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THE FUTURES OF LIVESTOCK FARMING
IN AGRI-FOOD SYSTEMS

Foresight analysis and multicriteria assessment of scenarios

Aurélie Wilfart and Jonathan Vayssières, eds

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Preface

“What do we want to eat?” This is a very important question that may, in the future, very well become “what can we eat?”. Our biggest challenge today is to somehow find a way to reconcile these two questions, keeping in mind that the verb “can” in this sense refers to various issues such as climate, biodiversity, soil, water, the atmosphere and purchasing power, as well as health issues and even world peace.

The livestock sector often leaves a large carbon footprint and as such, it is a key component in the choices to be made in future food systems. Most (but not all) of the scientific community admits that livestock farming is a major lever for successfully bringing about out the necessary changes that we will need to make. In general, there are no scenarios or foresight analyses that allow us to consider sustainable agriculture (closed nutrient cycles) without including livestock farming. Therefore, the main aim of this book is to remind readers how important this sector is by using synoptic and recent data illustrated by various well-documented case studies.

The livestock sector is a major source of income, food security and social stability for millions of farmers and livestock holders around the world. Livestock farms help maintain soil fertility via the production of organic fertilizer, which will be used to gradually replace mineral (synthetic) fertilizers. These farms can also draw on draught animal power to work the fields and for transportation purposes, which can then in turn increase agricultural productivity in systems that combine livestock farming with crops (biomass transfer). Looking past production and employment issues, the livestock sector also provides various services, including the ecosystem services described in this book. This is important because this covers various geographic areas throughout the world. Naturally, this book also serves as a reminder that livestock production, despite its many advantages, still faces significant challenges that limit its contribution to the agroecological transition of agri-food systems. This means livestock farming cannot always reach its full potential as a lever for territorial development.

As a result, livestock farming is often both the problem and the solution, or the culprit and the victim, so to speak. For instance, it is key to the solutions that will be rolled out to address climate change and, at the same, it is often a source of environmental degradation. The animals themselves add to greenhouse gas emissions, while simultaneously enabling carbon fixation in grasslands and pastoral lands; livestock farms can cause soil degradation due to overgrazing and deforestation, but in other situations they facilitate the sustainable management of these same grazing lands and pastures depending on the related practices (degree of intensification). Lastly, they use a large amount of water resources, but they can also help protect this resource when these farms are grassland-based systems, and especially when these grasslands are permanent.

Another growing concern is the health of animals, humans and ecosystems. Comprehensive approaches are therefore required within this context, such as the One Health approach with livestock farming playing a central role, especially given the alarming zoonotic disease outbreaks. According to the World Organization for Animal Health, 60% of infectious human diseases are in fact animal-borne (FAO *et al.*, 2023).

The central aim of this work is to look past this general observation and to view this set of factors as a potential way to start thinking about the following questions: what are the possible actions that can be taken in the future so that livestock farming can contribute broadly to sustainable development and specifically to the food transition? What is/are the best scale(s) for dealing with this subject matter? Which methodological developments can and should research implement to be able to develop solutions in collaboration with the stakeholders involved?

In this book, the various authors will show that research and methodological tools may play a key role by clarifying the possible future pathways for livestock farming and how it can be integrated within territories. This will help readers better understand how the combination of territorial foresight analysis, scenario modelling-simulation and multicriteria assessment can be used to analyse changes in livestock systems while simultaneously taking economic, social and environmental factors into account.

Some of the more original chapters in this work contain case studies that touch upon a wide variety of themes, methods and scales, from the territory scale to national and supranational scales. Different qualitative and quantitative approaches are introduced for the purpose of anticipating the impacts of climate change, agroecological transitions and/or territorial restructurings. Additionally, methods are described for identifying solutions to conflicts surrounding pastoral herd mobility, the role agri-food production networks play in sectoral and territorial transitions, the sustainable resource use, market dynamics and public policies. It should be noted that although these chapters cannot be used as comprehensive or detailed guides to the various methodologies, each case study provides non-specialist readers with valuable examples and guidelines for the approaches used, and specifically how to set up ways to design solutions and assess their impacts.

Lastly, this book addresses the important question of what the future holds for the societies of tomorrow based on scenarios using foresight and modelling approaches, and especially the adoption of these scenarios in political and decision-making circles. Given the vast array of challenges ahead, we clearly need ambitious public policies that will focus on livestock farming as a lever for territorial development and sustainability. The challenge faced by research is that it needs to propose tools that can galvanize political decision-makers to act in support of public policies that help livestock farms play their full part in raising people's living standards, helping the transition toward more sustainable food systems and safeguarding natural resources.

This book gathers researchers, decision-makers and local stakeholders together, and uses science-based and participatory approaches to provide invaluable insight into the methods and tools that can be used to describe possible futures and, starting today, to help with the necessary transitions.

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General introduction

Aurélie Wilfart, Sandrine Espagnol, Mathieu Vigne, Olivier Mora and Jonathan Vayssières

Global food systems are faced with three key challenges in connection with the environment, food security and human health (Mottet *et al.*, 2020). Livestock farms play a vital role in this, which raises many questions about the different facets that may vary significantly from one region in the world to another.

The United Nations (UN) already called attention to the environmental impacts of livestock farming activities in 2006 in its report, "Livestock's Long Shadow" (Steinfeld *et al.*, 2006); today, these impacts are central to discussions about this sector. The contribution of livestock farming to global environmental impacts varies: ranging from the consumption of non-renewable resources to competition for land use including, of course, greenhouse gas (GHG) emissions. Various Intergovernmental Panel on Climate Change (IPCC) reports emphasize the climate emergency and indicate that anthropogenic GHG emissions must be reduced worldwide. Global food systems account for 34% of all GHG emissions (Crippa *et al.*, 2021). According to the Food and Agriculture Organization's most recent estimates (FAO, 2023), animal production generates 60% of global protein intake (Food and Agriculture Organization of the United Nations, 2022), and 12% of the total GHG emissions from human activities.

In addition to the climate issue, six other planetary boundaries are being exceeded: biodiversity loss, the disruption of nitrogen and phosphorus biogeochemical cycles, land-system change, freshwater use and the introduction of novel entities, such as plastic, into the biosphere, and ocean acidification (Figure i.1).

The use of nitrogen and phosphorus by livestock farming systems drive a substantial amount of international trade which then disrupts the biogeochemical cycles. For instance, Dourmad *et al.* (2019) report that 70% of the nitrogen content in the world's agricultural crops is used as animal feed (in Europe, this percentage goes up to 80%).

Moreover, global livestock populations either directly or indirectly use 75% of agricultural lands for the main purpose of feeding animals (Foley *et al.*, 2011); it has been estimated that all of Europe uses almost as much. However, most of this biomass does not compete with human food. As an example, according to Mottet *et al.* (2017) and Sandström *et al.* (2022), livestock farms around the world consume roughly 6 billion tons of dry matter (DM) in feed, 86% of which is not in competition with human food. Much of these feeding stuffs (60%) are grass and shrub resources consumed by ruminants on marginal land which is not suitable for protein crops that can be consumed by humans (Van Zanten *et al.*, 2015). In France for instance, Dourmad *et al.* (2019) estimate that although livestock populations either directly (grasslands and harvested fodder) or indirectly (concentrate feeds) use more than half of the usable agricultural area (UAA), this land is first and foremost grassland (3.2 M ha of temporary grasslands and 9.3 M ha of permanent grasslands), followed by land used to grow fodder crops (1.5 M ha) and cereals (1.5 M ha). Lastly, in recent years, the question of water resources has become an important issue. Agriculture represents approximately 90% of global freshwater use and is responsible for close to 70% of global water withdrawals (Govoni *et al.*, 2024). This means that between 30 and 40% of the world's food is produced on irrigated soil (Boulay *et al.*, 2021) whereas livestock farming represents roughly 30 to 40% of global water use (Mekonnen, Hoekstra, 2012; Govoni *et al.*, 2024). The production of raw materials for livestock feed represents 98% of the water footprint for the livestock sector (Mekonnen, Hoekstra, 2012), with rainwater making up 94% of this footprint.

However, this environmental emergency is becoming even more urgent against the background of increasing population growth and increasing global food demand. According to Miller *et al.* (2022), between 1990 and 2018, milk consumption doubled globally (+99%), cheese consumption increased by +56% and yoghurt consumption stayed roughly the same. For reference, the average consumption of unprocessed red meat per person over this same period almost doubled (+88%) worldwide. It is important to note

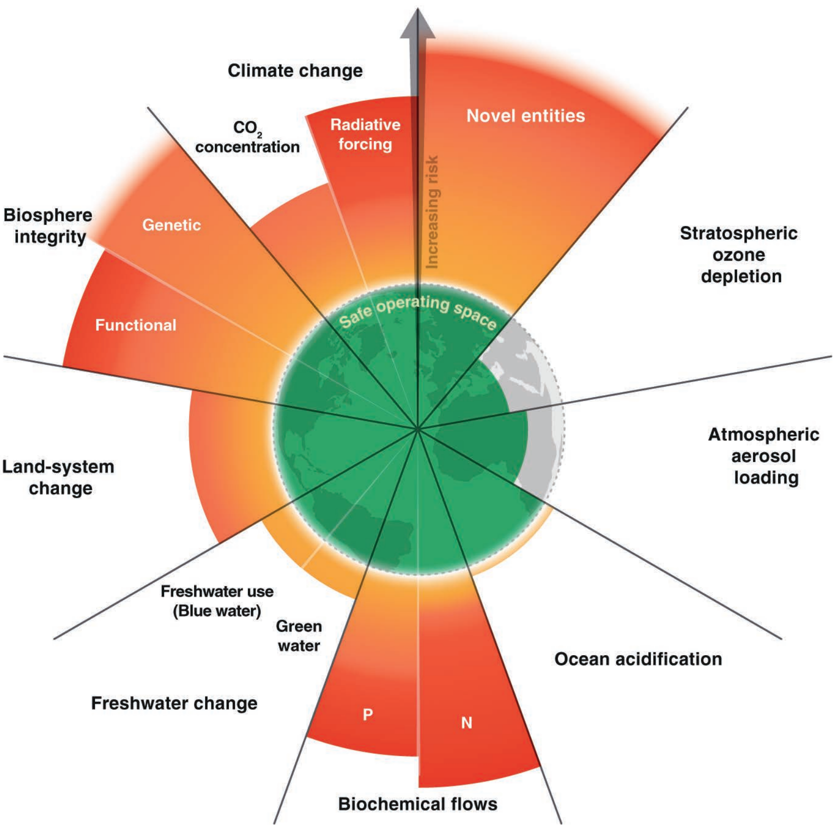

Figure i.1. Planetary boundaries (source: Azote for Stockholm Resilience Centre, based on analysis *in* Sakschewski and Caesar *et al.* 2025, following Steffen *et al.*, 2015).

that this global trend is due to an increase in consumption in only three regions: Southeast and East Asia (+266%), Latin America and the Caribbean (+58%) and sub-Saharan Africa (+26%). This consumption is sharply declining in high-income countries but is being substituted by processed meat. In addition to growing environmental awareness, high-income countries are eating less meat, especially in Europe, due to other concerns such as animal welfare (Delanoue, Roguet, 2015), production models (highly criticized off-land and industrial models) and, more recently, the place of livestock farming in territories and food systems.

The resulting public policies in Europe include setting targets and deadlines, and to do so, this means that changes and developments must be carried out in agricultural systems – which of course includes the livestock sector. The European Climate Law and its Carbon Neutrality Roadmap have set a target for Europe to be carbon-neutral (i.e. net-zero greenhouse gas emissions) by 2050. In France, the National Low Carbon Strategy (SNBC for Stratégie Nationale Bas-Carbone) has set objectives to reduce greenhouse gas (GHG) emissions by 2050, with intermediate targets in the short-term (-18% by 2030) and medium-term (-46% by 2050, using 2015 as a reference). These are additional objectives that have been added to the ones set forth in France's Energy Policy Framework from 13 July 2005, known as the POPE Law, which is hoping to achieve a four-fold decrease in GHG emissions between 1990 and 2050 (Martin *et al.*, 2015).

Quite different dynamics are observed in developing countries, particularly in sub-saharan Africa. High population growth rates go hand in hand with nutritional transitions toward animal products (Popkin, 2006). These changes in diet are explained by increasing population sizes in urban areas and rising income levels (Delgado, 2003) and therefore, within this context, the main goal of public policies is to increase livestock productivity and production nationally. This involves taking steps at all levels, such as improving animal genetics, organizing collection and processing systems, introducing new fodder species and, more generally, making changes to fodder systems (Pica-Ciamarra *et al.*, 2013).

This whole context is calling the future of agriculture into question, particularly for livestock farms across the world. Change is necessary. There are several existing levers for change at various scales: from farm holdings and farming households (through the choice of different livestock farming practices and systems) up to the territory level (through the choice of spatial distribution of livestock farms and the choice of local or imported food resources, etc.). At the agricultural system level, we can find partial solutions for some of these challenges through the development of agroecological practices and systems. At the sector level, an important lever has to do with reducing the amount of loss and waste along the whole value chain for animal products. In 2011, the FAO estimated that one-third of the food produced globally is lost or wasted (FAO, 2011) at different stages in the food supply chain depending on the region of the world. In developing countries, food losses mostly occur upstream in the food supply chain due to problems with harvesting and preserving products whereas in industrialized countries, food waste occurs further downstream during the processing steps and due to household behaviour. For consumers, besides reducing food waste, another lever we have at our disposal is our diet itself. For instance, we can choose to support production methods that prioritize local, healthy, fair-trade and environmentally sustainable sectors.

Reducing the percentage of animal proteins in human diets is a public health issue as much as it is an environmental issue for high-income countries, especially OECD (the Organisation for Economic Co-operation and Development) countries. The recommended daily allowance of protein in diets is between 0.6 and 2.2 g/kg of body weight per day, with an average recommendation of approximately 0.83 g/kg of body weight per day for adults in good health (French Agency for Food Safety [AFSSA], 2007; World Health Organization [WHO], 2007). In France, the average person consumes 1.4 g of proteins/kg of body weight per day, which is higher than the recommended average. At present, the ratio between animal-based proteins and plant-based proteins is 60/40 worldwide (FAO, 2022) and 65/35 for France. Based on current estimates, agri-food systems[1] (Figure i.2) represent between one quarter (Barbier *et al.*, 2019) and more than one-third (Crippa *et al.*, 2021) of anthropogenic GHG emissions in France and worldwide, respectively, and animal products have a higher carbon footprint per kilogram than plant-based products. However, more support is needed for these transformations through public policies that meet society's expectations regarding the re-territorialization of agricultural activities (RAA), i.e. shifting from global-scale to local-scale activities, and, more generally, the role that livestock farming plays in global agricultural systems.

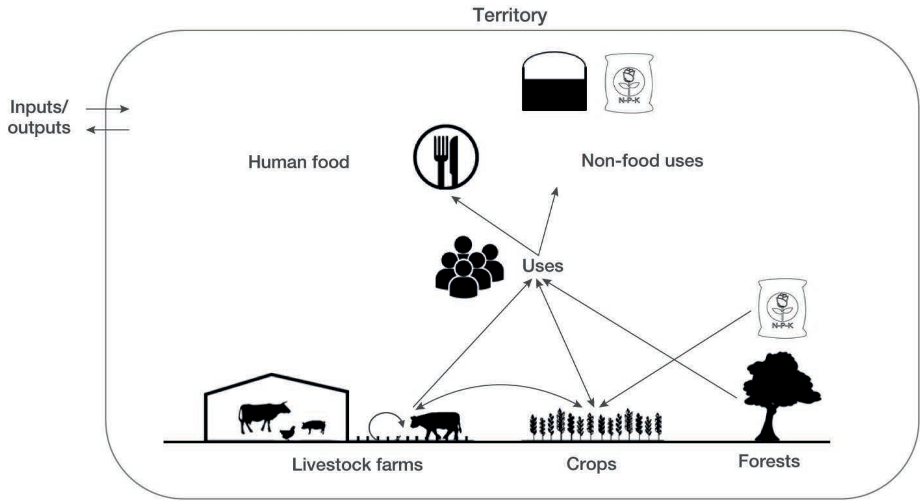

Figure i.2. Simplified representation of the agri-food system.

Foresight analysis generates anticipatory knowledge for research and action purposes which can then be used to shape public discussion and to give decision-makers the information they need without resulting in specific and operational recommendations. It can help steer discussions by laying out the potential impacts of current and future actions and so, to this end, several foresight studies have been conducted to help guide the options for change in agri-food systems. Each study was based on all

1. The term "agri-food system" refers to how people organize themselves socially, in space and in time, to obtain and consume their food (Lamine, 2012) taking into account local and imported resources, the use and processing of co-products and waste, as well as the consumption and possible local production of energy needed for the proper functioning of this system.

or some of the above-mentioned issues and attempted to either qualify scenarios that explore possible futures (exploratory scenarios constructed on trends or disruptions) or to construct scenarios that try to achieve desirable futures that meet predefined objectives, e.g. carbon neutrality (normative scenarios). Foresight studies have an intricate relationship with public policies and can be used in various stages of the public policy cycle (Jacquot, 2019). Normative (or target-seeking) scenarios are developed upstream of transition policies so that the implementation conditions can be examined. The main objectives include addressing the climate emergency and food demand (with an objective to increase food sovereignty within territories) and, more specifically in Europe, to move towards an agroecological and local agriculture that meets society's expectations. Several European countries (France, Denmark, the Netherlands, etc.) are also closely looking at issues regarding nitrates and livestock manures, and there could very well be other issues that arise in the future, such as issues relating to energy or health issues. Consequently, it could become difficult to address several different objectives within the same scenario and therefore, scenario building (or scenario planning) is heavily influenced by how these multiple objectives are considered and prioritized.

This book is based on what was learned during the Researcher School organized by the MAELE joint technology network[2]. It focuses on foresight analyses and assessing transition scenarios for livestock farming in agri-food systems (Figure i.2) in various parts of the world. Given that the challenges, contexts, existing agri-food systems and livestock dynamics at play are so varied, specific foresight studies, modelling and assessments need to be conducted for each specific region. To this end, this book lays the methodological foundation for defining and assessing transition scenarios for livestock farming in agri-food systems using a generic approach that incorporates the challenges and characteristics of agri-food systems in industrialized and developing countries as much as possible.

The first part of this work introduces the foresight approach and illustrates it using four case studies in Brittany, West Africa, France and at the global scale. It also outlines the various steps used, ranging from defining the system, its components and variables, up to building one or more scenarios. The second part focuses on modelling and assessing scenarios at the territorial level. Here, a territory is defined as a given geographical area that accounts for some or all the activities that take place and the various stakeholders involved (see Box 6.1). It presents the flows to be considered, along with the development of multicriteria assessment grids. It also uses two case studies, one in France and one in Europe, to show why foresight studies should be combined with scenario assessments. The third and final part uses an across-the-board approach to build upon the lessons learned from sharing experiences. From a methodological perspective, it formalizes a coupling framework for scenario building and assessments. It also defines the background data matrix needed to conduct foresight analyses as well as to model and assess the resulting scenarios. From a thematic perspective, this last part outlines

2. The objective of the MAELE Joint Technological Network (RMT) is to assess the environmental impacts of livestock systems, in relation to their region and food systems. The goal is to produce a generic and robust scientific and technical foundation that allows us to reflect on the place of livestock farming in future agri-food systems. This would involve connecting livestock systems, territories and food systems around environmental issues.

some of the potential options for change relating to the future of livestock farming in territories and agri-food systems as discussed by policymakers and provides some first thoughts on how policymakers can take over foresight studies.

Consequently, this book addresses methodological questions relating to the construction of scenarios and their modelling-assessment:

– What are the goals?

– Which stakeholders are involved and at what stage(s)?

– What scales and organization levels are taken into consideration?

– What data are needed to perform foresight and to model and assess scenarios?

– What tools are used for simulation models and assessment methods?

– How can we better coordinate foresight analyses so that scenarios can be co-built, and then modelled and assessed?

Part 1

Foresight studies and changes in livestock farming within territories

Chapter 1

Foresight and questions surrounding livestock farming

Olivier Mora and Audrey Béthinger

This first chapter presents some of the definitions and methods used in foresight approaches, explores the place of livestock and animal products in foresight studies and, lastly, introduces four recent foresight studies that look at the prospects of livestock farming. These studies are discussed in detail in the next four chapters (Chapters 2, 3, 4 and 5).

⏩ Introduction to foresight approaches

Foresight analyses use specific methods to make assumptions about the future development of a sociotechnical, economic or ecological system, and to discuss them in a structured way (Barré, 2005; Mermet, 2005). This type of analysis is based on a methodical ordering of knowledge and skills relating to the future of society and environments. It also uses scenario building (or scenario planning) methods that may range from desirable scenarios to exploratory scenarios, all while including the development of transition pathways as well as different types of data (quantitative and qualitative). The goal is to anticipate future challenges and to reflect on possible courses of action to be able to start addressing these challenges today. One objective of foresight analysis is to increase the capability of stakeholders to prepare for and shape their future by including anticipated possible futures into their decisions. Consequently, foresight analysis has two functions: a heuristic function, to better understand contemporary dynamics in terms of their potentials and risks (Jouvenel, 1999), and an anticipation and decision-making function, to better prepare for possible future challenges (Godet, 2000; Miller, 2007).

The foresight approach is particularly relevant to complex systems and for dealing with high-uncertainty situations. As such, and for the very reason that it anticipates issues over the long-term, foresight analysis helps address social and scientific controversies, and can be applied to situations of environmental, climatic, social, economic and political crisis over global, continental, national or regional scales.

It is important to distinguish between foresight and scenario-based approaches. Foresight is a broader concept that refers to any work exploring a possible future, to provide information about and to guide the actions of today. More precisely, Miles and Keenan (2022) define foresight as "the application of systematic, participatory, future-intelligence gathering and medium-to-long-term vision-building processes to informing present-day decisions and mobilising joint actions".

Scenario-based approaches use a subset of foresight analyses to generate contrasting futures for the purpose of viewing the possible changes to come in a particular situation or system (see Cordova-Pozo, Rouwette [2023] for a literature review on the types of scenario approaches). Through a scenario-based approach, there can be meaningful debate about the future using a set of scenarios that explore uncertain changes that may occur in the future (*ibid.*). These scenarios can be quantitative (e.g. climate change scenarios) or qualitative (e.g. shared socioeconomic pathway (SSP) scenarios that interact with climate change), and sometimes, some scenarios are built using both qualitative and quantitative approaches (Wiebe *et al.*, 2018). There are several reasons why it's a good idea to involve stakeholders in scenario planning: to provide better insight into the complexity of the studied systems, to make the scenarios more relevant by incorporating tacit and practical knowledge, and to make it easier to incorporate scenarios into decision-making processes (Galang *et al.*, 2025). Lastly, scenario planning involves a specific vision of the future where a non-deterministic vision is explored by constructing a set of scenarios. Whereas short-term approaches generally use a deterministic vision of the future, long-term approaches need to develop a non-deterministic vision in which past dynamics are only used to determine the possible distribution of future scenarios (Magruk, 2020). However, some foresight approaches only generate one single scenario (instead of a set of scenarios), e.g. the TYFA scenario for agroecology in Europe or the Afterres scenario for the sustainable use of biomass (both of which are presented in Part 2 of this book). The resulting scenarios then can help identify the conditions needed to achieve a desirable future. These foresight approaches are used to build visions and to assess them quantitatively (see *visioning*, below).

There is a vast array of foresight methods in existence. Below, we provide a non-exhaustive list of these methods, and distinguish between methods that are based on scenario building and those that are not:
– *horizon scanning* methods systematically examine possible (future) problems, threats and opportunities by identifying weak signals and possible disruptions that could affect current trends (Amanatidou *et al.*, 2012).
– *tipping point* methods identify possible disruptions in the non-linear transition pathways of a system. This involves identifying the threshold effects in pathways that mark a tipping point in a system's dynamics, i.e. the point at which a small disruption can cause a qualitative change in the future state of a system (Lenton, 2013).
– the *Delphi* method relies on a collaboration with experts to reach a consensus on the identification of trends, future challenges or a shared vision of the future over a given time horizon (Kauko, Palmroos, 2014).
– the *fuzzy cognitive maps* method is used to construct influence diagrams that contain nodes, called concepts, connected by arrows to indicate the direction of influence between concepts. In foresight analysis, this method is used to represent complex systems with non-linear and multi-directional interactions, and to render implicit hypotheses explicit (Jetter, Kok, 2014).

Scenario building methods are different in nature depending on their objectives. This section presents three main scenario methods: *"scenario planning"*, *"visioning"*, and territorial foresight. However, before presenting these methods, the term "scenario" should be clarified as it has several different meanings. Sometimes "scenario" may be related to futures-thinking and sometimes not, and it can apply to academic fields as well as everyday conversations. In foresight exercises, a scenario describes narratives constructed for the purpose of exploring possible futures and testing or expanding the logic underlying each future situation (Cork *et al.*, 2023). Spaniol and Rowland (2019) reviewed various publications on foresight scenarios to look for shared criteria used to define a scenario (or scenarios). In their work, these authors define scenarios as possible and plausible forward-looking narratives or descriptions occurring in sets – i.e. sets of scenarios – that are systematically prepared to coexist as meaningful alternatives to one another. Therefore, in the literature on foresight, a set of constructed scenarios (and not one single scenario by itself) is used to draw meaning and to anticipate the future. Four criteria define the quality of a scenario: relevance (with regard to the question asked), transparency (of the scenario construction and its hypotheses), coherence (of the scenario's hypotheses) and plausibility (regarding what is known and anticipated).

The general nature of scenarios constructed in foresight analyses varies depending on the objectives pursued. A distinction is made between *exploratory* and *normative* scenarios. *Exploratory* scenarios envision all various possible futures imaginable based on past trends, weak signals and possible disruptions with the goal to identify all possible futures that would require preparation since these future situations are highly uncertain. *Normative* scenarios describe a pre-defined targeted future, usually the most desirable one, and aim to define the conditions needed to reach it. The objective of this type of scenario is to determine what conditions must be fulfilled for a scenario to be plausible and could even chart a possible pathway toward this target.

Scenario methods. The broad purpose of these scenario methods (also called *scenario planning*) is to explore the different possible futures. These methods insist that multiple possible futures exist by underlining the radical uncertainty of the future: since the future is uncertain, the goal is to imagine the different directions it could take. In general, two main scenario planning methods are discussed in the literature: one uses a 2x2 matrix, the other is based on morphological analysis.

In the 2x2 matrix method, two contextual variables that are causally independent from each other are used to structure four possible futures. These variables are ranked based on their degree of uncertainty and potential impact on the object being studied over the chosen time horizon. The first two independent variables with a high potential impact and high uncertainty are combined to create a 2x2 matrix scenario (Ramirez, Wilkinson, 2014). However, one disadvantage of this method is that the whole transition dynamics of a system are reduced to only two variables for which two contrasting states are considered.

The objective of scenario methods based on morphological analysis is to use n-dimensional matrices to take the complexity, interdependencies and non-linear dynamics of systems into account. Morphological analysis is "a method for systematically structuring and analysing the total set of relationships contained in multi-dimensional, non-quantifiable problem complexes" (Ritchey, 2011; Mora *et al.*, 2020). Unlike the 2x2 matrix approach, this scenario building method looks at what can or might happen, without making the system less complex *a priori* in either its structural dimensions or temporal dynamics (Börjeson *et al.*, 2006; Maier *et al.*, 2016). It meets the criteria for scenario transparency, coherence and plausibility mentioned above. Applied to foresight work, morphological analysis can "consider the entire field of possibilities and construct scenarios" (Durance, Godet, 2010; Amer *et al.*, 2013). First, the studied system and its main components and variables are defined. Next, the system is analysed retrospectively and hypotheses about future changes in each component over a given time horizon are developped. The morphological matrix regroups all these alternate assumptions of change so the combinations can be visualized and explored. All these possible combinations use abstract terms to describe possible changes in the system over the defined time horizon. However, it is important to assess the internal consistency and plausibility of the combinations to "eliminate incompatible combinations... and create plausible combinations" that make sense (*ibid.*). This systemic method is based on multiple plausible configurations allowing to study the causal links and possible interactions between the different components within a system. The entire process relies on collaborating with various expert panels at different stages of the foresight process to debate the assumptions of change for the components as well as their plausible combinations within the scenarios (Mermet, 2009). Moreover, this method can be used to improve the consistency and plausibility of each scenario, as well as to make systematic comparisons between them. Scenario building is an exercise in collective brainstorming that is not restricted by having to reach a consensus. This foresight method, when used as an exploratory approach, underlines that multiple possible developments may exist, i.e. it can define a variety of plausible futures for which it is better to be prepared. The diversity of scenarios ensures that future analysis remains relevant and of interest to the various stakeholders who will seek to make use of it. The advantage of using contrasting scenarios is that the challenges associated with long-term changes in the studied system can be better understood. By highlighting the major trends, major areas of uncertainty, desirable transition pathways and main risks of disruption, scenarios provide public decision-makers and private stakeholders with information that can help them formulate long-term strategies. Similarly, scenarios can pinpoint areas of research that need to be strengthened or developed to meet future challenges and objectives.

Visioning is a process of systematically creating visions of a desirable future state. This process partially relies on stakeholder participation to collaboratively develop normative futures. *Visioning* has at least two broad goals: first, to collaboratively create a representation of desirable futures (so we can share our goal), build a vision (aka a normative scenario) and then assess it using a simulation tool; and second, as a first step in a *backcasting* scenario (Wiek, Iwaniec, 2014).

Backcasting. The goal of this method is to develop a pathway or trajectory to a normative future state. The *backcasting* approach works by starting at a desirable future state and then moving backwards toward the present to identify what is needed (especially regarding actions and public policies) to achieve this future state. Although it is not used in the foresight studies presented in this book, there has been increased interest in the *backcasting* approach in recent decades as a way to address sustainability issues in sociotechnical systems (Kok *et al.*, 2011; Mora *et al.*, 2023).

Territorial foresight involves generating medium- or long-term visions of future states to help territorial stakeholders define the choices used in the action plan (Spohr, 2009). Territorial foresight is a strategic, systemic and participatory approach often used to help develop territorial projects. Within this context, foresight analysis is mobilized as a strategic decision-making tool for managing territorial projects (*ibid.*). This systemic approach helps to better understand the dynamics of the multiple dimensions at play within a territory, while considering the complexity and interdependencies between its components. The goal is to produce a shared vision of the future territory based on participatory approaches that allow the creation of a common vision for several stakeholders within a territory (Heurgon, 2006). This is a collective intelligence approach to taking action. It aims to ease tensions so as to open up the field of possibilities and to give stakeholders more room for manoeuvre so they can imagine desirable futures (Bailly, 2005). In France and Europe, territorial foresight is often used in the development of public policies for territorial planning, innovation policies or even to anticipate natural, political or economic risks within territories (Le Berre, 2013).

⏩ Role of foresight analysis and scenarios in addressing uncertainty and complexity

Scenario-based approaches are quite helpful for addressing the considerable uncertainty associated with future trajectories in complex systems (Figure 1.1). It is difficult to anticipate the future developments of systems as they can be rather complex. As a system becomes more complex, there is an increase in the interdependencies within the system, which means it can be quite difficult to anticipate the system's future. Conversely, less complex systems are easier to anticipate because, as a general rule, they stay stable over time.

This is why we first need to clearly differentiate between scenarios and *forecasting*. Forecasting looks at changes in situations with *all other things being equal*. That is

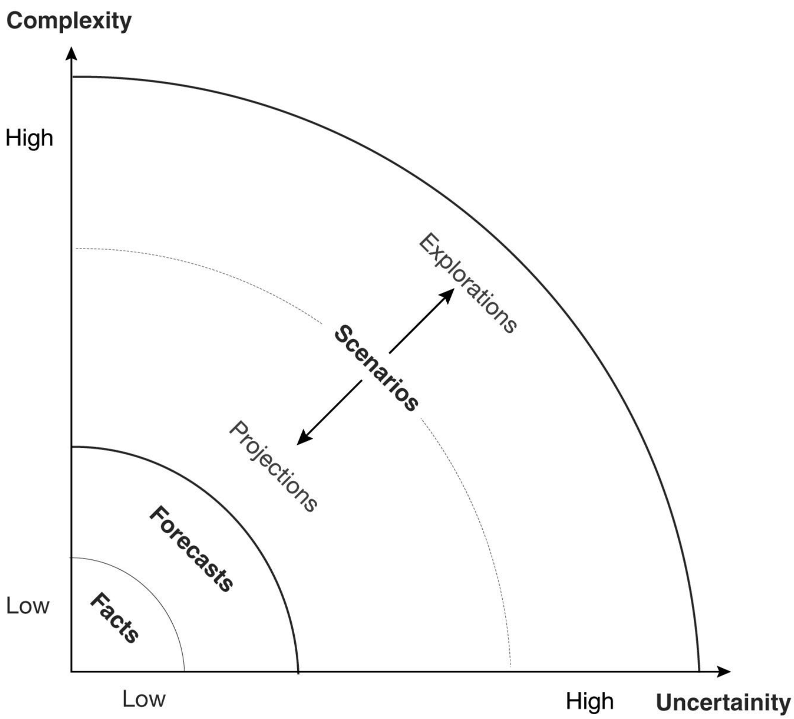

Figure 1.1. The role of scenarios in addressing uncertainty in complex systems (from Zurek and Henrichs, 2007).

to say, developments where future situations remain within the boundaries of what we already know today. Scenarios are used in all other situations, especially ones with multiple and interdependent changes. The use of scenarios in low uncertainty situations enable us to look ahead (project ourselves) into the future. This involves extrapolating, in the future, the trends for several components in the system and then by considering their implications. This is how we build so-called baseline scenarios, which are also called business as usual (BAU) or trend scenarios. When there is increasing uncertainty and complexity within a system, scenarios make it possible to describe the different possible futures that may arise from non-linear changes and bifurcations compared with the initial system. In this situation, scenarios provide a way to *explore* the future by generating a set of contrasting scenarios– this allows us to consider the implications of an entire range of possible futures. As such, these scenarios incite us to think about the various processes of transformation as well as the diverse causal sequences that will influence the future. They also allow us to reflect on how actions and decisions taken today may affect future dynamics.

Box 1.1. Some simple definitions to characterize the temporal dynamics and futures in foresight approaches

A few simple terms are used in foresight to discuss the temporal dynamics of systems and to describe scenarios. Temporal dynamics are described by three terms:

– *major trends* (or *megatrends*) are the changes observed over an extended period, and which indicate stable transformation processes, often documented by statistical series. They describe the (mostly) growing phenomena and require preparedness, even if it is not possible to control the pace at which these changes occur. Business as usual (BAU) scenarios result from the extrapolation of major trends.

– *weak signals* (or *seeds of change*) are factors of change that are barely perceptible in the present, but which are potentially capable of transformation in the future. These emergences, or seeds of change, are difficult to perceive, but promising for the future in that they may eventually become strong trends.

– *disruptions* are factors of change that go against the major trends. They are sometimes called *black swans* or *tipping points*. When a disruption occurs, it puts an end to the major trend and results in a new form of the system.

Steps in a foresight analysis

To give the readers an idea of the steps involved in foresight analyses, we take an example of morphological analysis used to create scenarios for exploratory purposes.

Defining the scope and time horizon of foresight studies

The first step involves the problematization of the question being asked in such a way that it becomes the subjet of a foresight exercice. Problematization first specifies how the temporal dynamics, multiple uncertainties and complexity of the subject matter make the use of a foresight method necessary. It also defines the problem, spatial scope and time horizon of the study. This time horizon is defined in relation to the issues likely to have an impact on the subject matter being studied (e.g. the expected impact of climate change, the forest management cycle, etc.), the timescale of the actions that will be carried out by the stakeholders behind the foresight study, as well as the contextual issues likely to transform the studied system (e.g. generational turnover). The aim of foresight analyses is to explore complex systems (with strong interdependencies between the component dynamics) and favour horizons with a high level of uncertainty about the future of the systems (usually long-term horizons, e.g. 20 to 50 years).

Building foresight systems

The second step is to define the studied system. The variables that exert or are likely to exert an influence on the future development of the object in question are identified as precisely as possible. These variables are then grouped into four to seven components that structure the system. As a result, the system is characterized by a certain number of interacting components.

Retrospective system analysis

Retrospective system analysis is a key component of foresight studies as it paves the way for forming hypotheses for future trends. Retrospective analyses look at past trends behind the changes in the system's various components. This type of analysis is based on literature reviews (scientific articles and grey literature) and expert meetings. The objective is to identify the major trends over the past few decades, *weak signals* of change that can be perceived today, and possible disruptions that could occur within the timeframe set by the study (see Box 1.1). This analysis of past trends is key to formulating hypotheses for future trends, and this phase makes sure that the foresight study is sound.

Formulating assumptions of change for each variable and component

Assumptions of change are based on the previously conducted retrospective analysis and involve forming hypotheses about possible changes over the defined time horizon. Contrasting assumptions of change are formulated for each variable (and then for each component): some are extrapolated to project major past trends, whereas others are based either on the expansion of currently observable weak signals into major trends or on the impacts of possible disruptions. This is a creative phase of the foresight process, one that is headed by the project team, and which makes full use of the contributions from the group of experts.

Scenario building

Constructing morphological charts

Morphological charts (or tables) list all the assumptions of change for each variable in each component, as well as for each of component within the system. This chart makes it possible to visualize all the various possible combinations of hypotheses and as such, it is a formal tool often used in debates within the expert committee. It uses a combinatorial process to generate multiple scenarios that anticipate the various ways in which the system may change.

Scenario development

Scenarios are built according to experts (within the group of experts) by selecting hypotheses for each variable and component in the morphological chart and combining them in such a way so as to construct plausible and coherent future states of the system over the defined horizon. For exploratory scenarios, the aim is to construct scenarios that contrast each other, so that the set of scenarios covers all possible futures. All the experts involved must agree with the set of scenarios developed, which often times represent divergent futures.

Finalizing scenarios

Each scenario is developped within a narrative that describes the causal links between the variables, and which provides information about the drivers of change. A visual representation of the scenarios can help make it easier to represent and understand the set of scenarios: e.g. diagrams combining the assumptions of change (Figure 5.1 in this work; Mora *et al.*, 2020), pseudo-choremes (Mora *et al.*, 2012), illustrative diagrams (Barlagne *et al.*, 2016; Mora *et al.*, 2023), a summary diagram presenting all the scenarios (Lacroix *et al.*, 2021) or video animations (Julhia *et al.*, 2018).

Analysing the issues raised by the scenarios about the initial question

By using a set of contrasting scenarios, the issues raised by long-term changes in the studied system can be better understand. As such, the set of scenarios is used to inform public debates and decision-making by showing not only the feasible pathways toward (a) desirable future state(s), but also how to avoid undesirable futures, while demonstrating the plausible long-term effects of actions or inaction. In this way, public decision-makers are presented with several viable options. This entails showing the respective advantages and disadvantages for each scenario developed. Each stakeholder will interpret these scenarios based on their specific interests and who they are/who they represent. By highlighting the major trends, major areas of uncertainty, desirable transition pathways and the main risks of disruption, scenarios provide public decision-makers and private stakeholders with information that can help them formulate long-term strategies. Similarly, the intent of scenarios is to highlight areas of research that need to be strengthened or developed in view of the future challenges and the objectives to be achieved.

Debating scenarios

The public presentation and debate of foresight scenarios might help decision-makers, and possibly society as well, widen their focus of attention and allow them to have a better understanding of what the future may bring. For the debate to be as successful as possible, foresight approaches should be transparent, the stakeholders should be involved in the thought process, and the scenarios should enable us to question current policy directions and to suggest avenues for change.

A very important step in foresight exercises is debating the scenarios. When scenarios are relevant and when they ask pertinent questions, they should open up a strategic conversation about possible and desirable futures with the stakeholders concerned. Therefore, in addition to the deliverables described above, foresight scenarios should be presented and discussed with the various interested parties: decision-makers, civil society actors, researchers, agricultural professionals, territorial forums, public actors, stakeholders in value chains, etc. The goal of scenarios is to change the way we look at the present so that the relevant stakeholders can anticipate all possible futures. As a result, their role is to shift the debate on possible future states using a process that breaks down and then reframes the issues, calls certain representations of the future into question while validating others and sometimes creating new ones, all while highlighting their long-term impacts.

For instance, to illustrate or demonstrate how stakeholders can use the constructed scenarios to think about their future, foresight exercises are often combined with specific illustrations at the territorial, regional or sector scale. The territorialization (or downscaling) of scenarios involves collaborating with stakeholders to imagine how generic scenarios can be applied to specific territories, regions or sectors (Mora, Banos, 2014; Lacroix *et al.*, 2021; Mora *et al.*, 2023). These illustrations in territorial scenarios create opportunities to work alongside stakeholders so that shared visions of a desirable future can be constructed together. In this way, stakeholders can better anticipate what the future may bring, but to do this, generic scenarios need to be replaced by scenarios that take specific and local dynamics into account. A morphological chart can be used to change the scale of a scenario by transforming a particular assumption of change into an assumption of change for a specific territory that takes its specific dynamics into account. One benefit of downscaling a scenario is that it can provide examples of the general dynamics for specific situations.

The aim of these scenarios is to help stakeholders improve their ability and capacity to imagine possible futures (see Riel Miller's "Futures Literacy", 2007). That said, whether a stakeholder uses a scenario depends directly on their strategic interests and the current projects they are working on. Just because one stakeholder favours a scenario, it doesn't mean that another stakeholder will favour it as well. There is still a fair amount of controversy and debate among the stakeholders involved regarding representations of the future and, therefore, a central theme in debates on forward-looking models and public deliberation processes has to do with the plurality of scenarios. As Chateauraynaud (2013) wrote, foresight, "by operating at a distance, visualises a plurality of futures to constrain reasoning and deliberation, and to make visible the expected cognitive and normative frames that make some future directions more plausible and desirable than others."

Coupling qualitative foresight methods and numerical simulation methods: quantifying scenarios

As the geographical scope of these issues (European, global) is growing, numerical modelling is being used more and more often in foresight analyses to assess the quantitative impact of various scenarios at different scales (e.g. see the Agrimonde-Terra foresight study on land use and global food security, or the Afterres 2050 scenario). This involves being able to simultaneously compare the impacts of different scenarios and to assess their capacity to meet normative targets (e.g. limiting the expansion of croplands, reducing GHG emissions, increasing food security and introducing agriculture without any chemical pesticides).

One method used in some foresight studies (Mora *et al.*, 2020; Mora *et al.*, 2023) and recommended in the related literature (Wiebe *et al.*, 2018) is to couple a scenario-based approach that uses morphological analysis with quantitative simulations. On the one hand, the scenario building process, based on morphological analysis, ensures that each scenario is consistent and plausible, and makes it possible to explore a wide range of possible futures. On the other hand, quantitative simulations can measure the extent of the changes described in the scenarios and provide quantified elements for comparing scenarios with each other (e.g. see the Agrimonde-Terra foresight study in Chapter 5). In order to be coupled with a foresight approach, the model needs to have certain characteristics: it must be flexible, easy to handle and transparent in its operation. The flexibility of a model is reflected by the capability of a numerical model to simulate widely varying states and dynamics of a system. Coupling between scenarios and quantitative simulations is based on the morphological chart and rules for transforming qualitative assumptions into quantitative input assumptions for the model which act as an interface between building qualitative scenarios and conducting quantitative simulations (Mora *et al.*, 2020).

It is important to note that due to the characteristics of the numerical model used, some scenarios cannot be simulated either because the state of the variables for the scenario exceed the model's validity range or because the model does not take the scenario's variables into account. Regardless, although it might not be possible to simulate a qualitative scenario, this does not mean that the scenario will never come to pass. To the contrary, such a scenario is still possible and plausible and therefore, it is better to be prepared for it.

⏩ The challenge of livestock farming in global foresight scenarios

Given that the world population is continuing to grow, the effects of climate change and limited natural resources, livestock production and the consumption of animal products have become the focus of debates on the future of global food systems.

On one hand, diets are rapidly changing as they are driven by multiple factors such as urbanization, increasing incomes, lifestyle and dietary changes, food supply chains, agriculture and nutrition policies (Swinburn *et al.*, 2011). Future diets could have a considerable impact on land use, the environment, climate change and health (Paillard *et al.*, 2010; Bajzelj *et al.*, 2014; Tilman, Clark, 2014). Consequently, the way in which assumptions about future diets are formulated is of paramount importance for improving our ability to anticipate future issues. Human diets have undergone a major historical shift with a higher intake of animal-source foods and a lower intake of cereals. This change has mostly been seen in high-income countries within the past century (Popkin, 1993) and are now currently happening in middle-income countries. Presently, we are seeing an increase in the consumption of animal-sourced foods due to urbanization processes and associated changes in income and lifestyle. This consumption is part of a broader change in dietary patterns in urban areas that is seeing more out-of-home consumption, ready-to-eat products and prepared meals, as well as fewer meals being eaten at home (Mendez, Popkin, 2004; also see Zhai *et al.*, 2014, for the specific case of China).

On the other hand, livestock farming has a significant negative impact on the environment and GHG emissions (Steinfeld *et al.*, 2006; Godfray *et al.*, 2010; Tilman, Clark, 2014).

Over the past two decades, a forward-looking debate has begun on the direction that changes in agricultural and food systems should take (Béné *et al.*, 2019). In the early 2010s, several foresight studies encouraged moving in the direction of sustainable agricultural intensification to increase food availability to feed a growing population without expanding agricultural lands (and thus putting a stop to deforestation) so as to limit GHG emissions and biodiversity loss (e.g. see Godfray *et al.*, 2010; Foley *et al.*, 2011; Tilman *et al.*, 2011; Alexandratos, Bruinsma, 2012). Later, other studies underscored the need to make dietary changes and to reduce food waste to offset the increase in food demand and to limit the negative impact of the global food system on natural resources and the environment. These works, published in part by the climate change research community, have shown that livestock farming causes significant negative environmental effects. Therefore, they encourage significantly reducing the consumption of animal-source foods (e.g. Stehfest *et al.*, 2009; Wirsenius *et al.*, 2010; Smith *et al.*, 2013; Bajzelj *et al.*, 2014; Searchinger *et al.*, 2018, among many others).

As often mentioned in foresight studies, one way to reduce the negative impacts of global food systems on the environment or health over the long-term could be to limit the growth rate of animal product consumption, especially meat and more specifically ruminant meat (Stehfest *et al.*, 2009; Bajželj *et al.*, 2014; Röös *et al.*, 2016; Springmann *et al.*, 2016; Popp *et al.*, 2017; Wirsenius *et al.*, 2017; Springmann *et al.*, 2018). Foresight studies with a focus on global food security have come to the same conclusion and propose global scenarios for changes in global food systems that see a transition toward low-energy diets with fewer animal-source products. These scenarios are some of the options put forward for feeding a growing global population in a sustainable manner (for a review of the literature, see: Le Mouël, Forslund, 2017).

In recent years, global foresight studies have confirmed that there is indeed a shift toward a food system approach. However, based on the review of the literature on global food system foresight studies conducted by Zurek *et al.* (2021), several points have been raised by recent foresight studies. First, these studies highlight the need for innovation to ensure the sustainability of agricultural systems. This would involve better coordinating innovations within food systems and better considering the market dynamics and policies that shape innovation processes (*ibid.*). Second, foresight studies agree that human diets need to shift toward a healthy and sustainable diet that includes more plant-based products, including fruits, vegetables and pulses (also known as legumes or leguminous crops) while decreasing the consumption of animal products. However, it is not an easy feat to reach this two-pronged goal of ensuring people have a good nutritional level and achieving sustainability on a global scale. As a result, the pathways of change in these foresight studies are relatively different and do not lead to similar scenarios (*ibid.*). Third, given that food systems must be transformed, these pathways of change will generate both winning and losing actors. This means that we need better governance of the transition processes so that they are fairer and more equitable. For this reason, equity is central to the sustainability of food systems (*ibid.*). Lastly, mounting uncertainties over geopolitical conflicts, the impact of climate change, health issues, economic crises and political transformations should be better considered (Gupta *et al.*, 2025). When faced with a situation that is more complex and volatile, foresight experts (futurists) recommend breaking with conventional frameworks for thinking, being more creative and being more receptive to radically different futures (*ibid.*).

⏩ Diverse ways of approaching the future of livestock farming

Four foresight studies on the issues in livestock farming are presented in the remainder of this section. They look at the future of livestock farming at three different scales: regional, national and global. The first two studies focus on territorial dynamics related to livestock systems, how they use their space, their supply chains and related practices. Territorial approaches to livestock production look at both the spatial coexistence of different uses within a given territory and the spatial impact (distribution) of livestock farming systems within a sector, as well as their social, economic, political and environmental impacts.

The first foresight study, "Agriculture in Brittany in 2040", conducted by the Regional Chamber of Agriculture of Brittany (CRAB) and presented by Maud Marguet, looks at how production systems (agriculture and agri-food) in Brittany will change between now and 2040. This region has a high number of cattle (dairy and meat) and pig farming systems. Given the specific nature of these activities and their dense concentration, there is a considerable amount of environmental pressure being placed on the regional production system to address soil and water degradation and biodiversity loss, issues related to reducing GHG emissions and changes in consumer demands. Even though there are significant goals in place to reduce livestock farming in Brittany and to subsequently reduce GHG emissions via low-carbon pathways, the foresight study considers how to align climate objectives with environmental and socio-economic objectives and explores the diverse possible futures for agriculture and agri-food sectors in Brittany by 2040. The result is five exploratory scenarios respectively looking at (1) the long-term impact of what happens when assets are not renewed and the decline in livestock farming, (2) the changes made in agriculture to reach carbon neutrality, (3) the reterritorialization of agriculture in Brittany within a context of renewed decentralization, (4) the role technology plays in the transformation of livestock farming systems, and (5) the turn toward plant-based agriculture in Brittany with livestock farming being replaced by crop production. The aim of this foresight exercise is to explore the possible futures of livestock farming in Brittany against a backdrop of uncertainty in sectors and institutions.

The second foresight study, "Towards peaceful transhumance at the border between Togo and Burkina Faso", led by CIRAD researchers Jean-Michel Sourisseau and Véronique Ancey, examines the future of the territorial integration of cross-border pastoralism within a context of high political tensions and border conflicts in West Africa. This territorial foresight study looks at the future of these territories and sets up a forum for dialogue, thereby effectively reopening the debate on the role livestock farming practices and pastoral systems will play in the development dynamics of a territory that is found in both Togo and Burkina Faso. The goal is to construct shared visions of the interactions between pastoralism and the notion of territory. This study uses a participatory approach to open up a space for dialogue in a conflict situation, and to get stakeholders involved in the co-construction of normative and desirable futures for these territories.

