Sustainable Food Consumption and Production in a Resource-constrained World. Summary Findings of the EU SCAR Third Foresight Exercise. EuroChoices 10:38–43. https://doi.org/10.1111/j.1746-692X.2011.00201.x

Froldi F, Lamastra L, Trevisan, et al (2022) Environmental impacts of cow's milk in Northern Italy: Effects of farming performance. J Clean Prod 363:12. https://doi.org/10.1016/j.jclepro.2022.132600

Gaitán-Cremaschi D, Klerkx L, Duncan J, et al (2019) Characterizing diversity of food systems in view of sustainability transitions. A review. Agron Sustain Dev 39:1. https://doi.org/10.1007/s13593-018-0550-2

Galli F, Prosperi P, Favilli E, et al (2020) How can policy processes remove barriers to sustainable food systems in Europe? Contributing to a policy framework for agri-food transitions. Food Policy 96:101871. https://doi.org/10.1016/j.foodpol.2020.101871

Garnett T, Godde C, Muller A, et al (2017) Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question – and what it all means for greenhouse gas emissions. Food Clim Res Netw FCRN Universty Oxf. https://www.oxfordmartin.ox.ac.uk/downloads/reports/fcrn_gnc_report.pdf

Gasselin P, Lardon S, Cerdan C, et al (2021a) Coexistence et confrontation des modèles agricoles et alimentaires. éditions Quae

Gasselin P, Lardon S, Cerdan C, et al (2021b) Ambivalences des modèles et défi de la gouvernance territoriale de la coexistence. In: Coexistence et confrontation des modèles agricoles et alimentaires. Un nouveau paradigme du développement territorial ? Editions Quae, Versailles, pp 225–238

Gaupp F, Ruggeri Laderchi C, Lotze-Campen H, et al (2021) Food system development pathways for healthy, nature-positive and inclusive food systems. Nat Food 2:928–934. https://doi.org/10.1038/s43016-021-00421-7

GD eiwitshift op ons bord (2025) Hoe zet VLAM zich in voor de eiwitshift? https://www.omgeving.vlaanderen.be/nl/green-deal-eiwitshift-op-ons-bord-010/hoe-zet-vlam-zich-in-voor-de-eiwitshift

Geels FW (2011) The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environ Innov Soc Transit 1:24–40. https://doi.org/10.1016/j.eist.2011.02.002

Geels FW, Schot J (2007) Typology of sociotechnical transition pathways. Res Policy 36:399–417. https://doi.org/10.1016/j.respol.2007.01.003

Gerber PJ, Steinfeld H, Henderson B, et al (2013) Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. Food Agric Organ U N FAO. https://www.fao.org/3/i3437e/i3437e00.htm

Germond C (2013) Preventing Reform: Farm Interest Groups and the Common Agricultural Policy. In: Societal Actors in European Integration. Palgrave Macmillan UK, London, pp 106–128

Gibson CC, Ostrom E, Ahn TK (2000) The concept of scale and the human dimensions of global change: a survey. Ecol Econ 32:217–239. https://doi.org/10.1016/S0921-8009(99)00092-0

Gliessman S (2016) Transforming food systems with agroecology. Agroecol Sustain Food Syst 40:187–189. https://doi.org/10.1080/21683565.2015.1130765

Gonzalez-Mejia A, Styles D, Wilson P, Gibbons J (2018) Metrics and methods for characterizing dairy farm intensification using farm survey data. Plos One 13:18. https://doi.org/10.1371/journal.pone.0195286

GoodPlanet (2025) Plantaardig weten. https://www.goodplanet.be/nl/plantaardig-weten/

Gordon LJ, Bignet V, Crona B, et al (2017) Rewiring food systems to enhance human health and biosphere stewardship. Environ Res Lett 12:100201. https://doi.org/10.1088/1748-9326/aa81dc

Gourlez de la Motte L, Jérôme E, Mamadou O, et al (2016) Carbon balance of an intensively grazed permanent grassland in southern Belgium. Agric For Meteorol 228–229:370–383. https://doi.org/10.1016/j.agrformet.2016.06.009

Gourlez de la Motte L, Mamadou O, Beckers Y, et al (2018) Rotational and continuous grazing does not affect the total net ecosystem exchange of a pasture grazed by cattle but modifies CO2 exchange dynamics. Agric Ecosyst Environ 253:157–165. https://doi.org/10.1016/j.agee.2017.11.011

Grabs J, Carodenuto S, Jespersen K, et al (2024) The role of midstream actors in advancing the sustainability of agri-food supply chains. Nat Sustain 7:527–535. https://doi.org/10.1038/s41893-024-01296-9

Green RE, Cornell SJ, Scharlemann JPW, Balmford A (2005) Farming and the Fate of Wild Nature. Science 307:550–555. https://doi.org/10.1126/science.1106049

Guerci M, Knudsen MT, Bava L, et al (2013) Parameters affecting the environmental impact of a range of dairy farming systems in Denmark, Germany and Italy. J Clean Prod 54:133–141. https://doi.org/10.1016/j.jclepro.2013.04.035

Gupta B, Zurek M, Woodhill J, Ingram JSI (2025) Advancing the next-generation of global food system scenarios: a critical review of existing narratives. Front Sustain Food Syst 9:1620374. https://doi.org/10.3389/fsufs.2025.1620374

Guthman J, Butler M, Martin SJ, et al (2022) In the name of protein. Nat Food 3:391–393. https://doi.org/10.1038/s43016-022-00532-9

Guyomard H (2025) What Impact Does Agricultural Research Have on the Common Agricultural Policy? EuroChoices 1746–692X.12470. https://doi.org/10.1111/1746-692X.12470

Haileslassie A, Craufurd P, Thiagarajah R, et al (2016) Empirical evaluation of sustainability of divergent farms in the dryland farming systems of India. Ecol Indic 60:710–723. https://doi.org/10.1016/j.ecolind.2015.08.014

Halberg N, Verschuur G, Goodlass G (2005) Farm level environmental indicators; are they useful? Agric Ecosyst Environ 105:195–212. https://doi.org/10.1016/j.agee.2004.04.003

Hasegawa T, Fujimori S, Takahashi K, Masui T (2015) Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. Environ Res Lett 10:014010. https://doi.org/10.1088/1748-9326/10/1/014010

Hashemi F, Mogensen L, Van Der Werf HMG, et al (2024) Organic food has lower environmental impacts per area unit and similar climate impacts per mass unit compared to conventional. Commun Earth Environ 5:. https://doi.org/10.1038/s43247-024-01415-6

Havet A, Coquil X, Fiorelli JL, et al (2014) Review of livestock farmer adaptations to increase forages in crop rotations in western France. Agric Ecosyst Environ 190:120–127. https://doi.org/10.1016/j.agee.2014.01.009

Herzon I, Mazac R, Erkkola M, et al (2024) Both downsizing and improvements to livestock systems are needed to stay within planetary boundaries. Nat Food 5:642–645. https://doi.org/10.1038/s43016-024-01030-w

Hirsch Hadorn G, Bradley D, Pohl C, et al (2006) Implications of transdisciplinarity for sustainability research. Ecol Econ 60:119–128. https://doi.org/10.1016/j.ecolecon.2005.12.002

HLPE (2017) Nutrition and food systems. Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome

Honnay O, Avermaete T, Govers G, Keulemans W (2021) Een slimme zonering van landgebruik verzoent landbouwproductie, biodiversiteit en klimaat. Natuurfocus 20:157–165

Hooghe L (1995) Subnational mobilisation in the European union. West Eur Polit 18:175–198. https://doi.org/10.1080/01402389508425097

Hooghe L, Marks G (2009) Does Efficiency Shape the Territorial Structure of Government? Annu Rev Polit Sci 12:225–241. https://doi.org/10.1146/annurev.polisci.12.041107.102315

Hou Y, Bai Z, Leschen JP, et al (2016) Feed use and nitrogen excretion of livestock in EU-27. Agric Ecosyst Environ 218:232–244

Huang J, Tichit M, Poulot M, et al (2015) Comparative review of multifunctionality and ecosystem services in sustainable agriculture. J Environ Manage 149:138–147. https://doi.org/10.1016/j.jenvman.2014.10.020

Hulot J-F (2025) Rethinking Food and Farming in Europe. In: Euroissues 2024. MDPI, p 1

Hundscheid L, Voigt C, Bergthaler D, et al (2024) Policy mix for the sustainable protein transition in Austria - Addressing repercussions of regime shifts as a prerequisite for acceleration. Environ Innov Soc Transit 51:100819. https://doi.org/10.1016/j.eist.2024.100819

Hundscheid L, Wurzinger M, Gühnemann A, et al (2022) Rethinking meat consumption – How institutional shifts affect the sustainable protein transition. Sustain Prod Consum 31:301–312. https://doi.org/10.1016/j.spc.2022.02.016

Income consulting - AK2C (2016) Pertes et gaspillages alimentaires : l'état des lieux et leur gestion par étapes de la chaîne alimentaire. ADEME

IPCC (2014) Contribution of Working Group III to Fifth Assessment Report of the Intergovernmental Panel on Climate Change - Chapter 11: Agriculture, Forestry and Other Land Use (AFOLU). Intergovernmental Panel on Climate Change (IPCC)

IPES-Food (2016) From Uniformity to Diversity. A paradigm shift from industrial agriculture to diversified agroecological systems. Int Panel Experts Sustain Food Syst. https://www.ipes-food.org/_img/upload/files/UniformityToDiversity_FULL.pdf

IPES-Food (2022) The politics of protein: examining claims about livestock, fish, 'alternative proteins' and sustainability. IPES-Food

Jaisli I, Brunori G (2024) Is there a future for livestock in a sustainable food system? Efficiency, sufficiency, and consistency strategies in the food-resource nexus. J Agric Food Res 18:101496. https://doi.org/10.1016/j.jafr.2024.101496

Jan P, Dux D, Lips M, et al (2012) On the link between economic and environmental performance of Swiss dairy farms of the alpine area. Int J Life Cycle Assess 17:706–719. https://doi.org/10.1007/s11367-012-0405-z

Jenkins WMN, Trindade LM, Pyett S, et al (2024) Will the protein transition lead to sustainable food systems? Glob Food Secur 43:100809. https://doi.org/10.1016/j.gfs.2024.100809

Jennings S, Schweizer L (2019) Risky business: the risk of corruption and forrest loss in Belgium's imports of commodities. WWF Belgium ; 3Keel

Jessop B, Brenner N, Jones M (2008) Theorizing Sociospatial Relations. Environ Plan Soc Space 26:389–401. https://doi.org/10.1068/d9107

Jordon MW, Buffet J-C, Dungait JAJ, et al (2024) A restatement of the natural science evidence base concerning grassland management, grazing livestock and soil carbon storage. Proc R Soc B Biol Sci 291:20232669. https://doi.org/10.1098/rspb.2023.2669

Jouan J, Ridier A, Carof M (2020a) SYNERGY: A regional bio-economic model analyzing farm-to-farm exchanges and legume production to enhance agricultural sustainability. Ecol Econ 175:106688. https://doi.org/10.1016/j.ecolecon.2020.106688

Jouan J, Ridier A, Carof M (2020b) Legume production and use in feed: Analysis of levers to improve protein self-sufficiency from foresight scenarios. J Clean Prod 274:123085. https://doi.org/10.1016/j.jclepro.2020.123085

Juri S, Terry N, Pereira L (2024) Demystifying food systems transformation: a review of the state of the field. Ecol Soc 29:art5. https://doi.org/10.5751/ES-14525-290205

Kaljonen M, Tribaldos T, Kortetmäki T, et al (2025) Deliberating justice in food systems transformation pathways: a transdisciplinary approach applied in Finland. Environ Res Food Syst. https://doi.org/10.1088/2976-601X/ae1dfa

Kalt G, Mayer A, Haberl H, et al (2021) Exploring the option space for land system futures at regional to global scales: The diagnostic agro-food, land use and greenhouse gas emission model BioBaM-GHG 2.0. Ecol Model 459:109729. https://doi.org/10.1016/j.ecolmodel.2021.109729

Kamau JW, Stellmacher T, Biber-Freudenberger L, Borgemeister C (2018) Organic and conventional agriculture in Kenya: A typology of smallholder farms in Kajiado and

Murang'a counties. J Rural Stud 57:171–185. https://doi.org/10.1016/j.jrurstud.2017.12.014

Karlsson JO, Carlsson G, Lindberg M, et al (2018) Designing a future food vision for the Nordics through a participatory modeling approach. Agron Sustain Dev 38:59. https://doi.org/10.1007/s13593-018-0528-0

Karlsson JO, Karlsson-Potter H, Lagnelöv O, et al (2025a) CIBUSmod 25.09: a spatially disaggregated biophysical agri-food systems model for studying national-level demand- and production-side intervention scenarios. Geosci Model Dev 18:8589–8611. https://doi.org/10.5194/gmd-18-8589-2025

Karlsson JO, Parodi A, Van Zanten HHE, et al (2020) Halting European Union soybean feed imports favours ruminants over pigs and poultry. Nat Food 2:38–46. https://doi.org/10.1038/s43016-020-00203-7

Karlsson JO, Röös E, Sjunnestrand T, et al (2017) Future Nordic Diets : Exploring ways for sustainably feeding the Nordics. Nordisk Ministerråd

Karlsson L, Keeling L, Röös E (2025b) What is a better chicken? Exploring trade-offs between animal welfare and greenhouse gas emissions in higher-welfare broiler systems. Sustain Prod Consum 55:203–216. https://doi.org/10.1016/j.spc.2025.02.015

Kazanski CE, Balehegn M, Jones K, et al (2025) Context is key to understand and improve livestock production systems. Glob Food Secur 45:100840. https://doi.org/10.1016/j.gfs.2025.100840

Kelly E, Latruffe L, Desjeux Y, et al (2018) Sustainability indicators for improved assessment of the effects of agricultural policy across the EU: Is FADN the answer? Ecol Indic 89:903–911. https://doi.org/10.1016/j.ecolind.2017.12.053

Kortleve AJ, Mogollón JM, Harwatt H, Behrens P (2024) Over 80% of the European Union's Common Agricultural Policy supports emissions-intensive animal products. Nat Food 1–5. https://doi.org/10.1038/s43016-024-00949-4

Kuczuk A, Widera K (2021) A Greater Share of Organic Agriculture in Relation to Food Security Resulting from the Energy Demand Obtained from Food—Scenarios for Poland until 2030. Energies 14:6959. https://doi.org/10.3390/en14216959

Kueffer C, Schneider F, Wiesmann U (2019) Addressing sustainability challenges with a broader concept of systems, target, and transformation knowledge. GAIA - Ecol Perspect Sci Soc 28:386–388. https://doi.org/10.14512/gaia.28.4.12

Kuivanen KS, Michalscheck M, Descheemaeker K, et al (2016) A comparison of statistical and participatory clustering of smallholder farming systems – A case study in Northern Ghana. J Rural Stud 45:184–198. https://doi.org/10.1016/j.jrurstud.2016.03.015

Landon A, Rosol M (2025) Overcoming the local trap through inclusive and multi-scalar food systems. Local Environ 1–21. https://doi.org/10.1080/13549839.2025.2450492

Latruffe L, Diazabakana A, Bockstaller C, et al (2016) Measurement of sustainability in agriculture: a review of indicators. Stud Agric Econ 118:123–130. https://doi.org/10.7896/j.1624

Le Noë J, Gingrich S, Pichler M, et al (2023) Combining biophysical modeling and Polanyian theory pleads for a re-embedding of the agricultural system in 2050 in Austria. Environ Sci Policy 139:228–239. https://doi.org/10.1016/j.envsci.2022.11.006

Lebacq T (2015) La durabilité des exploitations laitières en Wallonie : analyse de la diversité et voies de transition. PhD Thesis UCLouvain. https://sytra.be/wp-content/uploads/2020/05/2015_UCLouvain_FR_these_Lait_Durabilit%C3%A9.pdf

Lebacq T, Baret PV, Stilmant D (2015) Role of input self-sufficiency in the economic and environmental sustainability of specialised dairy farms. Animal 9:544–552. https://doi.org/10.1017/S1751731114002845

Lebacq T, Baret PV, Stilmant D (2013) Sustainability indicators for livestock farming. A review. Agron Sustain Dev 33:311–327. https://doi.org/10.1007/s13593-012-0121-x

Leeuwis C, Boogaard BK, Atta-Krah K (2021) How food systems change (or not): governance implications for system transformation processes. Food Secur 13:761–780. https://doi.org/10.1007/s12571-021-01178-4

Leip A, Caldeira C, Corrado S, et al (2022) Halving nitrogen waste in the European Union food systems requires both dietary shifts and farm level actions. Glob Food Secur 35:100648. https://doi.org/10.1016/j.gfs.2022.100648

Leroy EC, Cornu M-A, Baret P, et al (2021) Ouvrir un débat sur la valorisation des systèmes d'intégration culture-élevage comme leviers pour une gestion durable des flux d'azote en Région wallonne

Lessire F, Jacquet S, Veselko D, et al (2019) Evolution of Grazing Practices in Belgian Dairy Farms: Results of Two Surveys. Sustainability 11:. https://doi.org/10.3390/SU11153997

Levidow L, Birch K, Papaioannou T (2012) Divergent Paradigms of European Agro-Food Innovation: The Knowledge-Based Bio-Economy (KBBE) as an R&D Agenda. Sci Technol Hum Values 38:94–125. https://doi.org/10.1177/0162243912438143

Levidow L, Papaioannou T (2016) Policy-driven, narrative-based evidence gathering: UK priorities for decarbonisation through biomass. Sci Public Policy 43:46–61. https://doi.org/10.1093/scipol/scv016

Lin F, Li X, Jia N, et al (2023) The impact of Russia-Ukraine conflict on global food security. Glob Food Secur 36:100661. https://doi.org/10.1016/j.gfs.2022.100661

Liu T (2025) What scale for local food system planning? Insights from French case studies. J Agric Food Syst Community Dev 1–21. https://doi.org/10.5304/jafscd.2025.141.015

Loiseau E, Aissani L, Le Féon S, et al (2018) Territorial Life Cycle Assessment (LCA): What exactly is it about? A proposal towards using a common terminology and a research agenda. J Clean Prod 176:474–485. https://doi.org/10.1016/j.jclepro.2017.12.169

Loorbach D (2010) Transition Management for Sustainable Development: A Prescriptive, Complexity-Based Governance Framework. Governance 23:161–183. https://doi.org/10.1111/j.1468-0491.2009.01471.x

Loorbach D, Frantzeskaki N, Avelino F (2017) Sustainability Transitions Research: Transforming Science and Practice for Societal Change. Annu Rev Environ Resour 42:599–626. https://doi.org/10.1146/annurev-environ-102014-021340

López-García D, Cruz-Maceín JL, DiPaula M (2024) Agri vs. food? Perceptions of local policymakers on agri-food policies from a multilevel approach. Front Sustain Food Syst 8:1399746. https://doi.org/10.3389/fsufs.2024.1399746

Lumbroso S (2019) Prospective et stratégies pour l'environnement : entre fabrique des futurs et situation de gestion, quelles prises pour l'action ? AgroParisTech - Université Paris Saclay, Paris

Lynch J, Cain M, Pierrehumbert R, Allen M (2020) Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. Environ Res Lett 15:044023. https://doi.org/10.1088/1748-9326/ab6d7e

Lynch J, Skirvin D, Wilson P, Ramsden S (2018) Integrating the economic and environmental performance of agricultural systems: A demonstration using Farm Business Survey data and Farmscoper. Sci Total Environ 628–629:938–946. https://doi.org/10.1016/j.scitotenv.2018.01.256