A third foresight study, "Transition(s) 2050," carried out by ADEME (French Agency for Ecological Transition) and presented by Antoine Piérart, is more normative in nature. This study mostly focuses on how agriculture and the agri-food sector can help reach the national "carbon neutrality" objectives by 2050 but in passing also addresses the issue of livestock farming as they are interrelated. The Transition(s) 2050 foresight study develops four multisector scenarios to achieve "carbon neutrality" by 2050. These scenarios incorporate three interdependent levers for: reducing GHG emissions, natural carbon storage and mobilizing renewable biomass to replace fossil fuels. The assumptions of change for the agricultural and agri-food sector include two major levers for reducing emissions: livestock systems and the consumption of animal products. The provisions laid out in global perspectives suggest that the main way how food diets can help reduce GHG emissions in three out of four scenarios is to decrease (scenario S1) the consumption of animal products by 30 to 70%. This measure alone results in a 40% decrease in GHG emissions from the agricultural sector (in scenario S1). Among the other levers for action in the agricultural sector, three directly concern livestock systems: reducing herd sizes and transitioning to more extensive systems, agroecology and biomass production for energy-supply purposes (with biogas production, in particular). The study shows that unless the intensification of livestock systems is combined with changes in food consumption, GHG emissions from the agricultural sector will not be reduced by more than 6% (in scenario S4). In terms of reducing GHG emissions, this foresight study (conducted at the scale of France) underscores that technological developments are of limited help when it comes to reaching this objective and that the consumption of animal products play a key role.

The Agrimonde-Terra foresight study on land use and global food security in 2050, conducted by INRAE and CIRAD, and presented by Olivier Mora and Chantal Le Mouël, reexamines the terms of the debate on the place of animal production in land use and food security. This then leads to a reconsideration of what role it plays in the future of global food systems. The Agrimonde-Terra study combines a scenario approach with a quantitative simulation approach to assess the impact of scenarios in terms of production, land use and international trade worldwide. Four exploratory scenarios ("Metropolization", "Regionalization", "Healthy", "Communities") are used to describe the most diverse range of possible futures for land use and food security in 2050. The *Metropolization* scenario extends the urbanization trends seen worldwide. *Communities* are based on the weak signals of multiple and interlinked crises (environmental, economic, geopolitical) to explore the impacts they have on territories. Two scenarios show more desirable futures: *Healthy* explores the effects of a global increase in nutrition policies and a shift toward agroecology, whereas *Regionalization* looks at the impact a regionalizing food systems, which includes the relocation of production systems. Livestock farming plays quite varied roles in these four scenarios. *Metropolization* anticipates that monogastric animals will be intensively farmed and that there will be increases in animal feed production, *Regionalization* considers livestock systems to be autonomous and looks at interactions with cropping systems at a regional scale, *Healthy* envisions a lower consumption of animal products in high-income countries and a higher consumption in low-income countries related to the transition of systems towards agroecology, and *Communities* involves intensifying livestock farming on small areas of land and the accelerated degradation of the environment (determined by the tangle between climate, environmental and economic crises). In this set of scenarios, only the *Healthy* and, to a lesser extent, *Regionalization* scenarios make it possible to achieve sustainable agricultural systems and human health.

By comparing the foresight methods for these four studies, we can see the choices made to strategically position these works within debates on future developments.

The Agriculture in Brittany in 2040 study develops exploratory scenarios to address a low-carbon target for 2040 in the region of Brittany, which is considered too monocentric. The goal is to look at how we can widen the field of possible futures for the agricultural and agri-food sector by including diverse criteria, including socioeconomic objectives, and by producing contrasting scenarios of change. Therefore, a scenario method based on morphological analysis is used in this study. This method is first used to pool the variables into eight components and then allows to produce retrospective analyses and construct alternate assumptions of change. The final step is to combine them to generate five scenarios and a narrative for each one.

The foresight study on pastoral systems in West Africa has a normative objective. The goal is to move "towards peaceful cross-border transhumance" while looking for a way to open the field of possibilities for the future of cross-border territories. The method used develops scenarios for the future of cross-border territories which can then help stakeholders imagine the future of pastoralism. The political context and cross-border conflicts in the region support this strong methodological choice to place territorial dynamics above sectoral dynamics for livestock farming and animal mobility.

ADEME's Transition(s) 2050 study, covering mainland France, was developed to contribute to national debates on "carbon neutrality" ahead of collective deliberations on the future French Energy-Climate Strategy (SFEC). The idea was not to build a transition pathway but rather to propose several cross-sectoral scenarios for debate. From a methodological point of view, this study develops four normative carbon neutrality scenarios for France (S1, S2, S3, S4) in relation with the global scenarios in the IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels. Five components (called "structuring axes") were used to rework these former scenarios: technology, economy, society, governance and territories. In a next step, the scenarios were simulated using technoeconomic models for the sectors, so as to interlink the modelling of the energy system and contrasting societal transitions.

Lastly, given that there is increasing uncertainty about the future of food systems (climate change, dietary transitions, impact of agricultural production systems, urbanization dynamics and changes in value chains), the Agrimonde-Terra foresight project is working on an exploratory approach to changes in land use and food security on a global scale. Based on a retrospective analysis of the land use and food security components, this project imagines a variety of contrasting futures for land use and food security in 2050. The inclusion of morphological analysis in the scenario approach helps stimulate creativity and, when a common system analysis is used, a crisis scenario, trend scenario and two "more desirable" scenarios can be constructed. This exercise widens the scope of possible futures by developing both a desirable scenario based on healthy diets, and a deadlock scenario for technical systems. By combining the scenario approach with a quantitative simulation approach, the global impact of the various scenarios can be assessed in terms of production, land use and international trade.

As noted throughout these four foresight studies, foresight approaches are part of *strategic conversations* about the future (Van der Heijden, 2005). This is why the methods developed need to meet the intended objectives: to reopen debates by proposing a wide spectrum of possible futures to see how the designated objectives for livestock farming can be coordinated; to exceed political conflicts over pastoralism using a territorial foresight approach that includes multiple futures for cross-border areas; to respond to climate issues by proposing several transition pathways ahead of constructing a national strategy; or to imagine possible changes in land use and food security on a global scale so we can start preparing for them as soon as possible. It can be seen here that livestock farming is central to many issues in foresight analysis, for instance, coexisting land uses, the negative environmental impacts of livestock farming within territories, the effect animal product consumption has on global GHG emissions, or even land use and food security.

Chapter 2

Agriculture in Brittany in 2040: an exploratory foresight study in the region of Brittany

Maud Marguet

In 2020, the Regional Chamber of Agriculture of Brittany (CRAB) launched the Agriculture in Brittany in 2040 project. Its purpose was to identify scenarios of change for Brittany's agriculture and agri-food industry by 2040 and to assess their environmental and socio-economic impacts. An additional objective is to enable the employees and professional leaders of CRAB to familiarize themselves with the future challenges facing Brittany's agricultural sectors.

⏩ The start of the project

A context of regional discussions on climate issues

In March 2017, the Region of Brittany launched Breizh COP, a participatory approach inspired by COP21 encouraging regional stakeholders to commit to climate action and to formalize a "sustainable territorial project by 2040". This participatory approach came to fruition in December 2018, when the Regional Council adopted the 38 objectives agreed upon in the Breizh COP concertation meeting. As part of its goal to "accelerate our economic performance through transitions", especially in agriculture, the 11th Breizh COP goal is to "make Brittany the region par excellence for agroecology and eating well", as seen in the three sub-objectives below:

– accelerate agriculture's commitment to reducing its greenhouse gas emissions by 2040 in keeping with the transition pathway laid out in the "energy-climate" foresight study;

– generalize agroecology practices on all farm holdings to encourage the conservation of water, biodiversity and soils;

– accelerate the changes in the agri-food industry toward more added value, better quality, food security and less packaging.

Simultaneously, the Region organizes concertation meetings to develop a regional plan for sustainable development and territorial equality that is in line with the low-carbon target for 2050. Different technical assessments simulating the application of ADEME's "F4[3]" scenario to Brittany have been carried out and some of these data

3. The "F4" (or Factor-4) scenario aims to reduce 1990 emissions by a factor of four by 2050, as per the SNBC 1 objectives (National Low Carbon Strategy, 2015).

were presented during the Breton Energy Transition conference held on 6 December 2018. It was possible to provide precise figures for future changes in the livestock population in Brittany by 2040 and their impact in terms of non-energy emissions: a 29% decrease in dairy cow numbers, a 26% decrease in other bovines, a 16% decrease in pig numbers and a 6% decrease in poultry numbers. Only sheep and goat herds would increase (+13%). These changes would make it possible to reduce non-energy emissions related to livestock farming by 20%.

Decision making

These objectives and projections present a challenge to the regional and departmental Chamber of Agriculture council of elected representatives which, since late 2018/early 2019, have been advocating for an internal foresight study on the changes in agriculture in Brittany, as seen by the elected representatives in these offices. They consider that numerous studies have already explored the future of agriculture, often from an environmental point of view and with a normative approach. However, only a few of these studies have been led to or adopted by the agricultural sector, even though they raise questions and potential challenges for agriculture, especially for livestock farming, but also the agri-food industry. Thus, their expectation is that the future should not only be thought of in terms of energy and climate issues. It should also include a systematic approach to which they can contribute, and one that specifically takes economic and social issues into account.

The Chamber of Agriculture council in Brittany (CRAB) confirms that it will take an active part in the steering committees for national, regional and territorial projects associated with the National Low Carbon Strategy. CRAB will present their related expertise and field experience with an aim to provide suggestions for national and regional studies. Therefore, it is anticipated that the work conducted in-house will add valuable information to the studies conducted by the other stakeholders in the debates on the future of regional agriculture.

Project framework

The stated objectives of the Agriculture in Brittany in 2040 project for the Chamber of Agriculture council in Brittany are to: consider the issues at stake, create specific scenarios for agricultural professions, analyse their climate, economic, social and environmental impacts and, lastly, make this foresight exercise a central theme for the appropriation of and internal communication on transitions.

Professional leaders are also hoping that these studies will serve as a backdrop for discussions on how to create a vision for the future of agriculture in Brittany that will be defined for and adapted to various different territorial scales: Europe (CAP: Common Agricultural Policy, etc.), regions and territories (TCAEP: Territorial Climate-Air-Energy Plan, etc.) This study should also provide information to help identify transition pathways for farms, to establish a political strategy for Breton farms and CRAB as well as to reposition CRAB's support for farms and to identify the tools needed.

Thus, the expected deliverables after various trade-offs include formalizing a horizontal audit of agriculture and production chains in Brittany, creating foresight scenarios and carrying out a simplified impact assessment.

Project group

This work was carried out by a small group of eleven engineers with the following expertise:
– livestock farms: Élodie Dezat (monogastric specialist) and Céline Favé (herbivore specialist);
– energy, GHG, new production chains: Hervé Gorius and Laurence Ligneau;
– climate-air-energy environmental policies: Charlotte Quénard;
– economy-employment-consumer trends: Nicolas Debéthune, Arnaud Haye and Maud Marguet;
– territorial coordination: Hervé Le Goff;
– advisor for agricultural businesses: Geneviève Lamour;
– agronomy: Lionel Quéré.

Additional people were added to this team as the project proceeded, especially to document the variables for the study and to quantify one of the scenarios.

Steering committee and resulting working group

The steering committee, comprised of representatives from the four departments in Brittany, from diverse types of agricultural productions and from the agri-food industry, was designated by the CRAB office. Two co-chairs, Edwige Kerboriou (livestock farmer in Côtes-d'Armor, member of the Chamber of Agriculture of Côtes-d'Armor) and Loïc Guines (livestock farmer in Ille-et-Vilaine and Chairperson of the Chamber of Agriculture of Ille-et-Vilaine) were appointed to provide political oversight for the project.

The Breton association of agri-food businesses (ABEA) has also offered to take part in the steering committee.

Originally, eleven elected representatives in 2020, and then twelve in 2021, from this committee were trained in foresight analysis alongside other staff over a three-day period (June 2020, January 2021).

Study phases

This study was carried out in three phases, as summarized in Table 2.1

Afterwards, various impact assessments were conducted:
– Agriculture and agri-food impact assessment, depending on the agri-food stakeholders (September 2021 to January 2022).
- Thirty-nine agri-food industry executives were audited.
- Thirty-five agriculture and agri-food sector employees were collectively audited during the annual agri-food Employee Day.

– Production volume estimates and the carbon footprint for a scenario (March 2021 to January 2022) using the ClimAgri® tool (Eglin *et al.*, 2016).
– Environmental and social-economic assessment of these scenarios (launched in February 2022, finalized 1st quarter of 2024)

Table 2.1. From assessments to scenarios, the various phases of the study

Study phase	Subject	Teams/work groups mobilized	Accomplished deliverables/conditions	Steering committee meeting
Study assessment April to November 2020	Assessments by sector April to July 2020	Project team Economy-employment team	90 interviews 14 baseline studies	Launching committee (20/Mar/2020) Dissemination committee for sectorial assessments (6/Jul/2020)
	In-depth interviews late August to November 2020	Project team Territorial coordination management teams	7 major stakeholders audited 16 territorial authorities audited	Dissemination committee for regional assessments and interviews of experts (16/Oct/2020)
Foresight system construction June 2020 to January 2021	Variable identification June 2020 to January 2021	Project team Working group with elected steering committee representatives (11 elected representatives) Project team member service	2 action training days 24 selected variables	
	Documentation of variables August 2020 to January 2021	Project team, supplemented by ad hoc internal skills depending on the topics	24 foresight files	
	Assumption identification November 2020 to January 2021	Project team Steering committee members	3 to 4 hypotheses described for each variable 1 foresight workshop for partners on context variables (3/Nov/2020) 9 foresight workshops for partners-elected representatives (8/Dec/2020)	Monitoring Committee (review of context variables) (25/Nov/2020)
Scenario building and testing January to April 2021	Scenario building and drafting January to April 2021	Project team Working group with elected steering committee representatives (11 elected representatives)	1 action training day 5 scenarios constructed and drafted	Scenario dissemination committee (18/Feb/2021)
	Scenario testing, drafting and first internal appropriation February to April 2021	Project team	1 presentation of the provisional results to the persons audited in 2020 1 internal questionnaire geared towards elected representatives and partners	Dissemination committee for the internal questionnaire results, impact assessment launch (23/Apr/2021)

⏩ Baseline studies prior to constructing a foresight system

Baseline studies for each sector

Fourteen baseline studies were drawn up using reference data and interviews with the professional leaders and employees of CRAB, interprofessional representatives or stakeholders in the agri-food sector as well as industry experts. The number of interviews varied depending on the topics, economic weight of the sector in Brittany, number of potential contact persons, as well as the number of requests for an interview that actually transpired.

The Breton sectors listed in Table 2.2 were analysed. A few specific details should be mentioned. The approach taken to viticulture is essentially exploratory because the industry is still at an early stage of development and there is no real sector structure. The analysis of the energy sector focused on biogas production (also called anaerobic digestion), fuelwood and photovoltaic energy.

The questioning followed a traditional interview storyline for foresight assessments, with a question about the past ten to twenty years (identified changes, inertia, the relevant actors' degree of anticipation, identification of unexpected changes, analysis of the relevance of the responses and actions that it would have been advisable to implement), a projection over the next ten years (changes and inertia influencing the future), a ranking of the issues and an analysis of the strengths-weaknesses-opportunities and threats. For each production or sector, the information gleaned from the interviews and bibliography were presented using a standard template, providing an overview of the characteristics and trends identified. A summary of this baseline study was presented to the steering committee to expand upon and validate the results achieved.

Table 2.2. List of the ninety audit interviews conducted.

Sector or production	CRAB implementor	Number of people audited	Persons audited
Milk	Milk production advisor and researcher Agricultural economist	12 people A RES'Agri 56 group (departmental network for agricultural development groups in Morbihan) with roughly ten dairy farmers specialized in foresight exercises	3 employees from the French Dairy Interbranch Organization (Cilouest, French National Federation of Dairy Industries (FNIL), Agricultural cooperation) 1 expert (IDELE) 1 group of dairy farmers (6 farmers, some recently established, others in mid-career or close to retirement) 8 CRAB elected farmers (mostly trade unionism and farming confederation)
Beef – cattle	Agricultural economist	7 people	2 CRAB elected farmers 2 CRAB engineers 1 expert (IDELE) 1 agri-food/cooperative employee (Bigard) 1 interbranch administrator (elected Interbev member)

Sector or production	CRAB implementor	Number of people audited	Persons audited
Beef – calves	Agricultural economist	5 people	2 farmers (1 elected Jeunes Agriculteurs member and 1 manager from the producers' organization Coopeva) 2 agri-food/cooperative employees (Denkavit, Tendriade) 1 CRAB employee
Pig meat	Agricultural economist	6 people	4 farmers (2 CRAB elected representatives, an administrator from the Cooperl cooperative, a manager from the Syproporc group) 1 expert (IFIP) 1 employee of the professional agricultural organization (UGPVB)
Meat poultry	Agricultural economist	7 people	3 farmers (3 CRAB elected representatives) 1 CRAB employee 1 expert (ITAVI) 1 administration employee (DRAAF) 1 interbranch employee
Eggs	Agricultural economist Poultry researcher and advisor	5 people	1 CRAB elected farmer 1 expert (ITAVI) 1 administration employee (DRAAF) 1 interbranch employee (CNPO) 1 employee of the professional agricultural organization (UGPVB)
Field crops	Agricultural economist	10 people (9 interviews)	4 farmers (2 CRAB elected representatives, 1 administrator from the Nutrinoë association, 1 administrator from the Garun-Farmers Coop cooperative) 1 CRAB employee 2 agri-food/cooperative employees (UFAB, Avril) 2 interbranch employees (Intercéréales) 1 expert (Terres Inovia)
Vegetables for use in processing	Agricultural economist	8 people	2 farmers (2 CRAB elected representatives, including 1 EUREDEN administrator) 2 CRAB employees (1 UOPLI facilitator, 1 APILeg facilitator) 2 agri-food/cooperative employees (CLAL Saint-Ivy, Ardo) 1 employee of the producers' organization (Cénaldi) 1 interbranch employee (UNILET)

Sector or production	CRAB implementor	Number of people audited	Persons audited
Vegetables for the fresh product market	Agricultural economist	9 people (8 interviews)	4 farmers (1 CRAB elected representative, 1 Savéol cooperative administrator, 1 Caté research station administrator, 1 administrator from the vegetable growers association) 2 CRAB engineers 1 engineer from the producers' organization (Cerafel) 1 agri-food/cooperative employee (UCPT) 1 expert (Caté)
Forest, wood	Forest advisor - mixed fields (bocage) and woodfuel	5 people	3 CRPF employees (including 2 CRAB elected representatives) 1 transformation tool employee (SEFSB sawmill) 1 employee of the producers' organization (CETEF 29)
Horticulture, tree nursery	Agronomy advisor	2 people	1 farmer (1 CRAB elected representative) 1 employee of the professional agricultural organization (FNPHP)
Cider production and eating apples	Agronomy advisor	2 people	1 farmer (also administrator of the Maison cidricole de Bretagne (cider production) interbranch) 1 CRAB engineer
Viticulture	Agronomy advisor	3 people	2 farmers (1 project leader and 1 administrator from the Association pour la Reconnaissance des Vins de Bretagne (ARVB, wine recognition association)) 1 expert (University of Rennes 2)
Energy	Climate, Air, Energy, Trash, Health-Environment officer Carbon climate officer	10 people	5 farmers (4 CRAB elected representatives in energy production or who are professionally involved, a manager from a biogas plant association) 2 CRAB engineers 1 CRPF engineer (also a CRAB elected representative) 1 engineer from a specialized association (Aile)

Territorial analysis and in-depth interviews

Interviews with authorities from all four departments in Brittany

The assessment phase for the Agriculture in Brittany in 2040 study was not just limited to studying the sectors. This would have resulted in a partial view of the issues at hand, thereby possibly incorrectly identifying the cross-cutting issues and specific territorial characteristics. The purpose of carrying out a more territory-based analysis and compiling the views of major stakeholders was to expand the desired systemic analysis.

These interviews used the same questioning storyline as for the sector-specific interviews; however, the focus was on challenges in agriculture and the agri-food industry for the region. Interviews with territorial authorities were conducted by engineers of the Territories Department with CRAB. Various structures were audited to compile their viewpoints (see Table 2.3). Furthermore, special attention was paid to representing the four departments in Brittany when selecting these structures.

Table 2.3. Sixteen people were audited from 13 structures.

Departments	Structures audited	Number of people audited
Côtes d'Armor (22)	Saint-Brieuc Armor Agglomeration	1 elected representative
	Departmental council	1 employee 1 elected representative
Finistère (29)	Departmental council	1 employee
	Concarneau Cornouaille Agglomeration	1 elected representative
	ADEUPa's urban planning office	1 employee
	Haut-Léon community	1 elected representative
Ille-et-Vilaine (35)	The Meu River's watershed syndicate	1 employee
	Departmental council	2 partners
	Bretagne Porte de Loire community	1 employee
Morbihan (56)	Departmental council	1 elected representative
	Vannes Agglomeration	1 elected representative
	Pontivy community	1 elected representative 1 employee
22 – 29 – 56	Development council (CoDev) for the Pays Centre Ouest Bretagne	1 elected representative

These additional interviews were conducted after the selection phase for the variables. They underpinned the analysis of these variables, and the retained hypotheses. A summary was drawn up using the same storyline as for the sector-specific interviews.

Thereafter, the key messages were classified based on the eight thematic areas of the foresight system for the Agriculture in Brittany in 2040 study: climate change and resources; public policies; international context; territories; consumers and citizens; agricultural businesses and human resources; agricultural techniques and products, as well as markets and sectors.

In-depth interviews

Several additional interviews were conducted with major stakeholders to add new information to current insights, specifically regarding economic and agricultural policies, consumption and distribution trends, and development of the Brittany Region. The list of audits is provided in Table 2.4.

Table 2.4. Seven in-depth interviews.

Main themes covered	Persons audited
Economy, agricultural policy	Head of the Studies, References and Foresight Department (French chamber of agriculture)
Consumption, distribution	Founder of the Dauvers book publishing company (éditions Dauvers)
Brittany, environmental policies	Elected representative of the Regional Council of Brittany
Agriculture, Brittany, agricultural policies	Elected representative of the Regional Council of Brittany
Agriculture, Brittany, agricultural policies, agroecology, climate change	Mayor of Le Mans, former Minister of Agriculture
Agriculture, The Netherlands, agricultural policies, European Union, climate policies	Ministry of Agriculture of The Netherlands
Consumption, processing, production methods, product quality	Founder of Valorex and president of Bleu-Blanc-Coeur

Information collected from these additional interviews was added to the ongoing work and presented in the same manner as for the territory-based interviews.

Building foresight systems

Drafting the foresight system

In June 2020, the project team (11 engineers) and the working group of 11 elected representatives followed a two-day training course on foresight studies. This training course focused on breaking down preconceived ideas and the immediate application of what was learned. At the end of these two days, the result was a first draft version of the foresight system.

The eight different areas of analysis identified by this collective have remained practically the same, except for a few reformulations. The following areas were selected in this first version: climate change and resources (7 variables); public policies (5 variables); territories (7 variables); citizen consumers (4 variables); international context (4 variables); farm holdings and human resources (8 variables); agricultural production techniques (5 variables); sectors including agri-food and distribution (7 variables).

The forty-seven variables included in this draft were subsequently reworked: redundant variables were grouped together and certain variables that seemed to be less relevant were set aside. In the end, twenty-four definitive variables were selected. Special attention was paid to the name of each variable, so that each name is simple, precise and easy to understand.

These successive steps were used to construct the definitive foresight system, as shown in Figure 2.1.

Documenting the variables

Each variable was defined using the same method. First, two-person teams carried out a retrospective analysis of the structuring trends of previous decades and identified

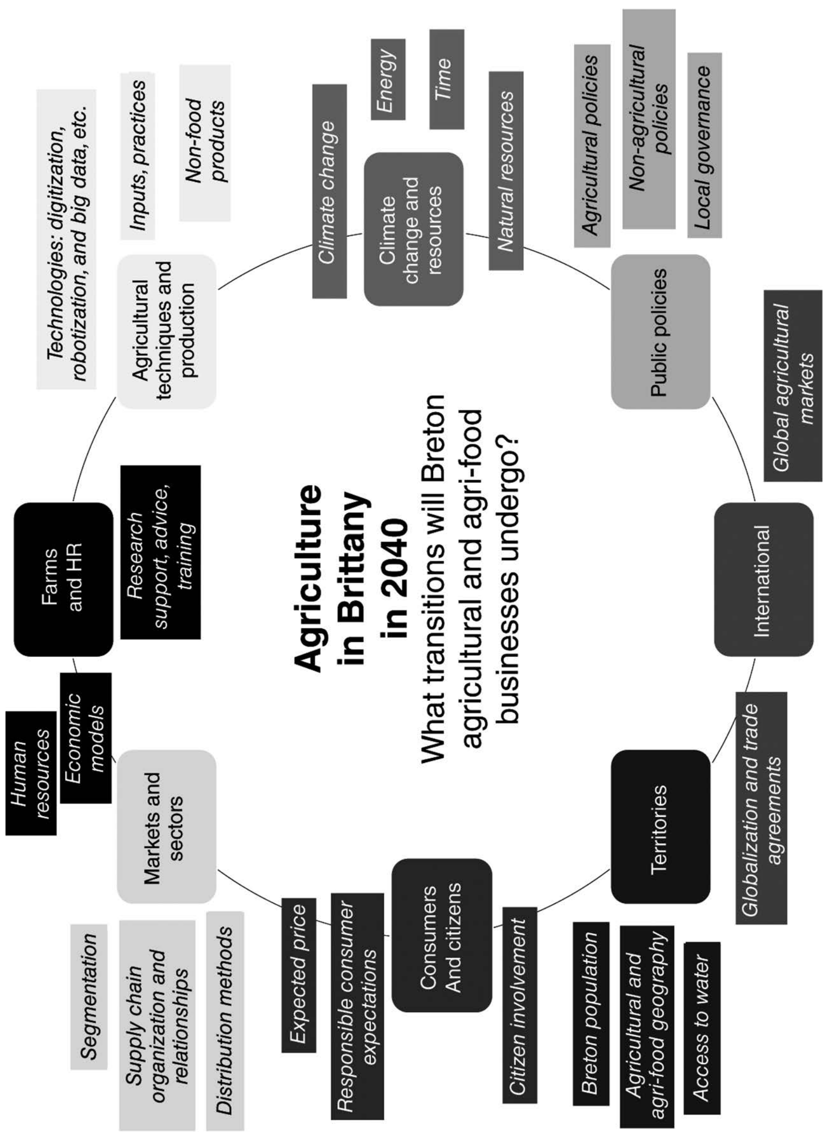

Figure 2.1. The foresight system used for Agriculture in Brittany in 2040 (source: Brittany Chamber of Agriculture).

current dynamics by making use of the bibliography and by conducting additional interviews if needed. This work was used to define three or four assumptions of change by 2040: trend hypothesis, alternative hypothesis and one or maybe two disruption hypotheses. The following methodological precautions have been taken. The hypotheses were presented in such a way as to ensure that each hypothesis and each variable is independent from the others. The intent is that they cover the entire range of possible futures as much as possible, based on the available information. Furthermore, each hypothesis needed to address the same aspects for each variable, i.e. clarify the same sub-variables. For the time variable, each hypothesis examined the society, the organization of activities, territorial options, agricultural options and the regulatory dimension.

More specifically, hypotheses were constructed by two-person teams. These hypotheses were then examined during small foresight workshops (three to six participants) for roughly two hours (December 2020) and on the third day of the action-training session (January 2021). Each working group was given the retrospective analysis, a description of the current dynamics, a proposal for a trend hypothesis and a series of proposals for an alternative or disruptive pathway to develop the final definitive hypotheses. These definitive hypotheses were often more radical than the drafts initially proposed by the two-person teams responsible for each variable.

From variables to scenarios

The set of hypotheses made for the twenty-four variables represents seventy-four modalities in the end. To be able to consistently combine them, the work group identified different possible nuances that emerged from reading the hypothesis tables. This scenario was developed in several phases. The first phase took place during the training session for the group of engineers and professional leaders and resulted in the construction of four scenarios. During the second work sequence, just with the engineers, one of the less coherent scenarios was divided into two contrasting scenarios: a territorial scenario and a revegetation scenario. The subsequent phases, which first included the farmer representatives of the working group followed by the steering committee for the study, enabled the validation of a first version of the five scenarios.

An external expert (Thierry Pouch, an economist from the French Chamber of Agriculture) critically assessed this work to make sure these scenarios were consistent, and to identify any possible biases that the group might not have been aware of otherwise.

A group of five writers then created the narrative. This group established a common editorial framework and made it an obligation to remain relatively concise:
– Brief description of the scenario's tone:
– Presentation of the drivers for the scenario (i.e. the key points that are decisive for carrying out the scenario, in other words, the driving forces at work);
– Actual narrative for the scenario, with details about the variables that were not presented in the previous section. In this case, it seemed that some of variables were less of a determinant factor in certain scenarios and therefore they were not as explored as much as the others. Thus, the writers included the description of as many relevant variables as possible but had to make compromises to ensure the scenario is easy to read.
– A few talking points may eventually be added.

The five drafted scenarios are as follows:
– Breton farms in resistance mode. Where environmental regulations and the non-renewal of farmers lead to a decline in livestock farming. This is the trend scenario;
– Agriculture's quest for carbon neutrality. Farmers working to the benefit of a social project;
– Breton agriculture on a territorial scale. Where a fourth act of decentralization happened without anyone knowing;
– Priority is placed on the economy. Sectors are betting on technology;
– Plant-based agriculture in Brittany. Livestock farming is declining and leaving more space for crop production.

A final external validation session was organized with the stakeholders audited during the first phase of the study. This resulted in some minor reformulations to the scenarios so as to consolidate them and to make them easier to understand.

⏩ Conclusion

The various Chambers of Agriculture will be able to contribute to the debate using a foresight approach. The allows the construction of finely tuned scenarios for the region based on the field expertise of the agricultural professional representatives, engineers from the Chambers of Agriculture and stakeholders from local and regional sections territory who were either auditioned or who were associated with the work.

This approach is the first time the CRAB has carried out a comprehensive regional foresight study that is not focused on either a single sector or a single theme. The foresight methodology used was streamlined and tailored to the specific requirements of the Chambers of Agriculture to allow agricultural professional representatives to be highly involved. During the assessment phase of the study, numerous interviews were conducted to reduce certain biases due to this simplification of the methodology, and the steering committee was entirely made up of CRAB members. However, most of these interviews were conducted with elected representatives from the CRAB. They were specifically involved to meet one of the objectives of the project: to make it easy for the elected representatives and employees to collectively take up these issues.

The idea was to also successfully create several scenarios that are contrasting enough. Various experience with disseminating scenarios since 2021 has shown that the five envisioned narratives have allowed stakeholders to explore more than one vision. If they had been limited to one single view, it would have been difficult to have the discussion CRAB was hoping to have on the major challenges facing agriculture in Brittany.

A few limitations have been identified, and there has been some criticism of the scenarios (see below). Even though the global context is discussed (albeit in a limited manner) using a few select variables, there has been a certain degree of frustration that these scenarios were wilfully focused just on the region of Brittany. If these scenarios had instead covered a broader geographical area, the CRAB scenarios could have been linked with global scenarios for the existing agricultural context worldwide found in the literature or even built together with other scenarios. Other similar foresight exercises should consider focusing on a much broader scale. The authors regret that they were not able to involve future and young farmers more in their work, but because they have shared their findings, it was at least possible for these farmers to make their opinions and views known. That said, the work conducted by the authors would have benefited greatly if they had been able to incorporate these views and opinions. Furthermore, it might have also been possible to build more detailed pathways for agriculture towards each anticipated future for 2040.

For the environmental compartments, more than one specific variable was used to analyse the soil: “natural resources”, “local governance” and “agricultural and agri-food geography”. Given the editorial framework selected for this work, water issues are seldom discussed in the narratives, although they are mentioned in the “natural resources” and “access to water” variables. Furthermore, if these scenarios were being built today, energy issues (which are addressed by only one variable) would have arguably played a more pivotal role, and additional points of consistency would have been added to these scenarios to clarify their implementation, especially the “priority to the economy” scenario, which undoubtably requires more energy. The environmental and social-economic analysis of these scenarios will help us to better understand the water, energy and soil issues mentioned in the scenarios.

However, there is one strong point in this study (compared with the other more normative foresight exercises)– the consideration given to the territorial and human dimensions. Farmers are often seen as a variable (from a qualitative standpoint) and not as a driving force. It is important to remember that their aspirations, their choice of economic model or systems and even how involved they are in their sectors and in their region, all have a significant impact. Therefore, it is imperative that the Chambers of Agriculture remember to include sociological issues in these types of exercises.

Lastly, each presentation systematically raises the question of which scenario to choose. By voluntary design, the goal of this approach was not to define the ideal scenario or a worst-case scenario. Instead, the aim was to simply explore them. This means that the next time is to look at how to use these scenarios to help direct strategies: but that is a different matter!

Chapter 3

Towards peaceful transhumance at the border between Togo and Burkina Faso. A territorial and anticipatory approach

Jean-Michel Sourisseau and Véronique Ancey

This chapter is based on the FAO's report "A territorial and anticipatory approach for peaceful transhumance at the border between Togo and Burkina Faso"[4].

⏩ Study background and objectives

In 2018, political instability in the Sahel region (especially eastern Burkina Faso) and fears of contagion within coastal countries (Togo in particular) led to an extremely tense context in the cross-border area between the Sahel region and coastal countries. This situation then exacerbated the already existing constraints and risks associated with seasonal pastoral mobility (Corniaux *et al.*, 2016; Benjaminsen *et al.*, 2018; Mercandalli, Losch, 2018; Krätli, Toulmin, 2020; Pellerin *et al.*, 2021). Since late 2017, border crossing restrictions and the enforcement of regulations limiting pastoralist (herder) mobility have been an additional risk factor, worsening the situation in the Sahel region (FAO, UNICEF and World Food Programme joint position paper, Niamey meeting, 2018). The lack of implementation of an inclusive regional transhumance policy and market regulation tools has had profound consequences on the economic and social lives of farmers, herders and their families (FAO, 2018). Conflicts have resulted in crop damage, the illegal killing of animals and human deaths, especially in Nigeria, Benin and Ghana (OECD, 2018).

Community legislation and local bilateral negotiations are in place. For example, the ECOWAS treaty for the free flow of persons, goods and services is a cornerstone of regional integration. Furthermore, in 2003, ECOWAS approved regulation C/REG.3/01/03 relating to the implementation of regulations on transhumance between the ECOWAS Member States. However, despite local initiatives used by cross-border transhumance committees to manage reception areas and transhumance routes, these regulations have not resulted in actions that match the challenges. There is a lack of regional programs capable of creating a systematic approach for developing pastoral areas and transhumance infrastructure.

Based on these findings and combined with continued initiatives to strengthen dialogue and support for pastoralism, it is assumed that the dual use of territorial approaches

4. Sourisseau, J.-M., Ancey, V. 2021. *Une approche territoriale et anticipatrice pour une transhumance apaisée à la frontière entre le Togo et le Burkina Faso – Synthèse.* Rome, FAO

and anticipation can meet some of the challenges of cross-border pastoralism. In our view, there are two additional advantages of territorial foresight analysis:
– The territorial dimension enables us to reposition animal mobility and sustainable resource management issues on a much larger scale than the one for only the pastoralist stakeholders, with a focus on the role of transhumance in territorial development (Corniaux *et al.*, 2012; Gonin, Gautier, 2015), sustainability as an interaction within and between ecosystems (Hubert, Ison, 2011), and the political conflict analysis framework (Rangé *et al.*, 2020);
– The foresight dimension enables us to overcome current tensions and to take the heat out of debates; by projecting into the future and allowing our imagination to run free, this dimension opens up new perspectives (Sourisseau *et al.*, 2017).

Thus, the goal of this study is to complement and build on the local initiatives that are already in place to move towards peaceful cross-border transhumance and, taking it even further, towards regional responses to the challenges of animal and livestock mobility (Corniaux *et al.*, 2012; Gonin, Gautier, 2015). It assesses how well anticipatory and territorial approaches can provide original and new spaces for dialogue. Lastly, it makes recommendations for developing the territory (and by proxy, the related sectors) in such a way that secures the place and role of transhumance and ensures it can peacefully coexist with the other sectors of activity in the area.

⏩ General approach

Study area

The study area covers northern Togo and eastern Burkina Faso. It is a perfect example of the economic and political challenges in a region with a constantly deteriorating security situation since 2010. It illustrates the issues related to trade between the coastal south, which has been relatively free of conflict, and the Sahel region which has been unable to regain stability and peace.

The Port of Lomé in Togo is the country's main asset. This port allows the country to trade with its neighbours by both sea and land, and therefore it is vital to the national economy that Togo can have access to Burkina Faso. Furthermore, it can be seen by the level of activity at the Cinkassé border post, that there is a rather high volume of trade flowing between the coast and the Sahel region via this international route. On the other side of the border, Burkina Faso has put in place an equally strategic position to facilitate trade with Togo. Despite having abundant natural resources, Burkina Faso's border areas are some of the most underserved areas in the country and they are especially hit hard by insecurity issues. In the face of this, inhabitants are moving southward as this area is currently easier to access than most of the other active areas in their country.

These trade flows generate a substantial number of related activities, on top of taxes that mainly help the country more than the border area itself. Pastoralists who move their animals to find food (forage resources) and to sell them also use the border as a reference point. Many animals cross the border; some are used as draught oxen by farmers and others supply the coastal residents with animal protein. Some animals make the reverse journey during the rainy season and cross from Togo into Burkina Faso. This flow of animals plays a part in the commercial dynamics, activities and wealth arising from cross-border trade, and the whole region (both Togo and Burkina Faso) can benefit from this.

Thus, the main reason for choosing this border area is because it is characterized by dynamic pastoralism within in a dynamic cross-border region. Another reason is that contrary to its other neighbours, Togo has committed to putting policies in place to help manage animal movements. The purpose is to regulate (and not reduce) trade, and to prevent conflicts with farmers by regulating movements instead of putting enforcement mechanisms into place. As a result, what we are seeing now are opposing cross-border movements within a territorialization context. There are two factors at play that tend to harden the border and restrict trade: the terrorist threat in Burkina Faso and increasing conflicts between farmers and herders. These conflicts are real and can be exacerbated by certain violent events. Conversely, in these challenging times, communities on both sides of the border tend to rely more on trade. There is also a need to strengthen cross-border social ties and to "define a territory" that has no administrative boundaries. Transhumance plays a specific role in these territorial restructurings; it can be an integrative tool for pastoralists, and it can also be a source of tension. This further reinforces why this is an interesting area for examining cross-border pastoralism.

Another reason why this study is interesting is because it straddles an area that is considered a territory, but which is divided between several administrations. This can make it difficult to carry out the study and has a strong impact on the logistics in the region. This area encompasses the Kompienga and Koulpélogo provinces in Burkina Faso, located in the eastern and central-eastern regions, respectively, and the Savanes Region in Togo, which covers the entire northern part of the country.

The Koulpélogo Province includes one urban commune (Ouargaye), seven rural communes (Comin-Yanga, Dourtenga, Lalgaye, Sangha, Soudigui, Yargatenga, Yondé) and 184 villages spanning an area of 2,492 km^2. The Kompienga Province covers 7,280 km^2 and has one urban commune, Pama (which counts 14 villages), and two rural communes, Kompienga (17 villages) and Madjoari (eight villages). The Savanes Region occupies a surface of 8,470 km^2. It is divided into seven prefectures: Cinkassé, Tône (and its capital city Dapaong) and Tandjouaré in the west; Kpendjal, Kpendjal-West, Oti, and South-Oti in the east). These prefectures were recently subdivided, and 16 new communes were created as a result.

Given this regional division in addition to the problems encountered with fully implementing these somewhat weak and often incomplete decentralization policies, these two provinces in Burkina Faso and the Savanes Region in Togo are encouraged to focus their strategic thinking on their respective national capitals instead. The respective administrations use national debate, objectives and indicators to draft development plans that are then applied to regional bodies. This centralization takes some of the decision making away from territories, which is something that should not be ignored. It means stakeholders in municipalities, prefectures and regions currently have extraordinarily little leeway when it comes to building alliances and implementing policies in their regional cross-border areas.

These organizational and administrative constraints also mean that it can be quite difficult to find homogenous, consistent and synchronized data between all the various administrative bodies operating in the cross-border area. As such, it is a major challenge to reconstruct a territorial trajectory.

Figure 3.1. Study area: two provinces in Burkina Faso, one region in Togo (source: FAO, 2021).

Methodological framework

This study is somewhat unique in that it uses a wide range of approaches. Each approach is basically a study within the study which, when put together, forms a cohesive whole as seen in Figure 3.2. As a result, the anticipatory approach was based on a territorial assessment and a foresight approach.

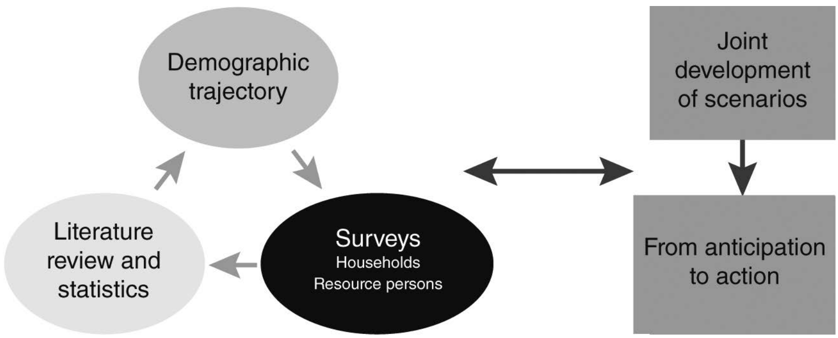

Figure 3.2. Summary diagram of the implemented methodological framework (source: FAO).

The territorial assessment was based on a combination of the following:
– a bibliographic review of the territory to compile data that were, until recently, somewhat patchy to get a rough idea of the territory's past and present. This has its limits though, since it is difficult to have a complete picture of the complex workings of the territory as a whole by simply analysing statistical datasets– there are so many other factors involved;
– identification of the demographic trajectories for the three administrative bodies governing the cross-border territory and their projections for 2035 and 2040 (Sourisseau *et al.*, 2017). These demographic projections are then used to estimate what the territory will need in terms of land, infrastructure and employment by 2035;
– collection of "first-hand" data using surveys, to be used in addition to the literature review and databases. Five hundred and sixty-eight (568) farmers and 61 other specialists on both sides of the border were asked about their perception of the past and the present, as well as their outlook for the year 2035. These surveys place more emphasis on transhumance and how it is perceived by the persons surveyed. The goal was to have an overarching understanding of how people either directly or indirectly involved in transhumance perceive the situation.

Two workshops were held by a team of seven people to co-construct the foresight scenarios. A total of 21 experts attended these workshops: 11 from Togo and ten from Burkina Faso. In the ten successive group working sessions, the group of experts was able to construct contrasting scenarios for the territory's future. They even wrote stories about the future that included diverse types of transhumance and how they contribute to the territory. Each of these ten sessions had a specific objective (Table 3.1). Lastly, a third workshop, spread out over three sessions, was held to discuss these constructed representations of the future. This workshop was attended by the same group of experts, who put forth initial recommendations for peaceful transhumance via local governance and cross-border cooperation.

Table 3.1. Objectives of the various sessions held during the foresight exercise.

Phase	Session	Objectives
Participatory scenario co-development	1	Define the system and the problem: the assessment was presented at the start of the workshop and then used to stabilize the problem and specify the time horizon of anticipation.

Phase	Session	Objectives
Participatory scenario co-development	2	Introduce the problem and anticipatory approach: the aim here was to create a timeline outlining the external and internal events that have had an impact on the territory, and to identify hopes and fears for events that may occur.
	3	Identify the factors driving change in the territory: these forces correspond to past, present and future dynamics that are perceived as potentially influencing the changes within the territory.
	4	Identify the driving forces (structural analysis): the classification of these forces into various groups (e.g. drivers, levers, products or unique forces) helped to define the system's structure and to select the main driving forces (i.e. "drivers") exerting a considerable influence on the other driving forces, but which are not highly dependent on them.
	5	Define future states (morphological analysis): for each driving force selected, a set of contrasting hypotheses was explored (i.e. "plausible future states").
	6	Jointly develop scenario storylines: a storyline is a combination of elements that include an assumption of change for each driving force. These storylines were presented as an outline form and described a future situation in the Togo-Burkina Faso cross-border region in 2035.
	7	Draft the outline: storylines were created in outline form, i.e. short paragraphs that combine the various future states of each driving force.
	8	Create narratives: the outlines were fleshed out into full narratives with consistent and plausible text. The experts involved included the other drivers of change at this stage.
	9	Integrate the transhumance variable: after having developed all the narratives, the group then chose scenarios that were as different from each other as possible to bring the issue of transhumance back to the table.
	10	Introduce backcasting approaches: in this session, participants were asked to project themselves into future scenarios to see what changes are needed in the present.
Recommendations for action	11	Choose the scope of recommendations and define a vision: stories about the future can be used to help stakeholders take decisions simply by disseminating this information to the public and encouraging debate. However, these stories could also be seen as a vision to be attained and could inspire the implementation of public policies.
	12	Conditions for action (stakeholders, changes, constraints and opportunities): the main stakeholders needed to attain the vision were identified; the changes to be made and the obstacles to avoid were precisely defined.
	13	Strategies and recommendations for action: during this last session, the experts focused on drafting very concrete proposals for action to improve cross-border governance in the following areas: security, cooperation between local authorities and transhumance.

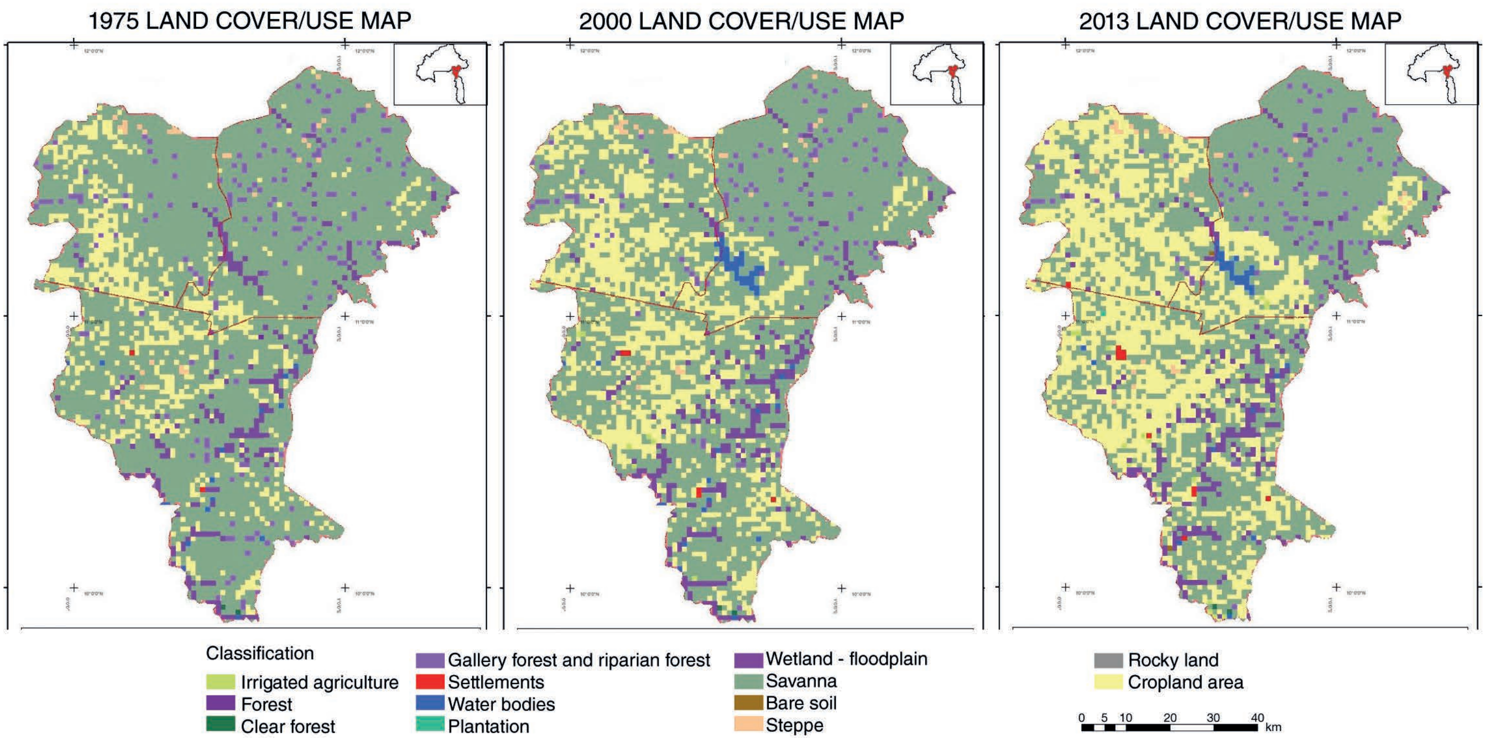

Figure 3.3. Changes in cropland areas 1973-2013 (source: FAO, 2021; based on data from the U.S. Geological Survey – Earth Resources Observation and Science Centre).

⏩ Outcomes and lessons learned

Territorial assessment

Influence of population growth on territorial dynamics

Over the last 50 years, the dynamics within territories have been guided by the west-to-east shift in cropland areas (Figure 3.3). This shift has had a significant negative effect on the Savanes Region and has resulted in the densification of cropland areas throughout the territory due to strong demographic pressure. It seems likely that this eastward shift in land use will continue in the future as the population is expected to increase from 1.65 million to 2.58 million people between 2020 and 2035. That is if human migrations patterns, especially related to the security situation, do not upset the existing equilibrium.

In addition to the massive increase in population size (densification), other major challenges related to health, education and employment will need to be addressed if the demographic forecasts are accurate (i.e. a younger population overtaking an older one, across the whole country). In 2015, 33,500 young people entered the labour market. This number is expected to rise to 53,400 in 2035 and will surpass 60,000 in 2040. This means that the close to 750,000 jobs will need to be created by 2035, with this figure rising to 950,000 jobs by 2040. Based on what has been achieved in recent decades, it seems unlikely that the projected needs in terms of healthcare and education personnel and infrastructure will align with international standards.

Necessary but difficult economic diversification

Agriculture and livestock farming still employs close to 90% of the labour force. Most people working these fields tend to stay there. Significant productivity gains are not being observed in these sectors; farmland expansion is directly related to demographic growth, even if some small adjustments are made to cropping systems (Figure 3.4). For the most part, the main livestock farms are mobile agro-pastoralism systems and suckler farming systems for cattle as well as small ruminants. It is not uncommon for farmers to have sedentary draught oxen on their holdings, especially to cultivate cotton. However, these animals come from mobile pastoral farming.