Mahon N, Crute I, Di Bonito M, et al (2018) Towards a broad-based and holistic framework of Sustainable Intensification indicators. Land Use Policy 77:576–597. https://doi.org/10.1016/j.landusepol.2018.06.009

Mahon N, Crute I, Simmons E, Islam MdM (2017) Sustainable intensification – "oxymoron" or "third-way"? A systematic review. Ecol Indic 74:73–97. https://doi.org/10.1016/j.ecolind.2016.11.001

Mari F (2020) The representativeness of the Farm Accountancy Data Network (FADN): some suggestions for its improvement : 2020 edition. Eurostat Stat Work Pap. https://data.europa.eu/doi/10.2785/06861

Marin FR, Zanon AJ, Monzon JP, et al (2022) Protecting the Amazon forest and reducing global warming via agricultural intensification. Nat Sustain 5:1018–1026. https://doi.org/10.1038/s41893-022-00968-8

Masi M, Vecchio Y, Pauselli G, et al (2021) A Typological Classification for Assessing Farm Sustainability in the Italian Bovine Dairy Sector. Sustainability 13:7097. https://doi.org/10.3390/su13137097

Matthews A (2024) Farmer Protests and the 2024 European Parliament Elections. Intereconomics 59:83–87. https://doi.org/10.2478/ie-2024-0018

McEldowney J (2017) Foresight – Contribution to the debate on the future of EU agricultural policy. European Parliament Research Service (EPRS), Brussels

Meul M, Van Passel S, Fremaut D, Haesaert G (2012) Higher sustainability performance of intensive grazing versus zero-grazing dairy systems. Agron Sustain Dev 32:629–638. https://doi.org/10.1007/s13593-011-0074-5

Meynard J-M, Cerf M, Coquil X, et al (2023) Unravelling the step-by-step process for farming system design to support agroecological transition. Eur J Agron 150:126948. https://doi.org/10.1016/j.eja.2023.126948

Micha E, Heanue K, Hyland J, et al (2017) Sustainability levels in Irish dairy farming: a farm typology according to sustainable performance indicators. Stud Agric Econ 119:62–69. https://doi.org/10.7896/j.1706

Mitter H, Techen A-K, Sinabell F, et al (2020) Shared Socio-economic Pathways for European agriculture and food systems: The Eur-Agri-SSPs. Glob Environ Change 65:102159. https://doi.org/10.1016/j.gloenvcha.2020.102159

Moallemi E, Castonguay A, Mason D'Croz D, et al (2025) Models of Future Food Systems Should Address Transformation Complexity and Uncertainty. Nat Food. https://doi.org/10.31223/X5WB19

Moore M-L, Riddell D, Vocisano D (2015) Scaling Out, Scaling Up, Scaling Deep: Strategies of Non-profits in Advancing Systemic Social Innovation. J Corp Citizsh 2015:67–84. https://doi.org/10.9774/GLEAF.4700.2015.ju.00009

Mora O, Berne J-A, Drouet J-L, et al (2023) Foresight: European Chemical Pesticide-Free Agriculture in 2050. INRAE

MOS Vlaanderen (2025) MOS Vlaanderen - Duurzame voeding. https://www.mosvlaanderen.be/themas/duurzame-voeding

Mosnier C, Duclos A, Agabriel J, Gac A (2017) What prospective scenarios for 2035 will be compatible with reduced impact of French beef and dairy farm on climate change? Agric Syst 157:193–201. https://doi.org/10.1016/j.agsy.2017.07.006

Mottet A, de Haan C, Falcucci A, et al (2017) Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Glob Food Secur 14:1–8. https://doi.org/10.1016/j.gfs.2017.01.001

Muller A, Schader C, El-Hage Scialabba N, et al (2017) Strategies for feeding the world more sustainably with organic agriculture. Nat Commun 8:1290. https://doi.org/10.1038/s41467-017-01410-w

Natagora (2020) Position sur la PAC 2021 - 2027. Le Plan Stratégique PAC wallon à l'heure du Green Deal Européen. https://www.natagora.be/position-sur-la-pac-2021-2027

Natagriwal Autonomie fourragère. Les Méthodes Agro-Environnementales et Climatiques (MB 9). https://www.natagriwal.be/fr/mesures-agro-environnementales/liste-des-mae/fiches/details/351

Navarro Garcia J, Marcos-Martinez R, Mosnier A, et al (2023) Multi-target scenario discovery to plan for sustainable food and land systems in Australia. Sustain Sci 18:371–388. https://doi.org/10.1007/s11625-022-01202-2

Newell R, Dring C, King L, Hemphill M (2025) Food System Scenarios in Uncertain Futures: A Case Study on Long-Term Local Food System Planning in Revelstoke, Canada. Agriculture 15:611. https://doi.org/10.3390/agriculture15060611

Nguyen TL, Hermansen J, Mogensen L (2010) Fossil energy and GHG saving potentials of pig farming in the EU. Energy Policy 38:2561–2571

Notarnicola B, Tassielli G, Renzulli PA, et al (2017) Environmental impacts of food consumption in Europe. J Clean Prod 140:753–765. https://doi.org/10.1016/j.jclepro.2016.06.080

Ossenbrink J, Finnsson S, Bening CR, Hoffmann VH (2019) Delineating policy mixes: Contrasting top-down and bottom-up approaches to the case of energy-storage policy in California. Res Policy 48:103582. https://doi.org/10.1016/j.respol.2018.04.014

Oxford Reference Dictionary (2008) Typology. Concise Oxf Dict Archaeol 2 Ed

Padró R, Tello E (2022) Exploring Agroecology Transition Scenarios: A Pfaundler's Spectrum Assessment on the Relocation of Agri-Food Flows. Land 11:

Padró R, Tello E, Marco I, et al (2020) Modelling the scaling up of sustainable farming into Agroecology Territories: Potentials and bottlenecks at the landscape level in a Mediterranean case study. J Clean Prod 275:124043. https://doi.org/10.1016/j.jclepro.2020.124043

Papangelou A, Mathijs E (2021) Assessing agro-food system circularity using nutrient flows and budgets. J Environ Manage 288:112383. https://doi.org/10.1016/j.jenvman.2021.112383

Parajuá N, Tello E, Duncan J (2025) A research framework to investigate food systems at a national scale. Ecol Econ 227:108428. https://doi.org/10.1016/j.ecolecon.2024.108428

Pay C, Gianoli A (2024) Securing the future: Analysing the protein transition in Singapore. Cities 150:105072. https://doi.org/10.1016/j.cities.2024.105072

Pe'er G, Kachler J, Herzon I, et al (2025) Role of science and scientists in public environmental policy debates: The case of EU agrochemical and Nature Restoration Regulations. People Nat pan3.70064. https://doi.org/10.1002/pan3.70064

Peeters A (2009) Importance, evolution, environmental impact and future challenges of grasslands and grassland-based systems in Europe. Grassl Sci 55:113–125. https://doi.org/10.1111/j.1744-697X.2009.00154.x

Penvern S, Lamine C, Derbez F, et al (2023) Addressing the diversity of visions of ecologization in research and in support to agroecological transitions. Agroecol Sustain Food Syst 47:1403–1427. https://doi.org/10.1080/21683565.2023.2246395

Persson L, Carney Almroth BM, Collins CD, et al (2022) Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environ Sci Technol 56:1510–1521. https://doi.org/10.1021/acs.est.1c04158

Petel T, Antier C, Baret P (2018a) Etat des lieux et scénarios à horizon 2050 de la filière viande bovine en Région wallonne. UCLouvain - Sytra. https://sytra.be/fr/publication/filiere-bovine-wallonie/

Petel T, Antier C, Baret P (2018b) Etat des lieux et scénarios à horizon 2050 de la filière lait en Région wallonne. UCLouvain - Sytra. https://sytra.be/fr/publication/filiere-lait-wallonie/

Phalan B (2018) What Have We Learned from the Land Sparing-sharing Model? Sustainability 10:1760. https://doi.org/10.3390/su10061760

Pinsard C, Martin S, Léger F, Accatino F (2021) Robustness to import declines of three types of European farming systems assessed with a dynamic nitrogen flow model. Agric Syst 193:103215. https://doi.org/10.1016/j.agsy.2021.103215

Popp A, Calvin K, Fujimori S, et al (2017) Land-use futures in the shared socio-economic pathways. Glob Environ Change 42:331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Poux X, Aubert P-M (2018) An agroecological Europe in 2050: multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (TYFA) modelling exercice. IDDRI

Prost L, Martin G, Ballot R, et al (2023) Key research challenges to supporting farm transitions to agroecology in advanced economies. A review. Agron Sustain Dev 43:11. https://doi.org/10.1007/s13593-022-00855-8

ProVeg (2025) Over ProVeg Belgie. https://proveg.org/be/over-proveg-belgie/

Quattrini S, Principi A, Lucantoni D, et al (2024) Identifying Active Ageing Policy Needs at the Meso-Level. Sustainability 16:437. https://doi.org/10.3390/su16010437

Rabeux V, Elias E, Dumoulin (2015) Engraissement de taurillons culards BBB. Impact de l'âge d'abattage sur la rentabilité. Wallonie Elev.

Reilly M, Willenbockel D (2010) Managing uncertainty: a review of food system scenario analysis and modelling. Philos Trans R Soc B Biol Sci 365:3049–3063. https://doi.org/10.1098/rstb.2010.0141

Reinsch T, Loza C, Malisch CS, et al (2021) Toward Specialized or Integrated Systems in Northwest Europe: On-Farm Eco-Efficiency of Dairy Farming in Germany. Front Sustain Food Syst 5:614348. https://doi.org/10.3389/fsufs.2021.614348

Renting H, Rossing WAH, Groot JCJ, et al (2009) Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. J Environ Manage 90:S112–S123. https://doi.org/10.1016/j.jenvman.2008.11.014

Resare Sahlin K, Carolus J, von Greyerz K, et al (2022) Delivering "less but better" meat in practice—a case study of a farm in agroecological transition. Agron Sustain Dev 42:24. https://doi.org/10.1007/s13593-021-00737-5

Réseau GAB/FRAB (2015) Fraisier, Fragaria ananassa, Rosacée. Fiches Tech Réseau GABFRAB - Fruits Légumes Fiche N°18

Riahi K, van Vuuren DP, Kriegler E, et al (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob Environ Change 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rieger J, Freund F, Offermann F, et al (2023) From fork to farm: Impacts of more sustainable diets in the EU -27 on the agricultural sector. J Agric Econ 74:764–784. https://doi.org/10.1111/1477-9552.12530

Riera A, Antier C, Baret P (2019) Study on Livestock scenarios for Belgium in 2050. UCLouvain - Sytra 245. https://sytra.be/publication/scenarios-livestock-belgium/

Riera A, Antier C, Baret P (2020a) État des lieux et scénarios à horizon 2050 de la filière légumière en Région wallonne. Cas des petits pois, haricots verts, carottes et oignons. Sytra - Earth and Life Institute - UCLouvain

Riera A, Antier C, Baret P (2020b) État des lieux et scénarios à horizon 2050 de la filière légumière en Région wallonne

Riera A, Baret P (2026) From micro to macro, local to global and farm to fork: a multi-scale framework for food system transitions. Forthcoming

Riera A, Duluins O, Antier C, Baret PV (2025) Which types of quantitative foresight scenarios to frame the future of food systems? A review. Agric Syst 225:104270. https://doi.org/10.1016/j.agsy.2025.104270

Riera A, Duluins O, Schuster M, Baret PV (2023) Accounting for diversity while assessing sustainability: insights from the Walloon bovine sectors. Agron Sustain Dev 43:30. https://doi.org/10.1007/s13593-023-00882-z

Riera A, Vandevoorde N, Squilbin A, et al (2026) Narratives, trade-offs and scenarios to explore the livestock transition in Belgium. Npj Sustain Agric. https://doi.org/10.1038/s44264-025-00122-9

Riley J (2001) The indicator explosion - local needs and international challenges. Agric Ecosyst Environ 87:119–120

Rivera-Ferre MG (2011) Framing of Agri-food Research Affects the Analysis of Food Security: The Critical Role of the Social Sciences. Int J Sociol Agric Food 19:162–175

Roberts A (2020) Bridging Levels of Public Administration: How Macro Shapes Meso and Micro. Adm Soc 52:631–656. https://doi.org/10.1177/0095399719877160

Rockström J, Steffen W, Noone K, et al (2009) Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecol Soc 14:. https://doi.org/10.5751/ES-03180-140232

Röös E, Bajželj B, Smith P, et al (2017a) Protein futures for Western Europe: potential land use and climate impacts in 2050. Reg Environ Change 17:367–377. https://doi.org/10.1007/s10113-016-1013-4

Röös E, Bajzelj B, Smith P, et al (2017b) Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. Glob Environemntal Change 47:1–12. https://doi.org/10.1016/j.gloenvcha.2017.09.001

Röös E, Mayer A, Muller A, et al (2022) Agroecological practices in combination with healthy diets can help meet EU food system policy targets. Sci Total Environ 847:157612. https://doi.org/10.1016/j.scitotenv.2022.157612

Röös E, Patel M, Spangberg J, et al (2016) Limiting livestock production to pasture and by-products in a search for sustainable diets. Food Policy 1–13

Rubens K, Wynants E, Moyersoen I, et al (2025) EI-MEET: Monitoring eiwitinname en -aankopen in Vlaanderen 2024. Green Deal Eiwitshift op ons bord. Departement Omgeving, Vlaamse overheid

Rubens K, Wynants E, Moyersoen I, et al (2024) EI-MEET: Monitoring eiwitinname en -aankopen in Vlaanderen 2023. Green Deal eiwitshift op ons bord. Departement Omgeving, Brussel

Sadok W, Angevin F, Bergez J-É, et al (2008) Ex ante assessment of the sustainability of alternative cropping systems: implications for using multi-criteria decision-aid methods. A review. Agron Sustain Dev 28:163–174. https://doi.org/10.1051/agro:2007043

Saujot M, Waisman H (2020) Mieux représenter les modes de vie dans les prospectives énergie-climat. IDDRI Étude 2:42

Schader C, Grenz J, Meier MS, Stolze M (2014) Scope and precision of sustainability assessment approaches to food systems. Ecol Soc 19:art42. https://doi.org/10.5751/ES-06866-190342

Schenk NJ, Moll HC, Schoot Uiterkamp AJM (2007) Meso-level analysis, the missing link in energy strategies. Energy Policy 35:1505–1516. https://doi.org/10.1016/j.enpol.2006.04.013

Schiavo M, Le Mouël C, Poux X, Aubert P-M (2021) An agroecological Europe by 2050: What impact on land use, trade and global food security? IDDRI, Paris

Schneider KR, Fanzo J, Haddad L, et al (2023) The state of food systems worldwide in the countdown to 2030. Nat Food 4:1090–1110. https://doi.org/10.1038/s43016-023-00885-9

Schneider KR, Remans R, Bekele TH, et al (2025) Governance and resilience as entry points for transforming food systems in the countdown to 2030. Nat Food 6:105–116. https://doi.org/10.1038/s43016-024-01109-4

Seghezzo L (2009) The five dimensions of sustainability. Environ Polit 18:539–556. https://doi.org/10.1080/09644010903063669

Singh BK, Fraser EDG, Arnold T, et al (2022) Food systems transformation requires science–policy–society interfaces that integrate existing global networks and new knowledge hubs. Nat Food 4:1–3. https://doi.org/10.1038/s43016-022-00664-y

Singh BK, Fraser EDG, Arnold T, et al (2023) Ensuring societal considerations are met when translating science into policy for sustainable food system transformation. Trends Food Sci Technol 137:104–108. https://doi.org/10.1016/j.tifs.2023.04.021

Slijper T, de Mey Y, Poortvliet PM, Meuwissen MPM (2022) Quantifying the resilience of European farms using FADN. Eur Rev Agric Econ 49:121–150. https://doi.org/10.1093/erae/jbab042

Smith LG, Kirk GJD, Jones PJ, Williams AG (2019) The greenhouse gas impacts of converting food production in England and Wales to organic methods. Nat Commun 10:4641. https://doi.org/10.1038/s41467-019-12622-7

SPW (2020) Evolution de l'économie agricole et horticole de la Wallonie. 110. https://agriculture.wallonie.be/documents/20182/43924/RAPPORT+2020+EVOLUTION+DE+L+ECONOMIE+AGRICOLE+ET+HORTICOLE+DE+LA+WALLONIE/e525b7be-3109-4573-a04a-05ea750b9853

Stassart PM, Jamar D (2008) Steak up to the horns!: The conventionalization of organic stock farming: knowledge lock-in in the agrifood chain. GeoJournal 73:31–44. https://doi.org/10.1007/s10708-008-9176-2

Statbel (2019) Chiffres agricoles 2018. https://statbel.fgov.be/fr/themes/agriculture-peche/exploitations-agricoles-et-horticoles#figures

Statbel (2021) Chiffres agricoles 2020

Statbel (2022) Estimation définitive de la production des cultures agricoles - 2021

Statbel (2024) Chiffres agricoles 2023

Statistics Belgium (2024a) Meat supply balance in Belgium (2010-2023). Statistics Belgium (Statbel)

Statistics Belgium (2024b) Agricultural figures 2023. Statistics Belgium (Statbel)

Steffen W, Broadgate W, Deutsch L, et al (2015) The trajectory of the Anthropocene: The Great Acceleration. Anthr Rev 2:81–98. https://doi.org/10.1177/2053019614564785

Steinfeld H, Gerber PJ, Wassenaar T, et al (2006) Livestock's long shadow: Environmental issues and options. Food Agric Organ U N FAO. https://www.fao.org/3/a0701e/a0701e.pdf

Stokols D (2006) Toward a Science of Transdisciplinary Action Research. Am J Community Psychol 38:79–93. https://doi.org/10.1007/s10464-006-9060-5

Stylianou A, Sdrali D, Apostolopoulos CD (2020a) Capturing the diversity of Mediterranean farming systems prior to their sustainability assessment: The case of Cyprus. Land Use Policy 96:104722. https://doi.org/10.1016/j.landusepol.2020.104722

Stylianou A, Sdrali D, Apostolopoulos CD (2020b) Integrated Sustainability Assessment of Divergent Mediterranean Farming Systems: Cyprus as a Case Study. Sustainability 12:6105. https://doi.org/10.3390/su12156105

Teeuwen AS, Meyer MA, Dou Y, Nelson A (2022) A systematic review of the impact of food security governance measures as simulated in modelling studies. Nat Food 3:619–630. https://doi.org/10.1038/s43016-022-00571-2

Tessier L, Bijttebier J, Marchand F, Baret PV (2021) Identifying the farming models underlying Flemish beef farmers' practices from an agroecological perspective with archetypal analysis. Agric Syst 187:103013. https://doi.org/10.1016/j.agsy.2020.103013

Therond O, Duru M (2019) Agriculture et biodiversité : les services écosystémiques, une voie de réconciliation ?Innovations Agronomiques 75, 29-47. Innov Agron 75:29–47. https://doi.org/10.15454/GLDZ6I

Tirado R, Thompson KF, Miller KA, Johnston P (2018) Less is more: Reducing meat and dairy for a healthier life and planet - Scientific background on the Greenpeace vision of the meat and dairy system towards 2050. Greenpeace

Tittonell P (2014) Ecological intensification of agriculture—sustainable by nature. Curr Opin Environ Sustain 8:53–61. https://doi.org/10.1016/j.cosust.2014.08.006

Tittonell P (2023) Chapter 10. Pathways for Agroecological Transitions. In: A Systems Approach to Agroecology. Springer Nature Switzerland, Cham, pp 355–393

Torpman O, Röös E (2024) Are Animals Needed for Food Supply, Efficient Resource Use, and Sustainable Cropping Systems? An Argumentation Analysis Regarding Livestock Farming. Food Ethics 9:15. https://doi.org/10.1007/s41055-024-00147-9

Tuninetti M, Ridolfi L, Laio F (2022) Compliance with EAT-Lancet dietary guidelines would reduce global water footprint but increase it for 40% of the world population. Nat Food 3:143–151. https://doi.org/10.1038/s43016-021-00452-0

Vallone S, Lambin EF (2023) Public policies and vested interests preserve the animal farming status quo at the expense of animal product analogs. One Earth 6:1213–1226. https://doi.org/10.1016/j.oneear.2023.07.013

Van der Ploeg JD (2010) Farming styles research - the state of the art. Melk, Austria

Van der Straeten B (2015) Rentabiliteits- en kostprijsanalyse melkvee op basis van het Landbouwmonitoringsnetwerk. Boekjaren 2007-2012. Departement Landbouw en Visserij

Van der Straeten B (2016) Rentabiliteitsanalyse appels en peren. Resultaten op basis van het Landbouwmonitoringsnetwerk: Boekjaren 2009-2014. Departement Landbouw en Visserij

van Meijl H, van Rheenen T, Tabeau A, Eickhout B (2006) The impact of different policy environments on agricultural land use in Europe. Agric Ecosyst Environ 114:21–38. https://doi.org/10.1016/j.agee.2005.11.006

Van Passel S, Meul M (2012) Multilevel and multi-user sustainability assessment of farming systems. Environ Impact Assess Rev 32:170–180. https://doi.org/10.1016/j.eiar.2011.08.005

van Selm B, Frehner A, de Boer IJM, et al (2022) Circularity in animal production requires a change in the EAT-Lancet diet in Europe. Nat Food 3:66–73. https://doi.org/10.1038/s43016-021-00425-3

van Selm B, Hijbeek R, Van Ittersum MK, et al (2023) Recoupling livestock and feed production in the Netherlands to reduce environmental impacts. Sci Total Environ 899:165540. https://doi.org/10.1016/j.scitotenv.2023.165540

van Vuuren DP, Zimm C, Busch S, et al (2022) Defining a sustainable development target space for 2030 and 2050. One Earth 5:142–156. https://doi.org/10.1016/j.oneear.2022.01.003

van Wagenberg CPA, de Haas Y, Hogeveen H, et al (2016) Sustainability of livestock production systems : a comparing conventional and organic livestock husbandry. Wagening Univ Res. https://research.wur.nl/en/publications/54a95a75-72fb-47ba-92d4-da7b119fc241

Van Zanten H, Herrero M, Van Hal O, et al (2018) Defining a land boundary for sustainable livestock consumption. Glob Change Biol 24:4185–4194

Van Zanten HHE, Duncan J, Van Meijl H, Heimovaara S (2025) Scientific reflection on the European Commission's Vision for Agriculture and Food. Nat Food 6:653–656. https://doi.org/10.1038/s43016-025-01189-w

Vanhemelen C (2017) Projet «Zéro phyto»: son impact en horticulture. http://www.fwa.be/wordpressfwa/index.php/projet-zero-phyto-son-impact-en-horticulture/

Veerkamp CJ, Dunford RW, Harrison PA, et al (2020) Future projections of biodiversity and ecosystem services in Europe with two integrated assessment models. Reg Environ Change 20:103. https://doi.org/10.1007/s10113-020-01685-8

VEKA (2023) Vlaams Energie- en Klimaatplan 2021-2030. Vlaams Energie- en Klimaatagentschap, Brussel

VEKA (2025) Evaluatienota VEKP – actualisering 2030-prognoses Vlaamse ESR-sectoren. Vlaams Energie- en Klimaatagentschap, Brussel

Velthof GL, Lesschen JP, Webb J, et al (2014) The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000–2008. Sci Total Environ 468–469:1225–1233. https://doi.org/10.1016/j.scitotenv.2013.04.058

Vermeulen SJ, Campbell BM, Ingram JSI (2012) Climate Change and Food Systems. Annu Rev Environ Resour 37:195–222. https://doi.org/10.1146/annurev-environ-020411-130608

VILT (2015) Twee derde Vlaamse leghennen zit in verrijkte kooi. Vlaams Infocentrum Land-en Tuinbouw

VILT (2024) Florerende kalverhouderij kijkt tegen “onmogelijke stikstofdoelstellingen" aan. VILT

VILT (2022) Dit staat in het stikstofakkoord van de Vlaamse regering. VILT

Vlaamse Land Maatschappij (2025) Bemestingsnormen en richtwaarden - versie februari 2025. Vlaamse Land Maatschappij (VLM)

Vlaamse overheid (2025) Website MVOO criteria. https://www.mvoocriteria.be/nl

Vlaamse Regering (2024) Decreet over de programmatische aanpak stikstof. Brussel

VLAIO (2022) Steun land-en tuinbouwsector (coronavirus)

VMM, IRCEL-CELINE, Federal Public Service of Health, Food Chain Safety and Environment, et al (2020) Belgium's greenhouse gas inventory (1990-2018) - National Inventory Report submitted under the United Nations Framework Convention on Climate Change. https://unfccc.int/documents/224891

Vrints G, Deuninck J (2014) Technische en economische resultaten van de varkenshouderij op basis van het landbouwmonitoringsnetwerk. Boekjaren 2011-2013. Departement Landbouw en Visserij

Vrints G, Deuninck J (2015) Rentabiliteits- en kostprijsanalyse vleesvee. Departement Landbouw en Visserij

Vrolijk H, Poppe K (2021) Cost of Extending the Farm Accountancy Data Network to the Farm Sustainability Data Network: Empirical Evidence. Sustainability 13:8181. https://doi.org/10.3390/su13158181

Weber H, Poeggel K, Eakin H, et al (2020) What are the ingredients for food systems change towards sustainability?—Insights from the literature. Environ Res Lett 15:113001. https://doi.org/10.1088/1748-9326/ab99fd

Weiss F, Leip A (2012) Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agric Ecosyst Environ 149:124–134. https://doi.org/10.1016/j.agee.2011.12.015

Weituschat CS, Pascucci S, Materia VC, Blasi E (2023) Understanding the role of value chain formation in the scaling of crop diversification. Agron Sustain Dev 43:25. https://doi.org/10.1007/s13593-023-00866-z

Westbury DB, Park JR, Mauchline AL, et al (2011) Assessing the environmental performance of English arable and livestock holdings using data from the Farm Accountancy Data Network (FADN). J Environ Manage 92:902–909. https://doi.org/10.1016/j.jenvman.2010.10.051

Westhoek H, Lesschen JP, Rood T, et al (2014) Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. Glob Environ Change 26:196–205. https://doi.org/10.1016/j.gloenvcha.2014.02.004

Westhoek HJ, van den Berg M, Bakkes JA (2006) Scenario development to explore the future of Europe's rural areas. Agric Ecosyst Environ 114:7–20. https://doi.org/10.1016/j.agee.2005.11.005

Wezel A, Bellon S, Doré T, et al (2009) Agroecology as a science, a movement and a practice. A review. Agron Sustain Dev 29:503–515. https://doi.org/10.1051/agro/2009004

Wezel A, Herren BG, Kerr RB, et al (2020) Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. Agron Sustain Dev 40:40. https://doi.org/10.1007/s13593-020-00646-z

Willett W, Rockström J, Loken B, et al (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet 393:447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

Wood A, Queiroz C, Deutsch L, et al (2023) Reframing the local–global food systems debate through a resilience lens. Nat Food 4:22–29. https://doi.org/10.1038/s43016-022-00662-0

Woodhill J, Peters B, Ingram J, et al (2024) Foresight for Food Systems Change - Using future thinking and scenario analysis for reslience and anticipatory policy making. Briefing paper. Foresight4Food

Zimmermann B, Claß-Mahler I, Von Cossel M, et al (2021) Mineral-Ecological Cropping Systems—A New Approach to Improve Ecosystem Services by Farming without Chemical Synthetic Plant Protection. Agronomy 11:1710. https://doi.org/10.3390/agronomy11091710

Zionts J, Bartlett H, Searchinger T, Allen M (2025) The utility of novel environmental impact metrics in UK ruminant mitigation. Environ Res Food Syst 2:025009. https://doi.org/10.1088/2976-601x/add93e

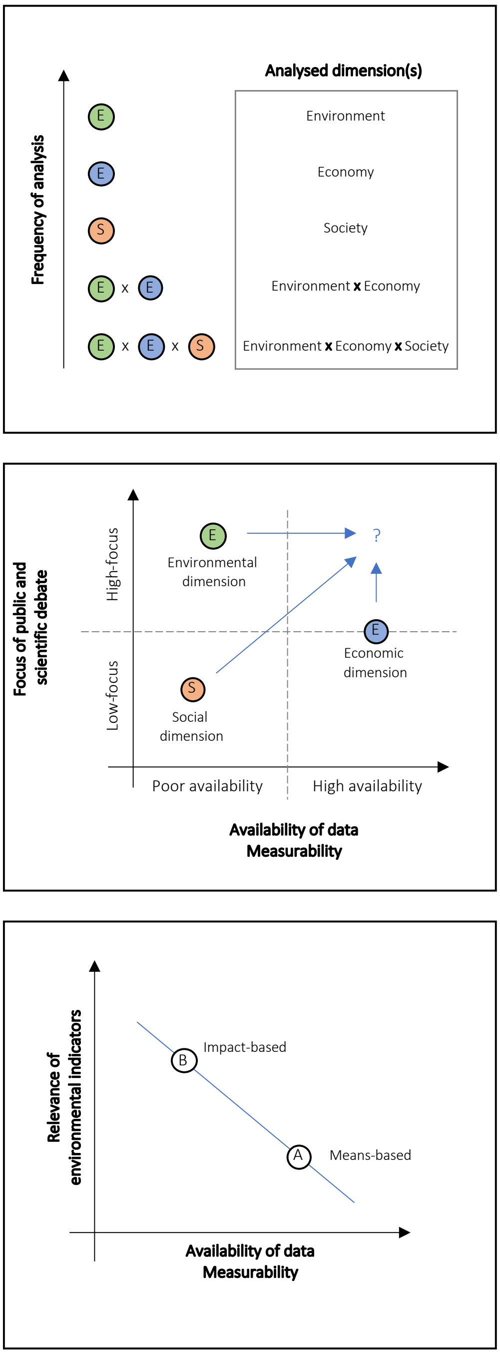
Zu Ermgassen EKHJ, Ayre B, Godar J, et al (2020) Using supply chain data to monitor zero deforestation commitments: an assessment of progress in the Brazilian soy sector. Environ Res Lett 15:035003. https://doi.org/10.1088/1748-9326/ab6497

Zu Ermgassen EKHJ, Bastos Lima MG, Bellfield H, et al (2022) Addressing indirect sourcing in zero deforestation commodity supply chains. Sci Adv 8:15. https://doi.org/10.1126/sciadv.abn3132

Appendices

Appendix to chapter 3

Additional figure on the three dilemmas of indicator-based sustainability assessments



I. Current sustainability assessments mainly focus on the environment. While there is a wide call for holistic assessments, the economic and social dimensions are in practice less studied.

II. The focus on the environment clashes with lower availability of data. In farm accountancy databases, economic indicators are readily available while environmental and particularly social indicators are less abundant.

III. Environmentally-relevant indicators are hard to measure and less available in farm accountancy databases. Means-based indicators are easy to measure but have a low power of prediction. Impact-based indicators have a high relevance but are hard to measure.

Figure S1. Three main dilemmas of data-driven, indicator-based sustainability assessments. The order of the dimensions on the top figure is not based on a comprehensive review of sustainability assessment studies. It merely indicates that the environmental dimension is more often analysed than the economic and social dimensions and that combined assessments covering two or all three sustainability dimensions are not yet systematic. A fourth dilemma, which is not illustrated here, is that sustainability assessments generally fail to account for diversity.

Additional detail on the data cleaning process

A two-step data cleaning process was performed:

1. **Exclusion of fattening farms in the beef sector:** All farms presenting a ratio "Young males 1-2 years/Suckler cows" higher than 10% were assumed to perform a fattening step and thus excluded from the sample. Indeed, specialized breeding farms generally sell their young bulls at about 10 months of age to specialized fattening farms. A 10% threshold was used as some bulls might be sold later.
2. **Exclusion of non-profitable farms:** This step results from the calculation methodology used by the DAEA to assess farm income. In order to facilitate comparison between observations in the dataset, some farms are attributed fictional renting and interest costs. These fictional costs can have negative impacts on the farms' income levels. Excluding all farms below the 10th percentile in terms of farm income allows to focus the analysis on farms which are not too affected by this situation.

Additional figure on the methodological steps of the study

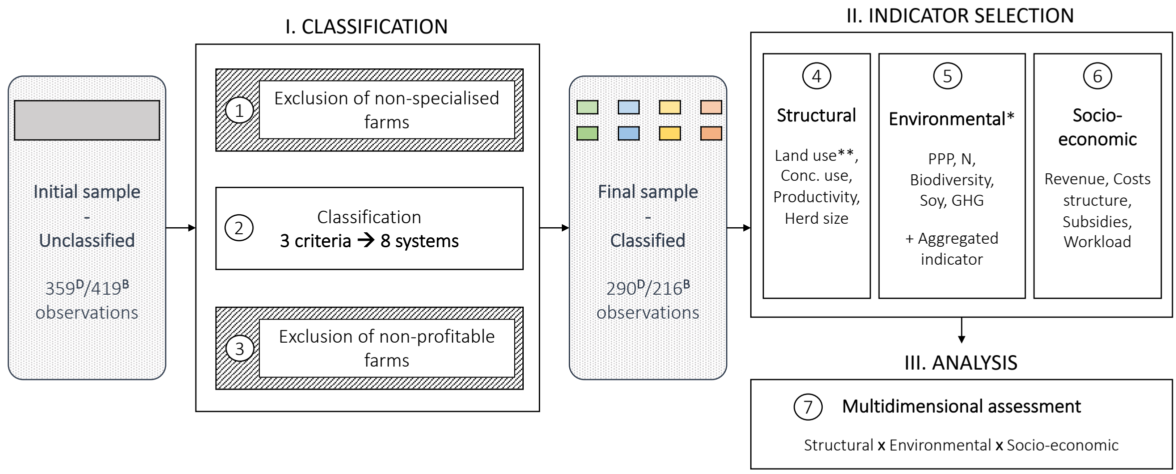


Figure S2. Methodological steps involved in the diversity and sustainability assessments of bovine systems ([D] Dairy farms; [B] Beef farms) in Wallonia. The hatched boxes (1 and 3) of the classification step represent the data cleaning process. Environmental indicators (*) had to be calculated based on the available data and external hypotheses. Land use data (**) was partially included in the initial dataset (core data) but needed some additional cleaning and processing.

Additional figure illustrating the classification steps

Figure S3. Classification steps of a sample of 359 observations of specialized dairy farms (top) and 419 observations of specialized beef farms (bottom) in Wallonia over the 2014-2017 period.

Description of on- and off-farm areas considered for the land use calculations

On-farm area dedicated to the bovine herd:

- **On-farm Forage area** (FA): Includes grassland, forage maize, other fodder crops (alfalfa, clover, forage cereals, secondary forage crops, etc.). All on-farm forage crops were assumed to be entirely destined to the bovine herd.
- **On-farm Concentrates area** (CA): For concentrates crops (e.g., cereals), only total areas were available in the original dataset, with no indication on the shares of these areas which were destined to be sold as cash crops or used as animal feed. Nevertheless, the quantities of consumed feed made the distinction between on-farm feed and bought feed. Hence, the areas of on-farm concentrates crops destined to the bovine herd were estimated from the consumed quantities of auto-produced concentrates (in kg) and the specific yields of these feed ingredients on each farm.

Off-farm area dedicated to the bovine herd: Data on off-farm areas was not available in the original dataset. It was estimated based on the quantities of bought feed and average yields.

- **Bought concentrates feeds**: The original dataset contains many composite feeds which cannot easily be disaggregated into different ingredients. Some assumptions thus had to be made. Based on Petel et al. (2018a, 2018b), the composition of bought concentrates was estimated to be the following:
    - 65% of bought concentrates are co-products (e.g., soybean meal, beetroot pulp, etc.), which were associated with a null land use.
    - 30% of bought concentrates are cereals. Their areas were estimated based on the average yield of cereal crops in Wallonia over the 2014-2018 period.
    - 5% of bought concentrates are pulses. Their areas were estimated based on the average yield of peas (*Pisum sativum*) in Wallonia over the 2014-2018 period.
- **Bought forage feeds**:
    - Mainly consist of co-products such as brewery dregs and beet pulp, for which no land use was assigned.
    - Forage maize, for which the land use was estimated based on average yields.

Total area mobilized by the bovine herd: Sum of on-farm area and off-farm area (Figure S4).

- **On-farm area:** on-farm forage area (FA) + on-farm concentrates area (CA)
- **Off-farm area:** areas associated with the quantities of cereals and pulses purchases (respectively 30% and 5% of the bought concentrated feed) and forage maize. Feed ingredients considered as co-products are not included.

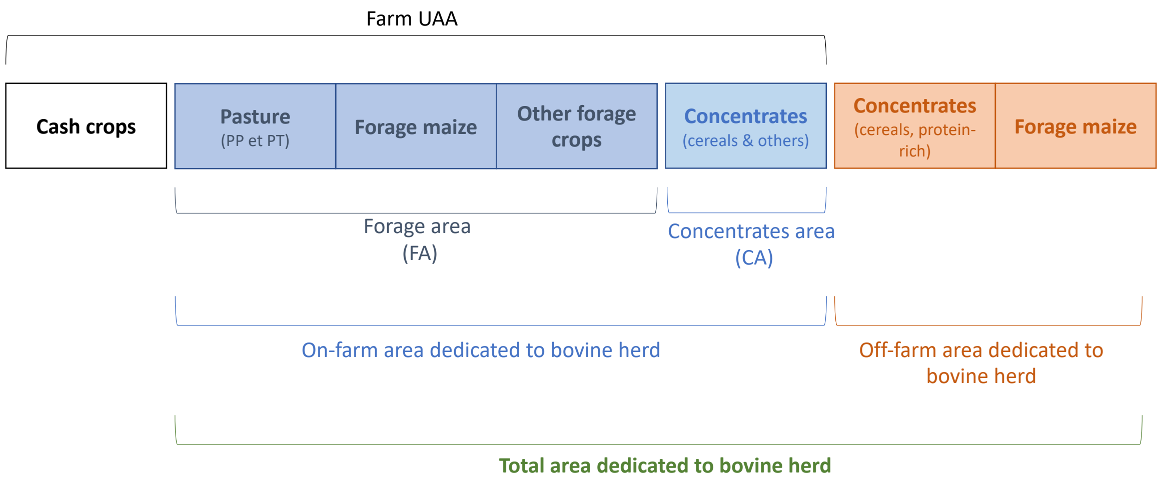


Figure S4. On- and off-farm areas dedicated to bovine herds which are considered in the land use calculations

Description of structural indicators

Four indicators are considered:

- **Stocking rate:** Number of livestock units per hectare of on-farm forage area (LSU/ha FA).
- **Use of concentrates:** Indicates the need for concentrate feed of the farm. Expressed per cow and progeny (C&P). A distinction is made between:
    - Concentrates produced on-farm;
    - Bought concentrates;
    - Total concentrates (= on farm + bought).
- **Concentrate self-sufficiency:** Concentrates produced on-farm divided by total concentrates.
- **Dairy yields:** Expressed in litres of milk per year and per cow.