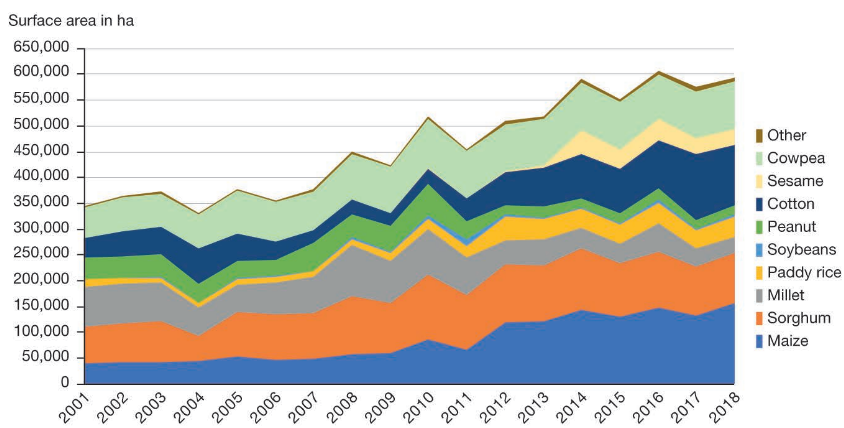

Figure 3.4. Changes in cultivated areas (excluding vegetable growing) across the whole study area (source: FAO, 2021).

The territory is still facing weak economic diversification, which suggests that there is limited room for manoeuvre in terms of the available strategic options. Apart from cotton, since its downstream activities take place outside the territory, the agri-food sector is having trouble finding sectors in which to develop. It does not help that there is not a wide-spread business network within the territory. For the most part, this is limited to small businesses and handicrafts. The mine opens up some potentially interesting possibilities but also comes with a definite risk of poor governance. Likewise, it has not been possible to fulfil the promises made to set up tourism activities around the nearby national parks due to uncontrolled human pressure, but especially because these areas in Burkina Faso are currently home bases for terrorists.

Marginalized territories within their country

The Savanes Region has long been much poorer than the rest of Togo, with more inequality found in the eastern and especially central-eastern regions of Burkina Faso. Yet, recent data have suggested that this indicator is catching up to the national level, and that both the poverty and inequality rates are closer to being equal between the three regions. Notably, the various national household surveys have underscored a positive trajectory in Burkina Faso's eastern region due to the urban development of Fada N'Gourma. However, it is difficult to determine the impact the political crisis of 2015 and the more recent worsening security situation have had on household income and poverty in the region. As a result, there is already concern that the objectively observed economic slowdown has already had repercussions on well-being indicators. There are also concerns that the income and inequality gaps have increased between Burkina Faso and Togo.

Contrasting views of the territory's future

The surveys conducted in a sample of rural households within the territory corroborate the harsh living conditions locally and have also helped us to better understand how individuals think about how their home territory is changing as well as what they imagine the future will be like.

For instance, the male heads of households surveyed consider the ideal family size to be roughly 5.5 children per wife, but this number is going down. Young people envision smaller family sizes (4.5). However, part of the population is unaware of family planning, even among some of the young people. Only 24% of women say that consulted for family planning reasons. Although the survey had certain limitations, these perceptions suggest there will be a slow and gradual demographic transition. Moreover, when asked about their children's future, parents replied that they expect a mass exodus from rural areas to the capital city as well as to other secondary cities (especially in Togo). This is corroborated by the fact that 81% of young people in Togo and 72% in Burkina Faso have stated they want to live in the city.

Co-developed scenarios

Based on selective key variables of change within the territory, the expert group identified the following eight driving forces which were used to construct future scenarios for the territory:

– human capital: quality of education and training of populations, and the capability of populations to be involved in the development of the territory;

– local governance: quality of local governance in the territory: turnover of elected officials, accountability, transparency, participation, etc.;
– security: level of property and people safety, and collaboration between security services on both sides of the border;
– demographic growth: level of natural population growth;
– professional structuring: structuring quality for local professional organizations (farmers, ranchers, crafts persons, merchants, fishermen, forestry operators, etc.);
– mining activities: level of mining development and management quality;
– decentralized cross-border cooperation: level and quality of cooperation between territorial authorities on both sides of the border;
– ecosystem conservation: the state of ecosystems: vegetation cover, and wildlife, plant and lake biodiversity.

Next, the group of experts drafted 15 scenarios based on the imagined future states of these driving forces and by combining them. These 15 scenarios were eventually brought to eight visions of the territory in 2035, including the role transhumance might play in these possible futures. By way of an example, two of these visions are presented in Box 3.1 and Box 3.2. They both touch upon the possible roles and functions of transhumance.

Box 3.1. "Desert Oasis" scenario

In 2035, the cross-border territory between Togo and Burkina Faso is a vast, desert-like area with sparse flora and fauna and water bodies that are drying up. The main activity is livestock farming, with a strong family tradition of cross-border transhumance that has been passed down for generations. It is estimated that the number of livestock in the area is higher than 850,000 tropical livestock units (TLUs). Although herd numbers have long been limited due to scarce water and food resources, significant investments have been made in livestock farming in recent years, which has enabled semi-sedentary farming. Subsistence farming is practiced using technologies suitable for the Sahel region (irrigation, zaï, half-moon, etc.). Adapted techniques for forage crops enable livestock farmers to make good hay and to build up large stocks in the cooperative's warehouses.

Additionally, there is dynamic cross-border cooperation that functions well, e.g. town-twinning, agreements and intercommunal cooperation between the authorities, and therefore it is possible to plan joint projects. The many projects stemming from this cooperation specifically focus on the challenges of livestock mobility. As a result, marked trails, rest areas, solar-powered boreholes and vaccination pens have been put in place, making it easier for livestock to move toward oasis points. In addition to the high population growth rate, there are also significant migration flows related to mining activities and prosperity due to transhumance. All persons who take part in these collaborative projects receive quality education and vocational training that addresses the existing needs, and which is open to everyone. However, given the nature of transhumance practices, not all pastoralists benefit from the traditional education system. To address this, literacy and vocational training centres specifically geared towards the needs of pastoralists have been set up.

Mining resources are exploited using modern methods in line with sustainable development and transparent management, allowing the population as a whole

Box 3.1. (continued)

to enjoy the positive benefits. Decentralization is a reality, and the principles of accountability, transparency, participation, gender equity and operational capability are applied. Thus, governance is ensured by local elected representatives. While in office, these local elected representatives have allowed various socio-economic infrastructures to be built and become operational with support from technical and financial partners as well as the government. These infrastructures include: cross-border livestock markets where livestock products are sold easily and hassle-free and exported to coastal areas; structures for storing cereals, animal feed and veterinary medicinal products, self-managed by women's self-help centres and community animal health workers; renewable energy and drinking water distribution centres for the whole population; and veterinary posts that are both well-equipped and staffed by qualified personnel.

In order to give a specific impetus to the livestock sector and pastoralism, pastoral infrastructures set up within the framework of cross-border cooperation (pastoral trails, livestock pens, boreholes) are managed by local elected representatives and professional livestock associations. On account of all these infrastructures, livestock farmers can move their herds unencumbered from one area to another, within the same territory, and around oases where forage crops are grown. Many people go to livestock markets, and farmers take advantage of this to buy young bulls for use as draught animals. In exchange for this substantial investment in pastoralism, communes are able to reap certain benefits from this mobility through cross-border taxes and taxes related to sales at livestock markets. Together, these taxes make up close to 60% of the commune's budget.

Local professional organizations (POs) are well organized and proactive. These POs have been working in partnership with security forces to introduce a system that provides transhumant pastoralists with safe passage. This system entails the compulsory use of an identification badge. The varied contribution of transhumance to the different links in the local economic chain (agriculture, trade, taxation) has helped reduce poverty (approximately at 3%) in the territory. To make sure that there are no conflicts within communities and to allow the free movement of people and goods within a secure environment, a cross-border defence strategy has been put in place which facilitates collaborations between communities and security forces and includes the use of robots. This implemented strategy helps safeguard the territory from terrorist attacks that can occur in certain areas of the sub-region.

Box 3.2. "The face of chaos: when humans contradict nature's generosity, chaos is almost always right around the corner" scenario

In 2035, the cross-border region between Togo and Burkina Faso is home to a vibrant ecosystem (forests, animals, waterways) with extensive and varied resources that function in a well-balanced manner. The area includes natural parks and animal reserves as well as vast pastoral and arable land. Transhumant herders from all across the region come to this area for its natural potential and the related socioeconomic benefits. Therefore, local communities, through their relationships with transhumant pastoralists, benefit from the impacts of livestock farming in agriculture as well as from trade exchanges between these two communities.

However, this advantage is under threat. In fact, there is no intercommunal cooperation because the communes fall under the central administration. Shared strategic visions for development do not exist at the territorial scale. There are no trade exchanges, and no development of local sectors and agro-silvo-pastoral and fishing infrastructures. Consequently, transhumance is impacted greatly by this lack of organization in the agricultural sectors. Livestock farmers are persecuted in the area. As a result, some farmers decide to move away to a different region so they can freely move about as well as to avoid paying the multiple taxes they would have to pay if they had stayed in the area.

The area is marked by widespread insecurity because the cross-border collaboration between security services and local populations has broken down, and tensions exist within the security services themselves. This erodes the social cohesion and integration between people on both sides of the border. Transhumant pastoralists are especially affected by this lack of collaboration as they have to go back and forth across the border in search of pasture. These pastoralists are even accused, sometimes falsely, of robbery, theft, kidnapping and other illegal activities such as letting animals graze in fields, cutting down trees for fodder, etc.

The territory is governed by local sovereigns. Joint assets are managed ethnocentrically and by families. Resources are confiscated by organized and violent pseudo-landowners, which means that mineral resources cannot be exploited. It is difficult to find ways to introduce innovative technologies in agriculture and livestock farming, the two largest sectors in the region. More importantly, populations lack basic infrastructure, equipment and social services.

Professional organizations have become fragmented and disorganized; individuals or family organizations are the acting stakeholders. The sectors are run by private and political actors. Livestock producers are not being given any support, not even a storage infrastructure for their products or medical assistance for their animals. This all means that it is difficult for transhumance practices to take place in the area. Furthermore, only a few individuals are drawing a benefit from the situation: those people who negotiate individually with the pastoralists and who make a profit from them at the expense of the community.

To further complicate the situation, the population is growing rapidly along with a high total fertility rate, against a background of scarce social services. This situation makes it even more difficult to have access to jobs, especially since no steps have been taken to support industrialization.

It is also important to note that there is political instability throughout the territory, threats to social cohesion, and unawareness of certain concepts such as gender inclusion. Far from an asset, the presence of transhumant pastoralists in the region is seen as a very serious problem. It is not surprising that populations are educated in obscurantist educational systems... the face of chaos.

Recommendations for action

The recommended actions address five key areas: producing regulatory documents for the cross-border context; providing training and raising awareness on good governance; institutional frameworks and monitoring mechanisms; financing governance and cooperation; and producing and managing both data and knowledge for governance and cooperation purposes. Examples of the recommendations are shown in Figure 3.5.

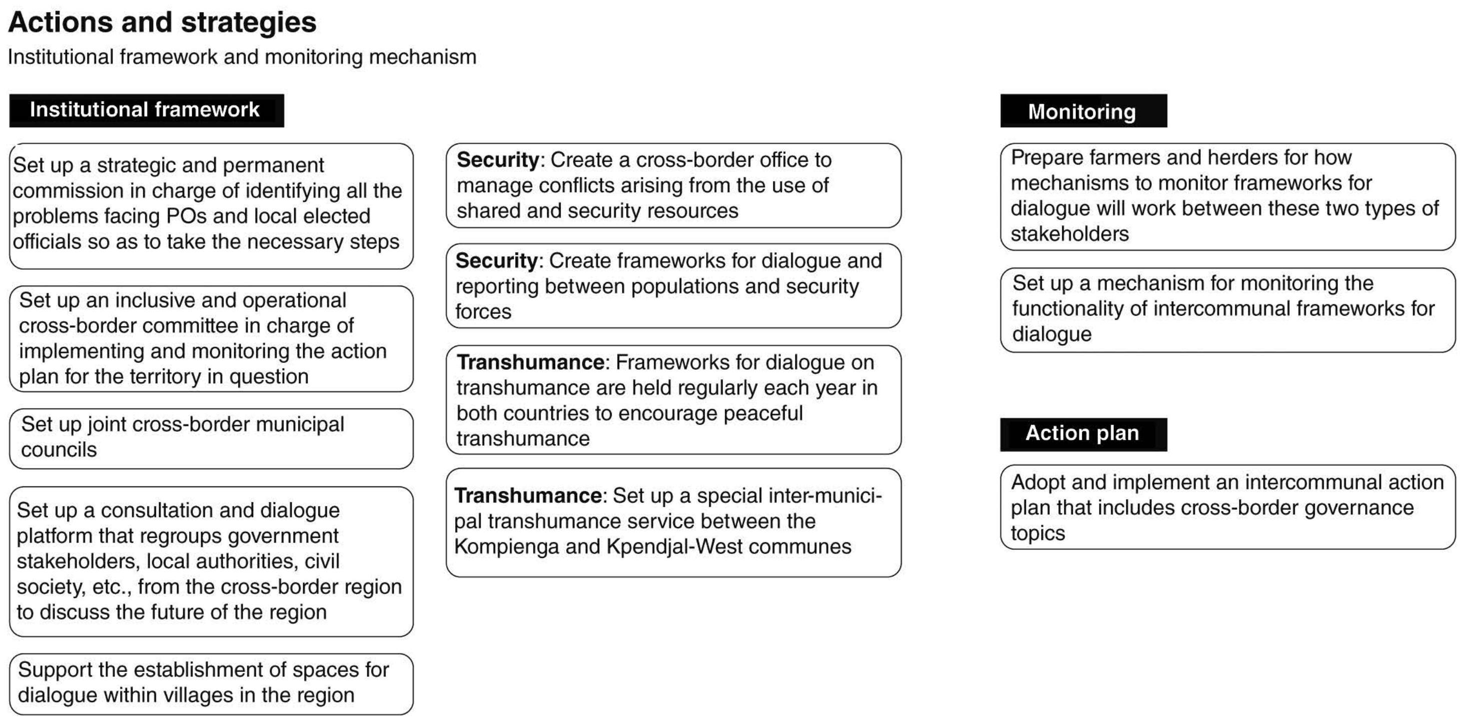

Figure 3.5. Example of recommendations made by the working groups regarding institutional frameworks and monitoring mechanisms. PO: professional organization (source: FAO, 2021).

The proposed actions only cover some of the potential key areas (local governance and cross-border cooperation) and still need to be fleshed out, especially to find ways to implement these actions. Despite this, they still provide a solid base for looking towards the future.

⏩ Perspectives

Towards a strategic cross-border approach: drawing on territorial resources

It seems that one promising way to develop this approach is to encourage a form of diversification that mobilizes specific resources within the territory. That said, it is not entirely clear that this will provide real benefits, especially since another problem is that this cross-border territory is somewhat isolated within their respective countries, thereby making this more difficult to put into practice. Solutions for the future will be found by drawing from the experiences of the women and men who live and are active in the area, in addition to their own resources and the various dynamics that explain how the region has been able to be so resilient for so long. One of these resources is cross-border trade and another is the complementarity of the areas on either side of the border.

Another important aspect of the assessment has to do with spatial imbalances. Compared to the more congested areas to the west, which have better market infrastructure and better connections to trade routes, these areas in the east are still relatively open space but they have less infrastructure. The trend is for agriculture and villages to slowly occupy the eastern part of the territory, with increasing pressure on natural resources. If there were to be improved access to the eastern areas without a global economic and territorial plan in place, then this will simply result in a repeat of the dynamics observed over the past few decades. As a result, imbalances are levers for action, provided that narrowing this gap between them is part of an overall plan that draws on the specific characteristics of each part of the territory.

Restructuring pastoral mobility and its role in territorial dynamics

The various challenges identified throughout the whole territory can be used to shed light on transhumance issues. This is obviously especially important for the region as transhumance provides economic benefits, and it can mobilize the available natural resources. As such, it may be a leading sector for figuring out how to reduce imbalances within the territory. It is still possible to keep corridors open in the east; it does not seem likely that they will reopen again in the very densely populated areas to the west.

Regardless, it should still be considered part of the overall dynamics within the territory. Transhumance by itself is not a territorial project, and its network of routes should be thought of in terms of their potential competition and how they complement other activities. Compromises will need to be found, and both human and animal movements must be supported via rules and regulation in relation to the overall flow of goods and merchandise moving across the territory.

Maintaining momentum

Some technical aspects of this study still need to be carried out and as a result, the study should be discussed and validated by the territorial experts who took part in the workshops, in addition to local and national authorities, centralized and decentralized technical departments and key civil society players. This is a joint effort to share the knowledge gained from this study, and hopefully it will encourage other stakeholders to "come on board" and take part in local cross-border development activities as well as a territorial and proactive approach to peaceful transhumance.

Upon request, interested partners can ask for and use any available communication media describing the applied territorial foresight method and presenting some of the scenarios. These films and drawings introduce the main principals discussed in this study and are presented in an accessible language and format.

The foresight exercise and assessment conducted in this chapter should be seen as starting points for a longer process that will have passed hands from the research teams to legitimate development actors, each within their own area of expertise. These first proposals and recommendations on cross-border governance and cooperation are only rough drafts and have a limited scope. This initial work should be pursued, and other relevant areas defined by the driving variables should be included. The idea is to use these territorial assessments, projections and scenarios to reflect on the actions to take and recommendations to make on security, birth rates, mining activities, ecosystem conservation, structuring professional fields and strengthening human capital.

Then, additional studies and workshops could be used to further develop and implement recommendations for cross-border cooperation and governance, as well as for the identified driving forces. The institutional and regulatory framework for this implementation, as well as the coherence and compatibility between public actions taken at the various scales, needs to be fine-tuned, with a particular focus on decentralization. Like in the previous step, this is not within the scope of this research.

Lastly, it is a priority to share this work at the regional scale. The method and its main results should be presented and discussed with territory and pastoralism partners in Togo and Burkina Faso (and perhaps other strategic cross-border territories as well). Consequently, it could be quite useful to involve northern Benin in territorial foresight studies.

More generally, the key results of the cross-border territorial foresight study could help fuel discussions at the Ministerial Conference on peaceful transhumance, and perhaps even other interested sub-regional bodies. This dissemination effort stems from the research efforts, and more broadly, the stakeholders who received foresight training for this study.

Conclusions

First, the study confirms the relevance of considering the border as a link between countries for which breakdowns in governance must be overcome. Therefore, it validates the fact that these three administrative entities make up one territory. It confirms that there are genuine prospects for a more integrated governance of this territory, first and foremost to facilitate transhumance but also with an aim to ease trade. This study also confirms that given how the governments and their administrations are current organized, there is a tendency to minimize these foresight analyses and to become somewhat insular.

Furthermore, it is important to keep in mind that these constructed scenarios are not predictions. Therefore, it is not particularly important whether they actually happen exactly as stated in the scenario or not. Likewise, any resulting recommendations are more like rough outlines, as they only address local governance and cross-border cooperation issues. What is most important is the jointly constructed mutual knowledge that enables the group of experts who came together for this study to have new representations of their territory, transhumance in this territory, the major dynamics shaping the area and the processes that could change current trajectories. With this latest information in hand, experts can take actions today to start making changes in the direction of the desired future scenarios or, at the very least, they can make sure that we are not heading down an undesirable trajectory.

Most importantly, this work opens the way for the experts involved to use these future representations to change the present, regardless of whether they choose to work together, separately, among themselves or with their other networks. This collective momentum and the innovative cross-border policy framework underway can be used as a stepping stone for new courses of action and, perhaps more importantly, collaboration between both sides of the border. These are highly contentious issues, and yet the expert group was prepared to respectfully listen to one another and to discuss these subjects, even if there was a bit of tension at times. By imagining the future and repositioning the roles and functions of transhumance within the entire cross-border territory, dialogue has been initiated between elected officials from both countries, between farmers and pastoral herders, but also with traders, teachers, decentralized government services, etc.

The long-term impact of this project on the future of pastoralism will mainly depend on the capability and willingness of its members, together with support from other development and research stakeholders, to maintain the momentum of the work and discussions that took place during the workshops. Although territorial foresight analysis may be able to start the process of change, the people directly involved in the territory will be responsible for making these changes a reality. From a research point of view, we may also be able to glean new and unique information about how pastoralism and space are interrelated, and more generally, about how pastoralism can be integrated into and contribute to territories, both today and in the future[5].

5. Today, the spread of violence in the study region over the five years since the study was carried out means that there are no new data or lessons to be learned from this case study. It also means that the approach described here may no longer be relevant for the current situation. That said, the authors still feel that this work has great testimonial value.

Chapter 4

Transition(s) 2050, prospective modelling of the French agricultural and food sectors

Antoine Pierart

This chapter is based on the summary of ADEME's "Transition(s) 2050" report[6].

Introduction

In line with its international commitments under the Paris Agreement (2015) and with the collective goal of stabilizing the climate below the threshold of a +2°C global temperature increase, France has built two initial National Low-Carbon Strategies (SNBC). These strategies set out the main objectives for reducing greenhouse gas (GHG) emissions and the carbon budgets that France must meet over the coming years. The trajectory for reducing GHG emissions and removals must achieve a goal of "carbon neutrality" by 2050, i.e. a balance between annual emission flows and removal flows (as per the French Energy and Climate Act of 2019). This implies that it will be essential to carry out rapid, profound and systemic transformations in a few years from now to considerably reduce harmful impacts on both the climate and ecosystems and to combat pollution. These transformations assume there will be unprecedented action by all members of society, major technical, institutional and social innovations as well as a profound change in individual and collective lifestyles, production methods and consumption patterns, land use planning, etc. ADEME published its work right at a time when decisions must be made to drastically reduce GHG emissions, ahead of the collective deliberations on the future French Strategy on Energy and Climate (SFEC) and one day before the debates for the 2022 presidential election.

The aim of this scenario-building exercise was to help collect technical, economic and social knowledge to fuel debates on possible and desirable development options. Collective decisions should focus as much on the sustainable society we hope to build together as on how to bring about the far-reaching, systemic changes that will make it possible. This is why ADEME is proposing four "standard" scenarios for achieving carbon neutrality, which deliberately present contrasting economic, technical and societal options, without exhausting the range of possible futures that could be pursued. These four scenarios are referred to as: S1 – Frugal generation, S2 – Regional cooperation, S3 – Green technologies and S4 – Restoration gamble.

In addition to the climate emergency we are facing, other environmental challenges are more pressing than ever, such as the quality and availability of water resources,

6. Prospective – Transitions 2050, Synthèse, 2021, Ademe.

the destruction and loss of soil quality, the erosion of biodiversity, etc. The strategy chosen by France will need to be justified in terms of all the ecological, social and economic challenges. ADEME wants to make it easy to take action, and it is for this reason that it has conducted this unprecedented foresight exercise based on two years of preparatory work involving roughly one hundred ADEME collaborators and regular discussions with a scientific committee. The assumptions and models were refined and improved through in-depth discussions with approximately one hundred external partners and service providers specializing in the various relevant fields. In addition, two webinars were organized in May 2020 and January 2021. Roughly 500 participants took part in each webinar to discuss the interim results.

This chapter places particular emphasis on the agricultural and food sectors, based solely on the presentation of the work stemming from the MAELE Researcher School held in 2022. It does not list all the key assumptions and insights from the Transition(s) 2050 report.

⏩ Methodology

General approach

The four carbon neutrality scenarios are inspired by the IPCC scenarios (P1 to P4 in the “Global Warming of 1.5°C” SR15 report[7]). The objectives of these scenarios are not a continuation of current trends (trend scenario) which, if no changes are made, would make the change trajectory incompatible with carbon neutrality (CN). The trend scenario and the four CN scenarios are applied across mainland France. Specific analyses for the French overseas territories will be carried out at a later point in time.

The four CN scenarios are constructed in such a way as to reach the target of carbon neutrality in 2050. This target only makes sense for the global climate. At the country scale, this target can help guide national strategies. We are therefore reiterating here what was written in the 2019 Energy-Climate law, which aims for zero net annual emissions in mainland France by 2050, as defined by the standards of the emissions inventory convention of the United Nations Framework Convention on Climate Change (UNFCCC). The assumption is that residual emissions in 2050 are at least offset by an equal volume of GHG absorption.

Each scenario is underpinned by a narrative, providing a representation of the world and the societal and political dimensions of the chosen trajectory. This qualitative approach is complemented by a quantitative technical and economic modelling component, along with sector-by-sector assumptions. As such, each of the four scenarios is comprised of a set of interdependent assumptions that ensure that the energy-resource-territory system is consistent with the scenario narrative. Consequently, this work goes well beyond simply modelling the energy system– it also describes contrasting societal transitions.

Table 4.1, taken from the Transition(s) 2050 report summary, summarizes the major demographic, climatic, and economic assumptions used to construct the scenarios.

7. https://www.ipcc.ch/sr15/

Table 4.1. Framework assumptions from the Transition(s) 2050 report.

	Trend	Frugal generation S1	Regional cooperation S2	Green technologies S3	Restoration gamble S4
Demographics	**65.6 million inhabitants in 2020; 67.4 in 2030; 69.7 in 2050 in mainland France** Birth rate: 1.8 children/woman, ageing populations (1/4 of the population will be +65 years old in 2050), net migration +70,000/year (source: INSEE, 2017; low fertility scenario, median life expectancy and median migration)				
Climate change	World: +5.4°C in 2100 France: **+3.9°C in France in 2100 (IPCC's RCP 8.5)**	World: +3.2°C in 2100 France: **+2.1°C in 2100** (2070-2100) compared to the 1976-2005 baseline (source: Météo France DRIAS 2021 – RCP 4.5 – NDC logic)			
Imported energy prices	**59 and 72 USD/barrel in 2030 and 2040** (source: IEA WEO 2020 – Delayed recovery scenario)	**82 EUR/barrel, 95 and 108 in 2030, 2040 and 2050** (source: European Commission framework, 2020)			
Economic growth potential	Long-term **potential growth** (workforce + productivity): **1.3%/year on average** over the period (including 1.1% productivity) (source: SNBC, 2020) Actual economic activity and employment vary depending on the scenario (see macroeconomic analysis).				

Figure 4.1. General narratives for the Transition(s) 2050 scenarios (source: ADEME, 2021).

Based on these cross-sectional assumptions, the method followed these main steps (below):

– For each scenario, a coherent narrative was constructed using structuring variables that describe lifestyles, the economic model, technological evolution, governance or the role of territories (Figure 4.1).

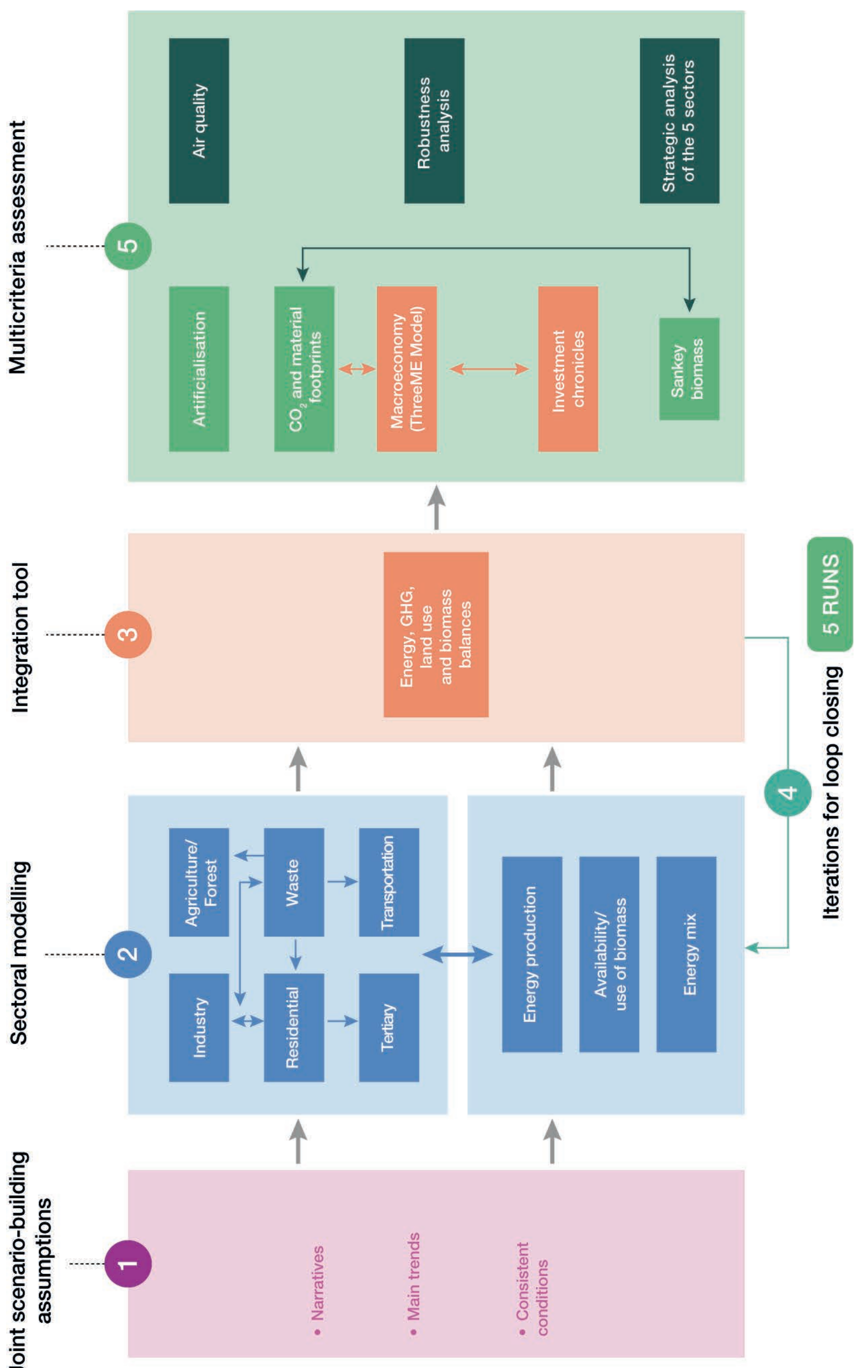

Figure 4.2. Flow chart showing the interactions between the various steps (source: ADEME, 2021).

– These narratives were then turned into quantitative assumptions in existing or tailor-made industry-level models (Figure 4.2).
– These sector-by-sector results were then grouped together to calculate the energy and GHG balances, as well as to define land or biomass use.
– Successive *iterations* were performed to unify the set of assumptions and to check, cross-reference and refine these quantifications, especially within *highly interconnected systems*:
– bioeconomy-food-agriculture-forest-soil,
– and use-buildings-mobility,
– industry-materials-circular economy,
– low-carbon energy systems.

Lastly, the following additional analyses were conducted: *macroeconomic, materials and GHG footprint*, electricity mix, social analyses and even strategic analyses of certain key sectors, etc.

Description of the food and agricultural sectors

The modelling of the bioeconomy sector was structured as follows (Figure 4.3).

The first assumption is based on the changes in diets needed to drive changes in production systems so that the demand can be met. This means that food needs (and non-food needs) can be transformed into technical itineraries and surface areas to calculate the biomass amount, land use and the various indicators used to monitor the resilience of agricultural production systems.

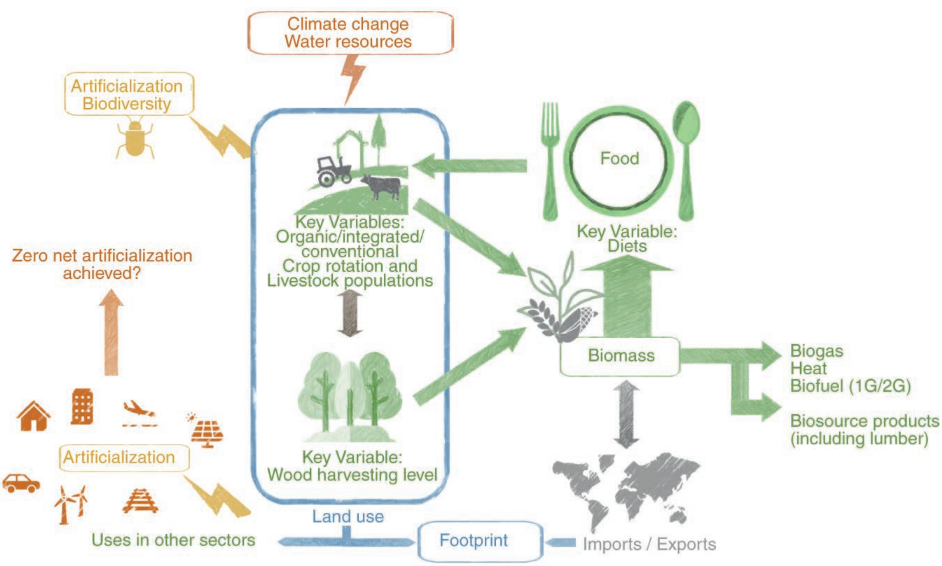

Figure 4.3. Diagram of the model chain and key variables in the bioeconomy sector (source: ADEME, 2021).

Data from the Inca2[8] survey were used to see the changes in diets. The current population was broken down into four consumer groups (Figure 4.4).

Next, nutritional constraints (calorie intake, need for a balanced diet, etc.) as well as constraints related to the quantity (and quality) and type of animal proteins were applied in each scenario to move the population groups towards one of the diets. The aim was to change the average animal protein consumption by -10, -30, -50 and -70% (S4 to S1, respectively).

Moreover, assumptions were also defined to move towards food demand and production methods that will ensure the provision of locally sourced products with high environmental value (seasonal, low synthetic input systems). These products are provided in varying proportions depending on the scenario. S1/S2: systematic training of operational and seasonal professionals, substantial easing of the specifications for distributors, development of alternative channels for the systematic disposal of non-compliant products, products within an optimized short-circuit supply, etc. S3/S4: fewer losses in the field (production and harvesting), primarily due to technical innovations (precision agriculture).

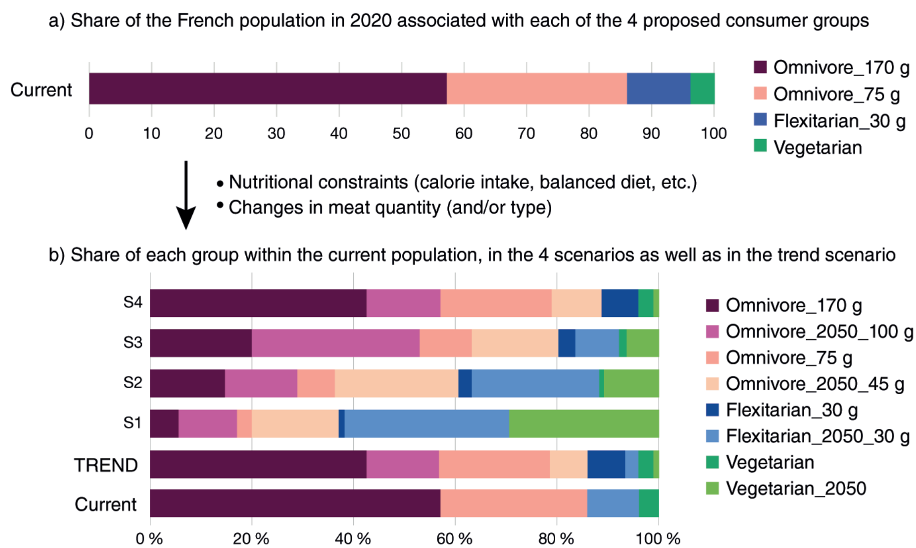

Figure 4.4. Percentages of the different dietary groups (source: ADEME, 2021).

These assumptions were used to create a representation of the average French diets for each scenario (Figure 4.5).

In keeping with these assumptions, work on the agricultural sector expanded upon the four narratives described in Figure 4.6 and reflected by the following variables (Tables 4.2 and 4.3):

Agroecology (nitrogen management, development of pulses, hedgerows and agroforestry, etc.): this has been gradually emphasized between the scenarios. The share

8. https://www.data.gouv.fr/fr/datasets/donnees-de-consommations-et-habitudes-alimentaires-de-letude-inca-2-3/

of low synthetic input systems, integrated production systems and sustainable conventional systems is clearly but consistently changing in response to the demand for biomass.

Livestock farming: in response to changing diets, the number of livestock animals, their productivity and related livestock farming practices are changing in contrasting manners. Released land is reallocated in diverse ways depending on the scenario.

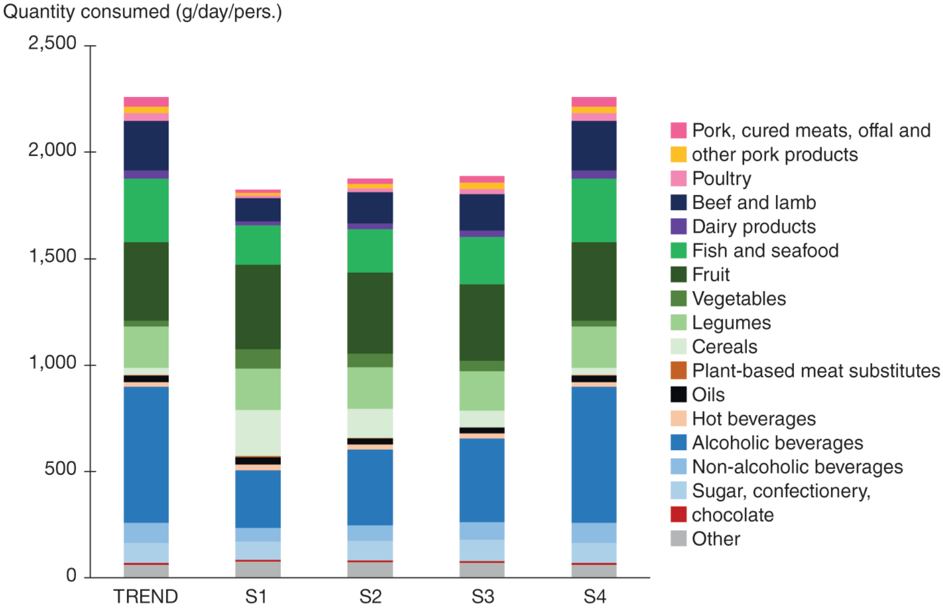

Figure 4.5. Quantities of the main food groups consumed (in g/day/person; source: Barbier *et al.*, 2022).

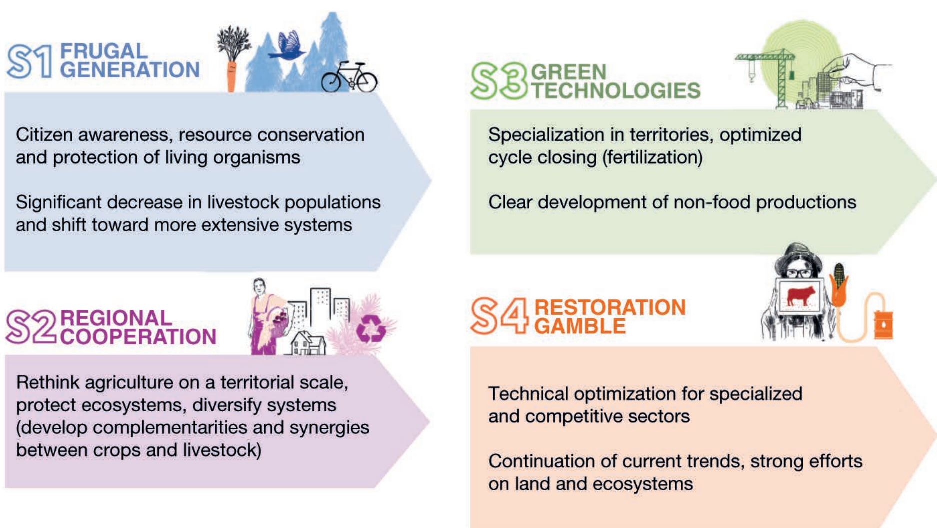

Figure 4.6. Summary of the agricultural sector narrative (source: ADEME, 2021).

Adapting systems to climate change: there is always a need to adapt production systems, this is a key point.

Non-food biomass production: to meet the demand for bio-based products and bioenergy that help reduce emissions in other sectors, the scenarios anticipate the maintenance and/or development of energy crops (perennial or not) linked to the spaces freed up by the changing demand for food.

Ecosystem services: agriculture provides various other services (carbon storage, water and soil quality, biodiversity reservoir) that are protected and encouraged to a certain extent depending on the scenario.

Territorial organization: international and national cooperation, or the reterritorialization of production.

Income diversification: the two main levers are the diversification of crop rotations and production of renewable energy.

A systemic land use modelling tool called MoSUT[9] (developed by SOLAGRO) was used to obtain details about and to model this set of assumptions.

Table 4.2. Use of the main decarbonization levers (the intensity increases as the colour changes from light to dark).

Lever	Trend	S1	S2	S3	S4
Reduced losses and waste	Very low	Medium	Medium	Medium	Medium
Reduced meat consumption	Very low	Medium	Medium	Low	Zero
Reduced use of synthetic nitrogen fertilizers	Very low	High	Medium	Low	Very low
Intensified livestock farming practices	Medium	Zero	Zero	Low	High
Carbon storage*	Very low	Medium	High	Medium	Very low
Reduced imported deforestation**	Very low	High	Medium	Low	Zero
Production of renewable energy***	Very low	Low	Low	High	Medium

Zero, Very low, Low, Medium, High

* In soils and agricultural biomass
** Related to changes in animal feed or imports for energy use
*** For the decarbonization of other sectors

9. https://solagro.org/travaux-et-productions/references/mosut-outil-de-modelisation-systemique-surlutilisation-des-terres-developpe.

Table 4.3. Share of the various agricultural models by 2050 and estimated decrease in the treatment frequency index (TFI).

		Trend	S1	S2	S3	S4
Low synthetic input systems	Share of UAA, %	20	70	50	20	10
	Estimated TFI decrease (excluding products used in organic farming), %	-100 (0 synthetic plant protection products)				
Integrated production	Share of UAA, %	10	30	50	50	20
	Estimated TFI decrease (excluding products used in organic farming), %	-25	-25	-50	-50	-25
Sustainable conventional	Share of UAA, %	70	-	-	30	70
	Estimated TFI decrease (excluding products used in organic farming), %	-15	-	-	-25	-15

⏩ Limitations and outlooks

Several limitations and outlooks were identified after these models were run on the food and agricultural sectors:

Food sector

S1/S2: major behavioural and organizational changes in food systems, representing either a dramatic acceleration of or a break with trends;

S3/S4: the expected leaps in technology are uncertain in terms of environmental benefits;

S4: introduction of a moderate level of major food innovations (synthetic meat, plant-based alternatives, customized nutrition, etc.).

These innovations could be developed on a much wider scale (if the environmental performance is proven), however they cannot be accurately assessed with present-day models;

S4: deterioration in the population's nutritional status and fewer environmental benefits, with efforts being shifted to other sectors.

Does another "technological" vision exist? The dramatic change in diets driven by nutrition challenges via digital and environmental tools or technological alternatives to animal products could result in the almost total disappearance of livestock farming.

The link with household budgets still needs to be investigated.

Agricultural sector

There needs to be a major paradigm shift in our relationship with the living world by transitioning towards production systems that are more input-efficient and more diversified (e.g. biomass energy).

Agriculture sustains our societies by providing essential environmental services: carbon storage, soil and water quality conservation, irreplaceable biodiversity reservoirs and socio-cultural services.

Ambitious trade-offs are needed to ensure the sustainable and balanced use of resources (water, soil, biodiversity, etc.) and biomass.

Major collective efforts are needed and must involve all stakeholders in the supply and demand chain (farmers, advisors, cooperatives, agri-food industries, retailers and consumers).

To make this transition a success, large-scale public policies must be put in place by incorporating these challenges in markets and with support from public policies.

⏩ Coupling "foresight and assessment"

Effective progress has been made in several areas, based on work carried out on the agricultural and food sectors as part of the Transition(s) 2050 study, by combining foresight analysis with an environmental assessment.

The tools that have been used (MoSUT, etc.) and developed (biomass conversion routes input spreadsheets) have made it possible to ensure good consistency between the available resources and potential uses of different biomasses to avoid double counting or inconsistencies between production and demand.

In the agricultural sector, scenarios were assessed using climate change resilience indicators (Table 4.4).

Table 4.4. Vulnerability and resilience indicators for the Transition(s) 2050 foresight scenarios. UAA = usable agricultural area, km^3 = thousand cubic meters, kha = thousand hectares, ktN = thousand tons of nitrogen, kt DM = thousand tons of dry matter, TWh = terawatt hour.

Vulnerability indicators	Current	Trend	S1	S2	S3	S4
Reliance on water						
Total irrigated area [Mha]	1.7	2.6	1.5	2	2.6	3.7
Share of irrigated UAA [%]	6%	10.3%	5.8%	7.2%	9.5%	13.8%
Share of irrigated areas for grain corn [%]	50.2%	34.3%	15.6%	20.8%	33.8%	33.2%
Total irrigation water volumes [km^3]	2.7	3.6	1.8	2.3	3.1	4.5
Summer irrigation water volumes [Mdm^3]	1.8	1.7	0.4	0.8	1.4	1.9
Summer irrigation water consumption [%]	68.3%	48.4	23.4%	35.2%	46.9%	41.7%
Ground cover						
Arable land with plant cover [kha]	1,091.8	2,163.6	16,549.5	17,538.2	11,234	4,918.5
Soil fertility and biodiversity						
Arable land surfaces using direct seeding [kha]	363.9	1,547	519	8,284	8,055	10,164

Vulnerability indicators	Current	Trend	S1	S2	S3	S4
Soil fertility and biodiversity						
Carbon stock variations in field crop soils (0-30 cm) compared to the trend, tC/ha (excluding hedges and agroforestry strips)*	-	-	+2	+5	+3	+1
Number of unit doses or NODU (synthetic product)	14.6	9.7	1.7	3	5.7	9.7
Organic nitrogen [%]	24%	32%	56%	71%	51%	44%
Use of pulses						
Nitrogen obtained via symbiotic fixation [ktN]	387.7	441.3	990.5	1,555.5	859.9	475.8
Forage resources (ruminants)						
Forage production from maize and crops [%]	23.2%	19.5%	8.2%	8.9%	18%	23.6%
Forage production from pastures [%]	32.3%	40.9%	44.1%	44.5%	35.3%	35.6%
Share of forage production from permanent and natural grasslands (stock) [%]	44.5%	39.6%	47.7%	46.5%	46.7%	35.6%
Forage estimates (grass surplus) [kt DM]	15,093	10,952.9	10,572.5	13,717.2	19,554.2	11,977.5
Linear hedgerows and agroforestry in agrosystems						
Hedgerows on grasslands and arable land [thousands of kilometres]	500**	547	935	939	619	500**
Agroforestry (arable land, grasslands and meadow orchards – 75 trees/ha) [kha]	140	232	597.7	1,499	1,212	232
Income diversification						
Agricultural bioenergy production [TWh/year]	39	106.8	163.2	150.8	199.8	165.8

*The variation in soil carbon stocks is used as a proxy for the variation in organic matter content, a critical component of agricultural soil fertility.
**Order of magnitude based on Pointereau's (2006) estimates. National estimates of hedgerow length are incomplete and can be clarified using the national hedgerow monitoring system.
***Primarily on grasslands and meadow orchards.

However, several focal areas will need to be looked at more closely in future foresight studies, such as:
– improving impact assessments for production systems and climate change (on soil health, biodiversity, water resources, etc.);
– developing a methodology that can be used to assess a global footprint (instead of just the footprint of our diet);
– developing a socioeconomic assessment of the envisaged scenarios;
– applying the modelling to the regional scale, while considering soil-climate constraints and water resources;
– further assessing the resilience and/or vulnerability of scenarios in more detail, particularly when we face more intense climate-related shocks.

⏩ Conclusion

The importance of healthy and sustainable diets

Three main levers can be used to substantially reduce the environmental impacts of food systems in order to develop win-win strategies for climate and health: i) a change in diets towards healthier and less meat-based diets, especially by reducing current meat consumption by one-third (S1) and half (S2), i.e. a 30% decrease (S3); ii) demand for products with high environmental value (low input systems) becomes predominant in S1 and S2; and iii) reducing losses and waste (this reaches 50% in all scenarios) either through behavioural levers in S1 and S2 or technological and digital levers in S4.

Taking only the impact of reduced meat consumption on agricultural emissions into account, the scenarios show reductions in carbon dioxide emissions close to 40% for S1 compared to present-day emissions, versus only 6% in S4. The estimated impacts on the footprint are of the same order of magnitude.

Agricultural production must undergo sweeping changes

By 2050, the agricultural sector will have to deal with numerous challenges: it must meet both food and non-food demands, provide various key ecosystem services (carbon storage, reservoirs of biodiversity, soil and water quality conservation, etc.) and adapt to climate change, while helping France achieve its goal of carbon neutrality.

Depending on the scenario, various interdependent levers are mobilized: agroecology, herd reduction and a shift to more extensive systems, a reduced demand for irrigation and biomass production for energy purposes.

The simulations show that GHG emissions from agricultural practices sector (Figure 4.7) can only be halved in S1 and S2, and only if we voluntarily act to reduce emissions and the crucial role the living world plays in maintaining our production capacities is better considered. Every stakeholder in the sector needs to make a transition, especially through dietary changes. For this to be successful, public policies must match this major shift in diet.

In addition to the GHG emissions component, the more extensive scenarios S1 and S2 also reduce the consumption of irrigation water (half of the present-day consumption in S1), as well as the use of pesticides (a five-fold decrease in S2 compared to 2020) and

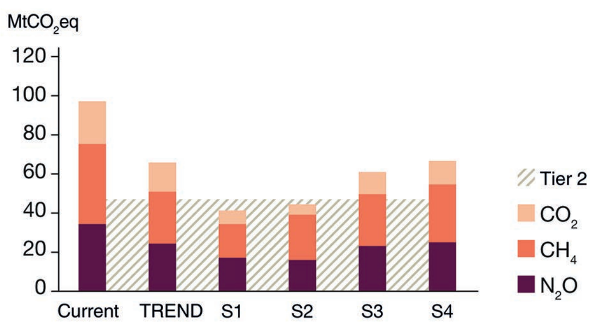

Figure 4.7. Territorial GHG emissions from the agricultural sector, now and in 2050, in millions of tons of CO_2 (source: ADEME, 2021).

synthetic fertilizers (i.e. mineral nitrogen) in favour of biological nitrogen inputs or the development of pulses, thereby ensuring symbiotic nitrogen fixation.

Conversely, S3 and S4 promote more intensive but technically optimized systems to reduce their impacts (compared to current systems and trends). S3 sees the highest contribution of the agricultural sector to biogas and biofuel production.

Protecting the living world

Living beings (e.g. livestock and biodiversity) are not just simply a means to an end, with different values depending on the scenario. Transition(s) 2050 encourages us to rethink our relationship with nature. The scenarios set out four possible balances between the following three interdependent levers: the potential for reducing GHG emissions, the potential for natural carbon storage, and the potential for mobilizing renewable biomass to replace fossil fuels.