Description of economic indicators

One main indicator is considered:

- **Farm income**: Difference between total products and total costs.
  - Products include:
    - Milk products, beef products, other products (cash crops etc.) and subsidies
  - Costs include:
    - Operational (variable) costs (e.g., feed, pesticides...)
    - Structural (fixed) costs (e.g., rent, water, electricity...)
    - Financial costs (e.g., loans...)
    - Several units are considered:

Several functional units are:

- Total revenue at farm level
- Per L milk (for dairy farms)
- Per unit of Family Work Unit (FWU)
- Per cow

Two additional indicators can be calculated based on the product and cost structure:

- **Share of subsidies**: Gives an indication of the importance of subsidies.
  - Importance of subsidies = Subsidies / Total products
- **Economic efficiency**: Gives an indication of the economic efficiency of the farm.
  - Economic efficiency = Gross margin* / Total products except subsidies.
  - *Gross margin = Total products (except subsidies) – Operational costs

Description of environmental indicators

Five environmental indicators were assessed:

- **Soy consumption:** Expressed in kg soy/cow. Based on ERM & UGent (2011), soy is assumed to represent 22% of bought concentrates for dairy farms and 5% of bought concentrates for beef farms (with the assumption that no soybean is produced on-farm).
    - ONLY one functional unit in this case: per cow and progeny.
- **Pesticide (PPP) use:** Expressed in kg active ingredient (a.i.). Depends on the on-farm and off-farm area mobilized for the bovine herd and the average pesticide use on each of the crops in the Walloon region (Table S1).
- **Nitrogen emissions:** Expressed in kg N. Only includes N emissions from animals. N emissions from fertiliser use are not included. Emissions from animals are calculated on the basis of emission factors used in the Belgian greenhouse gas (GHG) inventory (VMM et al. 2020) (Table S2).
- **Damage score:** The Damage Score (DS) is a measure of the biodiversity impact of certain management practices on certain land uses. Calculations were based on the methodology established by De Schryver et al. (2010). This methodology uses characterization factors (CFs) to estimate the ecosystem damage of certain land uses (grassland, arable land, etc.) and management levels (intensive, extensive, organic). They correspond to the relative change in terms of species diversity in the area of interest compared to an initial situation (Table S3).
- **GHG emissions:** These were not calculated specifically for each farm (unlike all other environmental indicators). Estimations were made based on results of carbon footprints calculated in a scenario study of the livestock sector in Belgium (Riera et al. 2019). These are based on the typologies developed by Petel et al. (2018b, 2018a) for the bovine sectors in Wallonia.

Several functional units are considered for each indicator:

- Total impact at farm level (-)
- Per unit of area (-/ha)
- Per animal (-/cow & progeny)
- Per unit of product (-/L milk)

Table S1. Average pesticide use (kg a.i./ha) of different crops in Wallonia over the 2014-2018 period.

Crop	Average pesticide use kg a.i./ha	Precision [1]
Permanent grassland	0.06	Walloon-wide extrapolation
Temporary grassland	0.07	Walloon-wide extrapolation
Forage maize	1.31	Walloon-wide extrapolation
Other forage crops	0.18	FADN sample average
Cereals [2]	2.68	Walloon-wide extrapolation
Field pea	2.36	FADN sample average

Reference: (Comité Régional Phyto 2015, 2017)

Notes: [1] The two precision levels result from the fact that, for the most important crops at a regional level, the CRP extrapolates average pesticide use for the entire region using data from farms in the FADN sample. For less important crops, the results are limited to the averages pesticide use of the farms in the sample and therefore have a higher uncertainty (as some crops are poorly represented in the sample). [2] Weighted average of the three main cereal crops in Wallonia: winter wheat, winter barley and spelt.

Table S2. Nitrogen emission factors (kg N/animal/year) of different animal categories.

Animal category	Nitrogen emission factor kg N/animal/year
Bovine < 0.5 year	13.4
Male bovine 0.5-1 year	37.5
Female bovine 0.5-1 year	30.8
Male bovine > 1 year for fattening	97.8
Male bovine > 1 year for reproduction	84.4
Female bovine > 1 year	58.9
Suckler cow	97.8
Dairy cow	120.5

Reference: (VMM et al. 2020)

Table S3. Biodiversity impact of different land uses and management practices.

Land uses	Management practices	Characterization factor Damage score/m^2/year
Arable land	Intensive	0.79
	Less intensive	0.44
	Organic	0.36
Fertile grassland	Intensive	0.65
	Less intensive	0.36
	Organic	-0.01

Reference: (De Schryver et al. 2010)

Additional figure illustrating the economic and environmental performances of sample farms

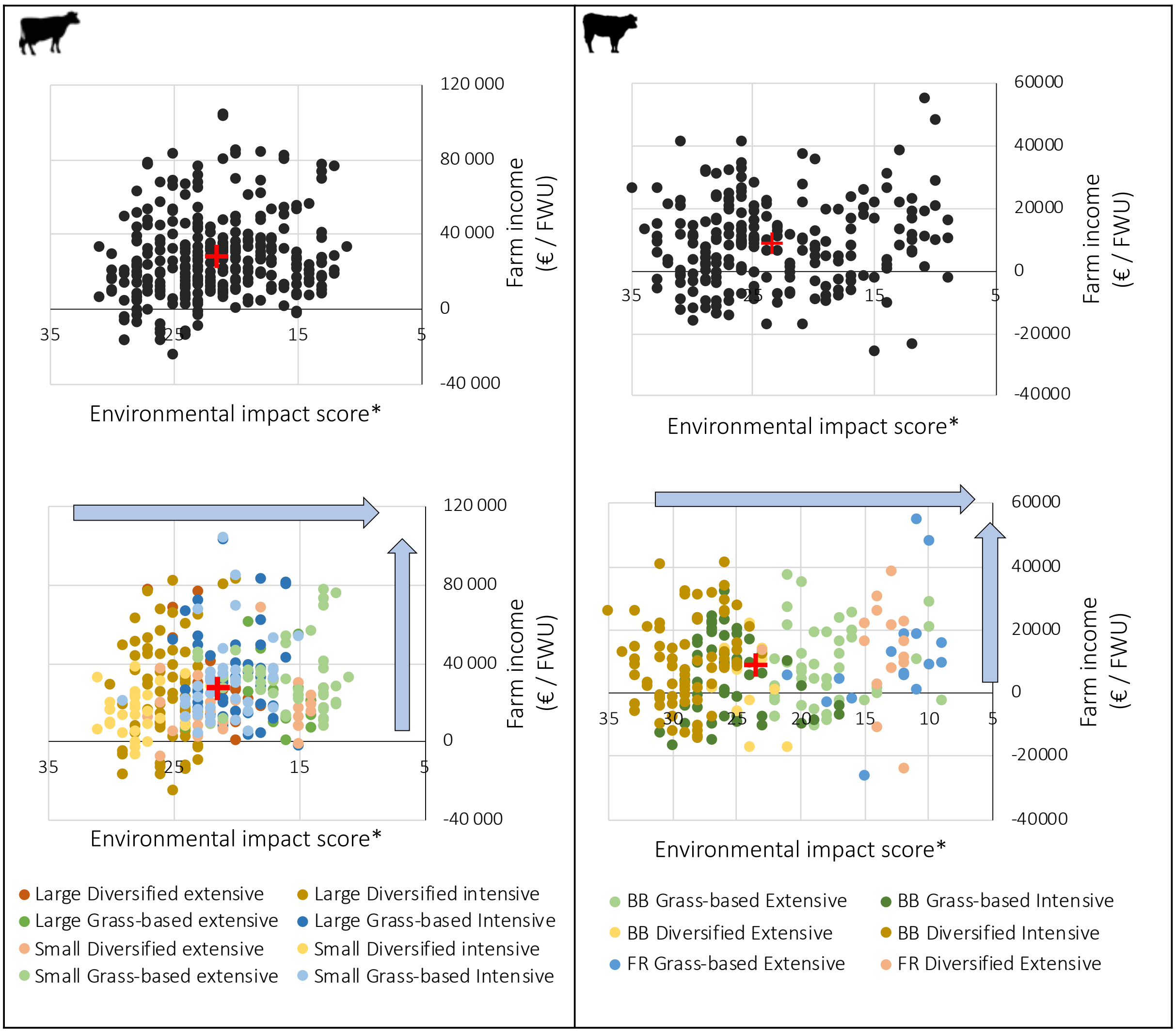


Figure S5. Combined economic and environmental performances of dairy (left) and beef-breeding (right) systems in Wallonia. Unclassified (top) and classified (bottom) sample observations.

Notes: *GHG emissions were estimated at the production system level and were considered similar for all farms within a system. Red crosses indicate sample averages.

Appendix to chapter 4

Table of reviewed studies

Table S4. Final set of studies used for the analysis (continued on following pages).

N°	Scenario/model	Reference	Type of document	Reference study?
1	Agrimonde: Scenarios and Challenges for Feeding the World in 2050	(Chaumet et al. 2009)	Report	Yes
2	Localising the nitrogen imprint of the Paris food supply: the potential of organic farming and changes in human diet	(Billen et al. 2012)	Scientific article	
3	A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade	(Billen et al. 2015)	Scientific article	
4	Le Scenario Afterres 2050 (Solagro)	(Couturier et al. 2016)	Report	Yes
5	Limiting livestock production to pasture and by-products in a search for sustainable diets	(Röös et al. 2016)	Scientific article	Yes
6	Agrimonde-Terra: Foresight land use and food security in 2050.	(de Lattre-Gasquet et al. 2016)	Report	Yes
7	What prospective scenarios for 2035 will be compatible with reduced impact of French beef and dairy farm on climate change?	(Mosnier et al. 2017)	Scientific article	
8	Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures	(Röös et al. 2017b)	Scientific article	
9	Future Nordic Diets: Exploring ways for sustainably feeding the Nordics	(Karlsson et al. 2017)	Scientific article	
10	Protein futures for Western Europe: potential land use and climate impacts in 2050	(Röös et al. 2017a)	Scientific article	Yes
11	Strategies for feeding the world more sustainably with organic agriculture	(Muller et al. 2017)	Scientific article	Yes
12	Et si la France passait au régime "bio, local et demitarien"? Un scénario radical de sobriété alimentaire et d'autonomie protéique et azotée pour l'agriculture et l'élevage	(Billen et al. 2017b)	Book chapter	
13	Scénarios prospectifs du système agro-alimentaire du bassin de la Seine à l'horizon 2040	(Billen et al. 2017a)	Report	
14	An agroecological Europe in 2050: multifunctional agriculture for healthy eating	(Poux and Aubert 2018)	Report	Yes
15	Two contrasted future scenarios for the French agro-food system	(Billen et al. 2018)	Scientific article	
16	Etat des lieux et scénarios à horizon 2050 de la filière céréales en Région wallonne	(Antier et al. 2020a)	Report	
17	Less is more: Reducing meat and dairy for a healthier life and planet	(Tirado et al. 2018)	Report	Yes
18	The livestock sector and planetary boundaries: A 'limits to growth' perspective with dietary implications	(Bowles et al. 2019)	Scientific article	
19	The greenhouse gas impacts of converting food production in England and Wales to organic methods	(Smith et al. 2019)	Scientific article	
20	Study on livestock scenarios for Belgium in 2050	(Riera et al. 2019)	Report	
21	Food in the Anthropocene: the EAT-Lancet Commission on healtyh diets from sustainable food systems	(Willett et al. 2019)	Report	Yes
22	Pathways to Sustainable Land-Use and Food Systems	(FABLE 2019)	Report	Yes
23	Modelling the scaling up of sustainable farming into Agroecology Territories: Potentials and bottlenecks at the landscape level in a Mediterranean case study	(Padró et al. 2020)	Scientific article	

24	Future projections of biodiversity and ecosystem services in Europe with two integrated assessment models	(Veerkamp et al. 2020)	Scientific article	
25	SYNERGY: A regional bio-economic model analyzing farm-to-farm exchanges and legume production to enhance agricultural sustainability	(Jouan et al. 2020a)	Scientific article	
26	Legume production and use in feed: Analysis of levers to improve protein self-sufficiency from foresight scenarios	(Jouan et al. 2020b)	Scientific article	
27	Global option space for organic agriculture is delimited by nitrogen availability	(Barbieri et al. 2021)	Scientific article	
28	Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity	(Billen et al. 2021)	Scientific article	
29	Robustness to import declines of three types of European farming systems assessed with a dynamic nitrogen flow model	(Pinsard et al. 2021)	Scientific article	
30	A Greater Share of Organic Agriculture in Relation to Food Security Resulting from the Energy Demand Obtained from Food—Scenarios for Poland until 2030	(Kuczuk and Widera 2021)	Scientific article	
31	Agroecological practices in combination with healthy diets can help meet EU food system policy targets	(Röös et al. 2022)	Scientific article	
32	Multi-target scenario discovery to plan for sustainable food and land systems in Australia	(Navarro Garcia et al. 2023)	Scientific article	
33	The compatibility of circularity and national dietary recommendations for animal products in five European countries: a modelling analysis on nutritional feasibility, climate impact, and land use	(Frehner et al. 2022)	Scientific article	
34	Circularity in animal production requires a change in the EAT-Lancet diet in Europe	(van Selm et al. 2022)	Scientific article	
35	Compliance with EAT–Lancet dietary guidelines would reduce global water footprint but increase it for 40% of the world population	(Tuninetti et al. 2022)	Scientific article	
36	Exploring Agroecology Transition Scenarios: A Pfaundler's Spectrum Assessment on the Relocation of Agri-Food Flows	(Padró and Tello 2022)	Scientific article	

Coding variables used for analysis

Table S5. Set of coding variables used for the analysis of the reviewed studies (continued on following pages).

Variable	Explanation	Possible values
Study number	Number in set of reviewed studies	-
Scenario/model	Study title	-
Authors	Authors of the study	-
Date	Year of publication	-
Type of document	Category of document in which the results are published and consulted for the review	Report; Scientific article; Book chapter
Commissioner	Organisation by which the scenarios were commissioned	-
Process	Does the scenario design include a process involving experts or other participants	Expert consultation; Participatory approach
Geographical scope	Geographical level of analysis	World; Europe; National; Regional; Farm; International; Regional and global; National and regional; Farm and regional; Farm and national
Geographical scope specifics	Name of location	-
Temporal horizon	Year used as temporal horizon in the scenarios	-
Type of model	Name of the model/model type (if mentioned)	-
Narrative entry point/focus	Main focus and entry point for the scenarios (e.g. Nitrogen balance, diets...)	-
Purpose/ intention	Main objective pursued through the scenarios	Assessing the consequences of different scenarios or trajectories; Demonstrating the feasibility of a specific scenario (or framing the conditions for its feasibility)
Topic	What is being studied and where	-
Approach	Horizontal or vertical approach, or combination of both	Horizontal approach (by geographical scope); Vertical approach (by farming sector); Horizontal and vertical approaches (geographical and sectoral); NA
Number of scenarios	Number of different scenarios tested	-
Scenarios tested	Detail on scenarios and their name	-
Sectors	Agricultural sector categories included in the scenarios	Crop production; Livestock production; Crop and livestock production; Non-food; Bovine sector; Aquaculture
Sectors details	Specific agricultural sectors included in the scenarios (e.g. cereals, poultry...)	-
Characteristics of diets*	Dietary patterns included in the scenarios (if any)	-
Number of production systems	Number of different production systems within the considered agricultural sectors	-
Production systems considered	Name of production systems considered	-

Characteristics of production systems	Type of production systems considered	Average production system; Farm types; Diversity; Not specified
Specifics for each production systems	Further details on the production systems considered	-
Sustainability dimensions	Dimensions of sustainability included in the scenarios	Economic; Social; Environment; Environment x Economic; Economic x Social; Environment x Social; Social x Economic x Environment; Biophysical factors; Biophysical x Social
Environmental aspects included*	Environmental themes included in the scenarios	Land use; Nitrogen; GHG; Biodiversity; Water; Climate; Eutrophication; Acidification; Phosphorus; Potassium; Afforestation; Soil carbon sequestration; Use of pesticides; Deforestation; Erosion; Energy
Environmental indicators**	Specific names of environmental indicators included in the scenarios	-
Comment	Further comment on the environmental indicators used	-
Socio-economic aspects included*	Socio-economic themes included in the scenarios	Trade; Economic results; Policy parameters; Prices; Food sovereignty; Producer value; Labour use; Labour productivity; Animal welfare; Feed imports; Synthetic fertiliser; Population; Technology; Macro-economic aspects; Profit; Income; Local exchanges of manure; Local exchanges of N fertilisers; Investment costs; Labour demand; Coupled support; No. of working hours; Accidents for farm workers; Toxicity for farm workers; Health
Socio-economic indicators**	Specific names of socio-economic indicators included in the scenarios	-
Productive aspects included*	Productivity-related themes included in the scenarios	-
Productive indicators**	Specific names of productivity-related indicators included in the scenarios	-
Deliberately not considered	Elements explicitly stated as being not considered in the study	-
Not considered by comparison with other models	Elements not considered in the study after comparison with similar studies included in the review	-
Resemblance with another model	Potential linkages with other studies included in the review	-

Notes:

* For diets, environmental aspects, socio-economic aspects and productive aspects, we indicate whether these elements are considered as input variables (i.e. constraints to the model), output variables (i.e. scenario results) or variable (i.e. both a constraint and result)

** For environmental, socio-economic and productive indicators, we indicate whether they are means-based (i.e. reflecting agricultural practices), impact-based (i.e. reflect the actual impact related to a specific theme) or intermediate.

Overview of descriptive indicators of reviewed scenarios

Table S6. Overview of descriptive indicators of reviewed scenario studies (based on coding variables) (continued on following pages).