These three levers are highly interconnected and must take other issues into account such as balances with food biomass production, other ecological (biodiversity, temperature regulation, erosion control, etc.) and social functions (e.g. use of forests for recreation), as well as the challenges of adapting forests to climate change.

The assumptions and results presented in this chapter only show some of the work conducted within the framework of Transition(s) 2050. We recommend that readers consult either the full report, the summary or the dedicated series[10] to get a full understanding of this foresight exercise as a whole, to avoid drawing incorrect conclusions.

All datasets are available online[11].

10. https://www.ademe.fr/les-futurs-en-transition/

11. https://data-transitions2050.ademe.fr/

Chapter 5

The importance of livestock farming and animal products in the Agrimonde-Terra foresight project on land use and global food security in 2050

Olivier Mora and Chantal Le Mouël

The Agrimonde-Terra foresight exercise on land use and global food security in 2050 (Mora *et al.*, 2020) can be used to re-examine the terms of debate on the role of animal production in land use and food security, and thereby its role in the future of global food systems. The goal of the Agrimonde-Terra foresight project, sponsored and led by INRAE and CIRAD, is to explore future land use and food security by 2050 to anticipate the sustainability and health issues that must be taken into account.

Five Agrimonde-Terra scenarios of land use and food security in 2050 were developed. They confirm that livestock farming and the consumption of animal products plays a key role in global land use and food security. In addition, these scenarios show that, as a global average, food diets need to shift toward a diet that has fewer calories, is more diversified and contains fewer animal products to ensure sustainable global food and nutrition security by 2050.

The Agrimonde-Terra scenarios are based on four alternate assumptions of change for food diets by 2050, in which animal products have a contrasting spatial and temporal role. Specifically, to achieve regional food security (as per Agrimonde-Terra), it is assumed that diets in low- and middle-income regions (sub-Saharan Africa and India) will have higher energy contents and will include more animal products in 2050, even if the general average global pattern for animal products evolves in the opposite direction. This is a very important assumption for the overall balance between biomass supply and demand and regarding global and regional land use given that the trend in the Agrimonde-Terra scenarios is for the populations in these densely populated low- and middle-income regions to continue growing quite rapidly whereas the productivity of their underperforming livestock systems (in terms of yields per hectare) will increase by 2050 but only to a limited extent, as observed in all other parts of the world.

This section is laid out as follows: first, the method used in the Agrimonde-Terra project is described (part 1), then the Agrimonde-Terra scenarios are presented with a particular focus on the importance of livestock farming (part 2); in a third step, the future challenges in livestock farming scenarios are clarified (part 3) as are the limitations to the modelling process as far as livestock farming is concerned.

⏩ The Agrimonde-Terra method: combination of a scenario method and digital simulation approach

The Agrimonde-Terra project is based on two different approaches to examine the future of global land use and food security by 2050. The first is a scenario method that applies morphological analysis (Ritchey, 2011) at various levels within the system, and which is implemented by the expert panels who helped develop the assumptions of change for the system (Mermet, 2009). The second involves the construction and use of a modelling and simulation tool, GlobAgri-AgT.

The method developed in the Agrimonde-Terra project incorporates methodological lessons from various scientific literature reviews on agricultural and food security scenarios. The literature review carried out by Le Mouël and Forslund (2017) points out "some lack of information in selected scenario studies on the hypotheses for the future of livestock systems... [even though] livestock future is a key factor as regards the land-use change impacts of scenarios". Van Dijk and Meijerink (2014) took a closer look at the future of diets by examining global food security scenarios. Their recommendation was to focus more on the demand for food and indicators such as "diet composition" when creating scenarios. These same authors also mention that food use and stable access to food products need to be better incorporated in global food security scenarios to be able to assess nutrition security, including all forms of malnutrition.

The foresight method developed in Agrimonde-Terra fills in the other gaps pinpointed in foresight studies on agricultural and food systems using the literature review published by Wiebe *et al.* (2018). First, it is important to choose a biomass balance model that will avoid "the potential mismatch between the dynamics generated endogenously in the computer model and the narrative assumptions about exogenous factors". Second, our method hopes to make up for the lack of "research on the qualitative–quantitative interface with simulation" and "the difficulty of translating narratives into model parameters" (ibid.; van Vuuren *et al.*, 2012). With this aim in mind, Agrimonde-Terra is working on a method to explicitly and transparently link the design of qualitative scenario design with the quantitative modelling of impacts (Wiebe *et al.*, 2018).

Agrimonde-Terra is defined as an *exploratory* study. Its aim is to prepare actors and research for various possible futures by providing scenarios that will help them both understand and anticipate future issues and challenges. The scenario method uses morphological analysis to consider multiple alternative scenarios at the same time. This method is based on a common analysis of the past and future dynamics within the system and can take a high degree of uncertainty into account (Durance, Godet, 2010; Ritchey, 2011). Morphological analysis has at least three advantages here: first, it underscores systemic relationships within the system; second, it can be used to explore a vast array of non-linear changes, which means it can also take into consideration the high level of uncertainty surrounding the future of food systems; and third, it ensures that all scenarios use the same exact set of drivers.

The Agrimonde-Terra method is a discursive group process based on expert opinions (Miller, 2007). The entire process has mobilized approximately 80 international scientific experts over three thematic workshops, as well as an international committee tasked with providing support for the construction of scenarios that includes scientists and stakeholders from international and national institutions (World Bank, Food and Agriculture Organization of the United Nations [FAO], International Fund for Agricultural Development [IFAD], International Food Policy Research Institute [IFPRI], and ministries of agriculture) and civil society (Oxfam, International Planning Committee for Food Sovereignty [IPC]).

In the Agrimonde-Terra systemic approach, the main drivers of the *Land Use and Food Security* system considered included: major drivers such as cropping systems, livestock systems, farm structures and urban-rural relationships, as well as external drivers such as climate change, diets and the global context. After having identified the system, the foresight process was conducted in six phases (lower green blocks, Figure 5.1) with five distinct groups of experts (four "groups of scientific experts" and one "scenario committee," upper blue blocks, Figure 5.1).

Phases 1 and 2 (Figure 5.1) analysed the long-term dynamics of the drivers for the *Land Use and Food Security* system. The drivers are listed on the left-hand side in Figure 5.1. The drivers of change were identified by analysis of the past trends and weak signals using data series from international agencies (e.g. FAO), when available, and by analysing any potential disruptions that could have an impact on future changes in these drivers. Thematic workshops were organized to analyse the four main drivers (cropping systems, livestock systems, farm structures and urban-rural relationships). Each workshop was attended by a specific group of researchers specialized in the workshop's theme. Two meetings were organized for each driver with the groups of experts: the goal of the first was to discuss the past trends, and the second focused on creating alternate hypotheses for the future changes in each driver by 2050. The retrospective analysis on the external drivers, carried out by the project team, used scientific literature reviews (along with available projections at different timescales) and available time series data. After these two phases were completed, alternate hypotheses about the possible changes by 2050 were constructed for each driver; these are the "building blocks" of the morphological chart (see Figure 5.1).

The next two phases (Phases 3 and 4 in Figure 5.1) are related to the development of scenarios and narratives. They are listed in the central column in Figure 5.1. Five contrasting scenarios were developed based on extensive discussions between the researchers and stakeholders on the scenario committee. First, the scenario committee assessed the alternate assumptions of change for all drivers by 2050 developed in the previous phase. Next, the committee constructed contrasting scenarios using the morphological chart. Each scenario combines one hypothesis or several assumptions of change for each driver (see the graph in the central column in Figure 5.1– each scenario is color-coded), while paying special attention to causal relationships, maintaining consistency between hypotheses and ensuring each constructed scenario is plausible. Based on this, five contrasting scenarios were constructed by a scenario committee made up of international experts. Each scenario describes a land use and food security situation in 2050.

Phases 5 and 6 (right-hand side in Figure 5.1) performed quantitative assessments of the scenarios. The GlobAgri-AgT model was used to assess the impacts of the scenarios in terms of land use (see Box 5.1). Each alternative assumption of change by 2050 for the various drivers of the system was first quantified to provide values for the model's input variables for each scenario and for each of the 14 regions considered.

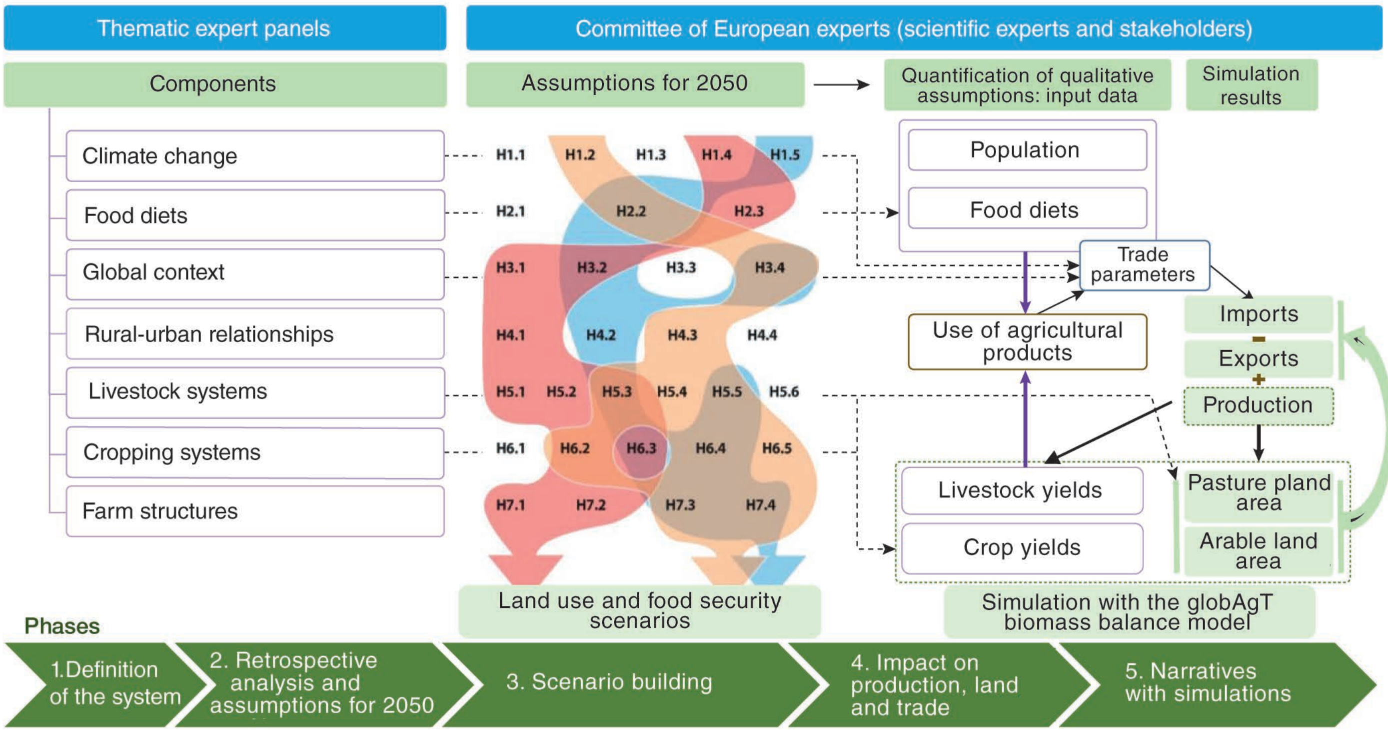

Figure 5.1. Linking method between a scenario approach and a quantitative simulation in the Agrimonde-Terra foresight exercise (source: Mora *et al.*, 2020).

Translation matrices were consequently built for each of these variables (see the matrices in Le Mouël *et al.*, 2018b). Then, simulations were performed on four of the five scenarios. The output was quantitative results on the impacts of these scenarios in terms of land use, agricultural production and international trade for each region and for the world as a whole.

Box 5.1. "GlobAgri and GloaAgri-AgT"

GlobAgri is a quantitative platform used to produce consistent databases and biomass balance models for agricultural and agri-food products based on FAOStat data and additional data shared by scientists from several institutions. The generated databases are balanced and consider the links between products (e.g. via animal feed or the combined oils-oilseed meals or milk-meat products). Biomass balance models create an equilibrium between resources (domestic production plus imports minus exports) on the one hand, and uses (human food consumption, animal feed consumption and other uses) on the other, for each product in each region. They can be used to simulate changes in land-use induced by changes in how products are used in different regions, given a set of assumptions of change for the other variables in the system (plant and animal yields, limited availability of land for agriculture, limited arable land, international trade conditions, etc.). The GlobAgri tool was used to generate a database and a biomass balance model explicitly specific to Agrimonde-Terra: GlobAgri-AgT.

GlobAgri-AgT includes 33 agri-food aggregates (26 plant aggregates and seven animal aggregates) and covers 14 regions around the world. Livestock farms are represented by five sectors (dairy, beef, small ruminants, pork, and poultry) and they produce six products (milk, beef meat, small ruminant meat, pork meat, poultry meat and eggs). Several livestock systems coexist within each sector: mixed, pastoral, urban and other systems for ruminant sectors, and mixed and other systems for monogastric sectors, as defined in Herrero *et al.* (2013). The input/output coefficients between the quantities of various plant products consumed by animals (including grass) and the quantities of animal products produced are calibrated by system using the ration and animal yield data provided in Herrero *et al.* (2013). These data are supplemented by data from Bouwman *et al.* (2005) and Monfreda *et al.* (2008). The generic tool GlobAgri and its application GlobAgri-AgT are described in detail in Le Mouël *et al.* (2018a).

In a last step that combines qualitative and quantitative analysis, a narrative was developed for each scenario. These narratives were drafted by the project team and discussed by the experts in the scenario committee. Each narrative provides a vision of land use and food security in 2050 as well as detailed information about the driving force and the system's trajectory toward this vision for 2050.

⏩ Land use and global food security scenarios and their quantified impacts

Narratives for the five Agrimonde-Terra scenarios

Agrimonde-Terra proposes a set of five scenarios, which are represented by the combinations of assumptions in Figure 5.1. The narratives for these scenarios are summarized below, and the corresponding detailed narratives can be found in Mora *et al.* (2020). Three scenarios, *Metropolization*, *Regionalization* and *Households*, are based on current competing trends seen in most parts of the world. Two scenarios, *Healthy* and *Communities*, concern potential disruptions that could change the entire land use and food security system.

The *Metropolization* scenario combines the development of megacities and conventional agricultural intensification, either with a nutrition transition driven by global agri-food businesses that market ultra-processed foods, or with increased consumption of animal products, within a global context of market-driven development that is characterized by rapid climate change. Small-scale farmers, disconnected from urban markets, are marginalized.

The *Regionalization* scenario links the growth of medium-sized cities and their connectedness with rural areas to the emergence of regional food systems based on family farming, traditional diets and regionalized supply systems, driven by a series of regional agreements, notably international trade agreements.

The *Households* scenario combines strong individual mobility between rural and urban areas and the development of multiple activities and off-farm employment, with the emergence of hybrid diets based on both traditional and modern value chains, in a globalized world where family farms and cooperatives are major players in land use.

The last two scenarios involve potential disruptions that could radically change the whole *Land use and food security* system.

As per the *Healthy* scenario, given the rising cost of malnutrition, there is a major shift towards healthy diets, driven by global cooperation and multi-sector public policies, within a context of climate change stabilization. This involves a reconfiguration of agricultural systems towards sustainability and agroecology, supported by new alliances between stakeholders.

As per the *Communities* scenario, which integrates significant climate change against a backdrop of multiple and recurring crises, there would either be either development based on small towns and rural communities (with a focus on managing common goods to ensure food security), or deadlocked technical systems characterized by conventional intensification and environmental degradation.

Impacts of scenarios on land use

Scenario quantification methods

The impacts of the scenarios on land use were simulated using the GlobAgri-AgT biomass balance model. Several assumptions of change for each driver by 2050 can coexist within the same scenario (Figure 5.1). For example, in the *Healthy* scenario, cropping systems may adopt a sustainable intensification pathway in some places and an agroecology pathway in others. However, to keep things simple, we focused the quantitative analysis on scenarios with one single assumption of change for each driver, in all parts of the world. This means that some scenarios were simulated using different variants, with each variant corresponding to a possible assumption of change for a driver (see Table 5.1). Lastly, since the specific aspects of the *Households* scenario (networks, mobility, multiple activities, agility) are more closely related to farm structures and the rural development model, it is difficult to include them in this model.

Even though this scenario is quite relevant here, it cannot be used to produce quantitative results.

The Agrimonde-Terra scenarios are based on four alternate assumptions of change for food diets by 2050 in which animal products have contrasting roles across both time and space: (1) a transition towards diets based on ultra-processed products (*Metropolization_Ultrap*); (2) a generalization of diets based on animal products (*Metropolization_Animp*); (3) regional diversity of diets and food systems (*Regionalization*); (4) a transition towards healthy diets based on food diversity including more fruits and vegetables, pulses and, on average, fewer animal products, sugars and ultra-processed foods (*Healthy*).

Four alternate assumptions of change for livestock farming in 2050 were used: (1) intensive conventional livestock farming (*Intensive*); (2) intensive conventional livestock farming with local resources (*Intensive_Local*); (3) agroecological livestock farming in synergy with agriculture or urbanization (*Agroecological*); (4) backyard livestock farming (*Backyard*).

Table 5.1 describes the variants that were simulated for each scenario.

Table 5.1. Scenarios and variants simulated with the GlobAgri-AgT model.

Scenarios	Variants	Scenario names
Metropolization	With the assumption of a transition to diets based on ultra-processed products	Metropolization_Ultrap
	With the assumption of a transition to diets based on animal products	Metropolization_Animp
Regionalization	With technology A: sustainable intensification for cropping systems; conventional intensification with local resources for livestock systems	Regionalization_A
	With technology B: agroecology for cropping systems and livestock systems	Regionalization_B
Healthy	With technology C: sustainable intensification for cropping systems; agroecology for livestock systems	Healthy_C
	With technology D: agroecology for cropping systems and livestock systems	Healthy_D
Communities	With agroecology: agroecology for cropping systems and livestock systems	Communities_AE
	With collapse: collapse of cropping systems and backyard livestock farms	Communities_Collapse

Changes in land use across the various scenarios

Almost all the scenarios and their variants result in an expansion of agricultural land across the world (Table 5.2). Only the *Metropolitanization_Ultrap* and *Healthy_C* variants would be able to feed a growing world population in 2050 without increasing the extent of global agricultural land or potentially resulting in additional deforestation. However, although the *Healthy* scenario predicts decreased overnutrition and malnutrition and helps protect against the development of diet-related chronic diseases, the *Metropolitanization* scenario predicts the reverse: an increase in malnutrition and diet-related chronic diseases. Thus, the *Metropolitanization* scenario does not meet the objectives for food and nutrition security.

Table 5.2. Impacts of scenarios on land use on a global scale (millions of hectares).

	Total agricultural land area	Arable and permanent crops area	Permanent grasslands and pastures area
Metropolization			
Metropolization_Ultrap	-54 (-1%)	+243 (+16%)	-297 (-9%)
Metropolization_Animp	+1,318 (+27 %)	+620 (+40%)	+698 (+21%)
Regionalization			
Regionalization_A	+249 (+5%)	+70 (+4.5%)	+179 (+5.5%)
Regionalization_B	+691 (+14%)	+174 (+11%)	+517 (+15.5%)
Healthy			
Healthy_C	+29 (+0.6%)	-56 (-4%)	+85 (+2.5%)
Healthy_D	+269 (+5.5%)	+50 (+3%)	+219 (+6.5%)
Communities			
Communities_AE	+142 (+3%)	+277 (+18%)	-135 (-4%)
Communities_Collapse	+2,013 (+41%)	+555 (+36%)	+1,458 (+43.5%)

However, the expansion of global agricultural land varies significantly both between and within scenarios, as well as between variants. This expansion is particularly high for scenarios involving either a significant increase in animal product consumption (+1.3 billion hectares or +27% compared to the initial situation for *Metropolization_Animp*), or a stagnation or general deterioration in the performance of agricultural production systems (+2 billion hectares or +41% for *Communities_Collapse*). It is substantially lower for scenarios with either fewer calories in food diets (+142 million hectares or +3% for *Communities_AE*), or a limited increase in animal product consumption in these diets, accompanied by the consumption of monogastric animals instead of ruminant meat (+29 million hectares or +0.6% for *Healthy_C* and -54 million hectares or -1% for *Metropolization_Ultrap*).

The global surface area for arable and permanent crops increases in all scenarios except *Healthy_C*. The scenarios with diets containing the highest animal calories or the gloomiest prospects for crop yields and the productivity of livestock production systems are the ones that drive the largest global expansions in croplands (+620 million hectares or +40% for *Metropolization_Animp* and +555 million hectares or +36% for *Communities_Collapse*, respectively). It can be noted that there is a relatively substantial increase in cropland areas in the *Metropolization_Ultrap* scenario (+243 million hectares or +16%). A large part of this result is explained by the assumed shift from ruminant meat and monogastric meat (mostly towards poultry), in addition to the inclusion of diets high in calories in this scenario. Similarly, in the *Healthy* scenario, there is a substantial decrease in the cropland area (-56 million hectares in variant C and +50 million hectares in variant D). This is primarily due to the reduced calorie content and limited number of animal-sourced calories in the food diets in this scenario.

Table 5.2 shows that the world's surface area dedicated to permanent grasslands and pastures also increases in most scenarios. The size of pasture areas increases considerably in the *Communities_Collapse* scenario (+1.5 billion hectares or +43.5%), which implies decreased livestock production between 2010 and 2050. Pasture areas increase substantially in the *Metropolization_Animp* scenario (+698 million hectares or +21%), given the high consumption of animal products, especially ruminants (a main characteristic of this scenario). The world's area of permanent grasslands and pastures also increases significantly in the *Regionalization* scenario, particularly in variant B (+517 million hectares or +15.5%). This is partly because traditional food diets, which underlie this scenario, represent a large share of small ruminant meat, especially in certain regions with very dynamic demographic trend (North Africa and sub-Saharan Africa). Conversely, the expansion of permanent grasslands and pastures on the planet is much more limited in the *Healthy* scenario, particularly in variant C (+85 million hectares or +2.5%), while these surface areas decrease in the *Metropolitanization_ Ultrap* and *Communities_AE* scenarios.

⏩ Future challenges of livestock production for food and nutrition security

To reach regional food security (included in the *Healthy* scenario), Agrimonde-Terra assumes that the diets of low- and middle-income regions (sub-Saharan Africa and India) will include higher calories and more animal products in 2050, even if the rest of the world will be consuming fewer calories and animal products on average. Thus, in the *Healthy* scenario, healthy diets combine two competing strategies for the issue of food and nutrition security in every region of the world. In high- and middle-income countries, the goal is to decrease the consumption of animal-source foods, whereas in certain low-income countries, where not enough protein is consumed, the goal is to increase the consumption of both animal products and pulses to increase the daily intake of proteins. For instance, compared to the situation in 2010, the *Healthy* scenario (by 2050) implies a 39% decrease in the daily consumption of animal products in North America and a 35% increase in Central, East and South Africa in addition to a 130% increase in the daily consumption of pulses. Agrimonde-Terra's *Healthy* scenario sets forth a broader strategy of diet diversification combined with the consumption of more varied plant-based foods, which may partly solve the problem of undernutrition and child stunting in low-income countries by reducing micronutrient deficiencies (Smith, Haddad, 2015).

This is a crucial assumption for the overall balance between biomass supply and demand and with regard to global and regional land use. This is because the Agrimonde-Terra scenarios forecast that the populations in these densely populated low- and middle-income regions will continue to grow very rapidly whereas the productivity of their underperforming livestock systems, in terms of yields per hectare, will increase by 2050 but not by much.

To summarize, the *Healthy* scenario generates the lowest global expansion of croplands, on the order of 0.3 to 5%, whereas the *Metropolization* scenario sees a significant increase in the consumption of animal products (*Metropolization_Animp*) and results in the largest increase in croplands, on the order of 27%, and the *Regionalization* scenario, with diverse diets depending on the region in the world, predicts intermediate land expansion on the order of 5 to 13%.

⏩ Limitations of livestock quantification in Agrimonde-Terra scenarios

The quantitative results stemming from the Agrimonde-Terra project should be treated with caution because they are contingent upon several limitations in the analysis. Two major difficulties were encountered for livestock systems during the analysis of these scenarios: the availability and quality of the initial data, and uncertainties in the assumptions of change for livestock system performances by 2050, especially in low- and middle-income regions.

The GlobAgri-AgT model uses the FAOStat database which only provides the total quantities of the various ingredients consumed by animals. However, GlobAgri-AgT first needs to distribute the total quantities consumed among the species and then for each species among the various livestock systems. This distribution cannot be carried out on a global scale because there is not enough research available to do so. The work of Bouwman *et al.* (2005) and Herrero *et al.* (2013) was used in the GlobAgri-AgT model, but when animal rations are aggregated by system and species (based on their work), these quantities often do not correspond to the quantities provided in the FAOStat database. Therefore, several adjustments need to be made, and the data need to be rescaled so that the various sources are harmonized. However, this then introduces bias and uncertainty in the initial data used. For example, as previously mentioned, we observed remarkably high input/output coefficients (the ratio between the amount of dry matter ingested and the amount of animal product produced) for the beef sector in India and for ruminant sectors in West Africa. In both cases, these high coefficients could reflect a bias in the initial data and/or be due to the data processing done to harmonize the various sources of data. However, both cases may underscore a major difference in why livestock is being raised in these regions compared to the rest of the world. Especially since other parts of the world only see livestock as a source of income. For instance, livestock farming in sub-Saharan Africa is often treated as an investment; it also carries a certain social, cultural and symbolic status (Alary *et al.*, 2011).

In addition, the FAOStat database does not contain any data on the quantities of grass consumed by animals– it only gives the area of permanent grasslands and pastures by country. Therefore, for GlobAgri-AgT, we used the quantities of grass in the rations per system and per species provided in Bouwman *et al.* (2005) and Herrero *et al.* (2013). However, when we combine these quantities and compare them to the areas classified as “permanent grasslands and pastures” in the FAOStat database, we see that grass productivity in these areas is quite heterogeneous from one area to another. Furthermore, the fact that this productivity is quite poorly understood globally suggests that the FAOStat “permanent grasslands and pastures” category covers vastly different types of pastures between regions: from natural rangelands in desert areas to very fertile grasslands. This also introduces bias and uncertainty in the initial data.

Lastly, it was quite difficult to quantify the alternate assumptions of change for livestock systems by 2050. There is not much literature, covering a wide geographic scale, providing quantitative information about the comparative technical performances of the various livestock systems in the different livestock production sectors or regarding their possible changes in the future. This is particularly the case for low- and middle-income regions, where there are often limited data and a lack of knowledge regarding livestock systems. This is a key issue for the future of land use and global food security, even more so since the results of the Agrimonde-Terra scenarios clearly show that these regions will likely significantly increase their consumption of animal products while their mostly extensive livestock systems require a lot of land. In summary, the results of the Agrimonde-Terra scenarios can clearly differentiate between scenarios that would and would not be able to ensure global food security in 2050, but these results are a lot less clear at the regional scale.

⏩ Conclusion

The results of the Agrimonde-Terra scenarios confirm that livestock production plays a key role in land use and food security in 2050. They show that in order to make a transition to sustainable and healthy food systems, there must be simultaneous action both on the demand side for animal products and on the supply side for plant and animal products. However, some minor changes will need to be made. The role of livestock production for food security in certain low- and middle-income regions needs to be underscored, as the daily protein intake in these regions is currently quite low and does not always ensure food and nutritional security.

The Agrimonde-Terra assumptions in all scenarios anticipate that land set aside for agriculture will significantly expand in certain low- and middle-income regions, especially sub-Saharan Africa. It could be possible to limit this expansion if a more optimistic assumption of the productivity changes in agricultural production systems was adopted for this part of the world. Another possibility could be to increase the import of animal products from other regions so that less land is taken up. The *Healthy* scenario simultaneously anticipates that high-income regions will consume fewer animal products, which would free up a substantial amount of land that is currently used for animal feed (in the area of origin or imported). This would reduce the pressure these regions exert on international markets to secure their animal feed supplies. This mechanism could increase the amount of land given over to crop production for human consumption. This would improve both food and nutrition security while easing the pressure placed on global ecosystems by agricultural systems.

Part 2

The inclusion of modelling and scenario assessments in foresight approaches

Chapter 6

Introduction to scenario modelling and assessments

Jonathan Vayssières, Mathieu Vigne and Aurélie Wilfart

Part 2 begins with a few aspects of modelling and assessment methods (including definitions of important concepts), before describing two modelling-assessment methods and two recent foresight studies linked to the modelling-assessment of foresight scenarios (Afterres 2050 and TYFA). These two foresight studies are described in detail in the remainder of the chapter, and specify the type of scenarios, the modelling-assessment methods used and their impact on several indicators.

⏩ Why do scenarios from foresight studies need to be modelled and assessed?

In view of the many challenges related to changes within territories and against a background of accelerating local and global changes and increasing awareness of the impact human activities have on their own sustainability in territories (Van der Ploeg, 2008; Millennium Ecosystem Assessment, 2005), technical and economic stakeholders and political decision-makers increasingly expect scenarios to be both modelled and assessed. Models and assessments are used in scenarios resulting from foresight exercises to anticipate the impact different scenarios have on the sustainability of human activities within territories. Depending on the study's goal, assessments can be conducted at different spatial and temporal scales. Examples of this include the Afterres 2050 scenario (France; Chapter 9), TYFA scenario (Europe; Chapter 10) and Agrimonde-Terra scenario (global; Chapter 5). This means we must be able to both compare the impacts of the different scenarios and determine if the scenarios can meet targets that have already been identified, for instance: to reduce GHG emissions, improve food security, reduce the use of chemical pesticides in agriculture, help territories become self-sufficient and restrict cropland expansion for the purpose of conserving biodiversity. Assessments can be used to measure the amount of change that scenarios produce and to provide qualitative or quantitative points of comparison between scenarios.

⏩ An introduction to modelling and assessment approaches

An assessment is defined as the act of determining the value of something. For instance, assessments may be carried out to measure, quantify and/or characterize a system in its present or future state, or in an alternate state to its baseline situation (which is often the present state). Often, this system is quite complex, making it somewhat difficult to determine its characteristics or assess its performance. In this case, we need to define some of the assumptions about how the system under study functions as well its dynamics, while keeping in mind that this assessment is part of a foresight study. If needed, a computer simulation model can also be used to summarize the foresight study. The assessment process uses different methods or tools depending on the target object that are chosen based on their assumptions, objectives and techniques (e.g. see Box 6.1 on territorial life cycle analyses). Assessments are routinely carried out in agriculture and do not just simply measure the performance of agricultural systems. This is a complex process that raises important methodological and ethical issues, and which helps support the learning curve on the systems under study while continuously improving these systems.

Assessments carried out in foresight studies on farmlands use specific methods to speculate on the future changes that could impact the sociotechnical, economic and/or ecologic dynamics within the territory. These assessments apply a methodical arrangement of various types of knowledge and expertise (qualitative and quantitative) from various sources pertaining to the future of the studied system. This is done in an aim to anticipate or meet present-day and future challenges and to devise a course of action that addresses these challenges right now.

These assessments make use of diverse methods (e.g. qualitative/quantitative, single criterion/multicriteria, aggregated/non-aggregated, etc.) and sometimes include numerical simulation models that convert scenarios into quantitative data which are then used in the assessments. Various types of models can be employed: static or dynamic, empirical or mechanistic, non-spatial or spatially explicit, etc. This modelling step may be quite time-consuming and entails a lot of time spent on its design. Conceptual modelling sets the scope of the studied system and its components and processes (e.g. storage and flows). It also determines what kind of scenarios can be simulated and which indicators can be calculated using the model.

Computer modelling or numerical simulation of socio-agro-ecosystems

Farmlands and agri-food systems are complex systems that are often referred to as *socio-agro-ecosystems* (SAEs), defined as a socio-ecological system under agricultural management. SAEs cover various aspects of the system, such as its ecological (soil, climate, biodiversity), technical (cropping, livestock farming, resource management techniques), economic (markets), social (cultural practices, networks of actors) and political dimensions (laws and regulations, incentives). What makes these systems distinct is the interactions between (a) agricultural practices and systems and (b) natural ecosystems and socio-economic dynamics (Lescourret *et al.*, 2015). Computer modelling or numerical simulations are performed on SAEs to better understand these complex interactions, predict the impact of changes in practices or land use and help devise sustainable resource management strategies.

Various modelling approaches

Many different methods can be used to model SAEs, such as empirical or mechanistic models, static or dynamic models, spatially explicit or non-spatial models, etc. These methods can be broken down into several categories depending on the aims, available data and type of processes being modelled. Below, we list several different modelling approaches along with their main advantages and limitations.

Econometric and optimization models apply statistical and mathematical tools to assess the relationships between agricultural practices, yields, socioeconomic factors and environmental factors. Optimization approaches help determine the best strategies for resource management and agricultural production, depending on the economic, environmental or social target. This quantitative approach yields robust and measurable results. It is quite common to use optimization techniques for the purpose of maximizing certain benefits such as productivity or economic outcomes and minimizing negative impacts such as environmental impacts (Berre *et al.*, 2014). The main limitations to this are that they employ static models that do not include long-term changes in behaviour, and it can be rather difficult to model the complex interactions between ecological and social factors.

The aim of *system dynamic models* is to show the material, energy and information flows in SAE systems using positive and negative feedback loops. These models often use differential equations to look at changes in certain variables such as nutrient stocks, populations or resources over time. This modelling approach generates a global view of system-wide causal relationships (Vayssières *et al.*, 2009) that is relevant for the analysis of long-term trends and feedback loop effects. It should be borne in mind though that this method sometimes oversimplifies the interactions between the various human stakeholders. It can also make it difficult to take the diversity of individual behaviours and stakeholders into account.

Explicit spatial models use geographic data (geographic information systems – GIS) to show the relationships between agricultural practices and the spatial dynamics of ecosystems. These models allow to simulate the effect of changes in agricultural practices and systems on environmental variables such as soil erosion, water pollution in drainage basins (Gascuel-Odoux *et al.*, 2009), deforestation and even habitat fragmentation (Degenne, Lo Seen, 2016). These models have high spatial accuracy, which means they can be used to analyse local scenarios. They are also particularly relevant for designing and assessing land management policies. The main limitation is that detailed geospatial data are in high demand and must meet high standards. As a result, these data are not always available, especially in the Global South. It is also difficult to include detailed social and economic dynamics in this type of model.

Agent-based models (or multi-agent systems, MAS) are used to simulate the interactions between several individual agents (e.g. animals, farmers, businesses, political actors, etc.) who make decisions based on their surroundings and their goals (Bousquet, Le Page, 2004; Grimm, Railsback, 2005). Specifically, these models do an excellent job of showing how diverse the various agents are as well as the dynamics of decision-making in situations of uncertainty (Grillot *et al.*, 2018a and 2018b). This is generally a bottom-up approach to looking at how individual decisions may impact the entire system (Kleinpeter *et al.*, 2024). The disadvantages of these models are that they are data-intensive, and they can be quite difficult to calibrate and validate (Manson *et al.*, 2012).

Challenges and outlooks for modelling socio-agro-ecosystems (SAEs)

SAEs are usually quite complex systems and therefore, in addition to the main types of modelling approaches defined above, several modelling approaches often need to be combined for these systems. A *multi-model integration* strategy combines ecological, agro-zootechnical, economic and social aspects to obtain a better picture of the interactions between the different subsystems. However, from a conceptual and data-processing point of view, is still scientifically challenging to integrate several models (Vayssières, 2021).

Moreover, it can be very difficult (almost impossible) to model SAEs because of limited *data availability and quality* in some situations. Socioeconomic and ecological data are often patchy and therefore it can be a challenge to collect accurate territorial data, especially in the Global South. Therefore, it is sometimes helpful to lower the level of detail (granularity) of the models by keeping only the performances of the main and key processes, especially for the defined representation and assessment targets, by making individual integrated models less complex (Grillot *et al.*, 2018a).

Another major challenge is the inherent *uncertainty* when modelling SAEs, since knowledge about ecological processes is limited and human behaviours are hard to predict, especially over the long term. One increasingly important source of uncertainty is climate change. There is a growing need for models to be able to represent climate change impacts, with a particular focus on variability in agricultural yields, the ability of animals to withstand higher temperatures and humidity (Thornton, Herrero, 2014), water resource availability and, more generally, ecosystem resilience.

Lastly, there is a growing push for participatory approaches and the co-designing of models with farmers, policymakers and other stakeholders as this helps align models with the reality of local situations and makes the results more acceptable. The co-construction of models could also include scenario building, which is actually quite logical for foresight exercises at the territory level as it will be easier for stakeholders to make use of tools, issues and simulation results (Collectif ComMod, 2005).

Multicriteria assessment

The multicriteria assessment (MCA) method is widely used in decision-making, especially for complex issues that need to take several (and often contradictory) criteria into account at the same time. MCAs can be used to analyse and compare alternatives from different angles; this makes it easier to take decisions, especially when in uncertain or conflicting situations.

This approach is particularly useful in instances when the complex decisions being made must be able to integrate technical, economic, environmental and social aspects, e.g. agriculture, resource and environmental management, and territorial dynamics.

This section defines the main concepts, methods and applications of multicriteria assessments.

Key concepts of multicriteria assessments

MCAs are built upon several key concepts (Lairez *et al.*, 2016).
– *Alternatives and criteria*: alternatives are defined as the options or solutions between which a choice must be made. In certain cases, these alternatives may be relevant to scenarios constructed in territorial foresight studies. Criteria are defined as the dimensions used to assess these alternatives; they can be either quantitative or qualitative, measurable or non-measurable and, often, they are contradictory.

For instance, when choosing a livestock system, a technical criterion (e.g. increasing productivity by making use of a high amount of concentrated feed) may conflict with an environmental criterion (e.g. preserving biodiversity by favouring permanent grasslands for animal feed).

– *Relative importance* of criteria: MCAs sometimes need to weight criteria based on their relative importance. This can be done in two ways: objectively (using measurements) or subjectively (using expert or stakeholder opinions). Since criteria weighting has a direct impact on the results, it is very important to properly define the criteria and their weighting.

– *Conflicting objectives*: given that certain criteria may be contradictory, it is usually impossible to optimize all the objectives at the same time. Consequently, decisions based on several criteria also usually entail certain *trade-offs*. The key to successfully conducting an MCA is managing these trade-offs, e.g. by trying to maximize certain criteria while minimizing the drawbacks of others.

– Typically, a distinction is made between *quantitative and qualitative assessments*. Quantitative assessments are built on numerical data (e.g. statistics, standardized tests) and can be used to "objectively" analyse performances. Qualitative assessments are built on observation, interviews and case studies, and provide a more nuanced and context-specific assessment. As there is currently increased interest in participatory methods, more focus is being placed on the latter type of assessment, with new challenges to make these methods relevant and useful in different contexts.

Box 6.1. Territorial life cycle assessment: a multicriteria assessment method that should be used more often in territorial foresight analysis

A *Life cycle assessment* (LCA) is a major multicriteria assessment method for measuring the environmental impacts of a product or service throughout its life cycle (ISO, 2006). It can provide a full picture of the impacts of products and services through every phase of its life and, as such, it plays a very important role when it comes to encouraging environmental sustainability. The aim of a LCA is to gauge the environmental impact of a system by quantifying all the material and energy flows exchanged between the environment and studied system. This method applies a systemic approach that is carried out in several steps to understand the potential impacts that occur during each stage of the life cycle.

At present, life cycle assessments (LCAs) are extensively used to compare different scenarios of change in livestock systems and animal product production chains (de Vries, de Boer, 2010). These assessments continue to evolve along with the development of territorial life cycle assessments (TLCAs), which seem quite promising for assessing scenarios that have been constructed in territorial foresight exercises (Figure 6.1). A TLCA looks at the territory as a whole; this includes infrastructures, production and consumption systems and interactions with the overall environment (Loiseau *et al.*, 2014). In theory, this systemic approach incorporates interactions between the various activities that take place within a given territory as well as their combined environmental impacts while accounting for inflows and outflows (e.g. raw materials, energy and waste; Loiseau *et al.*, 2018). In an aim to improve this method, future research could include the social and economic impacts (Vayssières *et al.*, 2019), the spatialization of these impacts and the construction of databases that are more complete and easier to access.

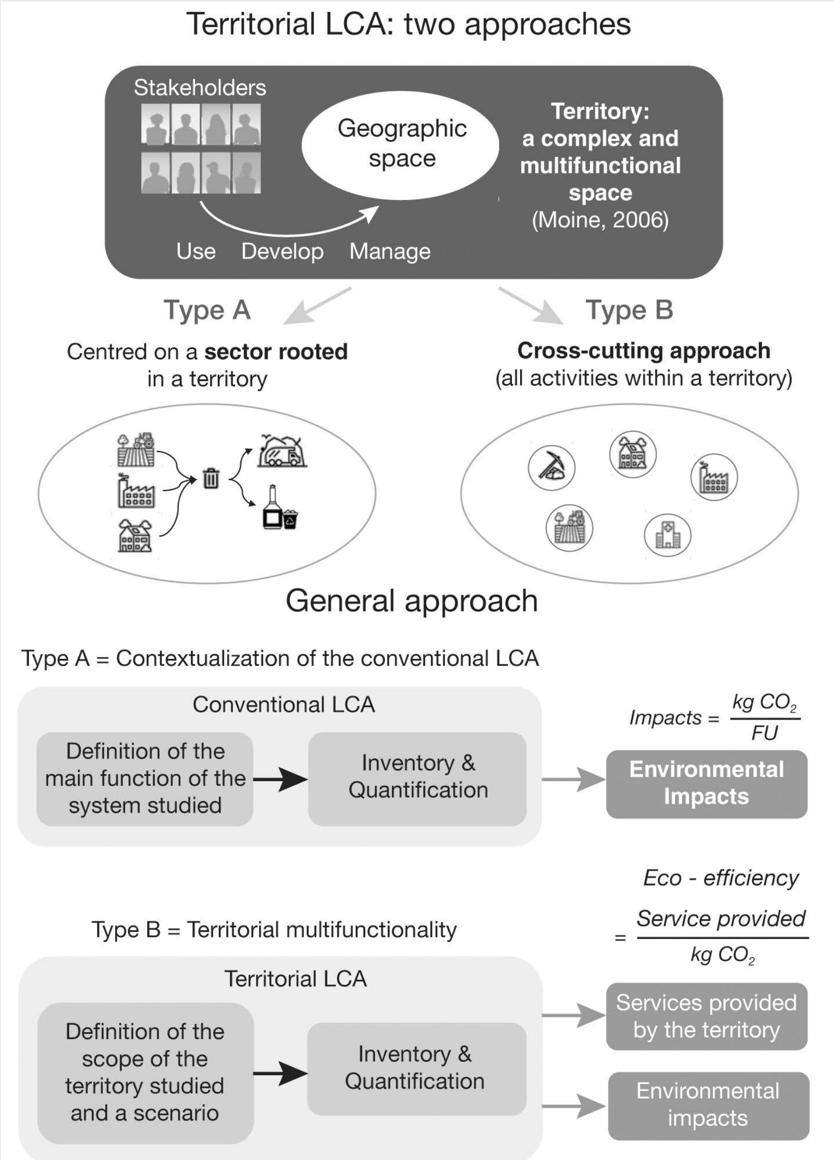

Figure 6.1. General principles of a territorial LCA, adapted from Loiseau *et al.* (2022).

Applications of multicriteria assessments

MCA can be applied to numerous domains in agriculture, such as:

Agricultural system dynamics within territories: particularly in agroecological transition situations, MCA can help assess the impact that changes in agricultural practices and systems have on several territorial sustainability indicators, especially the provision of ecosystem services (Kremen *et al.*, 2012; Duru *et al.*, 2015).

Land use planning: as part of land use planning, MCA applies several territorial socio-economic and environmental performance indicators to help decide between different development and land use options. Typically, this includes agricultural production criteria and the coverage of food and energy needs within territories (Russeil *et al.*, 2023), in addition to socioeconomic criteria (e.g. job creation and added value) and environmental criteria (e.g. the carbon footprint of the territory).

Resource management, especially natural resources such as water, forests and biodiversity, while taking multiple interests into account (Guitouni, Martel, 1998). MCA applies criteria such as the economic cost, sustainability and social acceptability of resource management strategies (e.g. prioritizing renewable resources and not non-renewable resources) to compare these strategies and natural and anthropogenic areas (*land sharing* versus *land sparing*, see Chapter 11).

Challenges and opportunities for multicriteria assessments

Complexity and subjectivity: it can be sometimes difficult to implement MCAs, especially since there is a certain amount of subjectivity when it comes to choosing the criteria and weightings. It might be possible to reduce these biases by using facilitation and stakeholder consultation techniques.

Taking uncertainties into account: in assessments, just like in modelling, there is a certain amount of uncertainty associated with descriptive data for systems and data on their dynamics. These aspects can be better managed if certain approaches such as sensitivity analysis or probabilistic methods are also used.

Integration of recent technologies: along with the rise of big data and artificial intelligence comes opportunities to improve MCA models, resulting in more accurate and dynamic evaluations of the criteria.

Socio-agro-ecosystem modelling and multicriteria assessments: complementary tools for supporting territorial transitions

SAE modelling and MCAs are burgeoning fields. They provide powerful tools to make the decision-making process easier since territorial systems can be quite complex and there are usually several ongoing issues and dynamics to contend with.

The modelling of SAEs brings about a better understanding and management of the complex interactions between agriculture, especially livestock farming, society and the environment. It seems that integrative approaches that combine spatial, dynamic, agent-based and participatory methods are the best way to show not only the dynamics of these complex systems but also how they function (e.g. see Chapter 7).

One benefit of combining multicriteria evaluations with SAE modelling is that they can take multiple dimensions of SAEs into account (e.g. functioning, properties, performances, impacts, services, etc.). The result is a holistic and integrated approach to addressing issues related to territorial dynamics. To overcome any challenges related to its implementation, a rigorous methodology must be applied, and stakeholders must be actively involved to ensure that the results are both relevant and legitimate.

Thus, it can be said that the modelling of complex systems and MCAs complement each other, and that they are indeed relevant when it comes to supporting participatory scenario-building approaches, especially territorial foresight studies. The use of these two methods should not be limited by the complexity of the systems under study and a lack of knowledge in certain contexts. Models should be simplified when needed, and the level of detail (granularity) in the models and data used in assessments should be lowered when building representations of complex and extensive territories such as agricultural areas. However, one prerequisite is that stakeholders and end users need to be informed about the assumptions and simplification choices that have been made in participatory modelling-assessment approaches.

⏩ Four studies illustrating the diversity of modelling-assessment methods and their use in foresight studies

Two contrasting modelling-assessment methods and two recent foresight studies linked to the modelling and assessments for scenarios from the Afterres 2050 and TYFA foresight studies are discussed in the remainder of this section.

Chapter 7, coordinated by Olivier Therond, a researcher at INRAE, describes a modelling platform (MAELIA) that carries out integrated simulations and assessments of agricultural systems and farmland. MAELIA's approach is centred on integrated modelling. The goal of this approach is incorporate knowledge, issues, stakeholders, spatial and temporal scales, disciplines, methods and pre-existing models into the models for the purpose of simulating the construction of emergent properties for the territorial system being studied (among other things). MAELIA is one of only a few modelling platforms that can carry out simulations in fine detail on the spatial and temporal dynamics of (a) production systems and (b) agricultural biomass processing and recycling sectors interacting with water resources in a territory. MAELIA draws from the advantages and functionalities of explicit spatial models and agent-based models (described above). The proposed modelling chain in MAELIA relies on a set of coupled models on ecological dynamics and human activities (and their interactions) at daily time steps over a period of several consecutive years. The platform is a way to explore diverse territorial scenarios of change and various contexts (climate, prices, etc.), entities (farm enterprises, resources, transformation units, etc.) and management strategies. It generates a set of intermediate variables for the SAE that can then be used to calculate measurable indicators of biophysical, environmental, economic and social performance. MAELIA has already been applied to various sustainability issues and levers specific to farmlands, such as water management and the agroecological transition. Many improvements are being made to the platform, specifically: i) to better show that livestock systems play an important role in how material flows are organized within territories and, more broadly, ii) to study territorialized bioeconomy systems with a view towards reaching carbon neutrality. The goal is for the MAELIA platform to be used much more often in foresight exercises, by jointly constructing exploratory scenarios that address the local and global issues pinpointed with the territorial stakeholders.

Chapter 8, entitled "Assessing the multifunctionality of livestock grazing systems within territories" and coordinated by Alexandre Ickowicz, a researcher at CIRAD, proposes a multifunctional conceptual model to describe the numerous functions of livestock grazing systems in territories. Developed for the "Restoring value to grasslands" network within GASL (Global Agenda for Sustainable Livestock), the model is based on four dimensions: the production of animal products, social dimensions, environmental dimensions and local development. This qualitative conceptual model looks at the functions within each dimension as well as the interactions between dimensions and between functions. It can also be used to pinpoint issues arising from the development of livestock farming. This is especially relevant when done prior to a MCA that uses different qualitative or quantitative modelling-assessment tools (depending on the context). This model has already been applied in different regions of the world: Argentina, Brazil, Senegal, Mongolia, Vietnam, China, France. Chapter 8 shows how the model can be applied by using two quite different contexts as an example: Vietnam and Senegal. In Senegal, a multi-agent system (MAS) was developed to assess the impact of scenarios looking at plant resource distributions and the development of the local dairy industry. In Vietnam, this conceptual model helped participatory and multi-stakeholders define indicators for livestock functions on three distinct levels: herd, farm and community. A cross-case analysis demonstrates that conceptual models encourage systemic, holistic and integrative approaches within territories (resources, stakeholders, activities) that also include various sustainability aspects. This model is also relevant to analysing livestock dynamics within territories. These analyses can also contribute to territorial foresight studies upstream of a territorial development strategy by specifically including the multiple functions of grazing livestock as well as any relevant interactions and trade-offs with respect to the other activities in the region.

Chapter 9, "Afterres 2050: from creating scenarios to assessing them", is coordinated by Christian Couturier, a scenario maker at Solagro. This chapter presents a scenario for land use and agricultural systems in metropolitan France in line with the objectives set by various national roadmaps for 2050. The watchword for this scenario is "agroecology", combined with the substantially reduced use of chemical inputs and imported livestock feed. The goal is to halve land taking, to preserve permanent grasslands and to increase hedgerow lengths and forest areas by reducing overconsumption by one third, reducing losses and waste by half and by shifting human diets toward more plant proteins than animal proteins (2/3 plant proteins and 1/3 animal proteins). The MoSUT model, developed by Solagro, and the ClimAgri® tool, developed by ADEME were used to assess this scenario.

Chapter 10, entitled "An agroecological Europe in 2050, 'Ten Years For Agroecology' (TYFA) scenario", was coordinated by Pierre-Marie Aubert, a researcher at the Institute for Sustainable Development and International Relations (IDDRI), and Xavier Poux, a researcher at the AScA (a study office for environmental management). The aim of this chapter is to describe what a 100% agroecological Europe could look like in 2050. The TYFA (Ten Years for Agroecology) modelling exercise developed by these two researchers, is distinctive by the fact that it is quite ambitious. The target is to completely phase-out the use of pesticides and synthetic fertilizers, while helping Europe become self-sufficient when it comes to food and even maintaining Europe's export capacity for cereals, dairy products and wine. The proposed scenario is based on dietary changes, mixed crop-livestock systems including extensive cattle ranching, and a major shift toward pulses and permanent grasslands. This scenario is constructed using a biomass balance model (TYFAm) and one of its main advantages is that it takes the interconnections between agronomic, ecological, social and political aspects into account.

Box 6.2. Models and tools used to model and assess the scenarios described in the foresight exercises presented in Part 2 (Afterres 2050 and TYFA).

MoSUT (editor: Solagro): MoSUT (systemic model of land use) is a biophysical model based on a balance sheet approach. It is used in the Afterres 2050 exercises to balance resources and uses in multiple dimensions. The "supply balances" of agricultural products is discussed first: resources (production and imports) are balanced against uses (food and non-food uses, processing, industrial uses and exports). A balance sheet approach is also used for the nitrogen balance and forage estimate. The former is used to calculate the mineral input requirements, which are the adjustment variables, and the latter checks whether there is a surplus of fodder. International trade assumptions are also considered. The model uses an iterative approach and adjusts both the assumptions and results.

ClimAgri® (editor: ADEME): this diagnostic tool, developed to estimate energy consumption and GHG emissions for agricultural and forestry activities within territories, was used to assess the scenarios constructed in the Afterres 2050 and TYFA exercises. Based on detailed descriptions of the activities (defined with the local stakeholders), this model can quantifiably evaluate fossil fuel and water consumption as well as emissions from agricultural activities using a life cycle approach, and by especially including the upstream phase along with the impact of inputs (fertilizers, animal feed).

TYFAm (editor: IDDRI): this biomass balance model was specially developed for the TYFA exercise. It is organized around several compartments: crop production, livestock production, food demands, non-food/industrial biomass demands (energy and biomaterials). It includes a mix of European production and imports. The nitrogen flows associated with the functioning of and interactions between the different compartments largely determine the level of biomass productivity for the first two compartments. The TYFAm model is also coupled with the ClimAgri® calculator to calculate GHG emissions from the food system.

ACCT (editor: Solagro): the AgriClimate Change Tool (ACCT) was jointly designed by Solagro and a working group chaired by the French National Federation of Organic Agriculture (FNAB), a network of organic producers. It can calculate energy consumption and GHG emissions at the farm level and by production unit.

Chapter 7

Use of the MAELIA platform to perform an integrated assessment and modelling of agricultural systems and farmlands within a foresight approach

Olivier Therond

⏩ From sustainability issues to integrated approaches

"Industrial" agriculture, which uses massive amounts of inputs, has such a substantial effect on the environment that it is one of the main forces driving human activities beyond the "planetary boundaries" (Rockström *et al.*, 2009). Several international bodies (e.g. the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) have come to the conclusion that, given the full impacts of this type of agriculture on health and the environment, it is no longer an option to keep going in the same direction (i.e. business as usual) if we want to address both present-day and future issues.

It seems that there needs to be new research and development approaches for supporting the decision-making processes used by the stakeholders involved in the management of natural resources and territories (Walker, 2002; Pahl-Wostl, 2007; Spielman *et al.*, 2009). This is because we need to take the above-mentioned environmental issues into account, new actors are managing natural resources (e.g. one single water management body), new technologies (e.g. digital) exist, and we are seeing rapid changes in both the economic and sociopolitical contexts. These new approaches would allow us to take stock of the socioeconomic and ecological processes involved, the various related temporal and spatial scales as well as the impact of the actors' behaviours on the system under study (Parrot, Meyer, 2012; Wu, 2013). The goal would be to develop and implement design/planning approaches that can be applied to landscapes/territories (Nassauer, Opdam, 2008; Parott, Meyer, 2012; Cumming *et al.*, 2013). As such, a landscape/territory is viewed as *"a complex socio-ecological system comprising a dynamic mosaic of land uses"* (Parott, Meyer, 2012). The difficult part of this process is representing the various key levels of organization and the emergent properties arising from interactions both within and between these levels (Parrott, Meyer, 2012; Wu, 2013; Cumming *et al.*, 2013). Given the challenges, costs (material, human and financial) and time needed to implement *in situ* experiments within territories, many authors are advocating for the development and use of digital modelling tools to examine the potential effects of new resource management procedures in territories.

To address this, substantial improvements have been made in integrated assessment and modelling (IAM) methods that integrate knowledge into models (Hamilton *et al.*, 2015). The goal is to use simulations to assess the sustainability of natural resource management procedures and to both develop and assess "scenarios" of change (Therond *et al.*, 2009). These assumptions and predictions (prior to application) are then used to assess the sustainability of biophysical (e.g. climate), technical-economic (human activities), political (rules and regulation, incentives) and/or even institutional (mode of governance) scenarios of change. Oftentimes, the aim of these scientific approaches is to generate knowledge that stakeholders can use to address any issues or problems that may arise regarding the sustainability of human activities (Jakeman *et al.*, 2006; Pahl-Wostl, 2007; Van Ittersum *et al.*, 2008). These approaches are often part of geo-prospective studies that require the construction of scenarios in an aim to give civil society the methods and tools they need to examine the relationships between the territorial organization of human activities and the stakeholders' local and global targets.

Chevassus-Au-Louis *et al.* (2009) underscore two major sectors (or domains) and challenges related to integration in agriculture: (i) in the knowledge domain, the challenge is to apply a "holistic" (compared to "reductionist") approach to the complex objects under study, i.e. it is important to take into account the key entities and interactions of the complex agronomic objects studied with regard to the issue underpinning the analysis, and (ii) in the action domain, the challenge is to develop objects and tools that functionally combine components that will represent the studied emergent properties (e.g. farm production, river flows). These authors point out that integration may concern ecological and socio-technical entities/objects just as much as management goals and success criteria.

⏩ Yes, there needs to be integration, but of what?

Hamilton *et al.* (2015) define ten major interrelated dimensions of integration and the related issues in integrated assessment and modelling (IAM) approaches (Figure 7.1):
– ***"Issues"*** to take the different areas of sustainability into account and to make sure to not put actions ("solutions") in place that would solve a problem in one area but create another or other problems in one or more other areas;
– ***"Stakeholders"*** to (i) involve diverse stakeholders, whether they are the cause of the problem, directly impacted by it or sensitive to it (e.g. people who use resources that are in a qualitative or quantitative state of degradation, nature protection association), in charge of solving it (e.g. political decision-maker or resource manager), hold important knowledge about the studied socio-ecological system and (ii) take their points of view and values into consideration throughout the whole IAM process;
– ***"Governance settings"*** to consider and represent the various characteristics and action strategies of private, public or collective governance systems, either for shared resources or resources used by everyone;
– ***"Natural setting"*** and ***"Social setting"*** to represent the various characteristics (structure and dynamics) of the two subsystems (social and ecological) that interact within a territory, especially the feedback loops within and between them;
– ***"Spatial scale"*** and ***"Time scale"*** to consider the various underlying levels of organization or spatial and temporal scales, either to represent ecological or socio-economic processes or produce information at scales that the different stakeholders can understand;

– ***"Disciplines"***, to allow scientists with different approaches, axioms, languages, semantics and methods to take part in the whole IAM process;
– ***"Methods, models, other tools and data"***, to provide the information and methods required to be able to address the other dimensions of integration. This involves two main sub-dimensions: (i) the integration of generic (academic) knowledge and the knowledge possessed by stakeholders (on a more local scale), and (ii) the integration of this knowledge in one or several "models" using a modelling process;
– ***"Uncertainty"***, to consider and provide information about the different sources of uncertainty linked to the various dimensions of integration (this includes the calibration and validation of models). Because this is both quite costly and technical, this dimension is not used as often as the other IAM approaches.

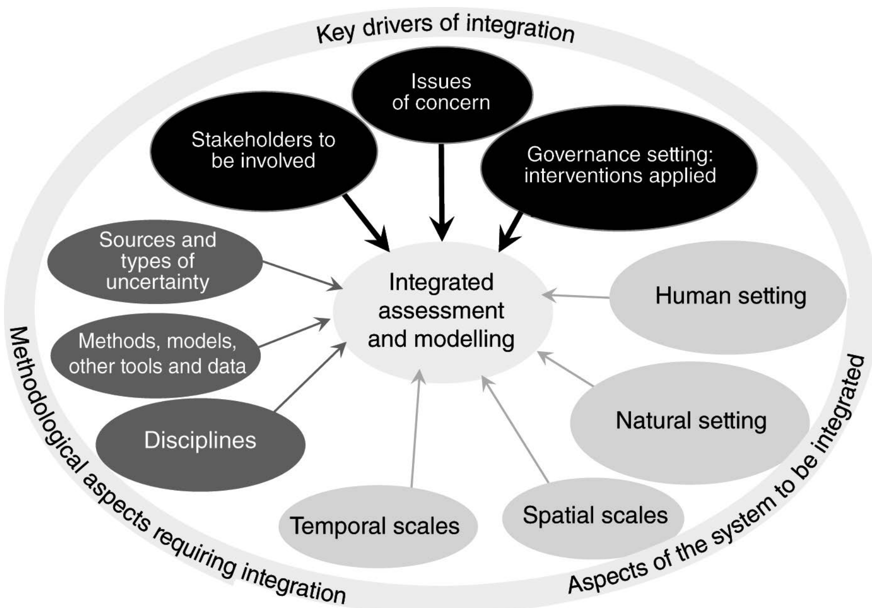

Figure 7.1. The ten key dimensions of *integrated assessment and modelling* (source: Hamilton *et al.*, 2015).

An integrated modelling approach to territories

Although management issues often apply to the territorial level (e.g. watershed), they usually occur within territories (e.g. a stretch of river) and are time-based (they occur over a given period of time). These issues can also be rather heterogeneous. Their frequency and intensity are linked to the interactions between ecological processes (meteorology, hydrology, crop growth) and human activities (resource use and governance) (Therond *et al.*, 2014). In other words, resource management issues occur within a territory because they are related to the "action situations" defined by the stakeholders (McGinnis, Ostrom, 2014). In agricultural systems, these situations include soil and climate conditions, cropping and production systems, individual (equipment, labour) and collective resources (e.g. water), resource governance (e.g. Cooperatives for the Use of Agricultural Equipment (CUMA), water police) and supply chains.

As a result, a prerequisite for modelling an agricultural area to simulate the impacts of individual and collective resource management methods is to have an accurate sense of how this territory is structured (what are the action situations?) (Therond *et al.*, 2014).

Each type of actor has their own action strategies that use different spatiotemporal units. These strategies interact with ecological processes, each of which has its own spatiotemporal dynamics. To simulate the emergent properties arising from interactions between human activities and ecological processes, the diverse social and ecological processes involved, and their interactions, must be represented. This means that there need to be simulations of (i) the impact human activities have on ecological processes, and by proxy, the state of the natural resources, and (ii) the impact this change has on the state of human activities. Therefore, in irrigated agricultural areas, there would need to be representations of the dynamics of water withdrawals, the impact these withdrawals have on water resources and the effect this change in water availability (i.e. the state of resources) has on irrigation practices.

Lastly, to ensure the relevancy of these simulations in terms of decision-making, there is a need to assess the indicators that make sense to the various stakeholders managing the resources at stake. As such, it must be possible to use these indicators to take a good look at these resources on spatiotemporal scales that make sense for each actor. As far as assessments are concerned, the challenge is to be able to assess both the sustainability of these new ways to manage these resources and their resilience to hazards. Consequently, this means that the (average) environmental, economic and social performance levels need to be assessed, as does the resilience of these performances over time (e.g. in years) given the variability in climate, markets and public policies and the related changes in trends.

⏩ MAELIA, an integrated assessment and modelling platform for agricultural systems and farmlands

The MAELIA[12] platform was developed in line with the scientific approach used in IAMs. The goal of this platform is to organize the integrated modelling, design and assessment approaches used for agricultural systems and farmland. The initial purpose of this platform was to address quantitative water management issues in irrigated agricultural areas. Today, the aim is to perform integrated modelling and assessments (IAMs) of agricultural areas and territorialized bioeconomy systems. With this goal in mind, it is used to assess the environmental impacts, ecosystem services and economic and social performance of scenarios pertaining to territorial organization and the management of biomass and natural resource production, processing and recycling systems (e.g. water retention). All this is against a background of climate change, volatile agricultural markets and variability in both agricultural and environmental policies.

The MAELIA platform is based on three main technologies: (i) a multi-agent system (MAS) that integrates (ii) a georeferenced database with high spatial resolution and (iii) a chain of dynamic activity models for humans and ecological processes. MAELIA

12. Modelling of socio-Agro-Ecological systems for Landscape Integrated Assessment (http://maelia-platform.inra.fr/).

was developed as part of the GAMA®[13] modelling platform for building spatially explicit agent-based simulations in a complete development environment using georeferenced data in the form of a grid (raster), vectors or a graph (Taillandier *et al.*, 2014).

Multi-agent architectures can model and simulate the behaviour of human-environment systems that include multiple and different agents acting on their own reasons (decision-making autonomy). It is becoming more common to use multi-agent models as "intermediate objects" in IAM systems to help stakeholders manage resource management issues within a territory. MAS are also particularly useful for simulating spatially distributed biophysical and anthropogenic processes together with the emergent properties and processes arising from the interaction between these processes. Traditionally, MAS are used to assess the impact of scenarios of change having to do with natural resource management rules and stakeholder strategies (Bousquet, Lepage, 2004; Bots, Daalen, 2008; Voinov, Bousquet, 2010; An, 2012). Lastly, it is a type of modelling architecture that represent socio-ecological systems in relatively accessible and transparent way for users. This is because the components of the model (entities and processes) may correspond to the conceptual models developed by experts in the domain (called thematicians), or maybe the stakeholders (Sibertin *et al.*, 2018). In addition, development platforms for multi-agent models typically generally make use of an extensive range of formal definitions for dynamics within the same model (equational, algorithmic, statistical, probabilistic, graph, cellular automata, etc.).

Georeferenced databases with high spatial resolution (*geographic information systems; GIS*) help provide accurate descriptions of a territory's structure and action situations. These databases include several national or regional databases which means that it should be somewhat easy to implement the MAELIA platform in the various geographic areas. For instance, it integrates representations of:
– diverse types of water resources by hybridizing the Carthage® vectors database (DB) (developed by IGN and water agencies) for watercourses, the Topo® DB (IGN) for small bodies of water such as so-called hillside reservoirs (dams), developed by the French Geological Survey (BRGM) for alluvial aquifers;
– soils and climate via the use of data from the Soil Geographic Database for France (at a scale of 1:1,000,000 or 1:250,000) and the Météo France database (8 x 8 km Safran grid);
– topography via the use of the Alti® digital terrain model (IGN) DB;
– parcelling of farmland via the Graphic Parcel Register® (GPR);
– land use by combining data from the GPR and CORINE Land Cover (CLC) database;
– agricultural, domestic and industrial water collection points and wastewater discharge points using the Open Access databases produced by water agencies and Sandre (the French National Service for Water Data and Reference Datasets Management).

Information about these databases and the specific processes used to integrate them can be found on the Maelia website[14]. Information about these databases and the specific processes used to integrate them is available on the Maelia documentation website.

13. GAMA: *Gis and agent-based modelling architecture.*
14. http://maelia-platform.inra.fr/

The modelling chain corresponds to a set of coupled models that provide representations of the ecological dynamics and human activities along with their interactions at daily time-steps spanning several years (e.g. 30 years). The following types of models were selected to facilitate the implementation of the MAELIA platform in numerous different territories: (i) robust models, (ii) models that are relatively simple to recode and understand, and (iii) models that have a calibration process that is not too time-consuming (or possibly data-intensive). As a result, the AqYield soil-crop model (Constantin *et al.*, 2015, Tribouillois *et al.*, 2018) was integrated and expanded by including nitrogen cycles and carbon cycles to be able to model ecological processes (Tribouillois *et al.*, 2020; Misslin *et al.*, 2022). It is possible to represent hydrology using recoded formalisms of the soil and routing phases in the SWAT (Soil and Water Assessment Tool[15]) model. An *ad hoc* module was constructed to represent the hydrology of each reservoir and dam in a watershed area.

The biomass production, processing and use sectors in the bioeconomy can be represented by a "sectors" module that was jointly developed with CIRAD (Recycling and Risk research unit), based on the UPUTUC (French acronym for Production Unit, Transformation Unit, Consumption Unit) model. The UPUTUC model was developed on the French island of Réunion to represent the organic waste processing and recovery sectors. As the research projects progress (see below), operating models for biomass production or processing units (e.g. biogas production, also known as anaerobic digestion) are integrated into this sector module to represent and simulate the dynamics of diverse biomass industries over the long term.

Agent-based models are used to represent human activities, and an agent-based model specifically for farmers is currently being developed. Based on a Belief-Desire-Intention (BDI) architecture, or coupled with CAPFarm (Bareille *et al.*, 2020), the choice of crop rotation systems can be simulated for fields on a farm using specific criteria (e.g. income level and variability, working time and cost of implementing change) and based on the previously made choices that have been memorized by the agent. Within this model, it is also possible to represent crop management strategies using decision rules with "if-then" statements that trigger a technical action (or operation) such as tillage, seeding, fertilization, irrigation, plant pest control treatments, harvesting, etc. Thus, each technical action is represented by a set of decision rules that may depend on the types of soil, previous crops or rotations, farms, soil and climate areas, etc. Operating constraints on agricultural holdings are also considered. As a result, because each technical action for each field lasts a certain amount of time (depending on how quickly the work can be carried out), this means that each action on the field is spread out over time depending on the available workforce and equipment, the soil to be worked and the weather conditions while the actions are being carried out. Moreover, the actions are carried out in such a way as to limit movements between the various fields to be worked. Specific instructions are also given on which technical action and which competing resource (e.g. water) to prioritize. Consequently, regardless of the size of the area being simulated (e.g. from a farm holding to several thousand square kilometres), in MAELIA, each field on each farm has its own specific dynamics, and these dynamics depend on the characteristics of both the field itself and the farm on which it is located. For this reason, it is possible to simulate the specific biogeochemical cycles for a specific field and to use statistics to extrapolate these results over longer temporal and spatial scales.

15. https://swat.tamu.edu/

The behaviour of the other stakeholders, such as low-water support dam managers, water police or processing unit managers, are represented using the same logic, mostly “if-then” rulesets.

In summary, the MAELIA platform can be used to configure diverse factorial or multi-factorial scenarios pertaining to climate, the price of agricultural products and inputs, agricultural and environmental policies, the type and distribution of cropping systems and resources (e.g. water), sectors and stakeholder (farmers and others) management strategies (Figure 7.2). MAELIA can then simulate these scenarios over a series of years and assess the indicators for the intra- and interannual water level and variability (resilience/vulnerability), nitrogen and carbon cycles (ecosystem impacts and services), yields, semi-net margin, amount and type of work, material flows, state of the water resources, duration and intensity of usage restrictions, etc. over various scales (e.g. from fields to resource management units to territories).

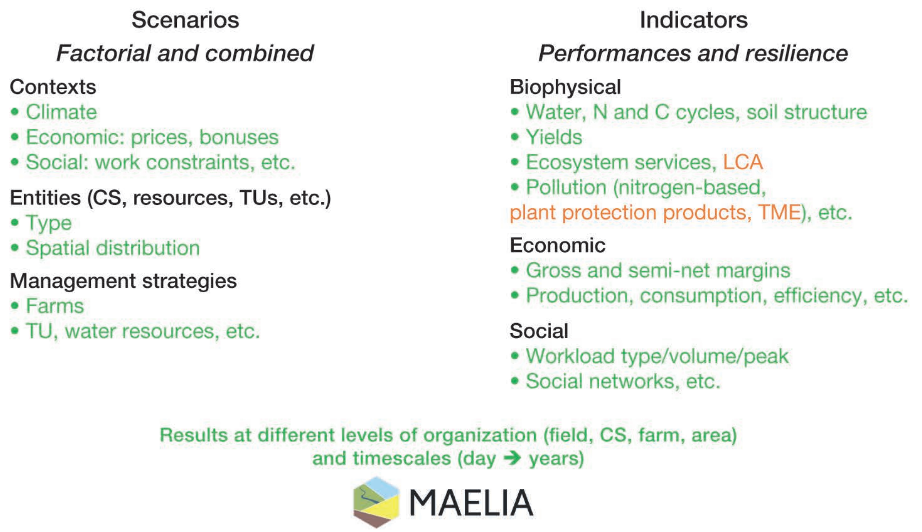

Figure 7.2. Types of scenarios that can be simulated in MAELIA and types of available assessment indicators based on their progress. Green = operational, orange = being developed. CS: cropping systems. TU: biomass transformation unit (e.g. biogas plant). LCA: life cycle analysis. TME: trace metal elements. N: nitrogen. C: carbon.

⏩ MAELIA, supporting dynamics in several application areas

MAELIA’s assessment and modelling capabilities have increased as research projects have progressed. Currently, it can address the specific range of key sustainability issues and levers applicable to farmlands and territorialized bioeconomy systems (Figure 7.3).

Territorial water management

The MAELIA platform is one of a few platforms that can accurately represent the spatiotemporal dynamics and interactions between the four water management subsystems: resource systems, resource units, user systems and governance systems (e.g. water police).

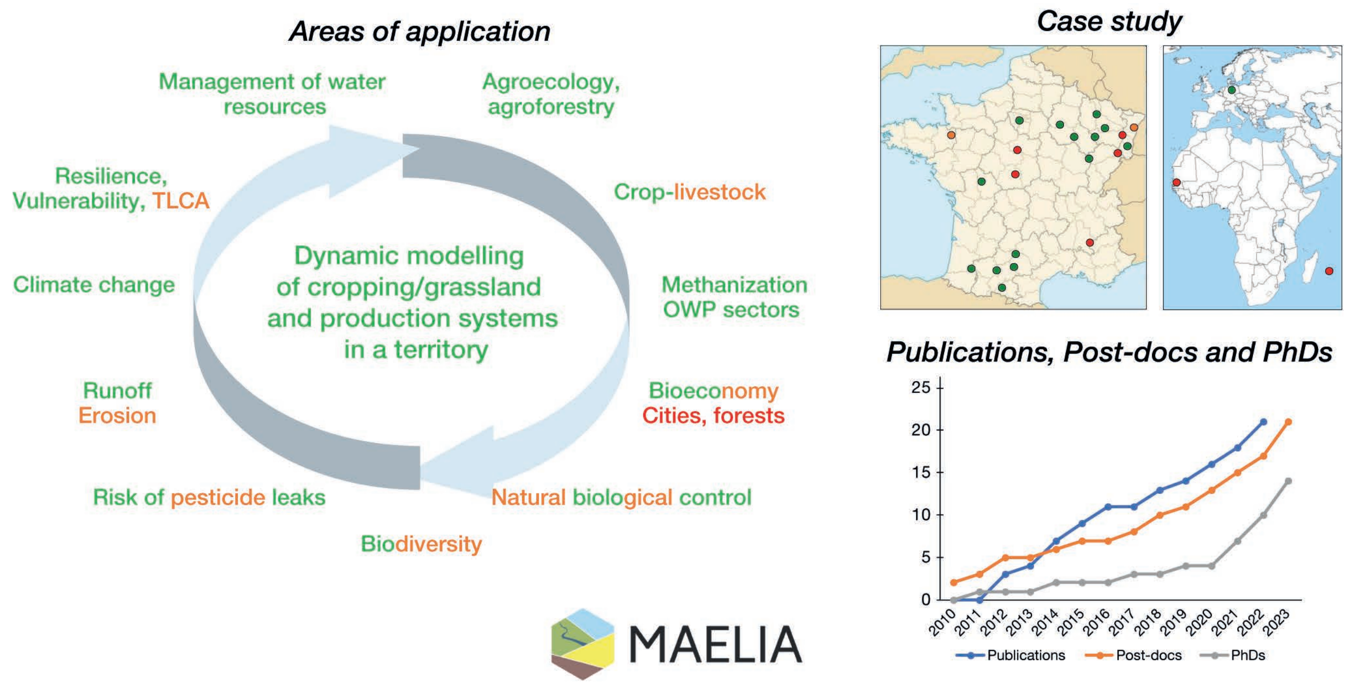

Figure 7.3. Diagram of the integrated assessment and modelling areas in the MAELIA platform (on the left), and map of the case studies (upper right) based on their progress status with colours ranging from green (operational) to red (being developed), and number of publications, post-docs and theses using MAELIA over time (lower right). OWP: organic waste products, TLCA: territorial life cycle analysis.

Specifically, MAELIA can employ high spatial and temporal resolutions to model the interactions between agricultural activities, domestic and industrial waste collection, the hydrology of the various water resources (watercourses, aquifers, hill reservoirs, dams), dam releases and usage restrictions within watersheds (from tens to thousands of square kilometres).

Clément Murgue (2011-2014) and Sandrine Allain (2015-2017), in their respective doctoral theses, showed that MAELIA can be used in a multi-actor system to design and assess territorial organizations of agricultural activities with an aim to reduce the occurrence of quantitative water management crises. By using MAELIA, these interactions can shed light on present-day water management issues and provide information that is considered relevant, credible and legitimate by local stakeholders in the lower Aveyron basin (Tarn and Garonne). For instance, simulations in MAELIA demonstrated that, for this basin, strategies that optimize irrigation or modify crop rotations are more effective for reducing water shortages than those that create alternate reservoirs.

Agroecological transition

Following on the work focusing on water issues, the capabilities of MAELIA were extended to be able to also assess the performance of agroecological systems. Within the framework of the Bag'ages project, MAELIA was used to assess the impact of catch crops (CC) and diversified crop rotations on green and blue water flows in watersheds (Figure 7.4). Here, the question is whether the use of intermediate cover crops can limit blue water flows to hydrosystems during the two recharging periods: autumn and spring. The use of MAELIA provided an initial first reply: there seems to be less risk than expected in the basin studied (Tribouillois *et al.*, 2022). As this was a somewhat basic and generic answer, a 2-year project, funded by the French Biodiversity Agency (OFB) was launched in 2023 to roll out MAELIA for the purpose of assessing the impact of these cover crops on contrasting territories in France.

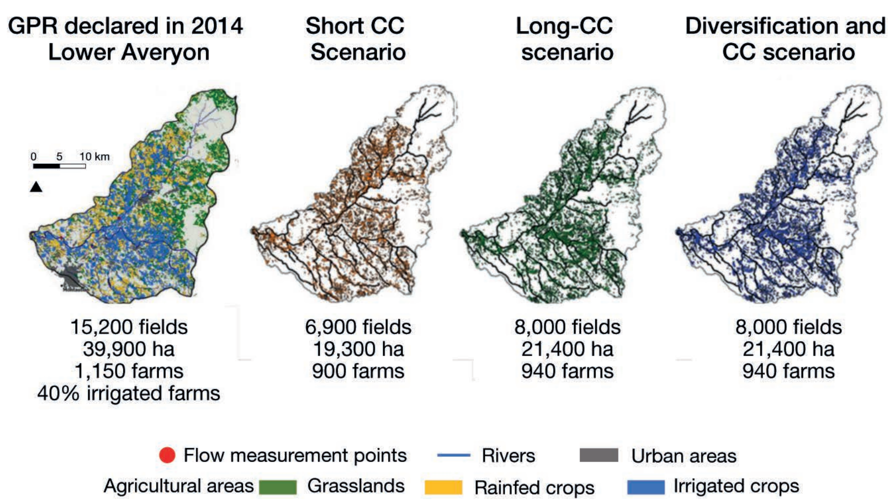

Figure 7.4. Spatial representation of land use in the lower Aveyron basin (south-western France) in 2014 and three scenarios for the use of short-term or long-term catch crops (CC), potentially combined with diversified crop rotations. GPR: graphic parcel register.

MAELIA's capabilities were then expanded to assess the effects of crop system diversification on a broad range of indicators in both France and Germany (H2020 DiverIMPACTS project). In the Vendée department, MAELIA was used to assess the performance of regional crop-livestock system scenarios (Catarino *et al.*, 2021). In Saxony, Germany, MAELIA was used to assess the impact of scenarios that introduce catch crops and crop diversification on water quality, GHG emissions and the socio-economic performance of farm holdings.

Meanwhile, the PotA-GE project coordinated by the Silva Joint Research Unit (UMR in French), allowed for an agroforestry module to be integrated within MAELIA. This was used to assess the impact of the use of these systems on water cycles within territories. Further work will be carried out to take account of the nitrogen and carbon cycles as well as to represent the impact of hedges on these cycles (within the framework of the Tetra'haies project coordinated by the Fare Joint Research Unit).

Ecosystem services and biodiversity

Based on its capacity to simulate organic carbon dynamics in soils and a full GHG balance, the MAELIA platform has been named one of the five tools that can be used for "low carbon" labelling in field crop farming systems.

Furthermore, several new projects have started with an aim to develop simulation models for the natural biological control (biocontrol) of crop pests using the natural enemies of said crop pests at the landscape scale. As a first step, Nirina Ratsimba's thesis (2016-2020) summarized what was known about this at the time and was then able to introduce both the conceptual groundwork and the first building blocks for this type of modelling in MAELIA. Following on this, research on biological regulation modelling enabled the development of a generic module that can be used to simulate crop-pest-disease-beneficial insect food chains. Within the framework of the French National Plan for research and innovation (PNRI), this model will be used to assess landscape management scenarios to better control aphid populations naturally, reduce the pressure of beet yellowing disease and, as a result, reduce the use of chemical pesticides.

More recently, several projects have been started to take account of the impact of agricultural systems on biodiversity. As part of an Interreg project and in collaboration with the French national radioactive waste management agency (Andra), the goal of Abdelhak Rouabah's post-doc (2022-2023) and Camille Gay's thesis (2021-2024) is to develop a model that simulates the various relationships between landscapes, agricultural systems and several groups of pollinators. These works endeavour to integrate models into MAELIA that can assess pollinator abundance and diversity, two issues in the conservation of animal diversity and a powerful determinant of wild plant diversity. Lastly, in collaboration with the Tour du Valat research institute, Rose Rodier started her thesis in late 2022, which involved using MAELIA to model and simulate the relationships between agriculture, water management, climate change, ecosystem services and biodiversity (birds and fish) in the Camargue wetland (southern France).

Resilience and territorialized life cycle analysis

Manon Dardonville's work in her thesis (2018-2021) helped create state-of-the-art methods for determining the resilience, vulnerability or robustness of agricultural systems and to help develop methods that can be used to assess them. These methods are now part of MAELIA and are currently applied to assess the resilience of ecosystem services and the socio-economic performance of crop-livestock systems against a background of climate change. Simultaneously, a collaboration was initiated with Éléonore Loiseau (ITAP Joint Research Unit) to include life cycle indicators in MAELIA, which would allow this platform to be used in the field of spatialized LCA.

Territorialized bioeconomy systems and carbon neutrality

During the EIP-Partage project, coordinated by the Regional Chamber of Agriculture Grand Est, the SYS-metha biophysical model for biogas production (Bareha *et al.*, 2021) was integrated within MAELIA and applied to various case studies in the Grand Est region (France). As a result, MAELIA is one of only a few tools that can use an integrated assessment approach to agricultural biogas production projects that depict the dynamics of and interactions between agricultural systems and a biogas plant[16]. Additionally, in partnership with Andra, there is an ongoing project to assess territorial bioeconomy scenarios on the Perennial Observatory of the Environment (OPE) terrain (Cigeos site). The aim of the LEGUMETHA project (2023-2025), funded by the GRDF, is to explore the potential of the combined use of pulses and biogas production to improve nitrogen autonomy on farms and their carbon footprint.

Lastly, the aim of the FairCarboN PEPR (Priority Research Program and Equipment) project Slam-B[17] (€6.5 million, 2023-2028) is to develop new functionalities for the MAELIA platform so that it becomes an operational and generic tool for assessing low-carbon strategy scenarios and territorial bioeconomy scenarios. MAELIA will be applied in six living labs (also called scenario labs) in mainland France (in partnership with the CNRS), on the island of La Réunion (CIRAD) and in West Africa (IRD and CIRAD). This ambitious project involves over 40 research units and roughly 100 permanent scientists. It will enable the integration of the following models in MAELIA: biorefineries, livestock farms, demography, forest growth and management, urban metabolism and socio-economic indicators used to measure sector performance, etc. Additionally, a new version of MAELIA will be developed and applied all throughout France so that stakeholders such as ADEME will have a tool for planning agriculture and the bioeconomy at this scale. Thus, the objective of the Slam-B project is to render the MAELIA platform much more accessible so that it can address challenges associated with the territorial bioeconomy. Therefore, this platform will be considered a key tool in this subject area, both in France and internationally. Slam-B will provide work for many post-doc and PhD students.

⏩ MAELIA, streamlining research and supporting agriculture and bioeconomy actors

Given the recent increase in the number of partners involved in the MAELIA project, a “MAELIA development contributors’ club” was created in 2016. The goal of this club is to make it easy to share information about the progress made with MAELIA

16. Cf. https://www.inrae.fr/actualites/methanisation-au-coeur-territoires.
17. Scenarios Labs and Integrated Assessment Modelling for Bioeconomy Development (targeted project no. 2 of the FairCarboN PEPR).

and its growing network and new collaborations between the members of the various projects. In 2016, this club included 15 people from ten academic and non-academic organizations. Today, it counts over 60 people from close to 30 different organizations[18]. It should grow even larger with the launch of the Slam-B project (see above).

Simultaneously with the scaling up of research activities (starting in 2014, relating to water issues, but especially from 2018 onwards in diverse fields), various public and private actors have repeatedly, and with ever more pressing need, been asking to use or be able to apply MAELIA to their own projects. This resulted in the creation of the start-up MAELAB[19] in July 2021 to support this increasing demand to use the platform which, as advised by ADEME, was no longer being managed by academics. MAELAB is responsible for exploiting MAELIA's potential in the economic sphere in addition to providing support to research projects that are using the MAELIA platform.

⏩ Specific features of the MAELIA platform

The MAELIA platform is presently one of the rare modelling platforms that can effectively simulate the spatial and temporal dynamics of production systems and agricultural biomass processing and recycling sectors that interact with water resources within a territory. It should be noted that other equivalent platforms have been developed by geographers or economists, however their assessments of agricultural matters are not as accurate or fine-tuned as MAELIA. The MAELIA platform was jointly developed by agronomists and computer scientists and, as such, can use daily time steps to represent and simulate the impact of the biophysical and sociotechnical characteristics of numerous production situations (pedoclimates, crop sequences and management) as well as agricultural biomass processing and recycling sectors on water resources and biogeochemical cycles within territories.

MAELIA can be used to assess the level and resilience of a broad range of environmental and socio-economic performances for farms and sectors within a wide variety of scenarios of change in cropping systems, biomass processing and recycling sectors along with water resource management methods affected by climate change.

MAELIA uses artificial intelligence (MAS) and data science to support stakeholders as they plan ahead for agroecological and bioeconomic transitions adapted to the specific characteristics of each territory and to climate change. As such, MAELIA can structure and help with the integrated design and assessment of scenarios that deal with the organization of territorial biomass industries, i.e. develop a territorialized bioeconomy system.

Over the years, MAELIA has been able to integrate generic knowledge on socio-agroecosystems from an extensive range of disciplines and also local stakeholder knowledge regarding certain case studies. Under a "free licence" (GPLv3), MAELIA is part of INRAE's open science initiative.

18. INRAE JOINT RESEARCH UNIT (UMR): Agir, Absys, Agronomie, Bagape, Dynafor, Ecosys, EEF, Fare, G-EAU, LAE, Lessem, Lisah, Miat, SAD-APT, SAS. Other research partners: GET, Irit, JRC, Cirad, Tour du Valat, Engees. Other partners: Arvalis, Terres Inovia, Idele, Veolia, CACG, AgroTransfert-R&T, Rittmo, CRA-GE, French Chambers of Agriculture.
19. https://www.maelab.fr/

⏩ MAELIA to support territorial foresight approaches

The MAELIA platform was developed with an aim to improve foresight approaches, by developing exploratory scenarios, so they can identify one or several territorial organizations that meet the territorial stakeholders' local and global targets.

In line with this, this platform is being used more and more often to respond to the requests made by territorial authorities (Région, intercommunal entities, etc.), Chambers of Agriculture, government agencies and services (ADEME, Water Agency, the French Biodiversity Agency, DRAFF, DREAL, etc.) or cooperatives to deal with issues surrounding the territorial organization of agricultural activities and bioeconomy sectors in a context of climate change. Additionally, starting in 2025, it will also be used to help stakeholders in the Bourgogne-Franche-Comté region carry out their ecological planning for agriculture and the bioeconomy. Besides providing regional stakeholders with support, this exercise is meant to demonstrate (proof of concept) the benefits of this type of integrated assessment and modelling platform with regard to ecological planning for biomass sectors in France.

Chapter 8

Assessing the multifunctionality of livestock grazing systems within territories: examples from the Sahel and South-East Asia

Alexandre Ickowicz, Mélanie Blanchard, Vincent Blanfort, Jean-Daniel Cesaro, Christian Corniaux, Arona Diaw, Bernard Hubert, Jacques Lasseur, Huyen Le Thi Thanh, Jean-Pierre Müller, Liz Wedderburn

⏩ Introduction

Livestock grazing systems (LGS) are systems in which 90% of ruminant diets are made up of forage grazed from native (i.e. natural) or cultivated grasslands, according to the FAO and International Livestock Research Institute (ILRI; Robinson *et al.*, 2011). LGS play a significant role in livestock production as they account for 39% of global domestic ruminant numbers, and 30% of animal derived proteins (Mottet *et al.*, 2017; Mottet *et al.*, 2018). One and a half billion hectares of land usually unsuitable for cropping due to poor rainfall, soil fertility and topography are utilized by LGS, i.e. 54% of the total land area. A large part this land (28 million square kilometres) is found in desert or marginal xeric shrublands areas (ILRI *et al.*, 2021). Most of these systems depend on the mobility of both livestock and people (socio-ecological systems) as they take advantage of the spatial and temporal variability in forage production throughout the year. These mobile systems rely on natural resources and processes such as existing fodder, water resources, livestock manures and the significant human capital involved. LGS and livestock management have a large land footprint, which affects the ecosystem dynamics. In turn, this leads to a wide variety of functions for the environment and human well-being at different scales and in a variety of dimensions (production, economic, cultural, environmental, local development, etc.). These functions are not always taken into account when assessing the impact of LGS, although there have been attempts to take a whole-system approach using the "Ecosystem Services" framework (Huang *et al.*, 2015). When the various functions, especially the positive impacts, of LGS within the three pillars of sustainability are underestimated, the results could be land policies (access to resources), economic policies (value chains, infrastructure), environmental policies (climate, water management, biodiversity) and/or social policies (provision of services) that are inimical to the development of these livestock farming systems. The numerous discussions that took place during the UN Food Systems Summit in 2021 have confirmed that food systems are now a global issue and that livestock farming models in industrialized countries cannot be seen as the only solutions for the rest of the world. In this chapter, we look at LGS, which is defined much more broadly here than it is by the FAO, within a conceptual framework for multifunctionality that highlights the numerous functions arising from LGS. We also document the results of its implementation in two situations in Vietnam and Senegal. The assumption is that the numerous functions of LGS described here are needed for a fairer and more balanced assessment of the role of these livestock systems in sustainable food systems and can be used to integrate LGS in better balanced foresight scenarios for a more sustainable livestock sector.

⏩ Why apply a multifunctionality concept to livestock grazing systems?

Current methods of assessing the distinct functions of LGS oversimplify and underestimate their impact and are limited in their capacity to simultaneously consider multiple intertwined dimensions and the ways they interact. We hypothesized that using the "multifunctionality in agriculture" concept which was developed during the 1990s (Cnued, 1992; Hervieu, 2002a and 2002b; Caron *et al.*, 2008; Huang *et al.*, 2015) is a better way for carrying out a more thorough assessment of the different functions of LGS and identifying possible trade-offs between these functions by helping the stakeholders involved to better envision desirable futures for livestock farming within territories. By using this methodological approach to multifunctionality (MF), we try to demonstrate that LGS play a significant role in the development of sustainable food systems throughout the world. MF accounts for the diversity of functions needed to assess the impacts of agriculture at local, regional and international scales and particularly production performances, the economy (employment, infrastructure and services development, financial flows, etc.) and the environment (landscape management, GHG emissions, soil fertility, biodiversity and nutrient flows, etc.). Given their large land footprint, from local to global scales, LGS have major impacts on ecosystem dynamics (biodiversity, nutrient cycling, land degradation, etc.) and climate change (GHG emissions, carbon sequestration) (Steinfeld *et al.*, 2006). LGS also support large social groups and populations all across the globe (ILRI *et al.*, 2021), providing revenues, livelihoods and both social and cultural assets.

In this regard, the MF framework has been adopted by the Action Network "Restoring Value to Grasslands" within the Global Agenda for Sustainable Livestock (GASL), a global multi-stakeholder partnership (https://www.fao.org/partnerships/livestock-dialogue) and is considered a viable approach for use with multiple stakeholders to describe, evaluate, discuss and promote the various functions provided by LGS. This MF framework is perfectly in line with the global framework for the Sustainable Development Goals (SDG) proposed by the United Nation's (UN) 2030 Agenda for Sustainable Development, as the multiple functions of LGS relate to at least eight SDGs out of the existing 17 (1: no poverty, 2: zero hunger, 5: gender equality, 6: clean water and sanitation, 8: decent work and economic growth, 12: responsible consumption and production, 13: climate action, 15: life on land). Lastly, based on the contribution of LGS to the emerging issues with developing sustainable food systems (SFS), as discussed during the UN conference in September 2021, the MF framework will be used to identify the key functions for the main principles supporting SFS: food availability, easy access to food, food security, food quality and environmentally friendly.

⏩ Building a multifunctional conceptual model to support the dynamics of local livestock grazing systems

A multi-party participative modelling approach was developed to incorporate a wide variety of contexts and perceptions within a common framework to analyse the diversity of global LGS contexts (Ickowicz *et al.*, 2022).

The participants included researchers from a variety of disciplines related to LGS from seven different countries (Argentina, Brazil, France, Mongolia, Senegal, New-Zealand, Vietnam), along with businesses from the agri-food sector, farmers and policy makers. An iterative approach was applied to ensure the robustness of the framework, consisting of: (i) a literature review that created the base platform for building the conceptual model during the first workshop (May 2016); (ii) this was followed by interviews with ten French farmers, and later with local stakeholders in five different countries (iii); two additional workshops (July 2016, December 2017) held with several rangeland experts focused on clarifying the definitions, discussing the structure of the conceptual model and testing its robustness against a set of defined indicators so that the impact of livestock could be assessed from various different viewpoints. There are four dimensions (productive, social, local development and environmental) in the resulting conceptual model (CM) for LGS multifunctionality. Various different entities (farmers, livestock herds, pastures, products, atmosphere, water, infrastructures, organizations, etc.) are at work within these dimensions through a number of various processes (trade, food supply, production, consumption, construction, retail, etc.), and are described using Unified Modelling Language (UML) together with their related indicators (Figure 8.1 and the indicators described in the case studies and in Table 8.1).

By building a CM, the behaviour within each dimension as well as the interactions between both the dimensions and the functions can be explored. Therefore, users of the model can explore how changes in the behaviour of any of the entities influence the interactions within and between the dimensions and functions. For instance, “Livestock” (Figure 8.1) contributes to all four dimensions but has distinct functions depending on the dimension: milk production, GHG emissions, income generation and the provision of cultural assets. When a change is made to livestock management methods, the livestock-related functions are also changed as well. This makes it possible to analyse the interactions between the various functions in each dimension. The same process can be described for entities such as “Farmer”. This then allows users of the CM to determine the different outcomes and to then render transparent the resulting trade-offs that may need to be explored. Starting in 2017, the CM has been applied to the various case studies listed below. The model was also improved with the application of the CM in the field.

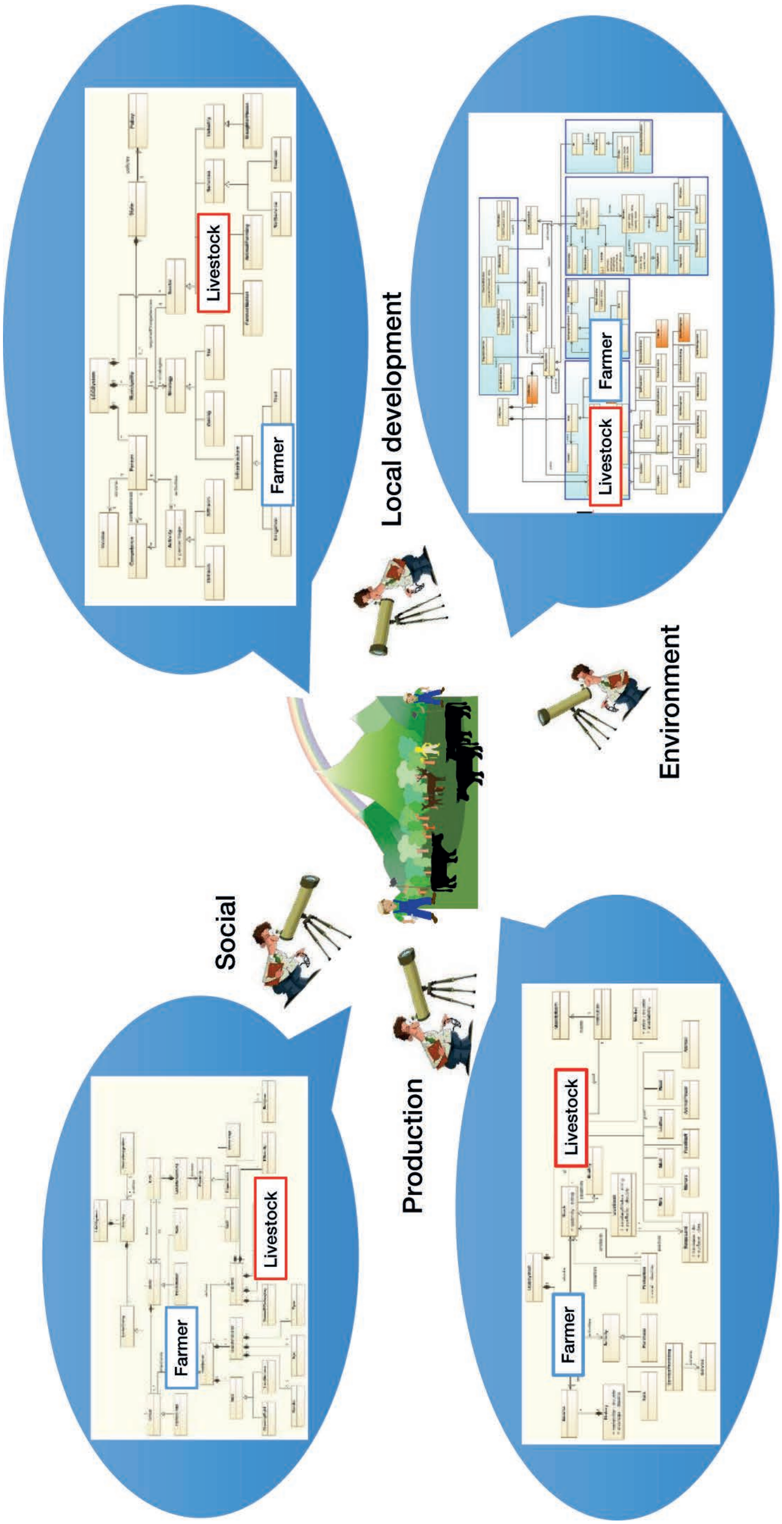

Figure 8.1. Construction of a multifunctionality conceptual model for livestock grazing systems, organized into four dimensions made up of entities, processes and indicators (source: Ickowicz *et al.*, 2022).

Table 8.1. Variety of contexts, challenges and outcomes to which the multifunctionality approach of livestock grazing systems was applied within the GASL LGS "Restoring value to grasslands" network (Ickowicz *et al.*, 2022).

Case	Usefulness of the multifunctional (MF) approach
Argentina, Puna	It was possible to explore the resilience and adaptability of the Puna herders at the household and community level by applying the four dimensions. The successful implementation of the approach involved a multidisciplinary team, which was not the norm in this context, thus strengthening the capacity to address such complex socio-ecological issues.
Brazil, Maranhao	Exposing a range of stakeholders, including students, farmers, and agri-food businesses, to a holistic analysis of the silvopastoral system using the MF approach had a positive impact on the adoption of agroecological practices by farmers. The students gained a better understanding of the complexity of the system and how it functions.
Senegal, Ferlo	The construction and use of a simulation model based on the MF approach has helped to facilitate dialogue between stakeholders to find solutions for sharing resources and finding synergies between the actors.
Mongolia, Bulgan	It was key to develop local indicators to ensure the relevance of the MF approach. In this case, the four dimensions were not equivalent, with greater emphasis placed on the social and environmental aspects. The approach was appreciated by planners for its contribution to policy development.
Vietnam, Dien Bien	The MF framework facilitated the dialogue between the stakeholders based on common indicators showing the complementarity of the different agricultural systems for the sustainable growth of the territory and for achieving the food supply objective for the population.
China, Tibet	The MF approach has shown that the Kobresia grasslands are a cultural landscape where, today, nature and society interact with each other to the benefit of the environment and the well-being of people.
France, Paca	The MF approach helps identify the main relevant LGS dimensions questioned by the local actors to improve the sustainability of the local socio-ecosystem. It also encourages the emergence of a local mechanism used to establish dialogue and to identify levers so that the various systems can evolve simultaneously over the medium term.

⏩ Case studies using a multifunctionality approach to livestock farming in Vietnam and Senegal

Amongst the other cases studied within the GASL Action Network "Restoring Value to Grasslands", the cases documented below illustrate how the multifunctionality framework has been applied using different tools and methodologies to a variety of contexts and issues relating to the sustainable development of LGS around the world.

Agropastoral dairying system in northern Senegal: considering the multifunctionality of milk production in a semi-arid environment

Context

Milk production in Senegal is primarily based on pastoral systems (Corniaux *et al.*, 2012). However, this production is too seasonal and dispersed to guarantee that dairy industries will receive substantial supplies. As a result, local industries collect very little of the local milk production; most prefer to use imported milk powder, mainly due to the lack of competitiveness of local milk, which is still an extremely expensive raw material. In northern Senegal, the local milk sector in the department of Dagana has been rather buoyant due to the development of an industrial dairy plant that uses local milk in 2007 (Bourguoin *et al.*, 2018). This business is subject to seasonal instabilities and strong inter-annual variability in production. The Dagana milk innovation platform (PIL), created in late 2014, brings together all the stakeholders involved in the local milk value chain (breeders, farmers, collectors, processors, NGOs, public institutions) to work on scenarios for the sector's development. Since 2018, there have been discussions on how to intensify milk production in an environmentally sustainable manner based on local agricultural and natural resources. The aim of this work is to better understand the local potential for milk production by adopting an analytical approach to the multifunctionality of this sector based on the Sahelian pastoral system.