N°	Reference	Scenario type	Purpose	Number of scenarios	Participatory approach	Time horizon	Geographical scale	Sectors	Number of production systems
1	(Chaumet et al. 2009)	D	Assessing the consequences of different scenarios or trajectories	2	Expert consultation	2050	Regional to global	Crop and livestock	NA
2	(Billen et al. 2012)	C	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	2	NA	2030	Regional	Crop and livestock	1
3	(Billen et al. 2015)	B	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	Many	NA	2050	Global	Crop and livestock	0
4	(Couturier et al. 2016)	D	Assessing the consequences of different scenarios or trajectories	4	NA	2050	National	Crop and livestock	Many
5	(Röös et al. 2016)	C	Assessing the consequences of different scenarios or trajectories	3	NA	No temporal horizon	National	Crop and livestock	NA
6	(de Lattre-Gasquet et al. 2016)	D	Assessing the consequences of different scenarios or trajectories	5	Expert consultation	2050	Regional to global	Crop and livestock	NA
7	(Mosnier et al. 2017)	D	Assessing the consequences of different scenarios or trajectories	4	Expert consultation	2035	Farm to national	Livestock	4
8	(Röös et al. 2017b)	B	Assessing the consequences of different scenarios or trajectories	Many	NA	2050	Global	Livestock	Many
9	(Karlsson et al. 2017)	C	Assessing the consequences of different scenarios or trajectories	2	Participatory approach	2030	Multiple countries	Crop and livestock	5
10	(Röös et al. 2017a)	C	Assessing the consequences of different scenarios or trajectories	6	NA	2050	Europe	Crop and livestock	NA
11	(Muller et al. 2017)	B	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	Many	NA	2050	Global	Crop and livestock	0
12	(Billen et al. 2017b)	A	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	1	NA	No temporal horizon	National	Crop and livestock	1
13	(Billen et al. 2017a)	D	Assessing the consequences of different scenarios or trajectories	4	Participatory approach	2050	Regional	Crop and livestock	2
14	(Poux and Aubert 2018)	A	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	1	Expert consultation	2050	Europe	Crop and livestock	1
15	(Billen et al. 2018)	D	Assessing the consequences of different scenarios or trajectories	2	NA	2040	Regional to national	Crop and livestock	1

16	(Antier et al. 2020a)	D	Assessing the consequences of different scenarios or trajectories	3	Participatory approach	2050	Regional	Crop	4
17	(Tirado et al. 2018)	A	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	1	NA	2050	Regional to global	Livestock	1
18	(Bowles et al. 2019)	D	Assessing the consequences of different scenarios or trajectories	4	NA	2050	Global	Livestock productions	Many
19	(Smith et al. 2019)	A	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	1	NA	No temporal horizon	National	Crop and livestock	1
20	(Riera et al. 2019)	D	Assessing the consequences of different scenarios or trajectories	3	Expert consultation	2050	National	Livestock	Many
21	(Willett et al. 2019)	B	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	Many	NA	2050	Global	Crop and livestock	0
22	(FABLE 2019)	D	Assessing the consequences of different scenarios or trajectories	Many	Expert consultation	2050	Multiple countries	Crop and livestock	NA
23	(Padró et al. 2020)	D	Assessing the consequences of different scenarios or trajectories	6	NA	No temporal horizon	Regional	Crop and livestock	2
24	(Veerkamp et al. 2020)	D	Assessing the consequences of different scenarios or trajectories	4	Participatory approach	2050	Europe	Crop and livestock	NA
25	(Jouan et al. 2020a)	D	Assessing the consequences of different scenarios or trajectories	4	NA	No temporal horizon	Farm to regional	Crop and livestock	Many
26	(Jouan et al. 2020b)	C	Assessing the consequences of different scenarios or trajectories	3	Participatory approach	2040	Farm to regional	Crop and livestock	Many
27	(Barbieri et al. 2021)	B	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	36	NA	No temporal horizon	Global	Crop and livestock	1
28	(Billen et al. 2021)	A	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	1	NA	2050	Europe	Crop and livestock	1
29	(Pinsard et al. 2021)	C	Assessing the consequences of different scenarios or trajectories	3	NA	2050	Regional	Crop and livestock	3
30	(Kuczuk and Widera 2021)	A	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	Many	NA	2030	National	Crop and livestock	2
31	(Röös et al. 2022)	D	Assessing the consequences of different scenarios or trajectories	5	Participatory approach	2050	Europe	Crop and livestock	1
32	(Navarro Garcia et al. 2023)	B	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	Many	NA	2050	National	Crop and livestock	NA
33	(Frehner et al. 2022)	B	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	4	NA	No temporal horizon	National	Livestock	NA

34	(van Selm et al. 2022)	C	Assessing the consequences of different scenarios or trajectories	4	NA	No temporal horizon	Europe	Crop and livestock	3
35	(Tuninetti et al. 2022)	A	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	1	NA	No temporal horizon	Global	Crop and livestock	0
36	(Padró and Tello 2022)	B	Demonstrating the feasibility of a specific scenario or framing the conditions for its feasibility	2	NA	No temporal horizon	Regional	Crop and livestock productions	Many

Occurrence of sustainability dimensions in reviewed scenarios

Table S7. Occurrence of sustainability dimensions and themes in reviewed scenario studies (based on coding variables) (continued on following pages).

N°	Reference	Environmental sustainability	Economic sustainability	Social sustainability	3D sustainability	Environmental aspects included	Socio-economic aspects included	Productive aspects included
1	(Chaumet et al. 2009)	x				Land use (I); Afforestation and deforestation (I)		Productivity and yields (I); Food balance (O)
2	(Billen et al. 2012)	x				Land use (I/O); Nitrogen (O)		Food demand (I); Feed production and demand (I/O); General production (O)
3	(Billen et al. 2015)	x	x			Nitrogen (O)	Food sovereignty; Trade (O)	Food demand (I); General production (I/O); Technology (I); Feed production and demand (O)
4	(Couturier et al. 2016)				x	Nitrogen; Phosphorus; Land use; Climate; Biodiversity; Water; Eutrophication; Acidification; Afforestation and deforestation; Soil carbon sequestration; Pesticides; Energy; Erosion	Trade (O); Population (I); Labour demand and use (O); Economic results (O)	General production (O)
5	(Röös et al. 2016)	x		x		Climate (O); Land use (O); Biodiversity (O); Nitrogen (O); Phosphorus (O); Soil carbon sequestration (O)	Labour demand and use (O); Health (O)	Food waste (I/O); General production (O); Feed production and demand (O)
6	(de Lattre-Gasquet et al. 2016)	x	x			Climate (I); Land use (O)	Trade (O)	Productivity and yields (I)

7	(Mosnier et al. 2017)	x	x			Climate (O)	Economic results (O); Policy parameters (I); Prices (I)	General production (I/O); Feed production and demand (I/O); Input consumption (O)
8	(Röös et al. 2017b)	x				Land use (O); Climate (O)		Productivity and yields (I); Waste (I)
9	(Karlsson et al. 2017)	x				Land use (I/O); Nitrogen (O); Phosphorus (O); Climate (O); Eutrophication; O); Acidification (O); Soil carbon sequestration (O)		General production (O); Food waste (I)
10	(Röös et al. 2017a)	x				Land use (O); Climate (O); Soil carbon sequestration (O)		Food waste (I); Technology (I); General production (O); Feed production and demand (O)
11	(Muller et al. 2017)	x				Land use (O); Afforestation and deforestation (O); Climate (I/O); Nitrogen (O); Phosphorus (O); Erosion (O); Energy (O); Water (O); Pesticides (O)		Agricultural area; Productivity and yields (I/O); Food waste (I)
12	(Billen et al. 2017b)	x	x			Nitrogen (O)	Trade (O)	Size of livestock herd; General production
13	(Billen et al. 2017a)				x	Nitrogen (O); Water (O); Phosphorus (O); Land use (O)	Population (I); Trade (I)	General production (O); Livestock density (I)
14	(Poux and Aubert 2018)	x	x			Land use (I/O); Nitrogen (O); Climate (O); Biodiversity (I/O)	Trade (I/O)	Food demand (I); General production (I/O)
15	(Billen et al. 2018)	x	x			Nitrogen (O); Phosphorus (O)	Trade (O)	Food demand (O); Agricultural area (I); General production (O); Feed production and demand (O)

16	(Antier et al. 2020a)	x				Nitrogen (O); Pesticides (O)		Food balance (O); Productivity and yields (I)
17	(Tirado et al. 2018)	x		x		Climate (O); Land use (O); Water (O); Biodiversity (O)	Health (O)	General production (I); Food demand (I)
18	(Bowles et al. 2019)	x				Land use (I/O); Nitrogen (I/O); Climate (I/O)		General production (O); Food demand (O)
19	(Smith et al. 2019)	x	x			Climate (O); Soil carbon sequestration (I/O); Land use (O)	Trade (O)	General production (O)
20	(Riera et al. 2019)	x				Climate (O); Eutrophication (O); Biodiversity (O); Pesticides (O)		Feed production and demand (I)
21	(Willett et al. 2019)	x		x		Land use (O); Nitrogen (O); potassium (O); Water (O); Climate (O); Biodiversity (O)	Health (O)	General production (O)
22	(FABLE 2019)	x	x			Afforestation and deforestation (I/O); Climate (O); Biodiversity (O); Land use (I)	Trade (I/O)	Food balance (I/O); Productivity and yields (I)
23	(Padró et al. 2020)	x		x		Land use (O); Nitrogen (O); Phosphorus (O); Potassium (O)	Food sovereignty (I)	Food demand (I); Agricultural area (I); General production (I); Feed production and demand (O)
24	(Veerkamp et al. 2020)				x	Climate; Land use; Biodiversity; Water	Population; Economic results	Food demand; Productivity and yields; Timber provision; Wild food availability; General production
25	(Jouan et al. 2020a)				x	Nitrogen (O)	Economic results (O); Local exchanges of manure (I/O); Local exchange of N fertilisers (I/O)	Agricultural area (I/O); General production (O); Food demand (O); Food balance (O)

26	(Jouan et al. 2020b)				x	Nitrogen (O)	Economic results (O); Local exchanges of manure (I/O); Local exchange of N fertilisers (I/O); Prices (I); Investment cost; Labour demand and use; Policy parameters (I); Trade (O)	Food balance (I); General production (I/O); Consumer preferences (I); Factor allocations (I); Technology (I)
27	(Barbieri et al. 2021)	x				Land use (I/O); Nitrogen (I/O)		Food demand (I); Food waste (I); General production (O); Size of livestock herd (I)
28	(Billen et al. 2021)	x	x			Nitrogen (O)	Trade (O)	None explicitly assessed in the paper
29	(Pinsard et al. 2021)	x	x			Nitrogen (I/O)	Trade (I)	Feed production and demand (I); General production (O)
30	(Kuczuk and Widera 2021)	x		x		Land use (O)	Population (I/O)	Nutritional value of food; Food waste (I)
31	(Röös et al. 2022)				x	Land use (I/O); Nitrogen (I/O); Climate (O); Biodiversity (O); Water (O)	Trade (I/O); Economic results (O); Labour demand and use (O); labour productivity (O); Animal welfare (O)	General production (O); Input consumption (O); Size of livestock herd (I); Food waste (I); Food demand (I)
32	(Navarro Garcia et al. 2023)				x	Afforestation and deforestation (O); Water (O); Climate (O); Biodiversity (O)	Population (I); Trade (I)	Food demand (I); Productivity and yields (I); Livestock density (I); Food waste
33	(Frehner et al. 2022)	x				Climate; Land use		Nutritional value of food; Food demand
34	(van Selm et al. 2022)	x				Land use (O); Climate (O)		General production (O)
35	(Tuninetti et al. 2022)	x				Water (O)		General production (O); Food demand (O)

36	(Padró and Tello 2022)	x	x			Nitrogen (I); Phosphorus (I); Land use (O)	Trade (I)	General production (O)

Notes:

[1] The column 3D sustainability refers to studies considering all three dimensions of sustainability (environmental, economic and social).

[2] In the three last columns, the letters I and O between brackets indicate whether the variable is considered as an input variable to the scenarios or as an output variable.

Visual representation of four scenario types

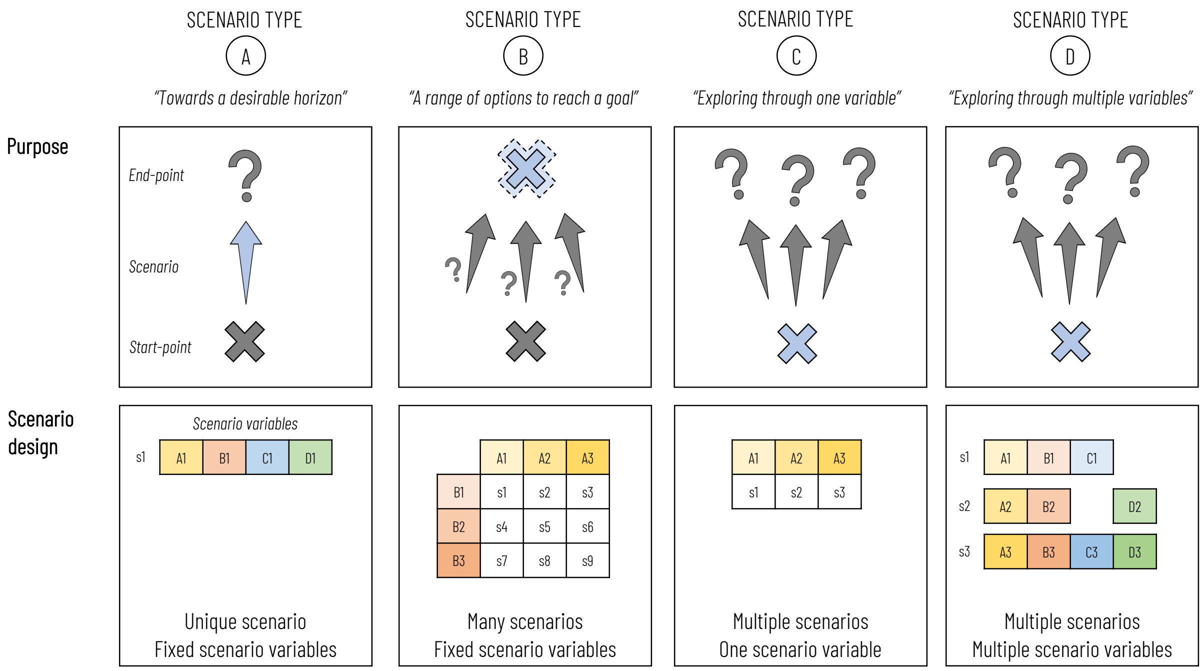


Figure S6. Visual representation of four quantitative food system scenario types, based on purpose and scenario design.

Comments on the figure

- **Purpose row:** The purpose row should be read from bottom to top. The bottom represents the start-point (current situation), the arrow represents the scenario, and the top represents the endpoint (outcomes of the scenario). *An "X" indicates that a point (starting or arrival) is known whereas as a "?" indicates that this point is unknown. The double border in the "X" of scenario type B is meant to reflect that the arrival point can be a space rather than a single point.* Blue elements indicate what is predetermined in the scenario exercises.
- **Scenario design row:** In the scenario design row, capital letters (A, B, C, D) refer to different scenario variables and numbers refer to possible values taken by these variables in different scenarios. Lowercase letters (s) refer to different scenarios.

Visual representations of sample characteristics

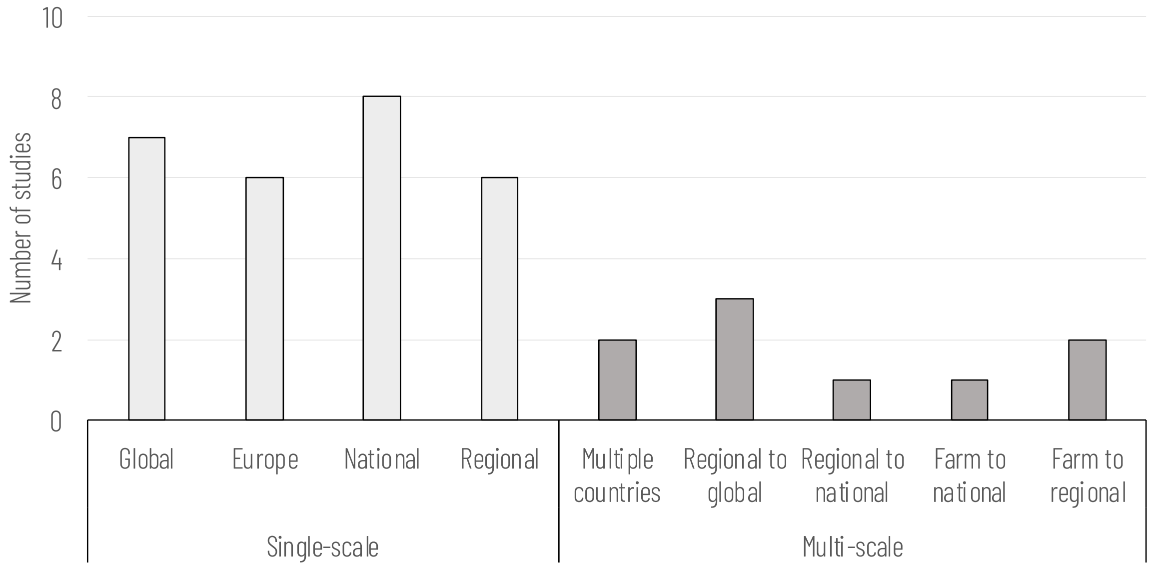


Figure S7. Geographical scale adopted in the 36 reviewed quantitative food system scenario studies.

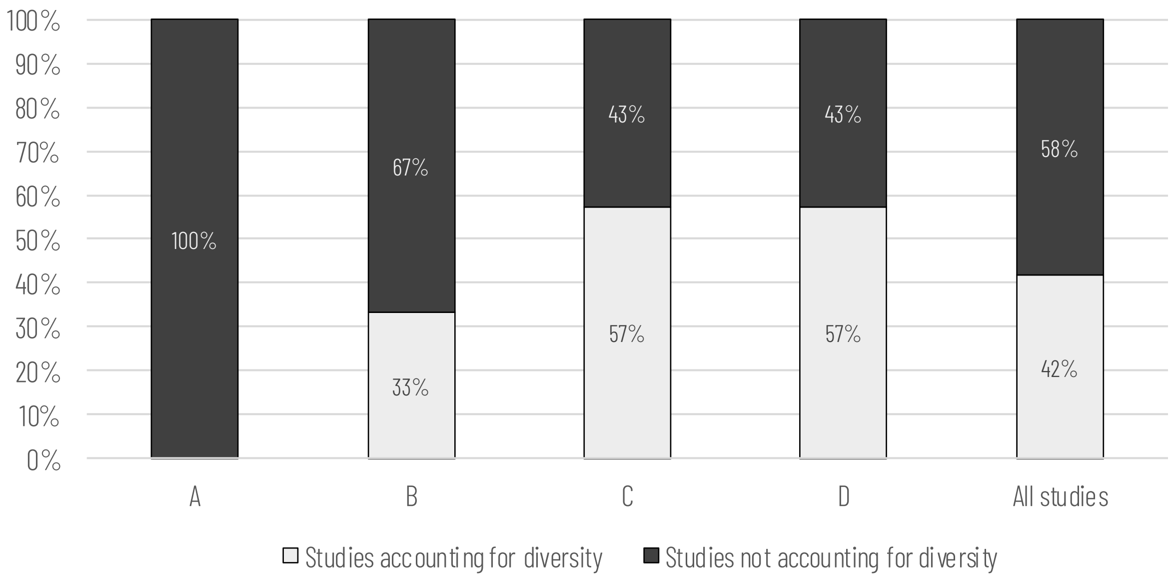


Figure S8. Consideration for the diversity of production systems (i.e. more than one production system) in the 36 reviewed quantitative food system scenario studies and through the lens of four scenario types.

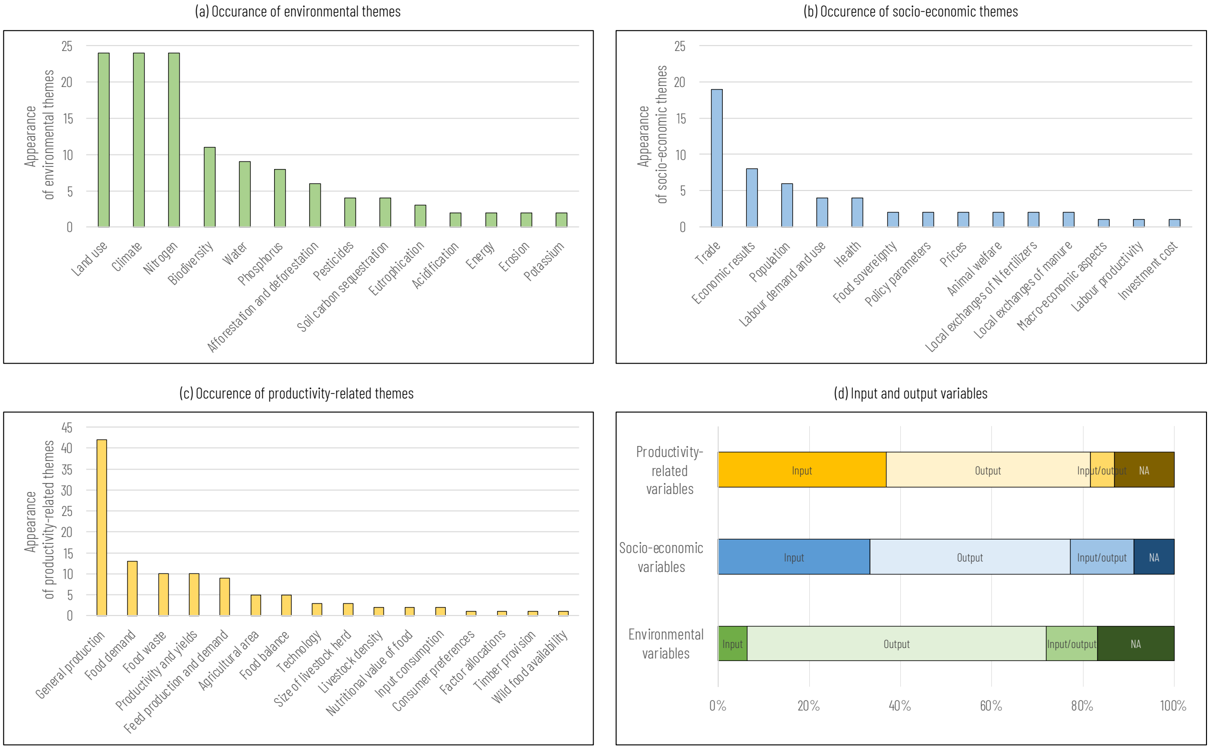


Figure S9. Occurrence of environmental (a), socio-economic (b) and productivity-related (c) themes in the 36 reviewed quantitative food system scenario studies and use of these variables as input or output variables in scenario design (d).

Appendix to chapter 5

Details on model construction and validation

Table S8. Categories, sectors and products included in the model.

Category	Sector	Product
Plant-based sectors	Fruits	Pears
		Apples
		Cherries
		Other orchards (walnuts)
		Strawberries open-air
		Strawberries greenhouse
		Other small fruit open-air (grapes)
		Other small fruit greenhouse (raspberries)
	Open-air vegetables	Green peas
		Green beans
		Onions
		Carrots
		Cauliflowers
		Brussels sprouts
		Leeks
		Witloof roots
		Spinach
		Celeriac
		Asparagus
		Other vegetables (average of all vegetables)
	Greenhouse vegetables	Greenhouse tomatoes
		Other greenhouse vegetables (lettuce)
	Cereals	Winter wheat
		Spring wheat
		Winter barley
		Spring barley
		Spelt
		Triticale
		Rye and meslin
		Oats and summer mix
		Grain maize
		Other cereals
	Potatoes	Potatoes
	Sugar beet	Sugar beet

	Oil-rich crops	Flax Rapeseed Other oil-rich crops
	Protein-rich crops	Protein-rich peas Beans and faba beans Other legumes harvested as dry beans
	Forage crops	Forage maize Forage beet Forage legumes Other forage crops
	Pasture	Permanent pasture Temporary pasture
Animal sectors	Beef - breeding Beef - fattening	Suckler cows Young bulls
	Dairy	Dairy cows
	Eggs	Laying hens Reproductive hens Young hens
	Pork	Productive pigs Reproductive pigs (sows)
	Poultry	Broilers

Notes:

Plant-based sectors (in grey), although included in the model, are not the main focus this research which is centred on the animal sectors. Interactions between both categories are however considered.

Table S9. Typologies of farming systems included in the model for each sector.

Category	Sector	Sector-specific farming system	Generic farming systems
Plant-based sectors	All	Conventional	Intensive
		Extensive (scenarios)	Extensive
		Organic	Organic
Animal sectors	Dairy	Diversified Intensive	Intensive
		Diversified Extensive	Intermediate
		Grass-based Intensive	Extensive
		Grass-based Extensive	Organic
	Beef - breeding	Belgian Blue Diversified Intensive	Intensive
		Belgian Blue Diversified Extensive	Intensive
		Belgian Blue Grass-based Intensive	Intensive
		Belgian Blue Grass-based Extensive	Intermediate
		French Diversified Extensive	Extensive
		French Grass-based Extensive	Organic
	Pork	Conventional	Intensive
		Conventional certified	Intensive
		Differentiated	Intermediate
		Differentiated +	Extensive
		Organic	Organic
	Poultry	Conventional	Intensive
		Conventional certified	Intensive
		Differentiated	Intermediate
		Differentiated +	Extensive
		Organic	Organic
	Eggs	Enriched cage	Intensive
		Indoor	Intermediate
		Free-range	Extensive
		Organic	Organic

Notes:

Plant-based sectors (in grey), although included in the model, are not the main focus of this research which is centred on the animal sectors. Interactions between both categories are however considered.

Data sources:

- Plant-based sectors: Antier et al. (2019, 2020); Riera et al. (2020)
- Dairy and beef (breeding): Riera et al. (2023)
- Pork, poultry and eggs: Riera et al. (2019)

Table S 10. Description and data sources of main control variables (continued on following pages).

Supporting variable	Variable detail	Variable source
Crop yields	On-farm agricultural yields are differentiated per product and farming system. They are adjusted for dry matter content.	- **Fruits:** (Réseau GAB/FRAB 2015; Delebecq et al. 2016; Van der Straeten 2016; Vanhemelen 2017; De Samber 2019) + FAOSTAT data - **Open-air vegetables:** (Deuninck and Vervloet 2016; Riera et al. 2020b) - **Greenhouse vegetables:** (De Samber 2021) - **Cereals:** (Antier et al. 2020a; Statbel 2022) - **Potatoes:** (Antier et al. 2019; Statbel 2022) - **Sugar beet:** (Courtois and Baret 2022; Statbel 2022) - **Oil-rich and protein-rich crops:** (Statbel 2022) - **Forage crops and pasture:** (Crémer 2015; Statbel 2022) Data has been complemented and validated by expert consultations.
Animal production cycles per year	For productive pigs and broilers, more than one production cycle occurs over the year. As official statistics report living animals at one moment in time, this allows calculating the total number of animals raised over a full year.	- **Productive pigs and broilers:** (Riera et al. 2019) Data has been complemented and validated by expert consultations.
Animal housing conditions	Animal housing conditions reflect the share of time spent by animals on pasture (grazing) or in different types of stables (slatted or straw).	- **Housing types:** (CELINE-IRCEL et al. 2023) Data has been complemented and validated by expert consultations.
Animal yields	Animal yields include slaughter weights, slaughter and carcass yields, egg yields and dairy yields. Dairy yields were initially based on Walloon data and were corrected for Flanders to account for higher average yields.	- **Slaughter weights (pork, broilers, beef):** (Nguyen et al. 2010; Rabeux et al. 2015; Riera et al. 2019) - **Slaughter and carcass yields (pork, broilers, beef):** (ERM and UGent 2011; Riera et al. 2019) - **Egg yields:** (Riera et al. 2019) - **Dairy yields:** (Riera et al. 2023) Data has been complemented and validated by expert consultations.

Feed use	Feed uses are expressed as feed conversion ratios (kg feed/kg live weight produced) for pigs, poultry (broilers and laying hens) and young bulls. They are expressed in terms of land use per cow and progeny for dairy and suckler cows.	- **Feed conversion ratios (pigs, poultry, young bulls):** (Nguyen et al. 2010; Rabeux et al. 2015; Riera et al. 2019) - **Land use per cow and progeny (dairy cows and suckler cows):** (Riera et al. 2023) Data has been complemented and validated by expert consultations.
Feed composition	Feed compositions reflect the share of different feed ingredients in animal feed of animal types in different farming systems.	- **Pigs, poultry, young bulls:** (Rabeux et al. 2015; Riera et al. 2019) - **Dairy cows and suckler cows:** (Riera et al. 2023) Data has been complemented and validated by expert consultations.
Food waste and loss	Food waste and losses account for all losses occurring at all stages along the supply chain from production to consumption (processing, distribution, retail, consumption) and including processing factors (e.g. turning wheat into bread). Losses are specific per product type but not per farming system.	**Food waste and loss factors per product and supply chain stage:** (Income consulting - AK2C 2016)

Table S11. Detail of included GHG emission sources, calculation data and sources (continued on following pages).

GHG emission source	Data detail	Data source
On-farm energy use	- Emissions related to on-farm energy use, including 'fuel consumption (machinery use) and 'other energy uses' (e.g. for heating). - Data is at the sectoral level but does not allow to differentiate for regions or farming systems. - Energy uses are transformed into GHG emissions through emission factors of Belgium's energy mix.	- **Sectoral level on-farm energy use:** (Baufayt 2022). - **GHG emission factor of energy:** (Climact 2024).
Enteric fermentation	- Enteric fermentation emission factors per animal type and per region (kg CH_4/animal/year), from Belgium's 2023 greenhouse gas inventory report.	- **CH_4 emissions from enteric fermentation:** Belgium's 2023 GHG inventory report (Table 5.10) (CELINE-IRCEL et al. 2023).
Manure management (CH_4 & N_2O)	- **CH_4 emissions:** emission factors per animal type and per region (kg CH_4/animal/year), from Belgium's 2023 greenhouse gas inventory report. - **N_2O emissions:** N_2O emissions from manure management are calculated departing from the N emissions from animals. They include three sub emission sources. For each animal type and stabling type (including grazing on pastures) generic emission factors from the IPCC guidelines or specific emission factors from the Belgian NIR are used. o *Direct N2O emissions:* A fraction of the N contained in animal manure will volatilise directly into N_2O. This fraction (emission factor EF3) is specific to stabling types. o *Indirect N2O emissions through atmospheric deposition:* A fraction of the N contained in animal manure will volatilise into NH_3/NOx. This fraction (FRACGAS in GHG inventory report) is specific to stabling types and animals. From this NH_3/NOx, a constant fraction will volatilise into N_2O (EF4). o *Indirect N_2O emissions through leaching and runoff:* A fraction of the N contained in animal manure will leach. This fraction (FRACLEACH) is specific to stabling types and animals. From this leached nitrogen, a constant fraction will volatilise into N_2O (EF5). - In calculating these emissions, we must pay attention not to double count the emissions of N_2O that occur from the deposition of manure (organic N) directly on pastures by grazing animals. These emissions can be considered both under manure management emissions (here) or under crop fertilisation emissions (below). In this case, we attribute these emissions to manure management.	- **CH_4 emissions from manure management:** Belgium's 2023 GHG inventory report (Table 5.16) (CELINE-IRCEL et al. 2023). - **N_2O emissions from manure management:** Emission factors EF3, FRACGAS, EF4, FRACLEACH and EF5 come from Belgium's 2023 GHG inventory report (CELINE-IRCEL et al. 2023).

Imported feed production	- Represents the emissions related to the production of imported animal feed. Only soybean meal is considered. - The emission factor for soybean meal production comes from LCA data.	- **Emissions factor soybean meal:** (ERM and UGent 2011).
Crop fertilisation (synthetic & organic N)	- N_2O emissions from N fertilisation are calculated departing from the N fertilisation of crops. They include three sub emission sources (as for N_2O from manure management). Generic emission factors from the IPCC guidelines or specific emission factors from the Belgian NIR are used. Emission factors differ for synthetic and organic N. o *Direct N2O emissions:* A fraction of the N contained in N fertiliser applied to soils will volatilise directly into N_2O. This fraction (emission factor EF1) is the same for all types of nitrogen (synthetic and organic), with the exception of manure directly deposited on pasture by grazing animals (EF3). o *Indirect N2O emissions through atmospheric deposition:* A fraction of the N contained in N fertiliser will volatilise into NH3/NOx. This fraction (FRACGAS) differs for synthetic and organic N. From this NH3/NOx, a constant fraction will volatilise into N2O (EF4). o *Indirect N2O emissions through leaching and runoff:* A fraction of the N contained in N fertiliser will leach. This fraction (FRACLEACH) is the same for all types of nitrogen (synthetic and organic, including manure directly deposited on pasture by grazing animals). From this leached nitrogen, a constant fraction will volatilise into N2O (EF5).	- **N_2O emissions from crop fertilisation:** Emission factors EF1, EF3, FRACGAS, EF4, FRACLEACH and EF5 come from Belgium's 2023 GHG inventory report (CELINE-IRCEL et al. 2023).
Synthetic input production (synthetic N fertiliser & pesticides)	- The GHG emissions related to the production of two types of synthetic inputs used on Belgian crops is assessed: synthetic N fertiliser and pesticides. - GHG emissions are assessed based the energy intensity of production.	- **Energy intensity of input production:** (Baufayt 2022). - **GHG emission factor of energy:** (Climact 2024).

LULUC	**Main land use categories: croplands and grasslands.** - Two main categories of land use are considered: croplands (remaining croplands) and grasslands (remaining grasslands), and the associated land use changes between those two categories: croplands converted to grasslands and grasslands converted to croplands. - For land use changes, emissions are attributed to the final land use (i.e. to croplands in the case of a land use change from grassland to cropland). A single emission factor for each land use is calculated, aggregating the emissions from the considered land use and from land use changes to the considered land use. **New biodiversity areas: forests** - Additionally, the conversion of croplands and grasslands into forests is considered in the scenarios when land is set aside for biodiversity conservation. - A 20-year conversion period is considered as per IPCC guidelines. During the conversion period (2022-2042), emission factors from cropland and grassland to forests are considered. After that (2042-2050), an equilibrium conversion factor is considered (forest remaining forest). - In reporting emissions, both the final annual emissions in 2050 are reported (when new forests are already at and equilibrium) and the average annual emissions over the full period (accounting for the transition from cropland and grasslands to forest).	- **LULUC emissions:** Average emission factor for 2018-2022, from Belgium's 2025 submission of its GHG inventory document (CELINE-IRCEL et al. 2025).

Table S12. Calculation details for nitrogen cycle indicators (continued on following pages).

Nitrogen indicator	Explanation	Data source
Animal emissions of N	Nitrogen emissions from animals (manure) are calculated based on: - Animal nitrogen intake: feeding practices and nitrogen content of feed ingredient - Nitrogen use efficiencies (NUE) Housing conditions (stable types, grazing) are taken into account to differentiate between manure which can be moved and used on any land (N emissions in stables) or not (N emissions while grazing, on permanent grasslands) **N emissions = N intake x (1-NUE)**	**Feeding practices (feed intake and feed composition):** - Dairy and beef: Riera et al. (2023) - Pork, poultry and eggs: Riera et al. (2019) **Nitrogen content of feed ingredients and nitrogen use efficiencies:** - Hou et al. (2016)
N needs on crops	Annual nitrogen fertilisation of crops (kg N/ha) considers the application of both organic and synthetic N on different crops and different production systems (organic vs. convention). N fertilisation rates are based on grey literature mainly containing specific data for Wallonia. In Flanders, given current manure surpluses, fertilisation rates are expected to be higher (than actual needs, and than fertilisation rates in Wallonia). While this may result in underreporting actual N fertilisation on crops in the current situation in Flanders, the scenarios provide an opportunity to better align needs and fertilisation rates in Flanders. **N fertilisation = Norg + Nsynth**	**Grey literature depending on crops:** - Antier et al. (2019, 2020a); Riera et al. (2020); Leroy et al. (2021); Courtois and Baret (2022)
Organic N self-sufficiency	Organic nitrogen self-sufficiency is calculated as the ratio between available N produced by animals (N emissions in stables) and the fertilisation of crops with organic nitrogen **Organic N self-sufficiency = N emissions / Norg fertilisation**	**Combination of rows above.**
Ammonia (NH_3) emissions from manure management in stables	Agricultural activities lead to different sources of NH_3, in particular from the manure emitted and managed in stables, from the manure emitted while grazing, from the application of organic or mineral fertiliser. In this case we focus specifically on the	**N emissions (stables):** - See first row of this table. - Only N emissions occurring in stables are considered here. **FRACGASMS:**

	emissions of ammonia occurring in stables, as this is the target of the nitrogen measures implemented in Flanders through the nitrogen decree. NH_3 emissions in stables are calculated as a fraction of animal N emissions, which is emitted as NH_3/NOx. This fraction (FRACGASMS) is reported in the Belgian NIR, and is specific to animal types, stabling types and regions (Flanders and Wallonia). NH_3/NOx emissions are then further disaggregated into NH_3 emissions only based on the share of both gases in total emissions reported in Flanders. **NH_3 (stables) = N emissions (stables) x FRACGASMS x Share NH_3/NOx**	- Emission factor from Belgium's 2025 GHG inventory document (CELINE-IRCEL et al. 2025). **Share NH3/NOx:** - Progress report on implementation of nitrogen decree in Flanders (Departement Omgeving 2025).

Table S13. Calculation details for biodiversity impact indicators.

Land use types & intensities in this model	**Corresponding land use types & intensities in Chaudhary and Brooks (2018)**	**Data source**
Arable land – non-organic Arable land – organic	Cropland – Intense use Cropland – Light use	- Table S5 in Chaudhary and Brooks (2018). - Sum of mean characterisation factors (CF) for Belgium across five taxa (mammals, birds, amphibians, reptiles, plants). - Impacts (CFs) are null for forestland under minimal use *(reduced impact logging; RIL)* and light use *(selective logging)*
Temporary pasture – non-organic Temporary pasture – organic	Pasture – Intense use Pasture – Light use	
Permanent pasture – non-organic Permanent pasture – organic	Pasture – Light use Pasture – Minimal use	
Forests *(only in scenarios T1, T2 & T3)*	Managed forests – selective logging or reduced impact logging (RIL)	

Table S14. Diets considered in the scenario exercise. Daily individual intake of different food groups (g raw product/cap/day)

Food group	Belgian diet	Belgian FBDG	TYFA diet	EAT-Lancet diet
Cereals	164	125	300	232
Fruits	113	270	400	250
Vegetables	145	300	0	300
Legumes	12	45	30	75
Oils	6	15	34	40
Potatoes	44	295	80	50
Sugar	81	0	23	31
Meat	159	82	92	43
Dairy	180	435	300	262
Eggs	10	17	10	13
Fish	26	24	10	28
Residual products	438	0	218	0

Notes:

Values represent intake of raw products (not cooked). Residual products include alcoholic drinks, soft drinks, sweet and salted snacks.

Sources:

- Belgian diet: De Ridder et al. (2016)
- Belgian FBDG: Conseil Supérieur de la Santé (2019)
- TYFA diet: Poux and Aubert (2018)
- EAT-Lancet diet: Willett et al. (2019)

Table S15. Validation data and sources used for verification and calibration of the model.

Dimension	Validated indicator	Validation source
Production and consumption	Food consumption	Previous studies by Sytra research group
	Production - plant-based	Statistics Belgium - yield and production estimations
	Production - meat	Statistics Belgium - supply balance sheets Statistics Belgium - slaughter data
	Production - dairy	BCZ-CBL report (Belgian Dairy Federation)
Environment	Animal manure production and nitrogen fertiliser use	*Mestrapport* (Flanders) Master Thesis Cornu & Leroy (Wallonia) *Etat de l'environnement wallon* (Wallonia)
	Greenhouse gas (GHG) emissions	Belgian GHG inventory report
Socio-economy	Employment	Statistics Belgium - 2020 agricultural census
	Gross value of production	Statistics Belgium - 2020 agricultural census

Detailed scenario results

Table S16. Full overview of scenario outcomes and indicators (continued on following pages).