Materials and methods

Based on the MF conceptual model, this work involved constructing a computer simulator together with PIL stakeholders that can model zootechnical, ecological, agricultural, socioeconomic and geographical parameters (Delay *et al.*, 2021). This model reproduces the production conditions of livestock farmers in the Sahel Belt who live near (within a radius of 50-60 km) a river used to irrigate intensive agriculture on its banks. During workshops, stakeholders were able to put forward various hypotheses on the organization of the sector and to discuss the constraints of each type of stakeholder. A first workshop for the general public focused on the role of biomass flows in the sustainability of pastoral dairy systems. A second workshop focused on the organization of the milk collection system with local stakeholders in an aim to have better efficiency and social inclusion.

Results

It was estimated that the milk potential of the Richard-Toll dairy basin was between 2,000 and 10,000 litres/day depending on the season and according to three levels of productivity: pure pastoral, intensified pastoral and intensified pastoral with livestock stalling (Cesaro *et al.*, 2020). During discussions in the workshop, the stakeholders considered that these estimated potentials were credible because they were sufficiently close to the reality on the ground (collections varied between 3,500 and 9,500 litres/day between 2018 and 2021), while taking local fodder resources into account. To this end, to meet the objective of efficiently and sustainably exploiting the milk potential, there must be cooperation between stakeholders from various sectors (rice, sugarcane and milk). However, the rules for access to agricultural by-products by livestock farmers must be discussed between the various stakeholders so that biomass can circulate within the whole territory. The maximum scenario estimates a material flow of 4,000 tons of dry fodder (rice straw and sugar cane) and 2,000 tons of agricultural by-products (rice bran). Moreover, dairy intensification may also ensure fairness in the allocation of natural and economic resources between groups of herders and have social (concentration of resources) and environmental consequences (concentration of herds and therefore the livestock manures produced and grazing pressure). Intensive pastoral land use produces between three and four times more milk than a traditional pastoral system but need eight times more inputs. Cattle reproduction is also three times higher in intensive pastoral land use than in traditional systems. This new distribution may increase the differentiation between herders living near agricultural areas and those living in sylvo-pastoral areas. During the workshops with various stakeholders, several indicators that can assess the impact of the various development scenarios for the milk sector were identified in the four dimensions (see Figure 8.2). Most of these indicators, especially in the environmental and social dimensions, still need to be further developed in the field (household resiliency, food security, nutrient and GHG flows, etc.).

Conclusion

By using the concept of multifunctionality (Ickowicz *et al.*, 2018) during the simulation workshops, stakeholders were able to see what levels of interdependence should be considered to achieve the sustainable dairy intensification scenarios and to better grasp and understand the points of view of the other stakeholders in the territory as well as where compromises could be made. Here, the conceptual and simulation models were used to compare the stakeholders and selected indicators, using predetermined technical intensification options proposed upstream by livestock farming technicians (type of farms, biomass management, livestock feeding). One priority input discussed between the stakeholders had to do with biomass flows linked to feeding livestock; later, other social and environmental indicators were added to the list of concerns. The environmental dimensions, especially related to climate change, were driven more by agro-industries that were worried about their impact and image (use of renewable energy such as biomass, carbon footprint), whereas the socio-economic dimensions (food security, income, jobs) were driven more by the herders. As a result, compromises needed to be made, particularly for the use of residual biomass from agro-industries, as an example.

Livestock grazing system in the mountainous Northwest Vietnam as a sustainable option for local development

Context

In the mountainous region of Northwest Vietnam, small livestock holdings are largely dependent on natural pastures for feeding animals (cattle, buffalo). However, livestock grazing systems (LGS) are not sufficiently productive enough to meet the increase in national meat consumption to reduce reliance on imports and to ensure a sufficient income for the stakeholders in the value chain stakeholders, thereby helping to reduce poverty. Livestock farming competes for space and resources with other economic activities (fruit and forest plantations) or conservation of the environment (forest protection). Consequently, these systems still receive little support from the local authorities and are not considered in livestock development strategies. If the multiple functions of livestock grazing systems in mountainous regions were to be reconsidered at the landscape level, this could change the assessment of their role in local sustainable development strategies by changing how the various territorial stakeholders see the impact of livestock farming.

Materials and methods

Based on the example of livestock farms in Quai Nua commune in the Dien Bien Province, this study was able to estimate the impact of multiple LGS contributions on the sustainable development of farms and territories. In this mountainous commune, extensive grazing systems coexist with livestock systems undergoing intensification using trough feeding, forage production and fattening systems. This approach involved identifying indicators of the multifunctionality framework in the four dimensions covering the herd, farm, community and landscape in addition to services and the value chain (Figure 8.2). The indicators were identified and used in discussions on how LGS contribute to sustainable development with a wide range of local stakeholders (livestock farmers, agricultural extension personnel, representatives from the livestock cooperative, stakeholders in the beef value chain).

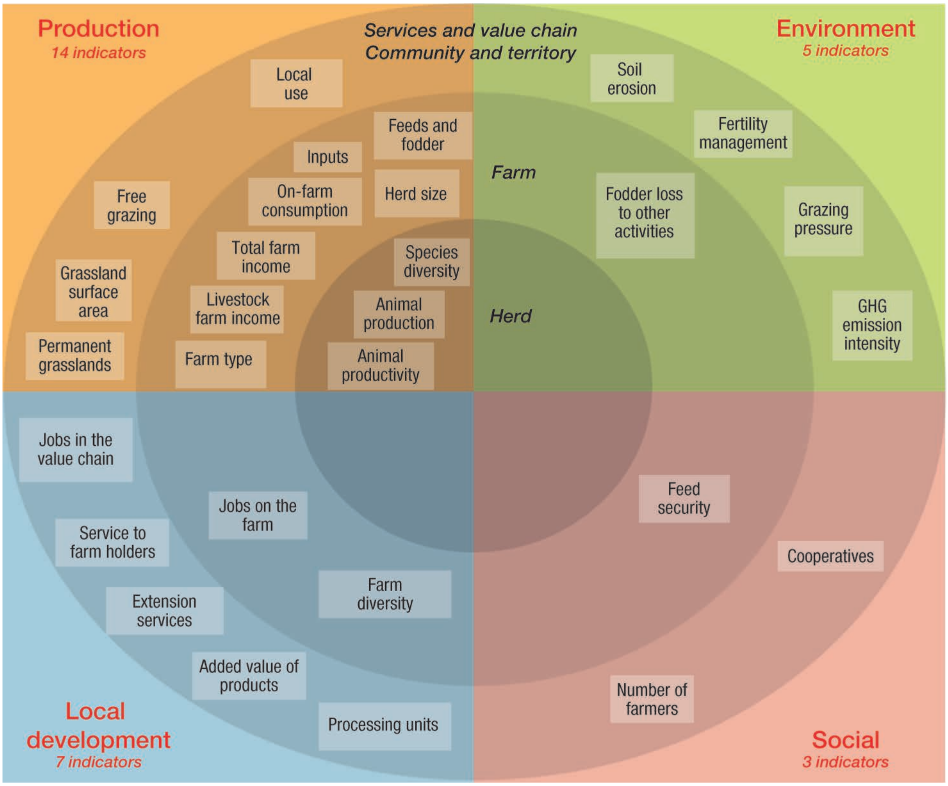

Figure 8.2. Participative and multi-stakeholder definition of the indicators over three levels (territory, farm, herd) to analyse the multifunctionality of livestock farming systems in the Quai Nua commune in Vietnam.

Results

This study produced references on the contribution of LGS to sustainable development in the Quai Nua Commune. With regard to the *production dimension*, livestock grazing systems produce roughly 49% of cattle and approximately 48% of beef in the beef value chain (fresh meat, meat meal and dried meat, typical for this region). For the *environmental dimension*, LGS support organic soil fertility and productivity of cropping systems by providing roughly 18% of manures produced in communes. The remainder comes from zero-grazing livestock (permanent stalling). It has not been possible yet to assess the contribution of these systems to landscape management. LGS contribute to *local development* with 11% of the beef value chain actors' profits (collector, slaughterhouse, restaurant and meat processor). Other profits come from more intensive livestock systems and monogastric livestock; 66% of farm labourers are directly linked to these systems. However, even though consumers show a preference for meat from grazing systems, a differentiated marketing approach has not been used for the products from these systems. It was possible to identify different points of view using the MF framework. Livestock farmers emphasize the importance of income and low input production practices. *In terms of the social dimension* of these systems, farmers underscore the importance of the social links that exist between farmers who practice grazing methods (taking turns supervising animals at pasture). Lastly, in addition to their function as a savings account (with potential accidents or planned events in mind), these herds also fulfil certain basic roles during social events (weddings, funerals, etc.). Agricultural extension agents explain that LGS provide jobs in a region that does not have many employment opportunities, thereby contributing to the livelihoods and living standards of the population. Even though these systems clearly help alleviate poverty, the other stakeholders in the beef value chain are still concentrating on the production of meat and quality products.

Conclusion

These discussions underline the complementarity (described by the territorial stakeholders) between the contributions of livestock grazing systems and both production and the economy, in addition to the social dimension and local development within the province. Grasslands are essential for feeding animals and they simultaneously significantly contribute to meat production, job creation, incomes and profits all throughout the beef value chain, as well as to help to make the best use of the natural resources within the territory. To be able to describe, share and jointly develop this integrated view of livestock farming within the region, it would be important to make sure that there is a visible, logical and sustainable approach to the management of grasslands as well as its contribution to the sustainable development of territories interacting with other activities that are sometimes more profitable and economically visible.

Transversal multifunctionality analysis

The strength of this approach lies in the fact that the common multifunctionality framework can be applied to wide-ranging international contexts. Table 8.1 provides a summary of the cases, various contexts and issues used by the network to develop this approach (including the Senegal and Vietnam case studies).

Creating a space for dialogue and a process for multi-stakeholders to hear, respond and decide. In all the case studies, the MF framework provided a common language and forum for explicitly showing the worldviews of the various stakeholders with an aim to achieve a shared understanding of the issues, prospects for public action and adoption of concerted management practices. This was facilitated by defining local indicators that were allocated to each of the four dimensions in the MF framework so that the context and the stakeholders' diverse worldviews could be taken into account. In order to identify a wide rage of indicators, it is necessary to resort to using a series of qualitative and quantitative methods so as to obtain a baseline. Then, the impact of the public policy and resource management choices made need to be assessed.

A conceptual model of multifunctional LGS that can be applied to a variety of contexts. The case studies show that the MF framework is operational and relevant for a variety of contexts and issues. The processes and tools developed and designed were just as varied as the workshops, brainstorming sessions, surveys, participatory films, action research processes and participatory simulation models to analyse and identify the four dimensions, their entities and processes and their indicators. The heuristics of our approach depend on maintaining consistency between its suitability for each case study and its contribution to global debates on livestock farming in response to climate change, the erosion of biodiversity, food security and the reduction of poverty and inequality. In keeping with the intensification model for monogastric livestock farming, numerous herbivore farming systems have become disconnected from local resources as they use commercial feeds, often containing imported ingredients, assessed on the sole criterion of their cost efficiency. As a result, these livestock systems have distanced themselves from their social and ecological environment and are increasingly being criticized by their neighbours as well as conservationists or animal rights advocates. Therefore, many social groups have lost their connection with domestic animals. Our aim is to use the multifunctionality framework and science to provide information about the other dimensions related to livestock grazing systems in a wide array of natural, social and political contexts. The diverse nature of the above-mentioned cases demonstrates that intensification is at work in many other places around the world, creating tension between the increase in production, worker specialization, changes in animal breeds, finding animal markets and the traditional role animals play within families or communities (as in Senegal or Vietnam). The case studies from Argentina, Tibet and Mongolia illustrate the importance of these links which form the basis for the social dimension and indicated that only minor and prudent changes can be made. Conversely, when changes have already taken place, like in Brazil and France, stakeholders look for new arrangements between livestock farming and their human and ecological environments. Hence, the multifunctional framework helps us to understand the complexity of each situation and what makes it capable of changing, by mobilizing the same levers but in diverse ways. It allows us to overcome the fact that each situation is of course different, while following a common framework that captures the essence of livestock farming all around the world.

Supporting sustainability on different levels. The MF framework has also shown that it is quite robust when applied to different levels, such as the farm (Brazil), household (Puna), territory (Tibet, France), region (Mongolia) and economical sector level (Vietnam, Senegal), and in different socioecological contexts ranging from communal, transhumant, individual and sedentary systems. In the discussions among stakeholders, it became clear that multiple levels need to be addressed and represented in order to have a holistic and collective understanding of the sustainability of systems and territories.

Use of the multifunctionality framework to coordinate activities within territories. Our objective was to build a strong common conceptual framework in order to move past the specificities of each case study and to show that LGS can play another role besides simply producing animals. These very contrasting situations confirm that LGS are not an isolated activity. Given its large landscape footprint, LGS are intricately linked to a specific area that provides resources and is also used by other stakeholders. Sustainable territorial management highlights the need to coordinate and facilitate synergies between activities and sectors with a view to developing a collective vision of the future. The multifunctionality framework helps to organize the discussions on the priorities, interactions and compromises to be made.

Managing the different points of view and compromises. The case studies show just how closely these different dimensions are interconnected in addition to the various dilemmas stakeholders need to address in order to strike somewhat of a balance between them. It becomes clear that LGS provide a multitude of functions in addition to the various ways in which these functions are mediated by humans. It is no longer acceptable to focus solely on productivity or the environment when considering these systems. Instead, these multiple functions and their interdependence need to be recognized, nurtured and respected.

The multiple functions of LGS are still present but fragile. The diverse nature of the cases analysed shows that, in most contexts where there are existing traditional LGS, the broad range of functions and indicators within the four dimensions truly works (Figure 8.2) and helps make socio-ecosystems more viable and sustainable. However, it also appears that, in the face of environmental, economic, and political dynamics, some of these functions could be undermined, raising questions about the sustainable future of a significant of the local society and perhaps even the environment.

⏩ Conclusion

At the territorial level, the multifunctionality framework applied to a range of livestock grazing systems has shown the existence of strong and operational interactions between production and the social, environmental and local development impacts that sustain sustainability in these socio-ecosystems. This interconnection of functions can be used to determine which policies and practices should be prioritized to ensure that they are all undertaken simultaneously and fairly. People, their well-being and related institutions are key to fulfilling these functions. In addressing issues related to food sovereignty and food security, we can adapt a holistic approach, as these cases illustrate, that simultaneously accounts for land governance, access to resources, cultural identity and the livelihoods of people living in rural areas. This is a way to guarantee sustainable food systems, including livestock grazing systems, which are grounded in territories through multi-sectorial synergies, providing local goods and services but oriented towards larger value chains and trade.

This international overview illustrates the diversity of LGS in a range of geographical, historical and political contexts. It also shows that it is consistent with an ancestral human activity that is based on the interactions of human settlements with the natural world through positive relationships with domestic animals. This activity has led to the development of various herbivore breeds, each of which is well suited to the environment in which their breeders are living. Through many interactions with their environment, these livestock holders can adapt their practices to the availability of resources, their diversity and their temporal and spatial variability. However, in most industrialized countries – and elsewhere – we have noted a strong momentum toward the homogenization and standardization of livestock farming conditions, giving priority to meat or milk production, while disregarding the other functions of livestock farming. These dynamics are being increasingly challenged by social movements (consumers, environmentalists, animal welfare activists, etc.). Alternatives and novel solutions are being looked for to go past this industrialized vision of livestock farming, but within a context that has changed. By applying our common multifunctionality framework to an array of global livestock farming systems, we have been able to develop a systemic and dynamic point of view. Traditional situations such as those observed in Argentina, Tibet and Mongolia have made it clear that the relationships between human societies and the natural world are centred on LGS. This systems needs to be carefully managed when there is ongoing change, like in Senegal and Vietnam, and it needs to be rebuilt when the transformation that has been ongoing for years is not seen as satisfactory, like in Brazil and France.

These diverse situations illustrate that our conceptual framework for multifunctionality in livestock grazing systems is a relevant tool for analysing livestock dynamics in these territories by using a systemic, holistic and integrative approach (resources, actors, activities) and by covering the different dimensions of sustainability. These analyses can make it easier to determine the ongoing dynamics by complementing the functions being considered for greater sustainability. These analyses can also help feed territorial forward-looking methods upstream of a territorial strategy for growth, by specifically including the multiple functions of grazing livestock as well as their interactions and trade-offs that need to be taken into account in connection with the other activities going on within the region. We can summarize the lessons learned from using the multifunctionality framework to analyse LGS in our case studies as follows:

– The four dimensions resonate with all livestock farmers and result in an inclusive approach so that all stakeholders can fully participate. In the real world, livestock farmers do not separate production and profit from social and environmental outcomes, they try to achieve them all. The use of an inclusive approach helps develop social interactions, which leads to strengthened community resilience and the improved sustainability of agricultural and food systems within territories.

– The MF framework can be used to explore the entire system and demonstrates the importance of encouraging diversity (livestock species, livestock farming systems and practices, flora and fauna, etc.). To find sustainable pathways for food systems, it helps if most of the persons who take part in the system are able to clearly understand the complex nature of the context and situations involved.

– When LGS are seen as being part of the ecosystem and not separate from it, it then becomes possible to integrate LGS into nature and biodiversity conservation programs. This strengthens biodiversity productivity and the related cultural functions, while increasing the sustainability of LGS and food systems.

– Innovative value chains that include "traditional" and small livestock farming systems are an option for sustainable food systems.

– However, for this to work, sustainable food systems may need to build on the complementarity of different livestock systems in addition to building on the synergies with other land use activities. The question then becomes, can we in Europe and elsewhere in the world reverse this global trend toward the standardization and intensification of livestock farming systems, and benefit from the lessons learned from the Global South (detailed in this chapter), to reinvent and redesign multifunctional and sustainable LGS that are well-integrated and adapted to the diversity of our territories?

Chapter 9

Afterres 2050: from creating scenarios to assessing them

Christian Couturier

⏩ History and objectives of the Afterres 2050 scenario

The Afterres 2050 foresight scenario, developed by the Solagro Association, focuses on the land sector. It is largely based on the négaWatt scenario[20] which was developed by the Association négaWatt and is focused on energy. In conjunction with the négaMAT scenario, which was also developed by the Association négaWatt and is focused on materials and raw materials, these three scenarios cover all greenhouse gas emissions in France.

The scope covers metropolitan France but considers footprints on a much broader scale: imports and exports of raw materials, including biomass, are converted into a GHG footprint that extends outside of metropolitan France. Even though it is primarily focused on agriculture and forestry, the land sector covered by the Afterres 2050 scenario concerns all sources of biomass production –and its use: food, materials and energy.

These scenarios are updated regularly. The first edition of the négaWatt scenario, for instance, was published in 2003 and has been updated and published the year before each presidential election since then. The Afterres 2050 scenario was first published in 2011, and a second version was published in 2016. This scenario was updated in 2022 to coincide with the publication of a focused report on biodiversity[21].

The aim of these scenarios, which are normative, is to inform public debate by describing a possible and desirable future, based on a set of objectives and constraints. The approach draws from the "doughnut" concept popularized by the economist Kate Raworth (Raworth, 2017). The goal is to define a safe and just space for humanity, ensuring social wellbeing (floor) while respecting the various ecological limits (ceiling). Society's living conditions can be described using the UN's 17 Sustainable Development Goals (SDGs), and the ecological limits can be described using the planetary boundaries concept.

Ecological limits specifically concern the land sector, whether that has to do with climate, biodiversity and/or water. However, the scores for the various eligible options vary considerably for the different SDGs. The IPCC points out that there can be a range

20. négaWatt, 2022. The négaWatt 2022 scenario (including components of the négaMAT scenario) https://negawatt.org/Scenario-negaWatt-2022
21. Solagro, 2022. Afterres – Biodiversity, https://Afterres2050.solagro.org/2022/11/Afterres2050 biodiversite/

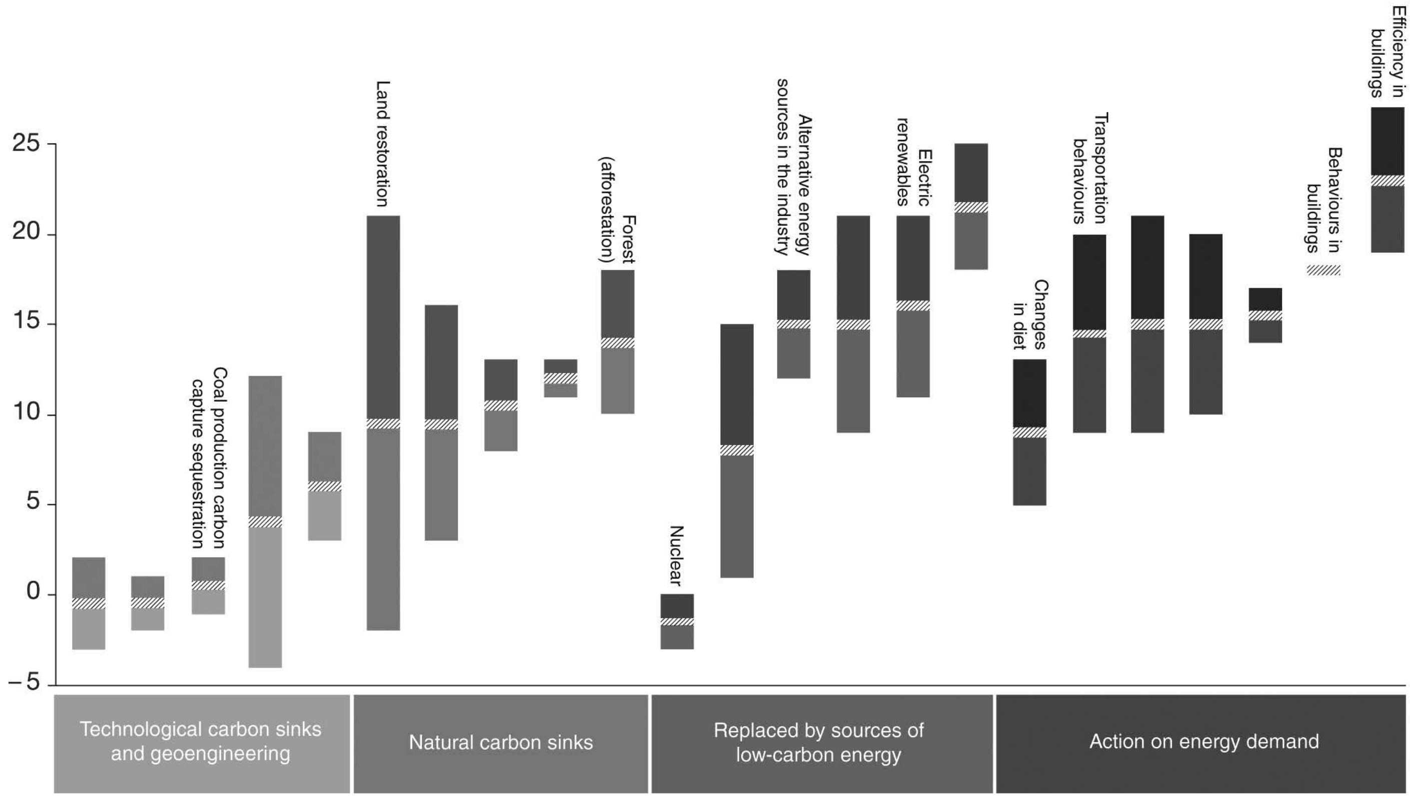

Figure 9.1. "SDG score" based on an aggregation of the minimum and maximum scores given by the IPCC (Special Report on Global Warming of 1.5, 2018) for each SDG for different decarbonization options. Data processing: Association négaWatt. (négaWatt, 2022. Full report, part 4, page 91 https://www.negawatt.org/IMG/pdf/scenario-negawatt-2022-rapport-complet-partie4.pdf)

of scores for the same option, from very low to very high, depending on the SDG. Figure 9.1 provides an example of the various decarbonization options – for instance, a tree planting program to store carbon might have a negative impact on the living conditions of local populations. Conversely, a collaborative agroforestry program may result in social and economic co-benefits in addition to environmental benefits for the residents.

The central issue in the land sector has to do with sharing uses of biomass. The concept of the 4 Fs of "Food, Feed, Fiber, Fuel" is often evoked in the scientific literature, which examines the tensions and competition between these four main uses of biomass. We can expand this concept of 4 Fs into 6 Fs by adding "soil fertility," which depends on the extent of organic manure use, and "forest" in the etymological sense of the word (land that is not for general use, upon which certain activities are banned, and upon which crops and habitations are prohibited) for the various ecosystem services provided, and to also express what nature itself needs. This 6 Fs concept describes the competition as well as the potential synergies between these uses of biomass. The current distribution of these uses is the product of a socio-economic organization, the legacy of both a history and a culture, and is not sacrosanct. Foresight exercises are carried out specifically to take another look at these balances and to explore new ways to distribute the use of this biomass to address the challenges of today.

⏩ Foundations of the approach

Based on existing national roadmaps, the objectives include, for example, achieving carbon neutrality by 2050, no-net-land take, compliance with nutritional recommendations, improved air and water quality, and biodiversity restoration. These roadmaps comprise laws, strategies and international agreements. Other objectives consider societal aspirations that may not be included in these roadmaps, such as the creation of jobs in rural areas and land use planning, animal welfare, landscapes, etc.

Borrowing the same wording from the IPCC, the land sector involves:
– both demand (food and non-food) and production (agricultural, plant and animal production systems, and forests);
– matching supply and demand;
– assessing the results obtained using a set of indicators.

Land use planning involves using a "balance sheet" to balance the uses and resources in various dimensions. The "supply balances" of agricultural products are discussed first: resources (production and imports) are balanced against uses (food and non-food uses, processing, industrial uses and exports). A balance sheet approach is also used for the nitrogen balance and forage estimate. The former is used to calculate the mineral input requirements, which are the adjustment variables, and the latter checks whether there is a surplus of fodder.

The MoSUT model, developed by Solagro, was used here. It is a biophysical model that describes masses, surfaces and energy flows (see Box 6.2 and Figure 12.2). A recursive approach is needed as this is a complex exercise given the multiple objectives and guidelines that are involved. Consequently, many revisions are required to reach a landscape that is more or less acceptable to the parties concerned.

Lastly, the approach is both top-down and bottom-up: "top-down" since it involves putting macroscopic objectives into practice locally, such as the rate of reduction in GHG emissions, which is measured on a global scale; and "bottom-up" since the scenario-building exercise accounts for the characteristics of the territory and the willingness of its stakeholders. The outcome of this type of approach is a constructed scenario which has been negotiated between the various stakeholders, and which incorporates a certain level of collective awareness of the global challenges in play, reflecting the ability of the stakeholders to take on the guidelines outlined in this way.

⏩ Exploring the Afterres 2050 scenario

Afterres 2050 is based on a fairly detailed description of production systems and possible transition pathways. These changes can be extrapolated to the regional and then to the French agricultural sector level.

In Picardy, for example, the description at the production system level is based on "model farms" which were used to calculate the agronomic and environmental balance sheets with tools such as ACCT (AgriClimateChangeTool) developed by Solagro. It then subsequently becomes possible to estimate the main indicators at the farm level. Among the systems in use, the scenario-building exercise was used to imagine how an arable crop system could evolve by adopting a series of agroecological practices that would lead to a system in 2050 that maintains its global production capacity but which has significantly reduced both the impacts (water, air, climate) and the use of synthetic inputs (nitrogen fertilizers, pesticides) while producing new services (ecosystem services, energy, materials). It allows the characterization of different production systems, from a current "conventional" system to a future system, very simply symbolized by "organic farming" or "integrated production," with several variants that are mainly characterized by the use or non-use of agroforestry, catch crops, agroecological infrastructures and companion crops. Each system is characterized by a level of production (yields in grains, crop residues, catch crops or companion crops, wood), a level of inputs (nitrogen fertilizers, energy, pesticides, water) and a level of carbon storage in the soil and biomass.

At the regional scale, the scenario-building exercise then involves selecting the proportion of these different systems between conventional, organic and integrated. Farming systems evolve with a change in crop rotations, and therefore in cropping patterns. In certain regional exercises, the main types of rotation were identified during the assessment phase, and the projected cropping plan for 2050 tries to take the evolution of these main types of rotation into account while introducing new ones (Table 9.1). For instance, in arable farming regions, in scenarios with a high proportion of organic farming but without the development of livestock farming, models of rotations include a large share of legume fodder crops and high-protein crops, while ensuring a consistent nitrogen balance.

When used at the national scale, the balance sheet approach can first check the balance between the different land uses: for instance, as changes continue to be made, a choice could be made to ban the conversion of grasslands to arable land, and to authorise their conversion to forest. In numerous scenarios, stakeholders may make a choice to switch from one type of land use to another to prevent the loss of carbon or biodiversity; however, this often results in the loss of both (Figure 9.2).

Table 9.1. Example of a crop rotation projection (in thousands of hectares, kha) for the Île-de-France region in 2050 based on the use of seven types of field crop systems (organic farming [OF] self-sufficient in nitrogen; variant with imported nitrogen; integrated production [IP], with or without beetroot; current or improved conventional systems [conv.]). The nitrogen-self-sufficiency OF system is based on an eight-year rotation, with four years of cereals, two years of oilseed and high-protein crops, and two years with alfalfa. The result is that pulses increase by more than 100,000 hectares and occupy 25% of the usable agricultural area (UAA), mainly to the detriment of cereals, which decrease from 69% to 51% of the UAA.

	Current cropping plan (kha)	**OF self-sufficient N**	**OF importing N**	**IP without beetroot**	**IP with beetroot**	**Cereals – rapeseed**	**Conventional without beetroot**	**Conventional with beetroot**	**TOTAL**	**2050 cropping plan (kha)**
Proportion in the cropping plan in 2050		30%	15%	10%	30%	0%	5%	10%	100%	
Rotation length (years)		8	6	5	6	3	5	5		
Cereals	345	4	3	3	3	2	3	2	51%	253
Oilseed crops	90	1	1	1	1	1	1	1	16%	81
High-protein crops	23	1	2	1	1		1	1	19%	94
Alfalfa	1	2							8%	38
Industrial crops	44				1			1	7%	35
Total (kha)	500									500

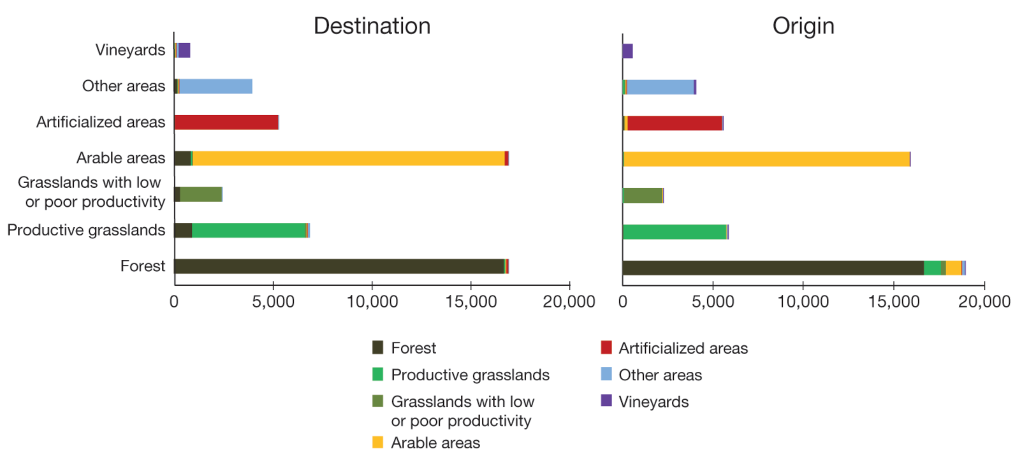

Figure 9.2 Destination (from 2020 to 2050) and source (in 2050 from 2020) of land areas, in thousands of hectares (source: Solagro).

The forest area increases from 17 million hectares (Mha) in 2020 to 20 Mha in 2050, with 1 Mha converted from permanent grasslands and 2 Mha from arable land. It should be noted that grasslands are being reduced exclusively in favour of forests and not arable land, yet a small fraction of this land will still be taken.

Assumptions are also made for the choice of cropping method and livestock farming method; each livestock farm type is also described using a set of suitable indicators (level of production per animal, feed, and livestock waste management).

The forage estimate compares resources and uses (Figure 9.3). The resources are made up of all the grass and forage production on permanent or temporary grasslands, fodder crops and catch crops. In terms of use, a distinction is made between grazed grass, which depends on the amount of time ruminants spend in grasslands, and conserved fodder. The resources used to produce energy, especially biogas production, are also identified, as is any surpluses or deficits.

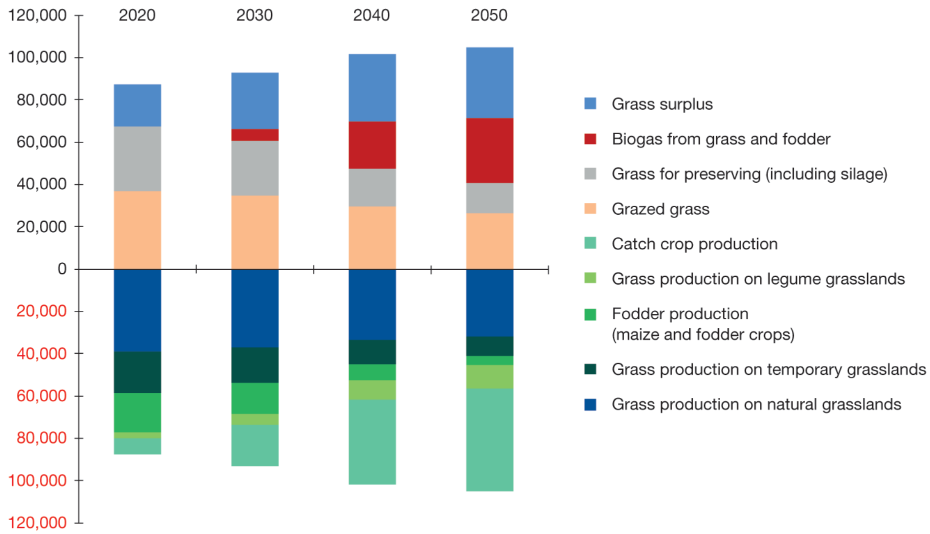

Figure 9.3. Forage supply balance, in thousands of tons of dry matter (source: Solagro). Grass production on native grasslands does not decrease by much, temporary grasslands decrease significantly, and forage grass is replaced by pulses. A significant additional resource is catch crop, and the share of pulses they contain is an important source of nitrogen. The system generates a large amount of surplus forage, some of which (half the catch crops and some of the surplus hay) is used in biogas production.

The same assessment is used for feed concentrates (Figure 9.4). The various resources used for animal feed take the changes in livestock farming systems into account. The extensification of all sectors thus results in a decrease in the "Consumption Index" indicator. It is possible to customize the composition of the concentrates. For instance, soybean meal imports can be reduced in favour of other types of protein (other oilseed meals and high-protein crops, companion crops and even insects).

The supply and demand balances determined for each product can be used to identify both import and export trends (Figure 9.5). Based on the FAO balances, they allow for the identification of resources (production and imports), sources (exports and domestic demand), and the various uses within domestic demand: human consumption, animal feed, transformation and industrial uses. It should be noted that there is a lower wheat production: the surface areas are slightly smaller (to allow more room for pulses) and yields decrease with the huge increase in low- and very low-input systems. Human consumption does not change much, and reduced waste offsets the increase in population.

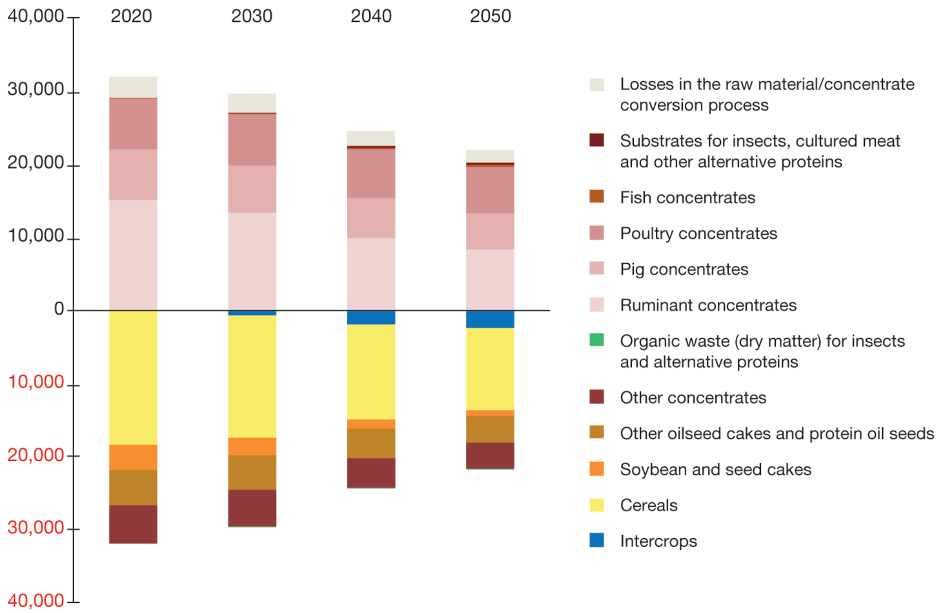

Figure 9.4. Concentrate supply balance for livestock farms, in thousands of tons (source: Solagro).

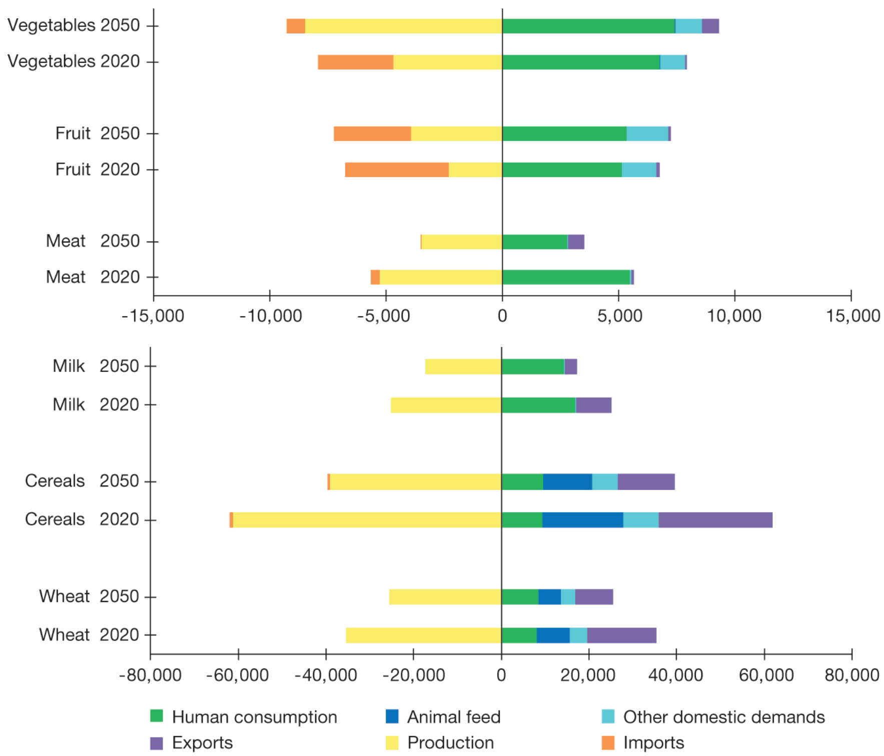

Figure 9.5. Supply balance for a few emblematic products and groups of products, in thousands of tons. FAO nomenclature (source: Solagro).

Animal consumption is reduced by half, given the decrease in herd numbers despite their extensification. Exports decrease but are still at an elevated level. They are primarily destined for human food markets in Africa and the Middle East, which are on the rise, whereas the markets for forage cereals (feed grain) in Europe have been halved, assuming that the rest of Europe is undergoing a similar food transition. The trade surplus for animal products stays positive since the drop in production is more than compensated by the drop in consumption. Lastly, there is a decrease in fruit and vegetable imports, although self-sufficiency is not attained. Production and vegetable consumption both increase significantly, whereas fruit consumption stagnates (a decrease in fruit juices but an increase in fresh fruit, and in particular, fewer losses).

GHG emissions decrease from 95 to 38 million tons of CO_2 equivalent (Figure 9.6). This is the "ClimAgri" scope, which includes direct emissions from agriculture, including emissions related to the use of energy on farms (Secten[22] format), and indirect emissions, which considers the production of inputs, notably nitrogen fertilizers. This overall cutting of emissions is shared among three gases: carbon dioxide (CO_2), attributed to energy savings and the decarbonization of energy; nitrous oxide (N_2O), via higher nitrogen use efficiency and reduced methane (CH_4) emissions due to there being fewer ruminants on the one hand, and also to gains associated with various factors (e.g. livestock feed). Livestock manure management is also important when it comes to reducing CH_4 and N_2O emissions.

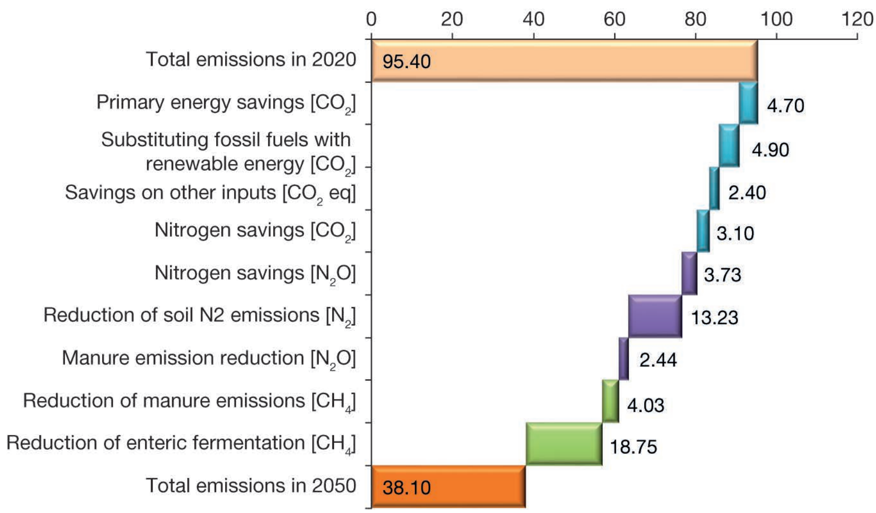

Figure 9.6. GHG emissions in 2020 and 2050, in millions of tons of CO_2 equivalent (CO_2eq), and allocation of gains by item (source: Solagro).

The reduction in N_2O emissions is not due to a decrease in nitrogen flows given that the overall flows do not change very much. The key change has to do with a partial substitution of fertilizer nitrogen with symbiotically fixed nitrogen and a slight reduction in the total primary nitrogen input. However, secondary nitrogen flows, i.e. the recirculation of nitrogen via plant matter (crop residue, catch crops) and livestock

22. Citepa. https://www.citepa.org/fr/secten/

waste (either raw or converted to biogas), stay at their current levels. In contrast, emission factors may be higher for organically derived nitrogen than for mineral nitrogen. As a consequence, the decrease in N_2O emissions has less to do with decreases in flows than with improved efficiency.

Emissions at the territory level are calculated along with an estimate of the footprint, which takes into account the imports and exports of agricultural and food products (Figure 9.7). Figure 9.6 does not include imports of animal feed, especially soybean, and does not account for exports. To make sure that the adopted scenario does not involve simply transferring the impacts across borders, and therefore outside the scope of this work, the GHG emissions generated by imports and exports are estimated, and the footprint is calculated by adding production-based emissions and the net emissions embedded in international trade. Note that although there is a decrease in exports, there is an even greater decrease in imports, and the GHG balance improves.

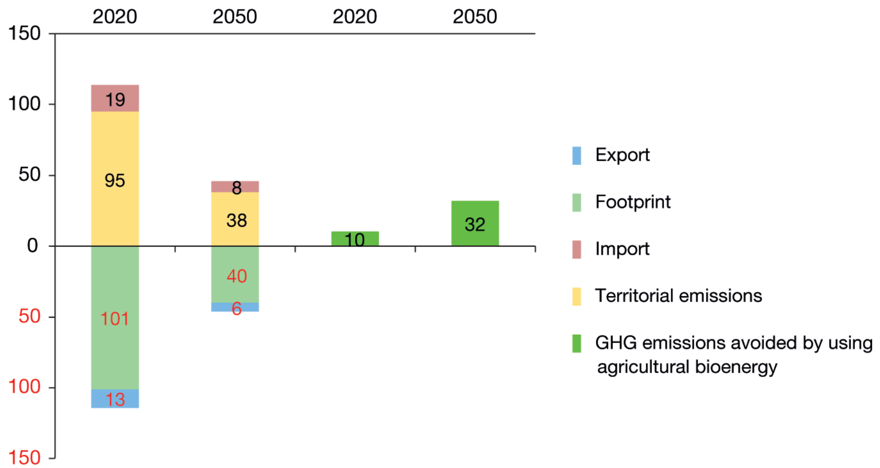

Figure 9.7. GHG footprint of agriculture, in millions of tons of CO_2 equivalent (source: Solagro).

The graph shows the value of production (i.e. territorial emissions in ClimAgri® format), imports, exports and, in comparison, GHG emissions related to consumption, i.e. the footprint of French consumers. On the right is shown the GHG savings related to agricultural bioenergy production, to replace fossil fuels like natural gas. Note that these savings are relatively comparable to the territorial emissions.

Figure 9.8 shows a set of agroecological indicators – ammonia emissions, nitrogen balance, irrigation water consumption and irrigated areas, details about agroecological infrastructures, carbon storage in agricultural ecosystems, consumption of phytosanitary products, etc. – in addition to a macroeconomic evaluation that was carried out on the Afterres 2050 scenario.

This evaluation only covers a ten-year horizon and therefore the transition is still in its preliminary stages. The speed of these transitions is assumed to change over time, or more simply put: 10 years of learning, 20 years of fast growth and 10 years of coming back down. We have learned a great deal from visualizing the variations in cash flows between the key sectors of the national economy. For the agricultural sector, the production by volume decreases by €4 billion, but intermediate consumption decreases by €5 billion, i.e. the agricultural sector sees a gain of €1 billion.

Households profit the most from this, which can be primarily explained by lower losses and less waste together with a shift towards a more plant-based diet. These values are based on the assumption that unit prices will increase, mostly due to the scaling up of low- and very low-input production methods. This gain of €10 billion is comparable to the current volume of the Common Agricultural Policy (CAP), and especially the value of the externalities. The ecological transition in agriculture and food could generate several tens of billions of euros in gains each year. These gains would be distributed among consumers, farmers and the healthcare system, a major indirect beneficiary of an agricultural and food policy that can be an immensely powerful tool for proactively preventing health risks.

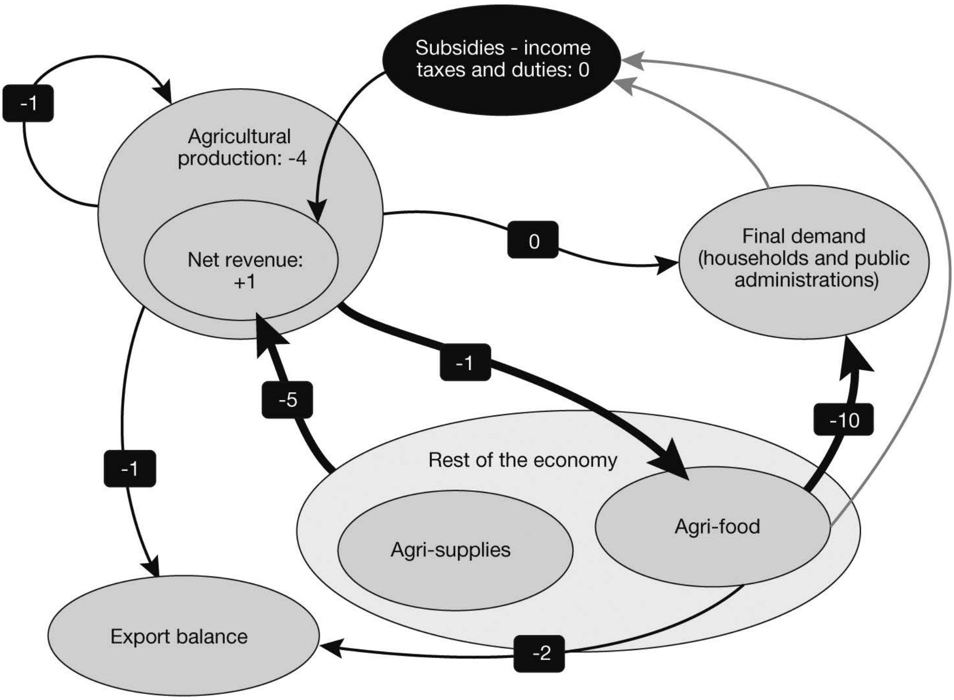

Figure 9.8. Changes in cash flows between the main groups of economic actors, in billions of euros, ten years after the Afterres 2050 scenario was implemented (source: Solagro).

⏩ Targets

A diverse range of stakeholders use this type of approach. The aim of the national low-carbon strategy, driven by the French Ministry of Ecology, is to define "carbon budgets" by sector and by period. The scenario-building exercise not only gives an opportunity to better identify the efforts needed in each sector, but it can also be used to estimate the reduction in GHG emissions from agriculture. ADEME is exploring several different climate neutrality pathways through four contrasting scenarios that are based more on demand or on production, so as to focus public debate between the austerity approach and the technological challenge approach. The Entreprises pour l'Environnement (EpE, Business for the Environment) association envisages a "Net-Zero Emissions" scenario driven by the business world. The WWF, together with

Pulse Fiction, hope to show that more support for pulses is needed in order to have a more holistic view of the food system. Regions and territorial authorities, such as the Grenoble Alpes Métropole and Grand Geneva (the Greater Geneva area), are hoping to define their territorial food projects by placing them within a forward-looking view over the long-term.

Chapter 10

An agroecological Europe in 2050, "Ten Years For Agroecology" (TYFA) scenario

Pierre-Marie Aubert and Xavier Poux

⏩ Introduction

There is no longer any question that there is a lack of sustainability in the European food system in most aspects (EEA, FOEN, 2020; the Farm2Fork Strategy within the European Green Deal, EC, 2020). Several different scenarios have been published in recent years at various scales (from a national scale to the European Union [EU] scale, while also including regional approaches) that propose ways to bring the EU food system back within the sustainable limits of our planet (Couturier *et al.*, 2016; EC, 2018; ECF, 2018; Karlsson *et al.*, 2018; Springmann *et al.*, 2018; Lóránt, Allen, 2019; Willett *et al.*, 2019; Billen *et al.*, 2021; Searchinger *et al.*, 2021; van Selm *et al.*, 2022). Most of these scenarios focus on the mitigation of climate change, although biodiversity may also be considered. Duru *et al.* demonstrate that in order to reach their climate targets, almost all of the scenarios are based on: (a) a decrease in livestock numbers (including ruminants); (b) increases in yield; and (c) major land use changes via the afforestation of freed-up land by means of both increased yields and the decreased use of permanent grasslands by ruminants.