Indicator	Unit	Current situation 2018–2022	BAU 2050	T1 2050 Land sparing	T2 2050 Land sharing	T3 2050 Radical
Production factors						
Animal population	Nb suckler cows	346 997	255 716	173 499	—	—
	Nb dairy cows	516 577	552 667	361 604	632 697	590 702
	Nb productive pigs	10 923 275	7 585 055	7 435 767	2 602 272	950 524
	Nb broilers	243 640 707	361 664 948	152 172 549	40 324 768	17 659 995
	Nb laying hens	9 124 326	10 714 565	6 387 028	2 186 788	989 366
	Nb Ruminants	**863 574** **—**	**808 383** **–6%**	**535 102** **–38%**	**632 697** **–27%**	**590 702** **–32%**
	Nb Monogastrics	**263 688 308** **—**	**379 964 568** **+44%**	**165 995 344** **–37%**	**55 771 7578** **–79%**	**19 077 862** **–93%**
Animal Farming systems	% Organic	2%	6%	19%	30%	99%
	% Extensive	2%	4%	2%	70%	1%
	% Intermediate	2%	5%	14%	0%	0%
	% Intensive	94%	85%	66%	0%	0%
Crop Farming systems	% Organic	7%	19%	20%	28%	92%
	% Extensive	0%	11%	8%	43%	0%
	% Intensive	93%	71%	53%	21%	0%
	% New biodiversity	0%	0%	19%	8%	8%
Production						
Meat production	kt meat	1 315 —	1 179 –10%	867 –34%	372 –72%	209 –84%
	g meat/cap/day	314 —	256 –18%	188 –40%	81 –74%	45 –86%
Milk production	kt milk	4 087 —	4 806 +18%	3 077 –25%	4 813 +18%	4 484 +10%
	g milk/cap/day	975 —	1 043 +7%	668 –32%	1 045 +7%	973 <–1%
Egg production	kt eggs	184 —	216 +17%	128 –31%	43 –76%	19 –90%

	g eggs/cap/day	44 —	47 +6%	28 –37%	9 –79%	4 –91%
Animal protein production	kt protein	430 —	428 –1%	297 –31%	235 –45%	188 –56%
	g protein/cap/day	103 —	93 –10%	64 –37%	51 –50%	41 –60%
Concentrate feed demand						
Energy-rich feed (1) *- of which cereals*	kt/year	3 973 *3 694*	3 343 *3 134*	2 625 *2 492*	1 154 *1 092*	520 —
Protein-rich feed (2) *- of which soybean meal*	kt/year	2 280 *1 064*	2 033 *985*	1 522 *716*	1 124 —	847 —
Other concentrates (3)	kt/year	620	513	350	170	107
Total concentrates (1+2+3)	**kt /year**	**6 873** **—**	**5 890** **–14%**	**4 497** **–35%**	**2 449** **–64%**	**1 473** **–79%**
Concentrate feed self-sufficiency						
Self-sufficiency for cereal feed (BE)	%	46%	51%	46%	100%	NA
Self-sufficiency for energy-rich coproducts (EU)	%	13%	16%	20%	46%	101%
Self-sufficiency for protein-rich coproducts (EU)	%	49%	55%	73%	114%	131%
Forage feed demand						
Total forage area *- of which forage maize* *- of which pastures*	ha	781 379 *176 023* *590 535*	722 559 *143 463* *562 757*	491 913 *79 077* *405 045*	645 159 *77 474* *552 730*	598 356 *45 451* *544 432*
Human food consumption						
Meat offer Meat demand Meat self-sufficiency	g meat/cap/day g meat/Cap/day Meat offer/meat demand (%)	271 141 192%	219 141 155%	164 87 189%	73 76 97%	41 43 95%
Animal protein offer Animal protein demand Animal protein self-sufficiency	g animal prot/cap/day g animal prot/cap/day Animal protein offer/ animal protein demand (%)	89 28.5 314%	81 28.5 283%	56 28.5 198%	45 28.5 159%	36 28.5 126%
Environment – Land use						
Land use for soybean meal demand (animal feed)	ha/year	332 387 —	307 734 –7%	222 739 –33%	— –100%	— –100%

Land use for legumes demand (human food)	ha/year	4 824 —	5 428 +13%	47 953 +894%	89 429 +1 754%	201 965 +4 086%
Environment – Climate						
GHG emissions – 2050 (1+2+3A)	**kt CO_2e/year**	**15 040** **—**	**13 443** **–11%**	**9 280** **–38%**	**8 061** **–46%**	**6 914** **–54%**
GHG emissions – average 22-50 (1+2+3B)	**kt CO_2e/year**	**15 040** **—**	**13 442** **–11%**	**6 170** **–59%**	**6 623** **–56%**	**5 476** **–64%**
(1) GHG emissions – Crop-related	kt CO_2e/year	3 945 —	3 741 –5%	2 989 –24%	3 028 –23%	2 542 –36%
(2) GHG emissions – Animal-related	kt CO_2e/year	11 095 —	9 702 –13%	6 779 –39%	5 242 –53%	4 581 –59%
(3A) GHG emissions – New biodiversity (forests)	kt CO_2e/year (2050)	0	0	–488	–209	–209
(3B) GHG emissions – New biodiversity (forests)	kt CO_2e/year (22-50)	0	0	–3 598	–1 647	–1 647
GHG emissions (animal-related) – relative	kg CO_2e/kg ani prot	25.8 —	22.7 –12%	22.9 –11%	22.3 –14%	24.4 –5%
Environment – Nitrogen cycle						
N emissions (animal manure) – total	kt N/year	242 —	216 –11%	150 –38	128 –47%	101 –58%
N emissions (animal manure) – relative	kg N/kg ani prot	0.56 —	0.51 –10%	0.51 –10%	0.55 –3%	0.54 –4%
Organic N needs for crop fertilisation	kt N/year	125 —	130 +4%	107 –15%	127 +1%	138 +10%
Org N self-sufficiency	% (available animal N/crop org N needs)	193%	166%	140%	101%	74%
NH_3 emissions from stables	kt N-NH_3/year	30 —	21 –29%	15 –48%	11 –65%	8 –74%
Environment - Biodiversity						
Biodiversity impact – Total	Damage score (potentially disappeared species)	0.117 —	0.116 –1%	0.094 –20%	0.105 –10%	0.099 –15%
Biodiversity impact – Relative	Damage score/ha (potentially disappeared species)	8.75E-08 —	8.68E-08 –1%	8.65E-08 –1%	8.59E-08 –2%	8.10E-08 –7%

Notes:

[1] **Animal populations:** In scenarios T2 and T3, the specialised suckler cow herd is replaced by a double-purpose dairy herd.

[2] **Production:** Production data is at farm gate, i.e. it does not account for losses and waste along the chain (except for slaughter and carcass yields in the case of meat).

[3] **Animal feed:** In scenarios T2 and T3, soybean meal is fully replaced by other protein-rich feed ingredients (rapeseed meal and sunflower meal). A replacement rate of 1.43 is accounted for as 1 kg of soybean is more nutritional than 1 kg of rapeseed meal or sunflower meal. The self-sufficiency indicators indicate to what extent the available amounts of different feed sources (Belgian cereals, EU energy-rich coproducts or EU protein-rich coproducts) meet the corresponding demands for those feed categories (cereals, energy-rich feed or protein-rich feed).

[4] **Human consumption:** Consumption levels represent actually consumed amounts (i.e. accounting for losses and waste along the chain). Each scenario is attributed to an animal product demand (e.g. meat) corresponding to a specific diet: current Belgian diet for current situation and BAU scenario; TYFA diet for scenario T1; Belgian FBDG for scenario T2; and EAT-Lancet diet for scenario T3. The animal protein demand corresponds to a daily protein demand of 0.8 g prot/kg body weight/person. In the perspective of operating a demand-side protein transition, we consider that 50% of this protein demand should come from animal sources, corresponding to 28.5 g animal protein/cap/day.

[5] **Land use:** The land use resulting from the demand of legumes (for human food) is calculated considering one specific diet (and the corresponding demand for legumes) for each scenario: current Belgian diet for current situation and BAU scenario; TYFA diet for scenario T1; Belgian FBDG for scenario T2; and EAT-Lancet diet for scenario T3.

[6] **GHG emissions:** In scenarios T2 and T3 soybean meal is fully replaced by other protein-rich feed ingredients (rapeseed meal and sunflower meal). A replacement rate of 1.43 is accounted for as 1 kg of soybean is more nutritional than 1 kg of rapeseed meal or sunflower meal. The GHG impacts of soybean meal are replaced by those of sunflower meal. In scenarios T1, T2 and T3, the agricultural area that is freed for biodiversity conservation is considered to be transformed into forests, thus leading to an additional storage of carbon (CELINE-IRCEL et al. 2025). Annual emissions can either be reported at the end of the scenario period (i.e. emissions in 2050), when these newly established forests are stabilised (*'GHG emissions - 2050'*), or considering the average annual emissions over the period, accounting for a 20-year transition period from cropland and grassland to forests, during which sequestration is assumed to be greater (*'GHG emissions - average 22-50'*).

[7] **Biodiversity:** The agricultural area that is freed for biodiversity conservation is considered to be transformed into forests, thus leading to a null biodiversity damage score (Chaudhary and Brooks 2018).

Table S 17. Evolution of ammonia emissions from manure management in stables (kt N-NH_3/year) in Flanders for different sectors in the current situation (2018-2022) and in four scenarios in 2050.

Sector	Current situation 2018–2022 kt N-NH3/year	BAU 2050		T1 2050 Land sparing		T2 2050 Land sharing		Evolution BAU vs. current	
		kt N-NH3/year	% vs. current	kt N-NH3/year	% vs. current	kt N-NH3/year	% vs. current	kt N-NH3/year	% vs. current
Beef	2,2	1,3	–41%	0,8	–64%	—	–100%	—	–100%
Dairy	4,7	4,2	–9%	2,2	–52%	2,5	–46%	2,2	–52%
Eggs	1,4	1,4	0%	0,8	–39%	0,3	–78%	0,2	–88%
Pork	11,4	6,2	–45%	6,6	–42%	2,7	–76%	1,3	–89%
Poultry	1,7	2,1	+21%	1,0	–43%	0,4	–78%	0,2	–88%
Total Flanders	**21**	**15**	**–29%**	**11**	**–46%**	**6**	**–72%**	**4**	**–82%**

Notes:

The Flemish nitrogen decree sets overall reduction targets in terms of ammonia emissions in Flanders, with specific targets per sector for emissions in stables. The reduction targets set for 2030 are the following (against 2015 emissions levels): -60% for the pork and poultry (broilers and laying hens) sectors; -15% for the beef and dairy sectors; -20% for the veal sector (Departement Omgeving 2025)

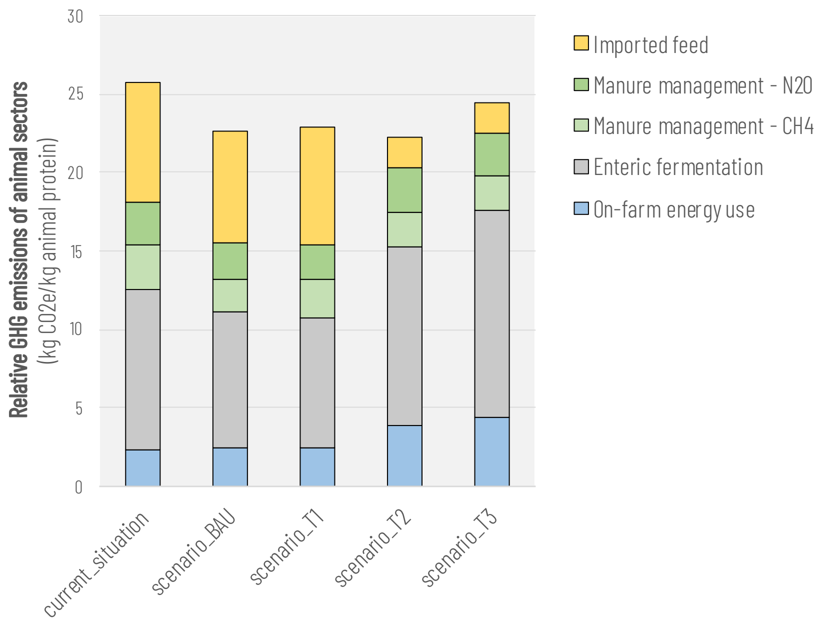


Figure S 10. Evolution of relative GHG emissions per unit of output of animal productions (kg CO2e/kg animal protein), per emission source.

Appendix to chapter 6

Barrier categories

Table S18. Nine categories of barriers, as proposed by Chevalier et al. (2026).

Barrier category	Description
Technical	Refer to factors impeding the practical implementation of an innovation, including (1) the limited availability of resources (incl. human or material but excl. financial); (2) limitations in the scale-up process; (3) absence of adequate procedures.
Organizational	Refer to the management of both time and tasks by individual actors of the system.
Financial	Refer to the allocation, acquisition, and utilization of financial resources, with two main themes: (1) the higher costs, and (2) the limited financial accessibility.
Market-related	Refer to obstacles linked to external market conditions, including three main themes: (1) lack of demand-side interest; (2) inadequate supply-side structure (competition); (3) obstructing marketing practices (greenwashing).
Knowledge-related	Refer to the gap of knowledge, awareness, and experience of actors, including three main themes: (1) insufficiency of existing knowledge, (2) imbalance in information distribution within the value chains, and (3) remaining uncertainty about benefits.
Governance-related	Refer to obstacles linked to decision-making processes, including regulatory frameworks.
Socio-cultural	Refer to obstacles that originate from the attitudes, beliefs, norms and value of actors within a value chain, including (1) a resistance to change; (2) a weak commitment; (3) a lack of alignment between actors' visions and objectives.
Relational	Refer to obstacles linked to the relations and interactions between actors of a value chain, including (1) a lack of coordination; (2) the existence of opposed visions; (3) power imbalances, and (4) a lack of transparency.
External	Include all other barriers that are currently beyond the influence or control of the system's actors (e.g. climate risk).

Policy analysis

Table S19. Analysis of eight policy initiatives targeting the protein transition in Flanders. The analysis includes a general presentation of each initiative and details the type of policy instrument and target areas, the target dimensions of the protein transition, the associated funding (if any) and the competent authority (continued on following pages).

1. Flemish food strategy *(Go4Food)*			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The establishment of a *Flemish Food strategy* was part of the 2019-2024 Flemish government agreement. The process was initiated in 2020 and gathered a broad *food coalition*. The *Go4Food* strategy was officially presented in November 2022, putting food system approaches on the Flemish policy landscape.	(Strategy) The strategy is published in the form of a non-binding strategic document (Departement Landbouw en Visserij 2022) aiming to give a general direction for the Flemish food system. Covering both the production- and consumption-side, it is divided into four main areas and objectives: (1) healthy and sustainable food for all; (2) a food system within ecological limits; (3) full commitment to a resilient food economy; (4) food connects farms to citizens.	Production & consumption Animal and alternative protein sources	No funding seems to be associated to the strategy as a whole (apart from funding associated to individual actions). The food strategy is mainly steered by the Agriculture and Fisheries Department. However, recognizing that food production and consumption span several policy areas, its conception and operationalisation bring together different public agencies.
2. Flemish protein strategy (*Eiwitstrategie*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The *Flemish protein strategy*[13] is part of the broader *Flemish food strategy Go4Food*, representing one of the topics crossing multiple policy areas (*voedselwerven*). It was published in in 2021.	(Strategy) The *Flemish protein strategy* was published in the form of a non-binding strategic document (Departement Landbouw en	Production & consumption Animal and alternative protein sources	No funding seems to be associated to the strategy as a whole (apart from funding associated to individual actions).

[13] General information on the protein strategy is available online: https://lv.vlaanderen.be/beleid/vlaamse-kost/eiwitstrategie

	Visserij 2021a). It aims to provide Flanders with a coherent vision related to the protein transition. Covering both the production- and consumption-side, and both animal-based and plant-based protein, it is divided into six main strategic areas and objectives: (1) sustainable animal feed; (2) sustainable animal production; (3) more pant-based protein; (4) more novel protein sources; (5) greater product diversity; (6) sustainable protein consumption. The Agriculture and Fisheries Department monitors the number of actions that have been undertaken since 2011, and which can be related to these six strategic areas[14].		The *Flemish protein strategy* is mainly steered by the Agriculture and Fisheries Department.
3. Research plan for the implementation of the protein strategy (*Relance plan realisatie eiwitstrategie*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
This research fund was launched in 2021 as part of the post-pandemic Flemish recovery plan and in the framework of the *Flemish protein strategy*, aiming at a practical implementation of its six objectives.	(Instrument – economic) Nineteen research projects have received funding through the call, covering five out of six priorities of the protein strategy (no project targeting objective 2: sustainable animal production). Both the production-side and the consumption-side are targeted, both for plant-based	Production & consumption Animal and alternative protein sources	The available budget amounted € 60.000 - € 240.000 per project, covering a maximum of 80% of project costs (VLAIO 2022). Given that 19 projects have been funded, this represents a total budget comprised between € 1,1 M and € 4,6 M. The research fund is steered by the Agriculture and Fisheries Department.

[14] The list is of actions is available online: https://analyse.lenv.be/spotfire/wp/analysis?file=/PubliekInternet/Website/Eiwitstrategie%20-%20acties%202024%20-%20website%20analyse&waid=PolwRmzMPESKgtmXZd6wy-09002654466yCo&wavid=0&options=13-0,10-0,9-0,5-0,6-0,17-0,11-0,12-0,14-0,1-0,3-0,18-0,7-0,15-0,19-0,4-1,2-0

	and animal-based protein (Agentschap Landbouw & Visserij 2024)[15].		
4. Green deal protein shift on our plates (*Eiwitshift op ons bord*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
Green deals are an initiative of the Flemish government to improve the sustainability performances of a number of economic sectors and individual companies, including projects related to water, food, circular economy, etc. They consist of voluntary public-private partnerships. Among a total of 20 green deals, one specifically targets the protein transition: the green deal protein shift on our plates (*eiwitshift op ons bord*).	(Instrument – informational) The *Green deal protein shift on our plates* is a public-private partnership that was launched in April 2021 and will be operating until April 2025. It brings together 80 partners from the whole food system with the aim of increasing the consumption of alternative protein. Each partner commits to take a series of (voluntary) actions and meet certain targets, which are being monitored by the green deal during the programming period (Departement Omgeving 2021). A specific objective of the green deal is to reach a protein intake balance of 40:60 between animal-based and plant-based protein (instead of the current 60:40). To reach this objective, a 'halve-halve'	Consumption Animal and alternative protein sources	No funding seems to be associated to the strategy as a whole (apart from funding associated to individual actions). The green deal is steered by the Environment Department. The green deal is nor a result nor part of the *Protein strategy*, but is presented as being in line with it.

By mid 2025, a total of 122 actions had been undertaken, of which 37 are directly attributed to the *Protein strategy* (e.g. projects funded for the implementation of the protein strategy; see policy measure 3), while the remaining 85 would have taken place in any case (e.g. projects related to the *Green deal protein shift on our plates* or the *CAP eco-scheme for protein crops*; see policy measures 4 and 8 respectively). With regards to the six target areas, sustainable animal production has received more attention (40 actions), followed by more plant-based and novel protein sources (23 and 19 actions respectively), and sustainable animal feed (16 actions). Sustainable protein consumption and greater product diversity receive less attention (13 and 11 actions respectively). In total, about half of the actions target the productions of animal protein (objectives 1 and 2) and the other half target the production of alternative proteins and a sustainable protein consumption (objectives 3 to 6).

[15] The list of 19 projects is available online: https://lv.vlaanderen.be/subsidies/scholen-groeperingen-vzws-organisaties/projecten-relance-2021/projecten-realisatie

	strategy is pursued, meaning that halve of the meals should be vegetarian and halve should contain animal products (allowing to reach the 40:60 objective). Such a message is seen as easier to vehiculate and is propagated through a specific communication campaign. Other actions are taken within the green deal, including monitoring protein consumption and purchase behaviours in Flanders (Rubens et al. 2024) and producing a series of resources on the protein shift (podcasts, reports, etc.).		
5. Energy and Climate plan (*Energie- en klimaatplan*) and Covenant bovine enteric emissions (*Convenant Entherische emissies rundvee*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
As part of the 2021-2030 *Flemish Energy and Climate Plan*, the Flemish agriculture sector is expected to reduce its greenhouse gas (GHG) emissions by 29% by 2030 compared to 2005 levels (compared to a -40% objective for the entire Flemish economy). Within this general strategic plan, specific targets are set for enteric fermentation emissions, with an objective to reduce emissions by 14% by 2030. Other targets are set for manure storage emissions, which are to be reduced by 22%. The plan also addresses plant-based sectors but make no mention of protein crops, rather mentioning the protein strategy as a	(Strategy) While the energy plan and the covenant for enteric emissions set general targets, these are non-binding and rely on a composite set of policy measures to reach them. Measures include a CAP eco-scheme on feed management to reduce enteric fermentation emissions (which so far has seen little uptake by farmers), but also reliance on the *Nitrogen decree* outlined above (e.g. through the 30% reduction of the pig herd). A mid-term evaluation from February 2025 concludes that Flanders is not on track to meet its GHG reduction objectives for the	Production Animal protein sources	No funding directly associated either to the *Energy and Climate plan* or to the *Convenant on bovine enteric fermentation*. Spread over multiple authorities depending on specific measures and instruments in place to reach the objectives. The *Energy and Climate plan* is monitored by the Flemish Energy and Climate agency (VEKA) while the *Covenant on bovine enteric fermentation* is steerd by the agriculture and fisheries department.

transversal measure across economic sectors (VEKA 2023). In parallel, of the Energy and climate plan, a *Covenant on bovine enteric fermentation emissions (convenant enterische emissies rundvee)* has been signed between the authorities (Agriculture and Fisheries Department) and actors from the bovine production sector to achieve the -14% goal for enteric fermentation emissions (Departement Landbouw en Visserij 2019).	agriculture sector, nor the specific objectives for enteric fermentation under the covenant for bovine enteric fermentation emissions (VEKA 2025).		
6. Circular Flanders – Circular food chain agenda (*Vlaanderen Circulair – Werkagenda voedselketen*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
Circular Flanders is a partnership between the Flemish government, businesses, civil society and research promoting the circular economy. It covers six priority work agendas, among which one focuses on food.	(Strategy) The work agenda for a circular food chain provides a general strategy aiming to foster more circularity within the Flemish food system. The objective is to decrease the material footprint of the Flemish agrifood chain while maintaining its economic importance. The work agenda is built around three pillars: optimal use of bioresources, food and coproducts. The Circular food chain agenda positions itself in support of the protein strategy and mentions improving the sustainability of protein consumption and production (both alternative and animal-based) and increasing the	Production & consumption Animal and alternative protein sources	The work agenda for a circular food chain is public-private partnership, co-managed by the *Agentschap Landbouw & Visserij* and *Fevia Flanders* (representative organisations of private sector in the food chain).

	diversity of protein products (Departement Landbouw en Visserij and FEVIA 2022).		
7. Nitrogen decree (*PAS; Stikstofdecreet*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The *Nitrogen decree* entered into force in February 2024. It aims to contain the deposition and impact of nitrogen on natural habits protected under the EU Habitats Directive (Vlaamse Regering 2024)[16].	(Instrument – regulatory) The *Nitrogen decree* is a binding regulation whose overall goal is to decrease the emissions of NH_3 by 40% by 2030 compared to 2015 levels, and the emissions of NO_x by 45% by 2030 compared to 2015 levels. A reference target value for 2030 (called *'PAS-referentie 2030'*) is calculated for each farm, constituting emission rights and setting reduction objectives compared to the 2021 reference year. Specific NH_3 reduction objectives are set for different animal categories (-60% for pigs and poultry; -25% for dairy cows; -28% for meat calves; -0% for suckler cows), which can be pursued either by reducing animal numbers, or through emission-reducing technologies in stables. Additionally, the legislation foresees that the pig herd will be reduced by 30% by 2030 (Vlaamse Regering 2024).	Production Animal protein sources	A 3,6 billion € budget is said to be put aside to implement the legislation by 2030, with 1,2 billion € dedicated to nature restoration and 2,4 billion € to compensate farmers (VILT 2022). The *Vlaamse Land Maatschappij* (VLM) is in charge of implementing the legislation, distributing emission rights and buying them up if objectives are not met.
8. Manure decree (*MAP; mestdecreet*)			

[16] General information on the nitrogen decree is available online: https://www.vlaanderen.be/stikstof-in-vlaanderen/maatregelen-om-stikstof-terug-te-dringen

General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The *Manure decree* was approved in 2024. It aims to contain the pollution of groundwater and surface water bodies by regulating the use of fertilisers, among which animal manure.	(Instrument – regulatory) The *Manure decree* is a binding regulation whose overall goal is limiting nitrogen pollution by water, defining the possible uses of animal manure (e.g. for crop fertilisation) and other fertilisers. In Flanders, the entire region is considered as vulnerable, thus limiting the maximum amount of animal manure to be applied to 170 kg N/ha (with possible exceptions allowing a maximum 150% increase in specific cases). For synthetic nitrogen fertilisers, specific application rates are set for different crops in different areas, accounting for soil type, location with regards to water bodies and their vulnerability. Given their nitrogen-fixing capacity, allowed fertilisation rates for legumes are lower than for other crops (Vlaamse Land Maatschappij 2025).	Production Plant-based protein sources	The *Vlaamse Land Maatschappij* (VLM) is in charge of monitoring the uses of manure, which must be declared on a portal (*Mestbank*).
9. CAP strategic plan – coupled income support to suckler cows			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The 2023-2027 Flemish CAP strategic plan (Departement Landbouw en Visserij 2021b) lays out the structure and foreseen budget for the implementation of the EU Common Agricultural Policy in Flanders over the 2023-2027 period.	(Instrument – economic) The budget allocated for coupled income support is meant to support farmers with suckler cows. Within the strategic plan, the budget foresees support for 100.000 cows (out of 116.425 in 2023 according	Production Animal protein sources	A budget of € 16 M per year is foreseen in the CAP strategic plan, representing € 83,6 M over the entire financing period (Departement Landbouw en Visserij 2021b).

Within its first pillar, a budget is set aside for coupled income support to suckler cow owners.	to Statbel (2024)), with different payment rates for the first 50 cows of a farm, the 51st to 100th cow, and beyond the 100th cow, ranging between 150 and 200 €/cow. The eligibility to such payments is coupled with certain management practices, including the preservation of grasslands, crop diversification and feed self-sufficiency, leading an expected extensification of practices.		The *Agentschap Landbouw & Visserij* is in charge of writing up the CAP strategic plans and distributing CAP payments.
10. CAP strategic plan – eco-scheme annual biodiversity-friendly or climate-resilient crops, including protein crops			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The 2023-2027 Flemish CAP strategic plan (Departement Landbouw en Visserij 2021b) lays out the structure and foreseen budget for the implementation of the EU Common Agricultural Policy in Flanders over the 2023-2027 period. Within its first pillar, an eco-scheme intends to promote the cultivation of protein-rich crops.	(Instrument – economic) This eco-scheme (new measure in the Flemish CAP strategic plan) is meant to encourage farmers to grow annual protein crops, including protein-rich peas and beans, soy and quinoa. Within the strategic plan, the budget foresees support for about 1000 hectares per year (i.e. less than 1% of the Flemish utilised agricultural area), with an area-based payment rate of 600 €/ha.	Production Plant-based protein sources	A budget of € 650.000 per year is foreseen in the CAP strategic plan, representing € 3,3 M over the entire financing period (Departement Landbouw en Visserij 2021b). The *Agentschap Landbouw & Visserij* is in charge of writing up the CAP strategic plans and distributing CAP payments.
11. Public support and subsidies for Flemish Centre for Agricultural and Fisheries Marketing (*VLAM*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The role given to *VLAM* by the Flemish government and by its members is to promote the products of Flemish agriculture. It conducts surveys to	(Instrument – informational) With regards to the protein transition, *VLAM* takes several actions which can be related to the protein transition.	Production & consumption Animal and alternative protein sources	Flemish government

monitor consumption habits, organises consumption campaigns and provides information on food products (e.g. recipes), including protein products.	On one hand, it promotes the consumption of animal-based products, e.g. through consumption campaigns such as the 'week of steak and fries'. Actions such as these are antagonistic with the objectives of a protein transition. On the other side, *VLAM* supports the protein transition through a series of fiches it has put together for farmers on protein crops. It also contributes data from the consumption surveys carried out by the centre, which serves for the protein monitoring report as part of the *Green Deal protein shift on our plates* (EI-Meet monitor) (GD eiwitshift op ons bord 2025).		
12. Public support and subsidies for Flanders institute for Healthy Living (*Gezond Leven*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The Flanders institute for healthy living (*Gezond Leven*) is an independent organisation aimed at fostering healthy lifestyles in the Flemish population, mainly through information access and dissemination.	(Instrument – informational) Among other health-related topics, Gezond Leven works substantially on food, producing different outputs to foster healthy and sustainable food consumption patterns. Relevant activities in the context of the protein transition include: nutritional recommendations through the Flemish food triangle, explicitly stating that red and processed meat should be consumed less; combined nutritional and sustainability	Consumption Animal and alternative protein sources	*Gezond Leven* receives funding from the Flemish government through different research projects.

	recommendations; prevention surveys, monitoring supply of healthy and sustainable food across settings; communication campaigns for the promotion of pulses (*'week van de peulvrucht'*), etc.		
13. Public support and subsidies for *Flanders Food*			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
Flanders Food is an innovation platform, created by *Fevia Flanders* and a series of Flemish food companies with the objective of fostering innovation and research in the food industry.	(Instrument – informational) *Flanders Food* acts as a central coordination point between sectors of the Flemish food industry, suppliers, consumers and research organisations, with the objective of establishing shared research and innovation projects. On of the organisation's research programs (roadmaps) specifically focuses on the protein transition, with the objective of establishing a strategic research and innovation plan to accelerate the protein shift in Flanders. Over 20 past and ongoing projects are part of the roadmap, mainly focussing on the production of alternative protein sources. In parallel, *Flanders Food* also supports research and innovation within animal production sectors, which may seem antagonistic with objectives of a protein transition (Flanders Food 2025a, b).	Production Animal and alternative protein sources	As a spearhead cluster for agrifood, Flanders Food gets public funding from the Agency for Innovation and Entrepreneurship (*VLAIO*), amounting 500.000 € per year during 10 years (to coordinate the consortium).
14. Coordination of Flemish platform for Agrifood research (*Platform voor Landbouw- en Voedingsonderzoeki*			

General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The *Flemish platform for agrifood research* aims to accelerate innovation in agriculture, horticulture, and the food sector through a strong innovation and research policy. The platform acts as a point of contact for agricultural and food research, bringing together research, policy, and industry.	(Instrument – informational) In an exercise to identify research needs as expressed by Flemish farmers, one of the conclusion points to fostering innovation on innovative crops, including protein crops (but also soils, local production, etc.). The document also calls for more systemic approaches (Agentschap Landbouw en Zeevisserij 2025).	Production Animal and alternative protein sources	The *Agency for Agriculture and Fisheries* is leading actor coordinating the platform.
15. Public support and structural funding of *ILVO*			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
ILVO is the Flemish research centre for agriculture and fisheries	(Instrument – informational) Through its research activities and projects, ILVO produces research on both the production of animal protein sources and of alternative protein sources (e.g. by participating in the LoCoSoy project). Although its research might span to the consumption side, its core research focus resides on the Flemish food production activities.	Production Animal and alternative protein sources	*ILVO* receives structural funding from the Flemish Government.
16. Public support and subsidies for *Food Pilot* plant			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
The *Food Pilot* plant is a pilot facility, supporting companies and labs in	(Instrument – economic)	Production	Flemish Government

agrifood innovation, either developing products or performing quality analyses.	In 2024, the experimental plant carried out more than 400 pilot tests for over 100 clients (private companies, farmers, research projects). The plant is closely linked to the protein transition as nearly half of the tests were carried out on alternative protein products (Food Pilot 2025).	Alternative protein sources	
17. Public support and subsidies for *ProVeg Belgium*			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
ProVeg is an international non-profit which advocates in favour of plant-based diets, thus pushing for an effective implementation of a protein transition.	(Instrument – informational) *ProVeg* works in collaboration with industry, producers, consumers and policymakers. The organisation provides information for consumers (e.g. recipes) and supports companies (e.g. caterers) to move towards plant-based meals and diets (ProVeg 2025).	Consumption Animal and alternative protein sources	In 2024, about a third of *ProVeg* income was supported through structural funding from the Flemish government (ProVeg 2025).
18. Public support and subsidies for *GoodPlanet*			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
GoodPlanet aims to provide and facilitate access to sustainability knowledge for both adults and children, at work and at school.	(Instrument – informational) *GoodPlanet* organises workshops on food sustainability, including information and specific workshops on plant-based diets and meals (e.g. over 200 *'PlantAardig (w)eten'* workshops organised in Ghent (GoodPlanet 2025).	Consumption Animal and alternative protein sources	*GoodPanet* receives public funding from the Flemish government.
19. Public support and subsidies for *MOS*			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority

MOS assists schools in developing sustainability strategies.	(Instrument – informational) Among other topics, *MOS* tries to push for sustainable food on schools, including discussing the impact of animal-based foods (MOS Vlaanderen 2025).	Consumption Animal and alternative protein sources	*MOS* is a collaboration between the *Environment Department*, the Flemish provinces and the Flemish Community Commission.
20. Development of sustainable public procurement criteria (*MVOO tool*)			
General presentation	Type of policy measure and target areas	Target dimension(s) of the protein transition	Funding and Competent authority
A series of criteria for sustainable public procurement has been developed for Flanders, with an online tool comprising 600 criteria on a series of products.	(Instrument – informational) With regards to food, several criteria relate to increasing the offer of plant-based diets in public events and meetings (Vlaamse overheid 2025).	Consumption Animal and alternative protein sources	Flemish Government

Value chain analysis

Table S20. Analysis of the current functioning and challenges of a small-scale organic soybean value chain (LoCoSoy) in Flanders, at different stages (production, post-harvest, processing, retail and consumption) (continued on following pages).

1. Production	
Current functioning	Challenges
Farmers: Within the *LoCoSoy* project, three organic farmers from the *Biograno* group have each cultivated approximately one hectare of soybeans for two consecutive years (totalling 3 hectares per year, 6 hectares over two years). **Seeds:** Various varieties and seed types have been tested. **Cultivation activities:** Weed control is done mechanically (organic farming), requiring extra attention. Wildlife (hares, pigeons, etc.) can pose significant challenges. **Contract work:** Sowing and harvesting can be performed by farmers themselves or by contractors. **Calculation of production costs:** All tasks and activities were recorded to determine production costs. **Yields:** Over the two-year trial, yields were overall comparable to yields in main-producing countries, but they remain variable and uncertain.	**New crop:** Soybean is a new/innovative crop in the Flemish agricultural landscape, bringing certain challenges: - Limited availability of varieties adapted to local conditions (e.g., short growing seasons). - Knowledge and expertise regarding cultivation practices is still developing. **Contract Work:** Finding a contractor can be difficult within the available time frame (after grain harvest and before grain maize season). Machinery must be adjusted for soybeans. Small-scale plots and limited areas may also be a low priority for contractors. **Calculation of production costs and profitability:** Costs remain highly variable and higher than market prices due to uncertainties in innovative crops (e.g., chickpeas face similar issues). Larger areas could reduce costs. Looking beyond pure economic results, soybean can contribute to diversifying crop rotation and does not necessarily need to generate the same profit margin as more profitable crops. Fresh beans could be considered as a reference crop. **Supply chain consolidation:** Agreements throughout the supply chain and among participating farmers can help strengthen the chain but remain a challenge as the sector is still new. Additionally, soybean crops offer limited opportunities for direct consumer sales through short supply chains.
2. Post-harvest: drying – sorting and dehulling – storage	
Current functioning	Challenges
Drying: Conducted within the *LoCoSoy* project at *ILVO* (Flemish research centre for agriculture). Drying is necessary to prevent mold formation, ideally down to 8% moisture content. **Sorting and dehulling:** This step was contracted to *Graines de Curieux* (GDC), an external partner in Wallonia (Southern Belgium).	**Volumes:** Few partners in Belgium are willing or able to process small volumes. **Innovative crop:** Post-harvest processes require further optimization. The extent of sorting needed and whether dehulling is necessary are still unclear. These factors affect costs (higher purity increases costs) and yield (dehulling leads to yield loss) and likely depend on processing requirements and final product specifications.

Storage: Part of the storage was done by farmers (with their own setups), while *ILVO* handled the rest.	**Allergen considerations:** Sorting, dehulling, and storage costs increase because processing lines must be thoroughly cleaned due to soy's allergen status. **Logistics:** The involvement of external partners (*Graines de Curieux*) brings logistical costs and challenges (transporting and retrieving soybeans). In-house sorting does not achieve a sufficiently clean and qualitative product for processors. Mobile optical sorting could be an alternative (e.g. via *Bioforum*, the Flemish agency for organic agriculture). **Buffer stock:** Storage capacity requires logistical planning and possible investments but provides flexibility to manage fluctuating demand and yields.
3. Processing	
Current functioning	Challenges
Exploratory phase: The initial objective of the LoCoSoy project was to focus on minimal processing techniques. **Soy flour:** The soybeans were first milled into soy flour at a mill, then processed at ILVO's 'Food Pilot' plant. Two final products were tested: pasta and bread. Different percentages of soy flour were used to replace a share of traditional wheat flour. **High-moisture extrusion:** No partner was found to test the production of textured soy products (high-moisture extrusion; mainly due to high processing costs). **Soy milk:** Another potential application explored was soy milk production. The *Damse Kaasmakerij* (an external partner specialized in cheese making) showed interest, and most soy from the two years of cultivation was delivered to them. *La Vie est Belle* could also use the soy milk for plant-based product development.	**Processing options:** Since soy is still a new crop in the region, identifying the best processing options, finding processors, and maintaining operations at an SME scale is difficult. **Milling:** The proportion of soy flour used in bread and pasta is relatively low (best results at around 30% soy flour). This requires careful consideration with regards to product marketing and storytelling (see next paragraph). **Regulations and quality standards:** There is a need for a regulatory framework to facilitates direct supply chains between farmers and processors. No standard quality benchmarks currently exist.
4. Retail	
Current functioning	Challenges
Retail partner: Colruyt Group participated in the LoCoSoy project as a potential retail partner.	**Market for soy products:** The retail market already offers many soy-based products, making differentiation a challenge. **Commitment and supply chain collaboration:** From the retailer's point of view, it is crucial to define the final product before engaging in a lasting commitment with other supply chain partners. Key considerations include the soy content in the product and how it affects pricing. A partnership with *Damse Kaasmakerij* could be an interesting option, given their existing collaboration with Colruyt Group. **Marketing:** Marketing should focus on taste rather than just emphasizing local sourcing, which is not the biggest priority for consumers (see next paragraph).

	Continuity: Once a product is launched, a stable supply is required. It is challenging to remove a product due to volume shortages and later reintroduce it in the next season.
5. Consumption	
Current functioning	Challenges
Tasting tests: Tasting tests were conducted for soy pasta (dry pasta) and soy bread.	**Food culture:** The shift toward plant-based proteins (the so-called protein transition) is still limited. Taste test results were mixed, with soy bread performing better than soy pasta. **Marketing strategy:** Product storytelling is a challenge. While local sourcing is a "nice to have," health, taste, and price are more important factors for consumers.