As such, it is generally considered that the best land to be used for reforestation are permanent grasslands, which we define here as herbaceous (woody) and non-herbaceous (non-woody) vegetation used for grazing and/or mowing, and which has not been tilled in at least the past five years. Although the ecosystem services they render can be identified (Couturier *et al.*, 2016; Ryschawy *et al.*, 2017; Karlsson *et al.*, 2018; Simoncini *et al.*, 2019; Schils *et al.*, 2022), they are not specifically addressed in the models guiding the scenarios (Bengtsson *et al.*, 2019). Additionally, although permanent grasslands are generally seen as being good, it is broadly accepted that the ruminants grazing on these grasslands are inefficient when it comes to converting feed into food, compared to poultry and pigs (Herrero *et al.*, 2013). Additionally, they are responsible for significant methane emissions (Steinfeld *et al.*, 2006). A recent report stemming from a joint workshop between IPBES and IPCC (Pörtner *et al.*, 2021) portrays the situation in a comparable manner: permanent grasslands should be conserved and not converted for the purpose of producing bioenergy, and both beef and dairy consumption should be minimized. With this in mind, it is still unclear how permanent grasslands will then be managed in order to deliver a variety of ecosystem services (e.g. in terms of regulating nitrogen and carbon cycles, providing nutritious food, regulating the water quality and cycle, landscape conservation or providing habitats for a wide range of species, see D'Ottavio *et al.*, 2018).

Within this framework, a specific scenario, the "Ten Years For Agroecology in Europe" (TYFA) scenario, was developed to determine what conditions are needed for an agroecological Europe to be able to feed 530 million European citizens by 2050 in a sustainable and healthy manner, while restoring biodiversity and reducing GHG emissions. A secondary aim of this scenario is to take better account of the role permanent grasslands and ruminants play in the transition towards a more sustainable European food system. The TYFA scenario uses a biomass balance model (TYFAm, Box 10.1) that is based on systemically connected compartments between which matter and energy flow (Figure 10.1).

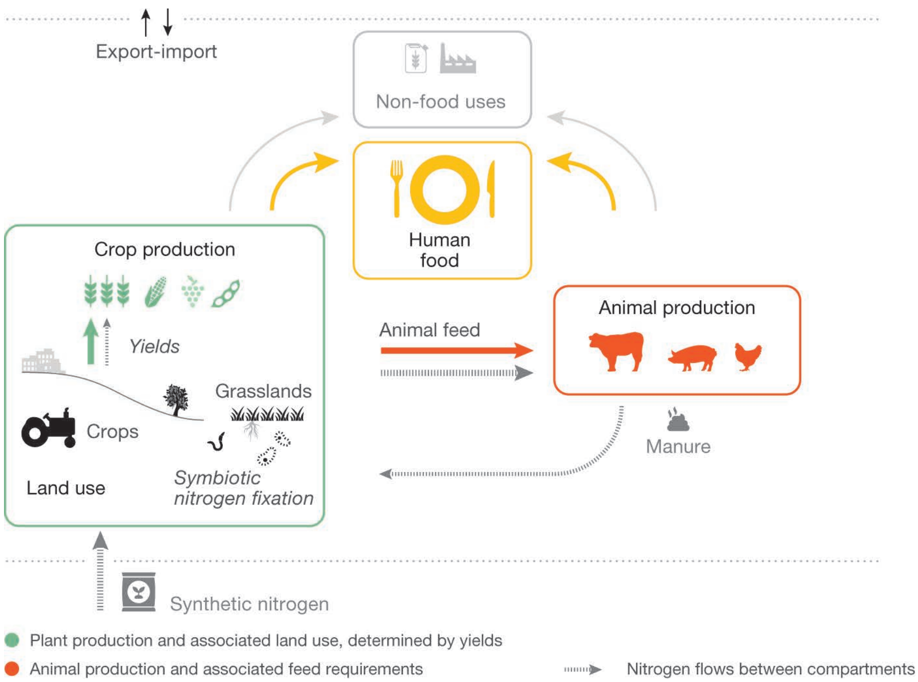

Figure 10.1. Logical structure of the model underlying the TYFA scenario (source: Poux and Aubert, 2018).

Box 10.1. TYFAm model specification and data sources

The four compartments of the TFYA scenario are as follows:
– *crop production*, resulting from a certain use of European land (allocated between arable land, permanent crops, permanent grasslands and agroecological infrastructures: hedges, trees, ponds, stone habitats, sunken paths) and the related average yields within the EU. The TYFAm model includes 36 types of annual crops (Eurostat database), permanent crops (olive trees, fruits), grasslands (permanent and temporary) and other agroecological infrastructures;
– *animal production*, supplied by a fraction of the crop production, which in some cases may compete with human food (e.g. cereals), but not always (grasslands and co-products). One or two typical livestock farming systems are considered for each type of animal;

– *food demand*, which is the result of individual *eating habits*, the *waste* coefficient and a given level of *population growth* in Europe, and which is covered by both European production and imported products. Food consumption is expressed in both the gross product equivalent (for each product category) and its macronutrient content (carbohydrates, lipids, proteins, fibres and sugar), so that it can be compared to the nutritional recommendations;
– *non-food/industrial* demand for biomass (energy and biomaterials), which can once again be covered by a mix of European production and imports.

To a large extent, it is the nitrogen flows associated with the functioning of and interactions between the first four compartments that determine the level of soil fertility. The analysis of nitrogen flows covers the diverse types of inputs (synthetic nitrogen, imported animal feed, symbiotic fixation and transfers via manure) and exports (animal and plant production).

Food and non-food demands are exogenous to the model; yields and input/output ratios for livestock farming systems are also defined by the user. The TYFA model (TYFAm) calculates the levels of production for each crop/livestock product category, land use and the nitrogen balance. This model is also used in conjunction with the ClimAgri® calculator to calculate the GHG emissions from the food system, for both the baseline and TYFA scenario.

The parameters in TYFAm are set to the EU scale, and the model uses the average values calculated from the Eurostat and EFSA database for the baseline scenario (calibrated using data from 2010) and from our assumptions for the TYFA scenario. Even if the model is calibrated at the EU scale (similar to the GlobAgri platform, as outlined in Mora *et al.*, 2020, see Box 5.1), it is still possible to obtain an idea of how likely the scenario is but, of course, it cannot be used to provide a detailed analysis of what the scenario means for each region.

⏩ TYFA scenario assumptions

The aim of the assumptions underlying the TYFA scenario is to ensure that any systemic approach to agroecology, understood here as a technical approach rather than a social movement or practical approach, is as straightforward as possible (see Wezel *et al.*, 2009). This means applying the concepts and principles of ecology to the management of agroecosystems, with a particular focus on biogeochemical flows (even if only nitrogen is modelled in TYFAm) and the functional interactions between organisms within complex agroecosystems (Gliessman, 2007). All the assumptions kept for the TFYA scenario are summarized in Figure 10.2.

These assumptions give a central place to permanent grasslands (Figure 10.3) and ruminants based on four key lines of thinking.
– The first has to do with the pivotal role permanent grasslands play in providing fodder and subsequently human food, and thus it is especially important to ensure that the biomass production can support this function of supplying fodder. However, Huyghe *et al.* (2014) pointed out that data on grassland productivity and distribution across Europe is quite scarce. There are no single-source and centralized statistics about this production in the Eurostat database. Smit *et al.* (2008) and Tóth *et al.* (2013) carried out research to evaluate grass productivity, while keeping the spatial distribution of permanent grasslands and related yields in mind. When the inherent

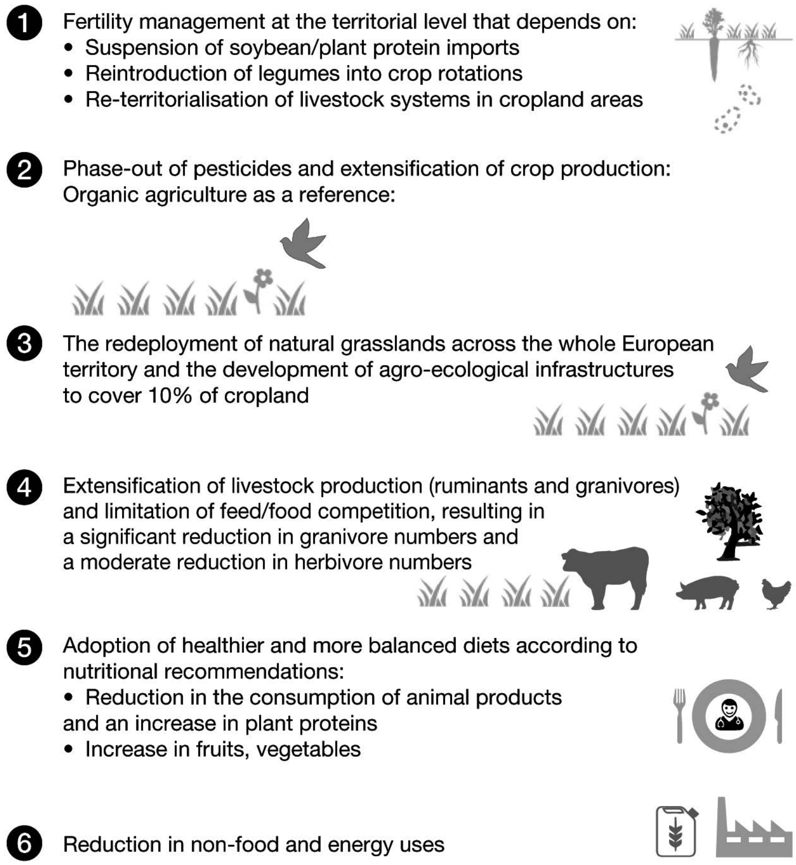

Figure 10.2. Main assumptions of the TYFA scenario (source: Poux, Aubert, 2018).

productivity of grasslands (i.e. defined by the natural soil fertility, without including any added fertilizer) is modelled, we obtain an average yield of 6.3 tons of dry matter per hectare (tDM/ha). In the TYFA scenario, we assumed an average productivity of 4.5 tDM/ha to reflect a loss in production compared with currently fertilized permanent grasslands and potential losses related to climate change (e.g. see Dibari *et al.*, 2021 for a case study in Italy).

– Through their various long-term processes, permanent grasslands play an essential role in safeguarding biodiversity in Europe (Pärtel *et al.*, 2005). Currently, slightly less than 30% of all habitats that the EU has said it will conserve as per the Convention on Biological Diversity depend on extensive livestock systems and, by proxy, on permanent grasslands (Halada *et al.*, 2011). Permanent grasslands help maintain high levels of biodiversity within agroecosystems and, as such, they are instrumental in providing fundamental ecosystem services, including pollination and pest control (Dainese *et al.*, 2019). In turn, it seems that maintaining these ecosystem services is pivotal to ensuring the long-term productive capacity of European agroecosystems against a background of yield stagnation and greater variability (Brisson *et al.*, 2010; Ray *et al.*, 2012; Wiesmeier *et al.*, 2015; Schils *et al.*, 2018), which is only partially due to the impact of climate change (Moore, Lobell, 2015).

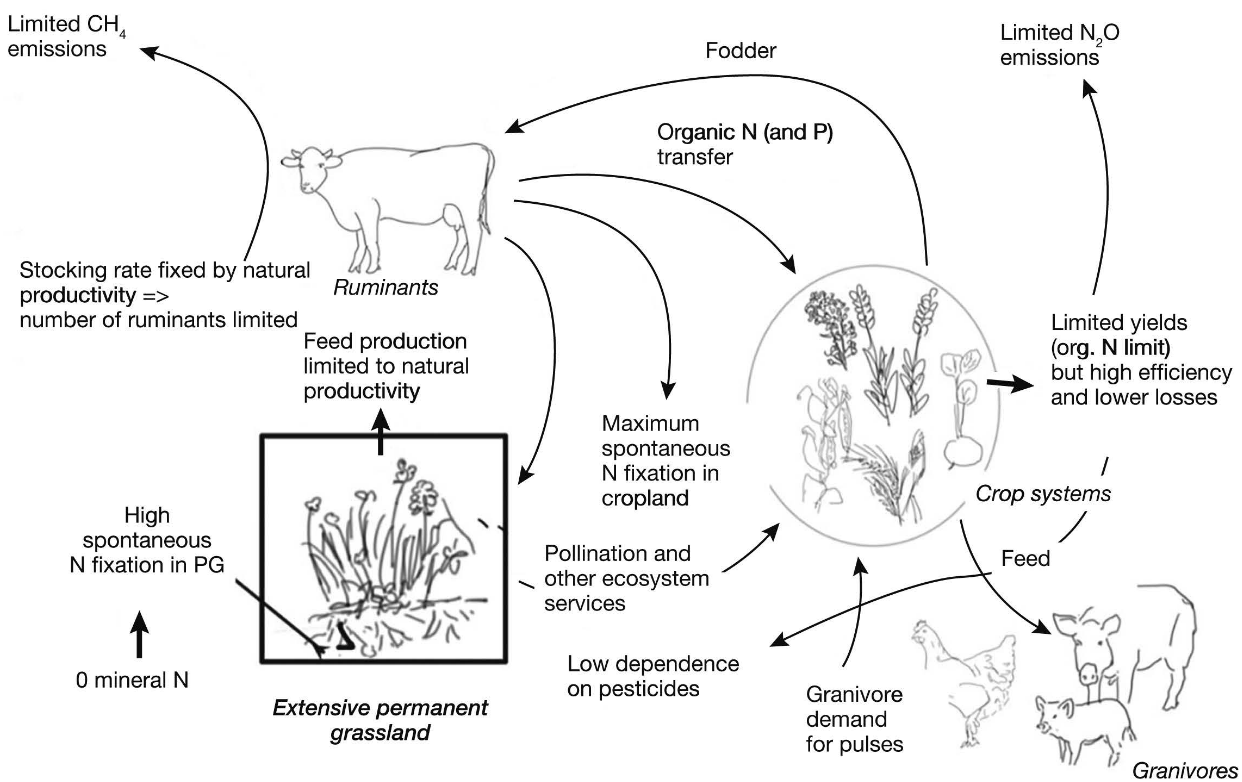

Figure 10.3. Summary of the role of extensive permanent grasslands in TYFA in the wider agricultural system. The arrows show the main components and causal relationship of the reasoning. PG: permanent grassland.

– Up to one third of the floristic composition could contain extensively managed forage legumes (i.e. leguminous crops that have not been sown or fertilized), which would enable significant biological nitrogen fixation. Permanent grasslands that have a low percentage of forage legumes often have an insufficient supply of nitrogen from symbiotic fixation, which can be offset by nitrogen supplied via aerial deposition and by nitrogen fixation by free-living bacteria, which is higher in natural grasslands (Roper, Gupta, 2016). Jeffrey (1988) states that "the occurrence of natural grasslands with few forage legumes and yet sustainable production indicates that this source of N input [from free-living bacteria] may be of great ecological and economic importance". Long-term experiments over one or several seasons have shown gains of 5-90 kg N/ha/year for grasslands (Dobereiner, De-Polli, 1980). As such, even though grasslands are currently net nitrogen sinks due to their intensive management, they may potentially become a key source of nitrogen in the food system (Einarsson *et al.*, 2021). Seen from this perspective, extensive mixed ruminant systems could be a unique way to transport this organic nitrogen to arable land, with much lower impact on the climate in temperate areas than that of mineral fertilizers (Buendia *et al.*, 2019). Consequently, the ruminant herd in the TYFA scenario was adjusted so as to graze the 60 million hectares of permanent grassland throughout Europe at an average of one livestock unit per hectare.

– More broadly, dairy and meat products from extensive livestock farming systems have a much higher nutritional value, especially in terms of omega-3 content, than the same products from conventional systems (e.g. Daley *et al.*, 2010).

⏩ Results

The key impacts of the scenario have to do with land use, food production and consumption and GHG emissions.

An agroecological Europe could feed 530 million Europeans while restoring biodiversity and reducing GHG emissions

Based on the above-mentioned assumptions, the first finding in the TYFA scenario is that agricultural production (both crop and livestock production) is sufficient to meet European demand for food in 2050 even with a significant decrease in the total production (-30% in equivalent kilocalories [kcal]). This result occurs when food diets shift to fewer calories and more plant proteins, and therefore diets that rely less on intensive agriculture. More specifically, animal production decreases by 45% in terms of calories, in large part because of the decrease in granivore and pig production but also dairy products (-31% between 2010 and 2050). The decrease in granivore herds is also exacerbated by a return to a zero-trade balance for these products, which represented 10% of pig production and 3% of poultry production in 2010. Conversely, the level of beef production is maintained at almost the same level by 2050 through the extensification of grass-fed dairy production. The two reasons for this include lower productivity in dairy cows (which means that more animals are needed to be able to produce the same amount of milk) and changes in how the milk herd is managed combined with increased number of lactations. In general, the ratio of "dairy beef per kilo of milk produced" increases due to the increase in the number of dairy cow offspring.

Plant production decreases by roughly 30% on average, expressed in kilocalories, cereal production is significantly reduced (-50%) whereas the production of protein-rich plants is four times higher. These changes need to be considered in a wider context that includes the respective changes in what humans are eating (food) and what animals are eating (feed). Animal feed consumption represents the largest share of this volume, and it specifically depends on the assumptions made for livestock farming systems. Specifically, this includes the use of fodder resources from temporary and permanent grasslands, together with assumptions on the yields from these grasslands. With the shift towards more grass-fed ruminants and fewer monogastric animals comes a decrease in the use of grain maize and, as a result, plant proteins (imported soybean or other types).

According to the assumptions made in the TYFA scenario, the total GHG emissions could be reduced by as much as 36% in-between both direct and indirect emissions. In addition, since TYFAm is based on putting a hold on importing plant proteins, much of which came from deforested land in Latin America in 2010 (Cuypers *et al.*, 2013), it could very well be possible to reduce GHG emissions by 40% or even more in TYFA 2050. This climate performance relies on four main levers: (i) a reduction in herd numbers by 18% for ruminants (dairy cows, cattle and small ruminants) and by 56% for monogastric animals, which would reduce the levels of enteric fermentation and emissions related to manure management; (ii) an overall reduction in the amount of nitrogen applied (from more than 20 million tons of nitrogen as synthetic nitrogen and manure in 2010 to 3.3 million tons of organic nitrogen as manure in 2050) due to the extensification of plant production and better efficiency for nitrogen use; (iii) a phase-out of mineral fertilizers in favour of organic fertilizers; and (iv) a significant increase in the percentage of pulses in crop rotations, enabling a large-scale carry-over effect (Figure 10.4).

Given the significant yield losses associated with the transition to organic systems, the amount of biomass that can be used for purposes other than food in the TYFA scenario is limited to biomaterials, as per the production levels in 2010. There is no potential, or limited potential, for bioenergy production based on biomass (through either anaerobic digestion or biofuel).

The role of permanent grasslands in the TYFA scenario: supplying nitrogen, maintaining biodiversity, producing nutritious foods

As per the assumptions, permanent grasslands and ruminants play a key role in the TYFA scenario in three ways: by helping to supply nitrogen to the overall food system, to maintain agrobiodiversity and to provide humans with nutritious foods. These grasslands are able to maintain a high level of biodiversity based on the assumption that permanent grasslands are redeployed across EU landscapes and make it possible for a threshold of 20% of semi-natural vegetation to be reached in each of the small regions (Benton *et al.*, 2003; Garibaldi *et al.*, 2020).

The same goes for the provision of nutritious feed, which is a direct result of the assumptions made for ruminant systems: TYFA includes the parameters for two dairy systems. The first one, which is responsible for 30% of the dairy production, is mainly grass-fed, with only 100 kg of concentrate/dairy cow (DC)/year and has an average yield of 5000 L/DC/year. The second one, which is responsible for 70% of the dairy production, has an average yield of 5700 L/DC/year and assumes there will be 700 kg of concentrate/DC/year. Both systems are associated with meat production via the fattening of heifers that will not be kept for replacement and all males. In each case, the share of grass in the overall ration produces a higher nutritional quality than that found in cereal-fed dairy and meat products (Daley *et al.*, 2010).

The nitrogen balance in TYFA (Figure 10.4) first shows that the nitrogen application from the nitrogen-fixing crops in rotation (including intercropping and temporary grasslands) covers 70% of the crop requirements.

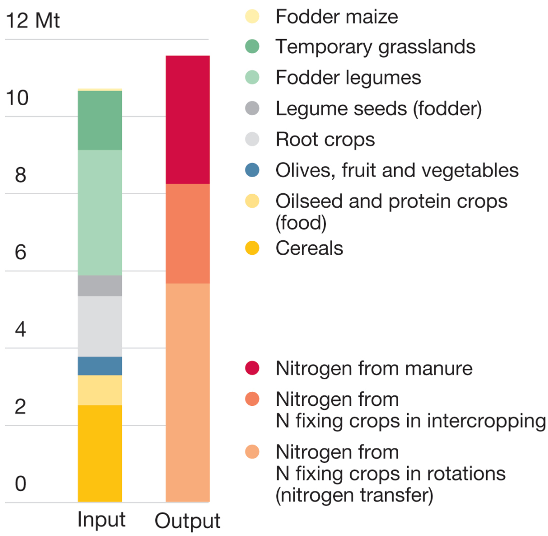

Figure 10.4. Nitrogen balance in the TYFA scenario (source: TYFAm).

In the scenario, the remaining 30% of nitrogen requirements are covered by manure, deducted losses due to ammonia emissions. Out of this total, 20% comes from monogastric systems and 80% from ruminant systems. These values depend on: (i) the total number of animals and (ii) the time spent indoors versus outdoors for each category of animals. Table 10.1 clearly explains the assumptions made for this purpose and for each type of livestock system.

Table 10.1. Assumptions regarding time spent in housing for animals and the resulting manageable nitrogen (N) fraction.

Type of animal	Time spent in housing per year (manageable N)	Comment
Dairy cows	90%	Dairy cows stay in or near housing
Suckler cows, heifers, calves 1-2 years, sheep and goats	50%	Pastures in warmer weather and housing in winter
Heifers, calves 3 years	70%	Fattening requires more time in housing
Granivores	100%	Inside housing

Following on from this, the net transfer of nitrogen from permanent grasslands to croplands ultimately depends on the share of grass from permanent grasslands in the overall feed ration. Here, the assumptions laid out in TYFA are that permanent grasslands provide an average of 70% of the feed needed (as dry matter) for all ruminants (dairy systems, cattle, small ruminants). This means a net transfer of nitrogen from permanent grasslands to croplands of just slightly less than the 20% of nitrogen needed by crops, whereas the main source of nitrogen in the system is based on the carry-over effect of pulses in crop rotations.

In general, the key role permanent grasslands play in closing the organic nitrogen cycle in the TYFA scenario has positive cascading implications for production (lower than what is seen today, but based on robust ecosystem services), biodiversity, natural resource management and climate. This set of key services is largely based on the sustainable nitrogen cycle stemming from the synergy between permanent grasslands and arable crops, and which needs to be looked at as a whole.

⏩ Discussion

The TYFA scenario raises important questions from both a scientific and political point of view, in terms of the role grasslands play in the supply of nitrogen and its cycle, the potential for redeploying grasslands across Europe (counter to the current trend toward specialization), the place of ruminant-based feed in EU food diets and the potential trade-offs between biodiversity conservation and carbon neutrality.

Ability to supply nitrogen from permanent grasslands

On the whole, the ability of extensive permanent grasslands to sustainably provide food and ecosystem services is determined by the balance between: (a) the maximum amount of nitrogen they can fix through symbiotic and non-symbiotic fixation, as well as the amount of nitrogen due to aerial deposition and (b) the subsequent net export of nitrogen by ruminants as milk, meat and manure.

The recently published food system scenarios have been based on empirical data with regard to how permanent grasslands are currently functioning and thus, the implicit assumption is these grasslands are net nitrogen sinks and they consequently cannot supply nitrogen to the rest of the food system (Einarsson *et al.*, 2021). Barbieri *et al.* (2021) showed a nitrogen shortage of 40-60% in organic food system scenarios globally and Karlsson and Röos (2019) indicate this shortage is between 21 and 28% for Nordic regions alone. However, both articles modelled permanent grasslands as net nitrogen sinks and not as potential sources of nitrogen, unlike in the TYFA scenario (see Figure 10.5 below).

The assumptions in the TYFA scenario for net exports, average herd structure and manure exports (40% of the nitrogen restored to permanent grasslands year-round) indicate that natural inputs need to cover the net nitrogen requirement, which is roughly 90-130 kg nitrogen/ha/year. In terms of nitrogen supply, the TYFAm assumes a yield of 4.5 tons of dry matter per ha of permanent grassland. This contribution is factored into the model as a “black box” and, on an empirical basis, it is presumed to be sufficient enough to cover the needs in fodder for an extensive dairy production (as per the empirical results and meta-analysis in Bignal, 2000; Smit *et al.*, 2008, respectively). Be that as it may, there is a question about whether the extensive management of permanent grasslands based on these yield assumptions can close the nitrogen cycle or if, rather, it would ultimately result in lower amounts of nitrogen being supplied to permanent grasslands,

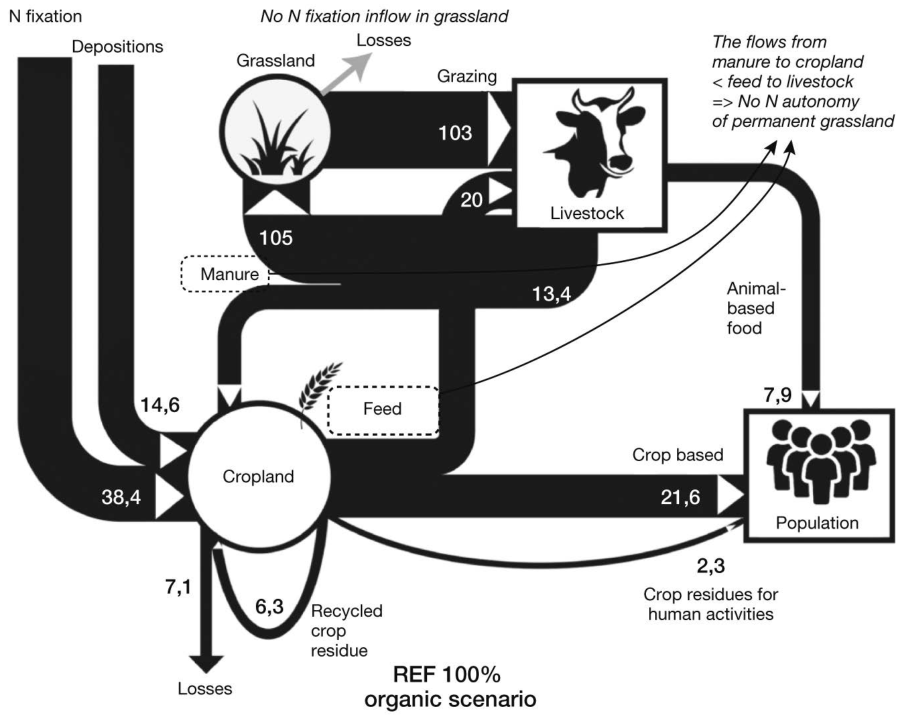

Figure 10.5. Representation of nitrogen (N) flows in Barbieri *et al.* (2021), expressed in tetragrams of nitrogen (TgN). We added the text in italics, arrows and boxes with dashed lines. This figure does not take nitrogen fixation in permanent grasslands into account, and therefore there are no transfers to croplands, unlike in the TYFA scenario.

compared to the current mineral supply and feed imports for animals (e.g. soybeans). We have assumed that permanent grasslands will be made up of 30% pulses, which would translate to an average fixation of nitrogen of 180 kg (both off-soil and below ground); this would be sufficient enough to cover the requirements in terms of nitrogen. It seems this value of 30% is a little too optimistic since the average in a large sample of permanent grasslands in France is only 10% (Jeuffroy *et al.*, 2015). Current models have also suggested that close to 70-80 kg/ha of nitrogen is supplied through symbiotic fixation, which is clearly below our net export assumption. It should be remembered though that these statistical models are calibrated using data covering a wide variety of grasslands, some of which are fertilized (Einarsson *et al.*, 2021), and as a result they do not reflect the specific nature of genuine semi-natural grasslands. In the above-mentioned sample, Jeuffroy *et al.* (2015) found that there was a higher share of pulses in the extensive grasslands, underscoring the conflict between nitrogen fertilization and a higher percentage of pulses. This assertion is in line with the assumption that the average proportion of forage legumes will increase in permanent grasslands, whereas fertilization would decrease as per the TYFA scenario. However, extensive permanent grasslands have been understudied and quantified as such, whereas the biological mechanisms involved are inherently different from the ones in fertilized systems (Jeffrey, 1988). It is important to remember that free-living bacteria may influence nitrogen fixation (as mentioned above; Dobereiner, De-Polli, 1980; Jeffrey, 1988; Roper, Gupta, 2016). In short, the TYFAm assumption about the supply of nitrogen by permanent grasslands is that a low-input permanent grassland ecosystem will develop a nitrogen fixation mechanism, along with other biological functions, that is inherently different from a permanent grassland with legacy nitrogen or high mineral nitrogen input, and that extensification can maintain sufficient levels of nitrogen (Loiseau *et al.*, 2005). As stated above, this assumption should be compared to empirical data (currently quite limited). However, it should be noted that Tilman *et al.* (1996) conducted a research project that agrees with our general assumptions on biodiversity supporting high grass productivity.

A discussion has been started regarding the fact that the TYFA scenario does not factor in phosphorus flows, as that there are no models that can model its cycle in the food system compared with nitrogen (for instance). This needs to be further analysed because a shortage of phosphorus could be limiting factor for nitrogen fixation which is central part of the reasoning in the TYFA scenario. At present, phosphorus is not yet a limiting factor, but it could be in the near future, at least in extracted mineral form (Cordell *et al.*, 2009). Even though we have not discussed this further, we are inspired by the prospects opened up by Faucon *et al.* (2015) on the management and supply of phosphorus in agroecological systems. Specifically, these authors mention the importance of soil organic matter in microbial and rhizospheric activity in the soil, as regards phosphorus mobilization and the positive plant-soil feedback on phosphorus availability in cropping and grassland systems involving multiple species. Furthermore, the assumptions about soil cover in winter and the occurrence of agroecological features in a landscape are key to preventing erosion, the main reason for a loss of phosphorus.

From nitrogen supply to nitrogen transfer: role and challenges of the spatial redeployment of grasslands

Not only is the TYFA scenario based on a net supply of nitrogen from permanent grasslands, but it also assumed that this nitrogen can be transferred to croplands. Aside from the manure management issue (see the assumptions above), one of the key questions raised by the TYFA scenario is the extent to which it could be possible to spatially redeploy permanent grasslands across Europe. This would imply the dual “despecialization” of areas dominated by croplands, where permanent grasslands may only cover 1.5% of the usable agricultural area (UAA), and grassland areas move towards mixed systems. One alternative, which still exists in Mediterranean regions, involves the transfer of nitrogen via transhumance in regions that are still dominated by croplands (e.g. Castilla y León in Spain). Three points can be used to check the feasibility of this dual dynamic of redeploying grasslands and despecializing field crop areas:

– Temperate regions in Europe (outside the Mediterranean area) that are highly specialized in field crop production are an exception to this. Elsewhere, it is more common to find a permanent grassland threshold of 8-15%, or even 15-24%.

– In Mediterranean regions, where herbaceous permanent grasslands are not all that common, we find certain types of semi-natural vegetation that could encourage reciprocity through transhumance (however, it would be necessary to clarify the percentage of available nitrogen).

– Conversely, there are regions that are truly specialized in grass-fed livestock farming (the British Isles and the Massif Central region in France) and which have an agricultural potential for partially going back to croplands, as suggested by historical data.

Thus it is not always as difficult to redeploy mixed crop-livestock farming systems within a territory (Martin *et al.*, 2016; Ryschawy *et al.*, 2017) throughout Europe as it is in regions that specialize in field crops. However, we cannot overlook the socio-economic challenges for this type of despecialization as it would go against the prevailing trends within the EU in recent decades: the abandonment of permanent grasslands in marginal areas, the tillage of permanent grasslands in favourable crop growing areas and the significant intensification of permanent grasslands in favourable areas for grass (Peeters, 2009).

Nutritional implications of making optimal use of permanent grasslands and ruminants

It is widely acknowledged that humans in OECD countries need to significantly reduce their animal protein intake for climate change mitigation purposes (Clark *et al.*, 2020). Therefore, a central theme in relevant scenarios concerns discussions about food diets. The TYFA scenario is not an exception to this– it assumes that the consumption of meat and dairy products will be reduced by half. That said, in TYFA, the function of permanent grasslands attaches relatively more importance on animal-source foods from ruminants than from monogastric animals, in keeping with the systemic perspective (Frehner *et al.*, 2020). For this reason, this systemic approach considers that ruminants have a major advantage in that they are able to feed on inedible vegetation, i.e. permanent grassland products, which is the focus of this chapter (Van Zanten *et al.*, 2016; Van Zanten *et al.*, 2018). With this in mind, and while remembering that not all agricultural land is arable, meat and dairy production from permanent grassland is not an inefficient use of land: in fact, it is the best use of non-arable land (Van Kernebeek *et al.*, 2016). Seen in a broader sense, this additional source of calories means that there is less need to produce food on arable land, which already covers a limited surface area, thereby reducing the need for intensification. When considering the fundamental difference between feeding animals with grains versus non-edible feed, ruminants become the most efficient land users provided that they are fed with products from permanent grasslands (Wilkinson, 2011; Mottet *et al.*, 2017). These assumptions are in line with the findings of van Selm *et al.* (2022), who suggest that resource recycling is factored into scenarios. When there is a balanced share of ruminants/permanent grasslands, this results in better performances, including for GHG emissions, compared to diets that minimize this share, e.g. the EATLancet reference diet (Willett *et al.*, 2019).

In the TYFA scenario, if the objective is met to maintain the total area as permanent grasslands and to reduce their average productivity to 4.5 tDM/ha (under the assumption that this corresponds to the productivity of semi-natural permanent grasslands without inputs), then there would be a 34% decrease in dairy production and the production of ruminant meat would more or less stay the same. The latter result comes from the extensification of milking stock, which means more meat by-products per ton of milk (e.g. one cow that produces 10,000 L milk/year is replaced with two cows producing 5,000 L/year, thereby doubling the number of calves produced with a comparable level of milk production). It should be pointed out that the share of grass increases in the ruminants' diet and therefore dairy cows are given supplemental feed from crop systems and concentrated feed supplements. On the whole, the resulting diet increases the share of ruminant meat from 15% in 2010 to 35%, which means that much of the meat supply comes from pigs and poultry, both in absolute and relative terms: monogastric meat consumption would be 56 g/person/day in the scenario (vs. 140 g today), i.e. approximately 65% of the total meat consumption (vs. 80% today). Monogastric animals are pivotal for "transforming" pulses included in crop rotations into organic nitrogen; simply put, imported soybean would be replaced by pulses grown in the EU, which would also increase symbiotic nitrogen fixation on arable land in the EU. As such, the food diet under the TYFA scenario (Figure 10.6), and other diets in similar models, is not vegan but "flexitarian", with a relatively large share of red meat compared with other healthy diets.

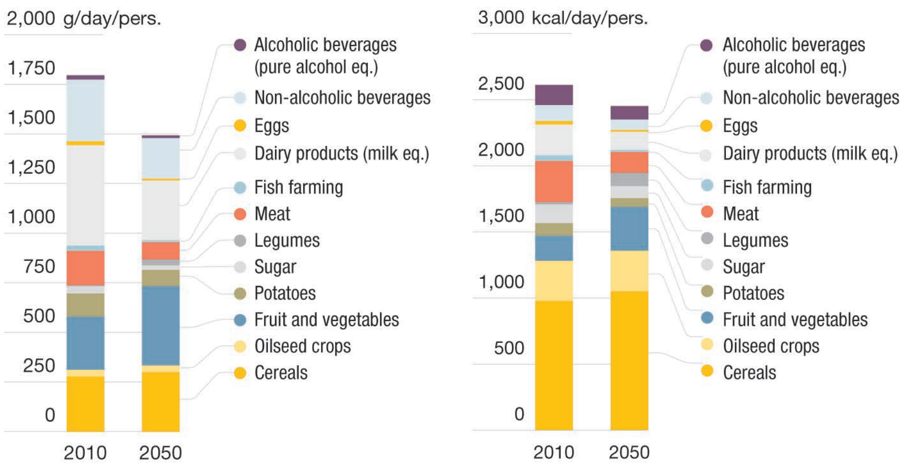

Figure 10.6. TYFA's assumptions for food diets compared to 2010 (EU averages; Poux, Aubert, 2018; based on TYFAm and EFSA data for 2010).

Permanent grasslands, ruminants and climate change

A central assumption of TYFA is that permanent grasslands need to be grazed/mowed as much as possible by/for ruminants, using extensive models, in order for them to be able to provide the full potential of ecosystem services. As a result, there is only a moderate reduction of the ruminant herd under the TYFA scenario compared to most sustainable food system scenarios (Couturier *et al.*, 2016; Lóránt, Allen, 2019; Willett *et al.*, 2019). In turn, this helps explain the potential for reducing GHG emissions in TYFA, which ranges from -36 to -40% (expressed in GWP100) compared to 2010. Simultaneously, the potential use of biomass for other uses than food will still be limited by lower yields and the preservation of permanent grasslands, both of which mean that the TYFA scenario is not really compatible with the EU's target of reaching carbon neutrality by 2050 (EC, 2018; ECF, 2018; Aubert *et al.*, 2019). Nonetheless, this needs to be viewed in a wider perspective by focusing more on at least three distinct aspects.

The first pertains to changes in the effect of ruminants on climate, primarily due to methane emissions. Most of the lines of argument include the use of GWP100 expressed in tons of CO_2 equivalent (tCO_2eq). This approach excludes the short lifespan of methane (CH_4), which has an enormous impact on temperature but does not last long since half of the molecules break down into CO_2 and H_2O after 12 years.

When methane comes from a biogenic cycle (as opposed to the release of fossil methane), which is what happens in agriculture, the conversion of CH_4into CO_2 at the end of the cycle is "compensated" by the CO_2 that was initially fixed in the cycle via photosynthesis. This distinctive feature completely changes how the impact of methane emissions on climate change is understood: a stable level of biogenic methane emissions from a sector does not increase the temperature of the planet (livestock farming in our case, but the same applies to irrigated crops like rice). In contrast, an increase or decrease in emissions will result in either higher temperatures (by increasing the powerful flash effect of CH_4) or a so-called "cooling effect" when emissions have decreased (Allen *et al.*, 2018; Lynch *et al.*, 2021). A more accurate analysis looking at the warming power of methane's flash effect on oceans indicates that methane emissions have a neutral impact for changes of -10% to -15% within a 12-year period (Allen *et al.*, 2022). To understand the full mitigation potential of the TYFA scenario, we need to look at the relative reduction of all gases, including the differential atmospheric behaviour. With this in mind, the complete reshaping of the nitrogen cycle has significant impacts that could outweigh the small reduction in methane emissions, e.g. the elimination of CO_2 emissions related to synthetic nitrogen production using the Haber-Bosch process, a considerable drop in N_2O since direct nitrogen application is more than halved (from over 20 million tons in the form of synthetic nitrogen and manure in 2010 to 3.3 million tons of organic nitrogen in the form of manure in 2050) and a phase-out of mineral fertilizers in favour of organic fertilizers, which have an emission factor that is 2.6 times lower (Buendia *et al.*, 2019).

A second aspect that needs to be better taken into account is the possibility to use some of the grass produced on grasslands to produce biogas through anaerobic digestion (Aubert *et al.*, 2019). The interest is three-fold: to reduce the number of ruminants needed to graze 60 million hectares of grassland (a 34% decrease in ruminant livestock units (LU) compared to 2010, versus 18% in the original TYFA scenario); to maintain grasslands and their related ecosystem services by using them for biogas production once every five years; and to produce bioenergy to replace fossil fuels. This option was also explored by Kizeková *et al.* (2018) in Slovakia. As it is not possible to define a clear point from which biogas production (i.e. anaerobic digestion) occurring in grasslands would changeover to bioenergy production, thereby fundamentally changing the nature of the intended agroecology, it is worth recalling that the scale used changes the very nature of the sector and therefore caution should be used.

The last aspect has to with the issue of adaptation. Even though it is debatable whether the TYFA scenario is compatible with the carbon neutrality target, the scenario would greatly improve the adaptation capacity of most agroecosystems throughout Europe by significantly increasing the diversification of crop systems (Lin, 2011; Muneret *et al.*, 2018), reconnecting crop and livestock farming systems and improving soil health (Mäder *et al.*, 2000; Gattinger *et al.*, 2012). These key aspects would help improve the ability of the agricultural sector to adapt to the impacts of climate change, for instance: increased water stress, the emergence of new parasites/diseases and irregular rainfall. In short, questions relating to the ability of the TYFA scenario to attain carbon neutrality versus other scenarios raise additional questions about whether these other scenarios can address climate change adaptation and thereby, about their overall resilience.

⏩ Conclusion: reviewing the role of permanent grasslands and ruminants in the sustainability agenda

In existing food-system scenarios for the EU, permanent grasslands are seen more as a problem than any kind of solution. At best, they are confined to areas where they are the only possible land use, and which can accommodate a certain density of ruminants. At worst, these grasslands will be replaced by forests or crops for bioenergy production. We have discussed the conceptual boundaries of these approaches and have proposed a scenario based on an alternative framework for the issues, combining a unique link between biodiversity, permanent grasslands, ruminants and climate change. Using the biomass model developed in the TYFA scenario, we factored in a scenario for the EU that has yielded positive outcomes for a healthy diet, biodiversity, natural resources and the climate. We stress the need to adopt a healthier diet, to reduce the consumption of both meat and dairy products by half in order to achieve this.

It is important to understand the role permanent grasslands and ruminants play in this model in terms of what they offer to cropping systems. The key is that the semi-natural functioning of permanent grasslands should provide an array of services (nitrogen fixation, organic matter, beneficial insects) that can be transferred to cropping systems by ruminants. We have also discussed how the impact ruminants have on climate change should be revised and be part of a wider analysis that accounts for the trade-off with nitrogen management and the related nitrous oxide emissions.

In addition to these biotechnological arguments that we hope will be added to the various future studies touching on sustainable food systems under TYFA, it is clear numerous aspects of the social and economic changes caused by this kind of scenario have not been addressed. Examples of this include reconnecting crops and livestock farming at the farm level and the needs in terms of a labour force if farm holdings are consolidated; changes in how flows are managed in the food chain and thereby the economic model for food industries and retailers; and lastly, consumers’ willingness to pay. Even though these key issues are outside the scope of the biophysical modelling under the TYFA scenario and presented in this chapter, they need to be examined further to make sure that the global approach to the scenario is consistent. Some of the aspects examined by Aubert *et al.* (2021) have not been discussed in this chapter, however we would like to point out that the difficulties and challenges of this type of scenario are not to be compared to the current situation, but rather to other plausible futures for food production and consumption in 2050. With this in mind, the TYFA scenario needs to be seen as an alternative to a possible and plausible European agricultural production crisis resulting from a combination of climate change, the collapse of biodiversity in landscapes and the soil and the depletion of energy and/or mineral resources. As a consequence, the socio-economic and policy challenges might be of a comparable magnitude with to the challenges arising from our assumptions. By comparison, it is possible that the socioeconomic and political conditions for the TYFA scenario could become more credible than they are today.

Part 3

Transversal analysis of foresight exercises and scenario modelling-assessment

Chapter 11

Analysis frameworks for coupling approaches to better combine foresight and assessment

Mathieu Vigne and Jonathan Vayssières

⏩ Why use a framework to help choose the type of coupling?

Many studies combine foresight and modelling-assessment approaches; the common goal of these studies is to propose practical solutions to facilitate decision-making and actions for numerous stakeholders. At first, it may seem that the published articles and examples cited in this book and arising from the Researcher School cover a very broad range of foresight methods and modelling-assessment tools. This gives the impression that there are infinite possible combinations of these two approaches. Anyone hoping to combine foresight and assessment methods might feel slightly overwhelmed with all these possibilities, regardless of what they are trying to achieve. This leads to the question: can a theoretical framework be constructed to analyse coupled approaches that would help practitioners choose the type of coupling that best addresses the question that was asked originally?

Numerous reviews of the methods and tools used in either foresight or assessment approaches can be found in the literature, but these reviews are sometimes incomplete, and they rarely lead to recommendations. For instance, the Futuribles association has developed a toolbox for foresight approaches that lists the available approaches, tools and software[23]. However, practitioners may struggle with creating a decision tree for the simple reason that there are just too many options available during the entire foresight creation process. Several references have suggested a decision-making approach for selecting assessment methods that can assess the sustainability of systems, including agricultural systems. ADEME (2020) used a map of 17 environmental assessment methods to develop a decision tree for practitioners in an aim to help them choose the method (or methods) the best meets their needs. This decision tree has five steps; practitioners are asked to answer questions about the purpose of their study, its scope or the presentation of the results (Figure 11.1). However, this only relates to one aspect out of many possible criteria that can be used in assessments. Lairez and Feschet (2016) used 42 methods and tools to construct classification trees used to assess the sustainability of agricultural systems. Sustainability was either considered as a whole, or focus was placed on

23. https://www.futuribles.com/la-prospective/methodes-et-outils/la-toolbox/

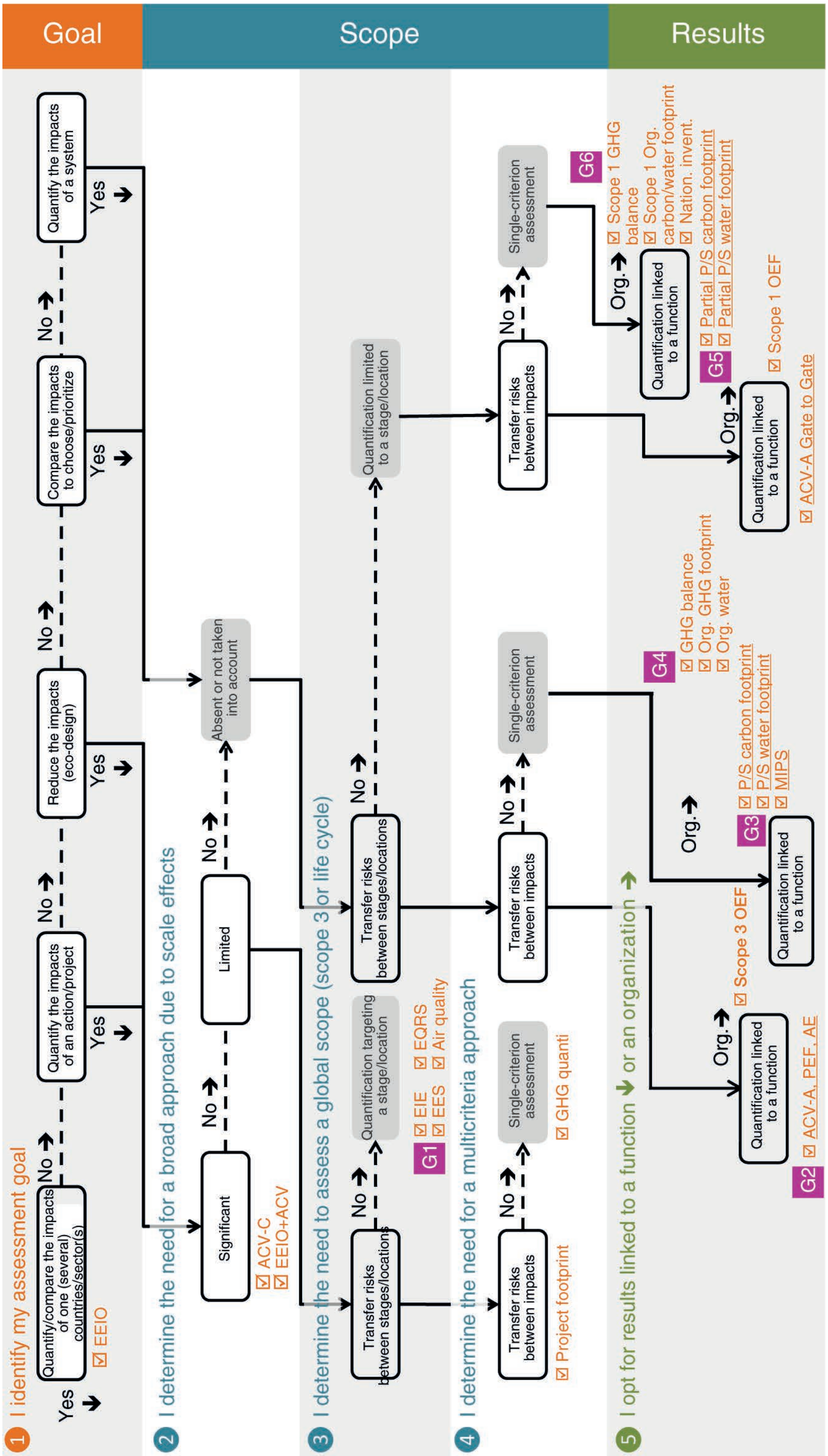

Figure 11.1. Schematic flow chart used to select environmental assessment methods (source: ADEME, 2020.

just one single aspect (e.g. environment, animal welfare or the technical-economic dimension). These trees will be useful to practitioners as they will help them choose the method that is best suited to their purpose. The first step in this process is to categorize the methods based on the aim of the assessment. These categories and then subdivided based on the differentiation criteria used (again, based on the aim) (Figure 11.2).

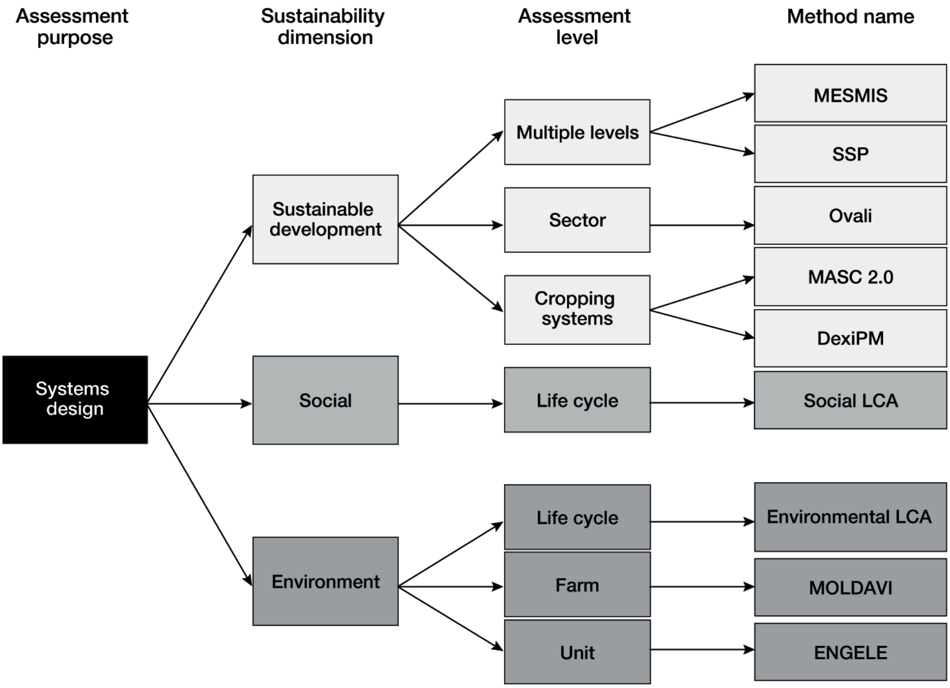

Figure 11.2. According to Lairez and Feschet (2016), decision trees help users choose a multi-criteria assessment method.

It is not easy to develop a decision-making tool that combines two separate approaches (foresight and assessment) that can each be carried out independently. Therefore, in a first step, this tool needs to draw from the specific differentiation criteria for each approach. The various foresight methods and their differentiation criteria were discussed in Chapter 1. By way of a reminder, each method differs based on certain criteria such as whether scenarios are constructed, the type of scenario (if constructed; e.g. exploratory or normative) or the scenario construction method used (if appropriate), the type of stakeholders involved and their level of involvement. As mentioned in Part 2, there are at least as many differentiation criteria for the assessment methods used on systems and the livestock sector, for example: the scale of the assessment, whether the assessment is based on a simulation model, the type of model (empirical or mechanistic), the number of indicators considered (is the analysis based on one or several criteria), the aspects in the assessment (technical, social, environmental, economic, etc.), the type of indicators produced (quantitative or qualitative) or even how these indicators are presented (aggregated indicators or gross values).

However, it is important to not limit the analysis to only the unique differentiation criteria specific to each approach. To construct a relevant decision-making tool, we first need to better understand the main guiding principles for the coupling approaches and all the different ways they can be implemented.

⏩ Assessments play various roles in the coupling process

According to Jahel *et al.* (2023), these principles should include two key aspects, the objective and process chain, to categorize approaches using qualitative and quantitative foresight methods. It seems to us that the role of assessment in this process is a main factor that differentiates between the various types of foresight-assessment coupling methods. Just like when foresight exercises or assessments are carried out individually, approaches that combine both these methods are also driven by specific requests from a stakeholder or group of stakeholders. At minimum, these stakeholders need information about a specific issue and possible futures. However, much of the time, these stakeholders need to carry out an action or change in the system or region being studied. This usually creates a cycle, or "loop", that may be repeated many times, and which often uses iterations to improve and clarify the results as well as to better address the initial request (Figure 11.3). Yet even though an assessment approach uses the same tools as a foresight approach, it doesn't meet the same objectives for the simple reason that assessments can be carried out before, during or after foresight exercises.

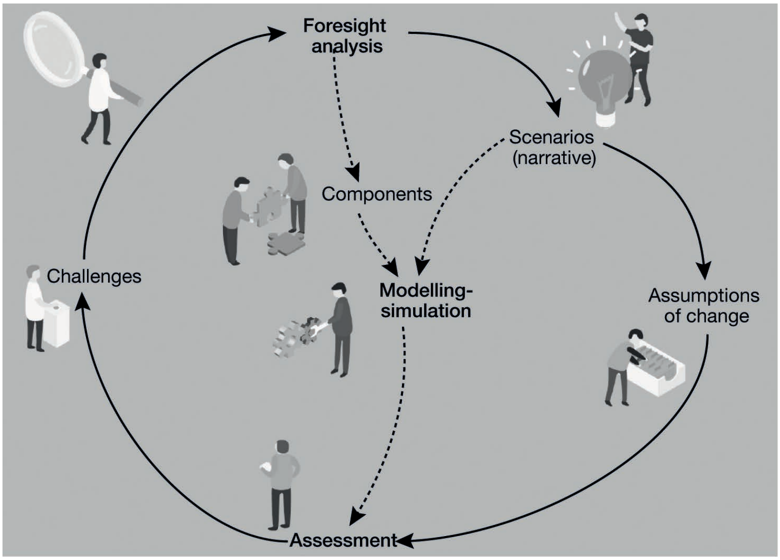

Figure 11.3. Generic representation of the joint foresight and assessment approaches.

When an assessment is carried out before a foresight analysis, it can help pinpoint issues and make them known to the stakeholders. An assessment can also be considered as a baseline for an exploratory foresight study (e.g. in the region of Brittany; Marguet, Chapter 2) or as a diagnostic tool (e.g. cross-border transhumance between Burkina Faso and Togo; Sourisseau *et al.*, Chapter 3). Actors involved in the scenario construction process have access to this information, before building the scenario, and therefore they can use it to address the issue and related challenges. Assessments can also be used to prioritize issues and challenges, which then makes it possible to refocus the issue around certain challenges by preselecting or developing indicators that make sense to the stakeholders (Pierart, chapter 4).

When foresight studies and assessments are used together, this can ensure the relevancy of constructed scenarios, e.g. they do not exceed the available resources. The Afterres 2050 scenario, for instance, uses a national balance sheet approach that first checks whether the land use is balanced (Couturier, chapter 9). This can lend credibility to the scenarios, i.e. by ensuring they are realistic, but in reverse, it could become more difficult to construct so-called "disruption" scenarios because this would limit the field of possibilities.

When an assessment is carried out after a foresight study, the main aim is to measure the impacts of the scenarios constructed during the foresight analysis. In this case, the assessment would include either i) qualitative assessments, to project the impact of the possible changes, "based on expert opinions" or ii) quantitative assessment tools, such as modelling-simulation approaches that use tools such as the MAELIA platform (Therond, Chapter 7) or the TYFAm model (Aubert and Poux, Chapter 10). Spatially explicit, agent-based modelling platforms such as MAELIA have been able to produce some of the most detailed results regarding the interactions between biophysical and decision-making mechanisms and depicting levels of complexity. Part of the research involves seeing how we can further boost the quality of scenario assessments by incorporating assessment methods such as a territorial LCA into these platforms. However, an assessment is not an end goal; rather, it is an iterative process. The results of a scenario assessment can be used more than once to better reframe the issues, to prioritize the various challenges and perhaps even to identify new ones once the stakeholders have weighed in on the assessment (Lopez-Ridaura, 2005).

⏩ The choice of coupling type is based on data availability

Coupling methods that use qualitative scenarios in quantitative assessments all have one intrinsic step in common: they must change narratives into quantitative representations that can be assessed.

For instance, it is possible to break down the data requirements for the MAELIA platform into two types:
– georeferenced data, which can accurately describe the structure of the territory (region/area) and the action situations;
– data on ecological process and human activity dynamics and their interactions (summarized as rules or mathematical functions).

According to Therond, even if the models representing these processes need to be calibrated, quantitative references (which may be scarce or even unavailable) are still needed to calibrate the structure of the territory and its processes.

For instance, there are many databases and platforms in France that provide GIS-type information (i.e. georeferenced data), especially through the National Institute of Geographic and Forest Information (IGN). However, it is not always so easy to have access to the kind of data in other countries, especially developing countries that usually lack specific departments that provide these data. For some time now, researchers have been working on developing mapping tools that use satellite data for mapping land uses to specifically address this issue. However, the accuracy of satellite data could be affected by climate conditions or the type of agricultural practice.

Another good example of how poor data can affect studies has to do with livestock herds, herd performances and herd dynamics in certain situations. For instance, in the Global North, the American National Agriculture Statistics Service (NASS) provides regularly updated data on livestock farming systems and the French Statistics and Forecasting Department within the Ministry of Agriculture, Agri-Food and Forests (Agreste) produces similar data each year. In addition, agricultural technical institutes and Chambers of agriculture make more detailed data available, especially through reference farm networks. However, these services are often quite time and data intensive, and they need a rather extensive information acquisition network. It can be difficult to even find such institutes and monitoring systems in the Global South, and when they do exist, they usually have limited resources. Using Mali and Madagascar as an example, the last general agricultural census was carried out in the 2004-2005 season due to all these issues. Therefore, FAOStat data are often used instead for analyses at the national scale, even if these data also have certain limitations (see Chapter 1 by Mora and Bethinger). Agricultural systems, including livestock farming systems, can also be described through specific studies that, mostly, produce structural and functional typologies of these systems. But here again, the high cost in terms of both human and financial resources often means that only a limited area can be covered. In other words, it usually is only possible to apply the approach to a local scale.

In summary, it seems that another key criterion for defining a typology for coupling frameworks is the availability of data that can be used to build, model-simulate and assess scenarios.

⏩ From an analysis framework to a typology for coupling frameworks

Based on these factors, we present here a first analytical framework for the various coupling methods (Table 11.1), based on two main themes: type of foresight analysis (rows) and type of assessment (columns). Each theme is then divided into separate differentiating criteria:
– whether or not scenarios are constructed, the type of scenario (exploratory or normative) along with the methods used to construct the foresight scenarios (local actors representing the persons responsible and stakeholders in these studied systems may or may not be involved in this);
– the role of assessments in the overall approach (only when assessing scenarios or in specific phases in the process) and the type of assessment (qualitative, quantitative or both).

Table 11.1 shows the position of the various case studies discussed in this book or in the Researcher School within the coupling framework, and highlights some of the main types of coupling.

Type 1 is based on a *bottom-up* approach in which the local stakeholder mostly guides the request using a tangible and clearly identified local problem. This usually covers a smaller scale (e.g. from small areas to regions). In addition to defining

Table 11.1. Positions of the case studies discussed in this book or during the Researcher School within the analytical framework of coupling types (in red: case studies that use modelling-simulation; in blue: case studies that do not use modelling-simulation).

		Assessment	Assessment of scenarios			Assessment at various stages		
Foresight analyses			**Qualitative assessment**	**Quantitative assessment**	**Quantitative and qualitative assessment**	**Qualitative assessment**	**Quantitative assessment**	**Quantitative and qualitative assessment**
With scenario building	**Exploratory scenarios**	Participatory approaches		**Type 2**		GASL	MAELIA Agriculture in Brittany in 2040	Peaceful transhumance
		Without local stakeholders		CLINORG Agrimonde-Terra				Type 1
	Normative scenarios	Participatory approaches		Afterres 2050				
		Without local stakeholders		Transitions 2050 TYFA				
	Exploratory scenarios	Participatory approaches		**Type 3**				
Without scenario building	**Normative scenarios**	Without local stakeholders						

the problem, local stakeholders also help build scenarios and sometimes also help assess them (especially when a qualitative assessment approach is used). This type of assessment can be carried out at any time; e.g. either before scenario building, to analyse the situation and challenges (especially since it is easier to produce data for the smaller scales), and/or after scenario building, to assess the constructed scenarios. This assessment may be qualitative, quantitative, or both. It depends on the issues that have been identified, the availability of data for the studied area and the availability of *ad hoc* modelling and assessment tools. Agent-based spatial modelling platforms such as MAELIA (Therond), GAMA (Taillandier *et al.*, 2012) or Cormas (Bommel *et al.*, 2016), or interaction-oriented platforms such as Ocelet (Degenne, Lo Seen, 2016) are excellent tools for performing assessments as they can represent the various stakeholders and their interactions in relation to the actions exerted by biophysical processes (e.g. plant growth, changes in livestock herds) and the environment (e.g. climate change and regulations).

Contrary to Type 1, Types 2 and 3 mostly use top-down approaches applied to larger scales (e.g. country, continent or the world) and include a wide range of dynamics (population growth, dietary changes, etc.). Types 2 and 3 broadly deal with global issues such as climate change or food security and, usually, they are steered by research. Their general goal is to clarify public policies or to advocate for a specific issue. Often, they are based on simpler balance models (partial or general) than the models used in type 1. Because the scales of analysis are broader, they do not go into as much detail. Where they differ is in the type of scenario they can construct. Type 2 approaches examine exploratory scenarios to broaden the field of possibilities, whereas type 3 approaches focus on normative scenarios to attain specific pre-identified targets.

Conclusion and outlook

The comparisons and analyses carried out in this book up until this point (e.g. comparisons between different foresight and assessment methods, the analysis of how we can combine these two approaches) have laid the foundation for us to propose a first framework for analysing foresight and assessment coupling methods. However, bear in mind that only a few case studies were used to construct this first framework and therefore it is not a comprehensive look at how to couple these methods. For example, in this book and in the Researcher school, the foresight studies all included a scenario building approach. Thus, it is legitimate to question how assessments could be used in a complementary manner to this type of foresight study, other than after the study has been carried for the purpose of pinpointing issues. More generally, it is also reasonable to wonder about possible limitations when coupling certain foresight and assessment methods. For instance, the analysis framework presented in this chapter does not take into account the data requirements for the selected methods and tools. This is an important factor to consider as data availability could be a major differentiating criterion for this type of coupling, and it could even have an impact on the choice of assessment method. Assessments do not always use simulation models, and their level of detail depends on the data availability. In turn, the degree of precision required by some modelling tools could mean that the scenarios constructed during the foresight analysis will be built to high standards with a high level of detail (see Chapter 12). In addition, case studies in this first framework are colour coded based on whether they use a simulation model. However, it could be useful to analyse their features (e.g. static or dynamic, empirical or mechanistic, spatialized or not, etc.) under the different foresight methods in an aim to better understand the potential complementarities or incompatibilities between the methods and tools used in both approaches.

Thus, it will be important to find a way to conduct a broad and detailed analysis of experiences focusing on the coupling of foresight studies and assessments. Like this, more differentiation criteria could be cross-referenced, and general recommendations could be made. These recommendations could be presented as schematic diagrams showing the main groups of methods, or they could be used to construct decision trees to help practitioners choose which type of coupling would work best for them based on their needs and limitations. This would also help them understand these methods and tools better and perhaps would encourage them to work together to find ways to improve each other . In this regard, the long-term goal would be to not just simple couple these approaches but to also fully integrate them into studies.

Chapter 12

Components of agri-food systems and variables in foresight scenarios

Aurélie Wilfart, Olivier Mora and Sandrine Espagnol

This chapter provides practical reference points for scenario building, modelling and assessment for the purpose of identifying the key variables, data and sources of data used in studies presented in this book. The aim is to make it easier to implement studies of this type in the future. Already, the workshops held during the Researcher School identified data availability and sources of data as being two of the biggest factors curbing scenario implementation and assessment.

Several of the foresight analyses presented in this book constructed and assessed scenarios describing an agri-food system with the following components: human population demographics, related food diets and supply chains, other non-food uses of biomass, land use, agricultural systems and linkages with other territories through imports and exports (Figure 12.1). These components are interrelated and form a system characterized by internal consistency. We have based this summary on the following foresight analyses:

– at the scale of France: Afterres 2050 (Chapter 9) and SISAE (Barbier *et al.*, 2022), with its four scenarios that make up the Food Transitions 2050 section (Chapter 4);
– at the scale of Europe: TYFA (Chapter 10); and,
– at the world scale: Agrimonde-Terra (Chapter 5).

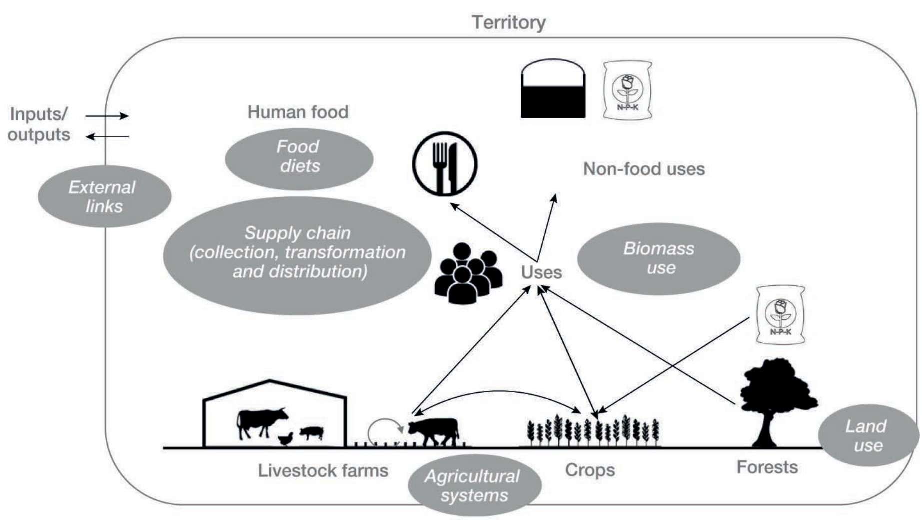

Figure 12.1. Components of agri-food systems in foresight scenarios.

⏩ Assumptions and background data for foresight scenarios

Food system

Food systems are based on assumptions about the size of human populations that may or may not take gender, age groups and socio-professional groups into consideration. These systems may be based on a single diet or a combination of different diets. For instance, SISAE looks at a combination of eight distinct diets: omnivore (between 50 and 170 g of meat consumed per day), flexitarian (between 20 and 50 g of meat per day) and vegetarian (see Table 12.1); whereas Agrimonde-Terra focuses on four alternative dietary assumptions (Table 12.2).

Dietary energy content is another variable considered in food systems. Agrimonde-Terra proposes four scenarios for future diets, including the *Healthy* scenario based on the nutritional recommendations of the World Health Organization (WHO). At the scale of Europe, the recommendation is to reduce the daily calorie intake[24] from 3,336 kcal/day in 2010 to 3,000 kcal/day in 2050 (-11%), to double the consumption of pulses, fruits and vegetables (from 200 kcal/day in 2010 to 450 kcal/day in 2050) and to reduce meat and dairy consumption by 31% (i.e. reduce the calorie intake from 794 kcal/day in 2010 to 540 kcal/day in 2050) in an aim to help prevent overnutrition. The TYFA scenario (Europe) shows a lower calorie intake of 2,450 kcal/day/person, whereas SISAE's *Frugal Generation* scenario (at the scale of France) predicts a 28% decrease in calorie intake by 2050 compared to 2020.

Diets can also be described by the percentage of label-certified products consumed. As an example, the Afterres 2050 scenario predicts that 55% of pig products will have a certified label (with organic productions or local breeds) compared to 5% today. Assumptions about food waste, related to agricultural production and consumption, are also taken into account. The SISAE and Afterres 2050 scenarios estimate that between 155 and 260 kg of food per person, respectively, is wasted each year; the TYFA, SISAE and *Healthy* (from Agrimonde-Terra) scenarios estimate food waste will decrease by an amount somewhere between -10% and -50%.

Land use

In these scenarios, land use defines how much land is used for agriculture purposes and how much is forested. Agricultural land depends on the types of production and the relative proportion of each type. Foresight studies on how to reduce GHG emissions (SISAE, TYFA and Afterres 2050, and Agrimonde-Terra's *Healthy* scenario) suggest that the main changes between now and the future will be a decrease in animal and cereal production and an increase in legume (pulses), fruit and vegetable production. Differences between these scenarios include the absolute changes (increase or decrease) in the categories, as well as the relative variations between these categories. For instance, the TYFA scenario estimates that the decrease in animal production will mostly affect monogastric animals; the current beef cattle numbers will stay the same and there will be a -20%, -70% and -50% decrease in the number of dairy cattle, meat

24. The Agrimonde-Terra scenario is based on data from the FAO database (FAOStat) that correspond to calorie availability (and not to calories consumed) because these data include waste related to food processing, distribution and consumption.

poultry and pigs, respectively). The Afterres 2050 scenario estimates a decrease in all livestock animals: -20%, -60%, -50%, -35% for beef cattle, dairy cattle, meat poultry and pigs, respectively. This is similar to Agrimonde-Terra's *Healthy* scenario, which projects a 16% decrease in all kinds of animal productions.

The future of grasslands is a key factor that needs to be considered in these scenarios, partly because they are closely linked with herbivore production, but also given their carbon storage capacity and ability to provide areas for biodiversity. Therefore, the future of grasslands is a key variable that needs to be considered in these scenarios. The *Healthy* scenario (Agrimonde-Terra) projects that grasslands will decrease by 25% in Europe, and that they will not be converted into arable land (estimated to be reduced by 6%) given the decrease in ruminant production. This then begs the question of what the future of grasslands will look like in Europe by the year 2050– will they eventually be turned into fallow land and then possibly forests, or will they be kept as is for energy biomass production? The *Healthy* scenario shows that there could be a 12 to 16% increase in the surface area covered by forests in Europe if grasslands were to be converted into forests, and if less agricultural land was needed in Europe. It is important to remember that the results for this scenario apply to the global scale; there would be a lower demand for food across the globe and Europe would not be under pressure to increase the amount of land set aside for agriculture within its borders. In other words, the growth of EU exports does not depend on the food demand in the rest of the world.

Another major adjustment variable is the proportion of pulses in a land use system, as pulses influence the overall ability of the system to fix symbiotic nitrogen, thereby decreasing the need for mineral fertilizers. One of the TYFA scenarios estimates that roughly two-thirds of the nitrogen required by crops will come from symbiotic fixation without the use of mineral fertilizers, and as such, the potential pulses have to fix symbiotic nitrogen is a decisive factor when modelling agri-food systems (Billen *et al.*, 2014). Livestock manures are another source of nitrogen, and their potential use in agronomy will depend on the spatial distribution of these livestock farms. Thus, agricultural activities can be spread out within a territory based on two different contrasting situations: "land sparing", which involves concentrating efficient and productive farming activities on a smaller area of land so that a larger percentage of the land (hectares) with strong ecological interests can be freed up, or "land sharing", which would cover the entire area by combining production and biodiversity conservation (Green *et al.*, 2015; Blanfort *et al.*, 2019).

Agricultural systems

Agricultural systems are defined as the various types of agricultural productions included in the scenarios, such as conventional, organic, agroecological or traditional. These productions may be found in differing proportions within a same territory, which affects unit productivity, land use and environmental impacts. On livestock farms, the type of housing and proportion of time animals spend in farm buildings (or stalls) determine the types of livestock manures and whether they can be collected for agronomic use, as well as the amount of straw exported from farm fields for use as stable litter. Most scenarios include pulses in crop rotations, either as a main crop, companion crops or intercrops. Intercropping is quite widespread in the TYFA and SISAE foresight analyses compared to today. Nitrogen input via symbiotic fixation is also strongly linked to the symbiotic fixation rates adopted, which vary depending on the scenario.

The annual agricultural production, defined by the land use and agricultural systems within the area focused on in the foresight analysis, is partly used for human and animal consumption (including for export), and partially used to produce renewable energy either through combustion or biogas production. In the SISAE scenarios, biomass production for non-food use in France increases by nearly four-fold and is mostly used for biogas production. Therefore, priorities of use need to be set for the production capacity of agricultural products. All the foresight studies mentioned here give priority to human consumption, followed by a preferred use as animal feed instead of for energy use (to meet animal feed requirements). Biomass that has been freed up due to the decrease in livestock numbers is redirected towards energy recovery (biogas production), except in the TYFA scenario which makes limited use of biogas production since grasslands are only used for biogas production once every five years in this scenario.

Imports and exports: balancing supply and demand and closing cycles

Human activities create needs that are rarely fully covered by the food and non-food biomass production capacity within a territory (France or Europe) and therefore, some biomass must be imported to meet these needs. On the flip side, certain productions produce too much biomass which is then exported. These parameters are not necessarily viewed as being adjustment variables in the agri-food system. As an example, the TYFA and Afterres 2050 scenarios assume that the share of exports either remains the same or is even increased so that the trade balance is maintained. In TYFA, 30% of the cereal production is still exported to Mediterranean countries. The scenario also produces dairy surpluses, corresponding to 20% of dairy production, that can be exported. In Agrimonde-Terra's *Healthy* scenario, dietary changes result in a significant decrease in the total imports within Europe (-27%), especially for animal feed (-57% for soybean and -89% for soybean meals), whereas exports increase by over 50%.

The assessment of foresight scenarios ensures an internal coherence by balancing supply and demand and by closing the nutrient cycles. For instance, crop nitrogen requirements are met by spreading livestock manures, through nitrogen fixing by pulses and possibly by mineral fertilizers. Consistency between the scenarios is ensured by finding the right balance between agricultural product needs and their production while accounting for their respective spatial distributions.

Tables 12.1, 12.2, 12.3 and 12.4 provide details about the descriptive variables and assumptions used in the SISAE, Agrimonde-Terra, TYFA and Afterres 2050 scenarios; the sources used are indicated in the publications cited.

Table 12.1. Details for the descriptive variables in the SISAE scenarios: baseline scenario and foresight scenarios (*in italics*).

Variables	SISAE scenario
Food diets	
Population size Types of diets Contents of diets (energy, protein, product type, proportion of labels, etc.) Food waste	Population size from INSEE (2017), *as well as the assumptions of change (low fertility, median life expectancy and median migration scenario).* Data on eating habits from INCA 3, ADEME (2016), BioNutriNet with two main consumer profiles: omnivores 170 g (meat), omnivores 75 g (meat), representing 86%. Food losses and waste considered: 155 kg/person/year. *Decrease in meat consumption from 10% (S4) to 70% (S1); percentage of organic food in the diet going from the current situation (S4) to 70% (S1).* *Four different consumer groups: omnivores 170 g, omnivores 75 g, flexitarians 30 g and vegetarians with different proportions in the four scenarios. The first two groups remain the same in S4 and are reduced by up to 39% in S1.* *Assumption that all quantities consumed reduced compared to the baseline scenario, by -10% (S4) to -30% (frugal S1).*
Land use	
Types of productions (animal and plant)	Organic production areas: 2.3 million hectares (8.5% UAA in France) (Agence Bio); livestock herds (Citepa, 2019).
Distribution throughout the territory	*Different approaches between the scenarios: more land sparing for S4 and land sharing for S1 and S2.*
Change in land use	*Increase in oilseed protein crops in S1. Increase in UAA in S2 (+2 Mha) with an increase in oilseed protein crops and land used to grow fruit and vegetables. Decrease in UAA (2 Mha) in S3 with no significant change in production distribution compared to the trend scenario. Also decrease in UAA in S4 due to 7 Mha of land being taken.*
Quantity of pulses in crop rotations	*Increased pulses in crop rotations: +40% in S4 and an increase by nearly 5-fold in S2.*
Quantity of permanent grasslands	Permanent grassland area spanning 9.3 Mha (ADEME). *Preservation of these areas in the four scenarios.*
Hedgerows and agroforestry	Hedgerow lengths spanning 500,000 km (Pointereau, 2006) and agroforestry over 140,000 ha. *Increase in hedgerow lengths to 930,000 km in S1 and increase in agroforestry to 1,500,000 ha in S2.*
Forest	*Forest development with +4 Mha (S1) and relative stabilization in the other scenarios.*
Agricultural systems	
Production methods (conventional, organic)	*Synthetic low-input systems between 10% (S4) and 70% of the UAA (S1); integrated production between 20% (S4) and 30% (S1) of the UAA; and sustainable conventional systems between 100% (S4) and 0% (S1).* *Development of aquaculture in S4.*

Variables	SISAE scenario
Agricultural systems	
Yields	Yield data from Reganold and Watcher (2016). *Increase in yield for S4 (+10% for wheat) and somewhat reduced yields for the other scenarios (up to -27% for wheat in S2).*
Pesticides	*Sharp decrease in the use of pesticides in S1.*
Symbiotic nitrogen	Symbiotic fixation in France estimated at 338 kt N (ADEME). *Percentage of nitrogen used from symbiotic fixation ranging from 15% (S4) to 45% or 55% for S1 and S2, respectively.*
Intercropping	Plant cover in France: 1,092,000 ha (ADEME) *Increase in plant cover, multiplied by 4.5 in S4 and by 15-16 in S1 and S2.*
Carbon storage	Data for forests from Roux *et al.* (2017) for the biomass and from Pellerin *et al.* (2019) for the soil. Change in land use from ClimaAgri® with a 20-year amortization as per IPCC recommendations (2006). Data for permanent grasslands and agricultural soils from Pellerin *et al.* (2019).
Livestock animal diets	*Percentage of diets higher in grass in S1 and S2 and lower in grass in S4 (zero-grazing for 1/3 of the dairy herd).* *Decrease in seed meal imports by half in S3 and S4 and removed in S1 and S2.* *In S4, insect farming provides 25% of the protein consumed by poultry farms and fish farms.*
Technical performance of livestock farms	*Improved performance in S4 (dairy production improved by 38%) and decreased performance in S1 and S2 (dairy production reduced by 16%).*
Time spent by animals in farm buildings	*Time spent in farm buildings, without grazing, in S4 for dairy systems, and up to 70% of systems with grazing in S1 and S2.*
Biomass use	
Use of biomass (human food, animal feed, biogas production, biofuel, etc.)	Data on areas used for biofuels taken from Pellerin *et al.* (2013): 800,000 ha (2015) i.e. 3% UAA (FranceAgrimer).
Outside links	
Imports (especially sources of protein for animal feed) and exports	3.5 Mt of soybean imports (2017; Barbier *et al.*, 2020) and 7,000 kt of fruits and vegetables. 26,000 kt of cereal exports. *Decreased fruit and vegetable imports of close to 10% for S4 and almost 100% for S1; cereal exports maintained for S4 and up to 30% in the other scenarios.*

Table 12.2. Details about the descriptive variables and assumptions for the *Healthy* scenario in Agrimonde-Terra's global foresight exercise (at the scale of Europe).

Variables	Agrimonde-Terra scenario
Food diets	
Population size Types of diets Contents of diets (energy, protein, product type, proportion of labels, etc.) Food waste	UN's median projection in 2050: 9.7 billion inhabitants (World Population Prospects, 2015) Four alternate assumptions of change for food diets by 2050: – Transition towards diets based on ultra-processed products; – Transition towards diets based on animal products; – Regional diversity in diets and food systems; – Healthy diets based on dietary diversity. Available calories including food waste (in distribution and consumption). Quantification based on reworked FAOStat data from 2010 (Le Mouël *et al.*, 2018b). *Healthy diets in 2050, as per WHO recommendations (2003)* *General principles of the healthy diet assumption:* *– Decreased calorie intake to 3,000 kcal/d for regions with diets above 3,000 kcal/d (with waste reduced by half), and increase to 2,750 kcal/d for regions with diets below 2,750 kcal/d* *– 15% fruits and vegetables, max. 20% animal products and pulses, 10% vegetable oils, and 2.5% sugars and sweeteners* *– Decrease in ultra-processed products* *– Transforming the Healthy assumption for EU27:* *– 10% reduction in calories: from 3,336 kcal/d in 2010 to 3,000 kcal/d in 2050* *– Doubled consumption of legumes and fruits and vegetables: from 200 kcal/d in 2010 to 450 kcal/d in 2050* *– Decreased consumption of meat and dairy products in 2050: -31%, from 794 kcal/d in 2010 to 540 kcal/d in 2050*
Land use	
Types of productions (animal and plant)	For the Healthy scenario *Global:* *– Increase in arable land from 1,535 million ha in 2010 to [1,479; 1,583] million ha in 2050, i.e. [-4%; +3%]* *– Increase in permanent grasslands from 3,338 million ha in 2010 to [3,423; 3,357] million ha in 2050, i.e. [+2.5%; +6.5%]* *– Change in total agricultural area between 2010 and 2050: [+0.6%; +5.5%]* *EU27:* *– Decrease in arable land from 121 million ha in 2010 to [113.5; 119] million ha in 2050, i.e. [-6.2%; -1.6%]* *– Decrease in arable land from 68 million ha in 2010 to [50.5; 51] million ha in 2050, i.e. [-25.7%; -25%]* *– Decrease in arable land from 189 million ha in 2010 to [164; 170] million ha in 2050, i.e. [-13.2%; -10%]*
Change in land use	For the Healthy scenario *Decrease in arable land and permanent grasslands for the EU27*

Variables	Agrimonde-Terra scenario
Land use	
Quantity of pulses in crop rotations	For the Healthy scenario *Increase in pulses in crop rotations to meet food demand* *EU27 legumes: from 1.33 million ha in 2010 (1.1% of arable land) to [1.66; 1.87] million ha in 2050, i.e. [+1.5%; +1.6%]*
Quantity of permanent grasslands	For the Healthy scenario *Decrease in permanent grasslands in the EU27 between 2010 and 2050: [-25.7%; -25%]*
Hedgerows and agroforestry	For the Healthy scenario *Increase in agroecological infrastructures (not quantified)*
Forest	For the Healthy scenario *Increase in forest land in the EU27: from 156 million ha in 2010 to [175; 181.5] million ha in 2050, i.e. [+12%; +16%]*
Agricultural systems	
Production methods (conventional, organic)	Four alternate assumptions of change for cropping systems by 2050: (i) Conventional intensification; (ii) Sustainable intensification; (iii) Agroecology; (iv) Collapse of cropping systems. The Healthy scenario is simulated using two options: – *Agroecology* system: crop diversification, crop-livestock systems, ecological infrastructures and biological ecosystem regulations, low use of external inputs (Altieri, 2011; Malézieux, 2012); – *Sustainable intensification* system: production intensification, precision technologies, high use of external inputs, reduced environmental impact by maximizing input efficiency (Griffon, 2010).
Yields	Assumptions of change for yields by crop group (cereals, protein crops, other crops): gaps reduced between potential and observed yields (potential yield data from GAEZ (Global Agro-Ecological Zones)). *Gap reduced for yields between 2010 and 2015: -40% for Sustainable Intensification, -30% for Agroecology.* *The projected yields in 2050 are affected by climate change. However, in the Healthy scenario, the climate change trajectory is controlled, and yields in 2050 are not affected.*
Pesticides	For the Healthy scenario *Sharp decline in pesticide use in agroecological systems (not quantified)*
Symbiotic nitrogen	For the Healthy scenario *Agroecology systems based on diversified crop rotations including pulses (not quantified)*
Intercropping	
Carbon storage	For the Healthy scenario *Carbon storage in agroecology systems (not quantified)*

Variables	Agrimonde-Terra scenario
Livestock farming systems	
Types of livestock systems	Five animal products were considered: milk, beef, small ruminant meat, pork, poultry and eggs; Different livestock systems were used to produce these products: ruminants (mixed/pasture/urban/other), monogastric animals (urban/other) (after Herrero *et al.*, 2013). *Five alternate assumptions of change in livestock systems by 2050 were examined: intensive conventional livestock farming (intensive); intensive conventional livestock farming with local resources (intensive and local); agroecological livestock farming in synergy with agriculture or urbanization (agroecological); backyard livestock farming (backyard); livestock farming that minimizes competition for land with agriculture (marginal livestock farming).* *For each assumption, by species, differentiated change in the proportion of the various systems and the quantity of dry matter intake/quantity of animal product produced coefficient for each system.*
Livestock animal diets	Composition of rations and input/output coefficients (quantity of dry matter ingested/quantity of animal product produced): Initial situation (in 2010), as per Herrero *et al.* (2013); Projections under the different assumptions of change for livestock systems, based on the projections of Bouwman *et al.* (2005) by 2030, extended to 2050.
Technical performance of livestock farms	Performance measured by input/output coefficients, quantity of feed ingested/quantity of animal product produced. Projections of Bouwman *et al.* (2005) extended to 2050. *Limited changes to the technical performance of livestock systems, except for improvements in West Africa, East Africa, Central Africa and Southern Africa, India, and the rest of Asia for the ruminant sectors.* *EU27 (in the Healthy scenario):* *– Decrease in the total production of animal calories by 16% between 2010 and 2050.* *– Variation in exports between 2010 and 2050 by [-10%; +31%], depending on the simulated livestock system.* *– Decrease in animal calorie imports by 30% between 2010 and 2050.*
Time spent by animals in farm buildings	Not specified
Biomass use	
Use of biomass (human food, animal feed, biogas production, biofuel, etc.)	For the Healthy scenario *Global: 106 million ha dedicated to biomass production for energy purposes in 2050 under the assumption of stabilization of climate change (incorporated into the Healthy scenario).* *EU27: 6.8 million ha dedicated to biomass production for energy purposes in the Healthy scenario.*

Variables	Agrimonde-Terra scenario
Outside links	
Imports (especially sources of protein for animal feed) and exports	For the Healthy scenario *EU27:* *– Decrease in total imports by 27% between 2010 and 2050.* *– Increase in total imports by [52%; 59%] between 2010 and 2050.* *– Decrease in feed imports for livestock between 2010 and 2050:* *– Decrease in the quantity of imported soybeans by 57%.* *– Decrease in the quantity of imported soybean meals by 89%.*
Environmental impacts	
Impacts considered	For the Healthy scenario *Reduced environmental impacts in the Healthy scenario with agroecological crop and livestock systems (not quantified)*

Table 12.3. Details for the descriptive variables and assumption in the TYFA scenario: baseline scenario and foresight scenario (*in italics*). With EFSA: European Food Safety Authority, WHO: World Health Organization, PNNS: French National Nutrition and Health Program, UAA: usable agricultural area.

Variables	TYFA scenario
Food diets	
Population size Types of diets Contents of diets (energy, protein, product type, proportion of labels, etc.) Food waste	Food habits from Eurostat: EFSA (2013, 2017) Nutritional recommendations according to WHO, PNNS, ANSES (2016), and EFSA (2017) data. Considering a calorie requirement of 2,300 kcal/person, a protein intake of 50 g/day/person, including a maximum of 35 g of animal protein and a maximum consumption of 70-80 g/day of meat, excluding poultry, and 25 g/day for cured (charcuterie) and processed meats. Food waste estimated at 30% (HLPE, 2014). *Diet of 2,265 kcal/day/person (-6%) with 82 g protein/day/person (including 25 g animal protein), 64 g sugar/day/person and 36 g fibre/day/person (+37%). There is a -3% change in meat consumption for beef, -60% for pork and -66% for poultry.*
Land use	
Types of productions (animal and plant)	Eurostat source used for crop rotations on arable land in the EU, then output from simulations (TYFA model) with agroecological infrastructures and permanent grasslands.
Distribution throughout the territory	*Reterritorialization of livestock farming in cropland areas with a "Land sharing" strategy.*
Change in land use	*Slight decrease in arable land in favour of permanent crops and agroecological areas. Within arable crops, decrease in cereals and fodder maize in favour of pulses (grains, fodder) and oilseed-protein crops.*
Quantity of pulses in crop rotations	*Reintroduction of pulses into crop rotations.*

Variables	TYFA scenario
Land use	
Quantity of permanent grasslands	*Preservation of permanent grasslands in the total area (34% of the UAA) but reallocated across the whole territory.*
Hedgerows and agroforestry	5% of the UAA accounted for in agroecological infrastructures. *10% increase in agroecological infrastructure areas.*
Forest	Not reported
Agricultural systems	
Production methods (conventional, organic)	*100% organic productions and extensification of livestock farming.*
Yields	*Differences in yield between conventional and organic systems: 25% decrease for cereals, 50-80% for oilseeds and protein crops and between 5 and 20% for fruits and vegetables – Ponisio (2015), Guyomard (2013), Agreste (2011 and 2012).*
Pesticides	*Pesticides not used.*
Symbiotic nitrogen	Symbiotic fixation of 150 to 250 kg N/ha/year in permanent grasslands (considered with a legume percentage between 25 and 40%) – Anglade *et al. (2015)* and Vertes *et al. (2015).*
Intercropping	*100% of intercrops are pulses. These cover the whole area with spring crops ("zero bare soil"). Estimated yield of 2 tDM/ha (Anglade, Billen, Garnier, 2015).*
Carbon storage ©	0.7 t C/ha/year for permanent meadows: Soussana and Lemaire (2014)
Livestock animal diets	*0% imports*
Technical performance of livestock farms	*Two types of dairy farming with 5,000 and 7,000 kg of milk/year, respectively; stocking rate 1 LU/ha: Institut de l'élevage (IDELE; 2006, 2013), Chambres d'agriculture [Chambers of Agriculture] (2014) and livestock farming networks (2005).* *Data on organic pigs from Calvar (2015) and Jurjanz and Roinsard (2014).* *Data on organic poultry farms from Bordeaux (2015) and Bouvarel* et al. *(2013).*
Time spent by animals in farm buildings	*Time spent in farm buildings: 90% for dairy cows, 50% for suckler cows and other herbivores (sheep and goats), and between 50% and 70% for heifers. Pigs and poultry stay indoors 100% of the time.*
Biomass use	
Use of biomass (human food, animal feed, biogas production, biofuel, etc.)	Source: FAOStat (2018) data on the use of oilseed and cereal consumption in Europe between human consumption, animal feed and industrial uses. Data from Hou *et al.* (2016) and Eurostat (2017) for the correspondence between available animal feed and feed consumed in Europe in 2010. *Priority given to human food, then animal feed, then non-food uses; 0% biomass used for biofuel and biogas production.*

Variables	TYFA scenario
Outside links	
Imports (especially sources of protein for animal feed) and exports	Source: Eurostat for the import-export balance of EU food products in 2010. *Cereal exports maintained and suppression of soybean imports for animal feed.*

Table 12.4. Details for the descriptive variables in the Afterres 2050 scenario: baseline scenario and foresight scenario (*in italics*). With RDI: Recommended Dietary Intake, WHO: World Health Organization, PNNS: French National Nutrition and Health Program, STH: permanent grasslands.

Variables	Afterres 2050 scenario
Food diets	
Population size Types of diets Contents of diets (energy, protein, product type, proportion of labels, etc.) Food waste	Population size based on INSEE data. Food habits via surveys by Santé Publique France, Esteban, Nutritnet Santé, INCA2. Food quality as per CIQUAL, OQALI and DREES. Nutritional recommendations based on data from PNNS, ANSES, WHO, RDI. Proportion of products with an Agreste label. Food waste estimated to be 260 kg/person/year (ADEME, 2016). Supply balance for households from FAOStat. Considering a calorie requirement of 3,800 kcal/day/person, a protein intake of 120 g/day/person with a daily requirement of 57.9 g of protein, a maximum consumption of 185 g/day of meat, excluding offal, 235 g/day/person of dairy products and 10 g/day/person of legumes. *Foresight scenario to reduce protein overconsumption by 50%, sugar consumption by 11%, milk and dairy product consumption by 40% (from 3 to 2 portions/day) and food waste by 58%.* *Diet of 3,500 kcal/day/person (-8%); 94 g protein/day/person (including 39 g animal protein). The change in consumption is equal to +24% plant proteins and -48% protein overconsumption (i.e. +59% of the calorie requirements).*
Land use	
Types of productions (animal and plant)	Solagro expertise for agricultural areas (based on typical cases). *Foresight scenario targeting cropping systems such as Main crop + intercrop + companion crops, 5% of the UAA in agroecological infrastructures and 20% of arable land used to grow companion crops.* *35% decrease in the pig stock, but a 13.5-fold increase in the number of label-certified pigs.* *25% decrease in the broiler stock with a 3-fold increase in label-certified chickens.* *In cattle farming, ¼ of the dairy stock is kept on a strict grazing system. 48% decrease in the dairy cow stock. Suckler cattle farming divided by 6 (to bridge the gap between the supply and demand of meat supply from dairy cow herds), trend toward mixed breeds. Stable goat herd, sheep herd increased by 50%.*

Variables	Afterres 2050 scenario
Distribution throughout the territory	Source: Eurostat (2018) used for France. *Decrease in the dairy cow herd by 60% (largest reduction in the west) and in the suckling herd by 31% (mountain breeds are maintained), milk production rebalanced throughout the territory.* *-40% pigs (including -75% conventional pigs), -22% meat poultry (-90% conventional systems) and -38% laying hens with a 96% reduction in caged hens.*
Change in land use	*Increase in grain production areas (+9%), decrease in temporary fodder areas (-43%), decrease in permanent grasslands (-11%) and decrease in industrial and permanent crops (-5%).*
Quantity of pulses in crop rotations	*Systematic companion crops (20% of arable land), long crop rotations (7–8 years). Pulses representing 25% of arable land.*
Quantity of permanent grasslands	In 2010, 7.7 Mha of permanent grasslands. *Decrease in permanent grasslands (continuation of recent trends), although this is limited in the scenario aimed at preserving them as much as possible: 6.4 Mha of productive permanent grasslands and 2.4 Mha of less productive grasslands (grazing land, heathland).*
Hedgerows and agroforestry	*Increase in UAA in agroforestry by 10% (50 trees per hectare i.e. a land footprint of 12%) and by 5% in agroforestry infrastructures.*
Forest	Percentage of forest from the Teruti-Lucas survey (Agreste), CGAAER data, and the annual branch survey (MAF) and the IGN-FCBA scenario.
Agricultural systems	
Production methods (conventional, organic)	*Distribution of cropping systems: 45% organic, 45% integrated production (including agroforestry or companion crops), 10% sustainable systems.* *Substantial livestock farming de-intensification with:* *60% organic pig systems, 20% free-range pigs, 4% very extensive systems, 10% conventional pigs,* *40% organic laying hens, 47% label-certified and free-range hens, 13% standard farms,* *45% organic chickens, 30% label-certified chickens, 15% standard free-range chickens and 10% standard caged chickens.* *Disappearance of dairy cows producing 10,000 l of milk and 220 g of concentrate/l as well as dairy cows producing 5,000 l of milk and 165 g of concentrate/l, in favour of 26% dairy cows producing 7,000 l of milk and 165 g of concentrate/l, 26% of dairy cows producing 6,000 l of milk and 100 g of concentrate/l, 28% of dairy cows producing 5,500 l of milk and 50 g of concentrate/l and 20% of dairy cows producing 5,000 l of milk, all fed on grass. Trend toward mixed breeds.*
Yields	*Yield assumptions from the CLIMATOR project (INRA, 2012) with incorporation of climate change impacts: -30% yields in organic farming and -10% yields in integrated production (wheat) but an average equivalent yield coefficient of 1.14 due to associated production.*
Pesticides	*Reduction assumptions from INRA-Ecophyto R&D.*

Variables	Afterres 2050 scenario
Agricultural systems	
Symbiotic nitrogen	Fixation of 120 t C/ha/year for permanent grasslands. *Total symbiotic fixation (oilseed crops and grasslands) representing 26% of nitrogen inputs.*
Intercropping	*Main crop accompanied by other crops (trees, companion crops or intercrops).*
Carbon storage	*Grasslands: ClimAgri®;* *Forest: CARBOFOR project, Citepa, ClimAgri®.*
Livestock animal diets	Adapted from Idele's standard cases for ruminants. *66% of time spent in pastures. Sharp reduction in concentrate consumption (-53%) and decrease in the fodder ration (-31%).*
Technical performance of livestock farms	References not provided but summary tables of the performances used are indicated for pigs, meat chickens, laying hens and dairy cattle. Sheep: Inosys 2014. *Development of an improved conventional system for pig farming.* *Goat and sheep performance from Bocquier* et al. *(2011).*
Time spent by animals in farm buildings	Adapted from Idele's standard cases for ruminants. *34% of time spent in farm buildings.*
Biomass use	
Use of biomass (human food, animal feed, biogas production, biofuel, etc.)	Data based on the négaWatt scenario. *Generalization of biogas production (90% agricultural) using 20% of the grass production (grasslands) and half of the catch crops.*
Outside link	
Imports (especially sources of protein for animal feed) and exports	Modelling using the balance sheet method (difference between national production and domestic demand). *Significant decrease in feed grain exports to Europe.*

⏩ Foresight scenario assessment methods

The assessment of the TYFA, Afterres 2050, SISAE and Agrimonde-Terra foresight scenarios is based on various models that take biomass and environmental flow balances (mostly GHG and energy) into account.

Biomass balance models align the available land with their production (agricultural and forestry, livestock) and demand (food requirements for the population, feed for livestock herds and bioresources). These models can also be used to pull the different levers such as agricultural systems, herd size, diet and eating habits, forest management and harvests, import and export arrangement, and even changes in land taking. Figures 12.2 and 12.3 illustrate the functioning of the MoSUT (Afterres, 2050) and GlobAgri (Le Mouël *et al.*, 2018a) models, respectively.

The ClimAgri® tool developed by ADEME is mostly used to calculate environmental flows in foresight exercises for France. It is used to generate a quantitative assessment of agricultural emissions (e.g. energy consumption in agriculture, GHG emissions, carbon sequestration, nitrogen cycle, agricultural raw material production) based on a life cycle approach. Specifically, it incorporates the upstream phase of the life cycle and includes the impact of input production and transport (fertilizers, animal feed).

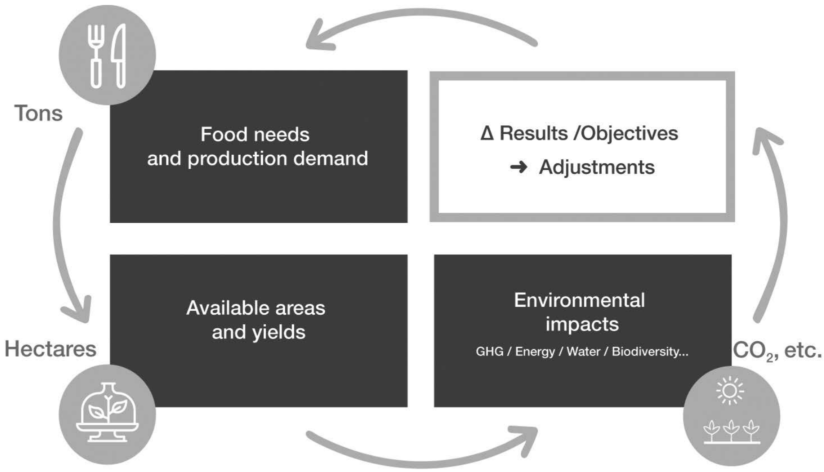

Figure 12.2. General functioning of the MoSUT model.

Tables 12.5, 12.6 and 12.7 describe the environmental flows accounted for in the foresight studies, as well as the related calculation tools used in the assorted studies analysed in this chapter. See Box 6.2 for more details about the models and tools.

Table 12.5. Environmental assessment method for the TYFA scenario.

Environmental flows assessed	Tools used
Nitrogen balance with inputs (nitrogen from manure, intercropping and nitrogen-fixing crops) and outputs in the various harvested crops	TYFAm
GHG balance: direct emissions (energy consumption, soil emissions, enteric fermentation and emissions related to manure management) and indirect emissions (energy production, fertilizers, food and equipment manufacturing, etc.)	TYFAm coupled with ClimAgri®

Table 12.6. Environmental assessment method for the Afterres 2050 scenario.

Environmental flows assessed	Tools used
Biodiversity assessment via HNV areas	Use of the HNV (High Nature Value farmland) indicator (Pointereau *et al.*, 2010)
Agronomic balance	MoSUT and AgriClimateChangeTool (ACCT) developed by Solagro
Land balance	MoSUT
Water balance	MoSUT and ClimAgri®
Forage estimate	MoSUT
Concentrates balance	MoSUT
Supply balance	MoSUT based on a job-resources balance and FAO statistics
GHG balance taking emissions and carbon sinks into account	ClimAgri® + Agribalyse® and Ecoinvent®
Energy flow	MoSUT

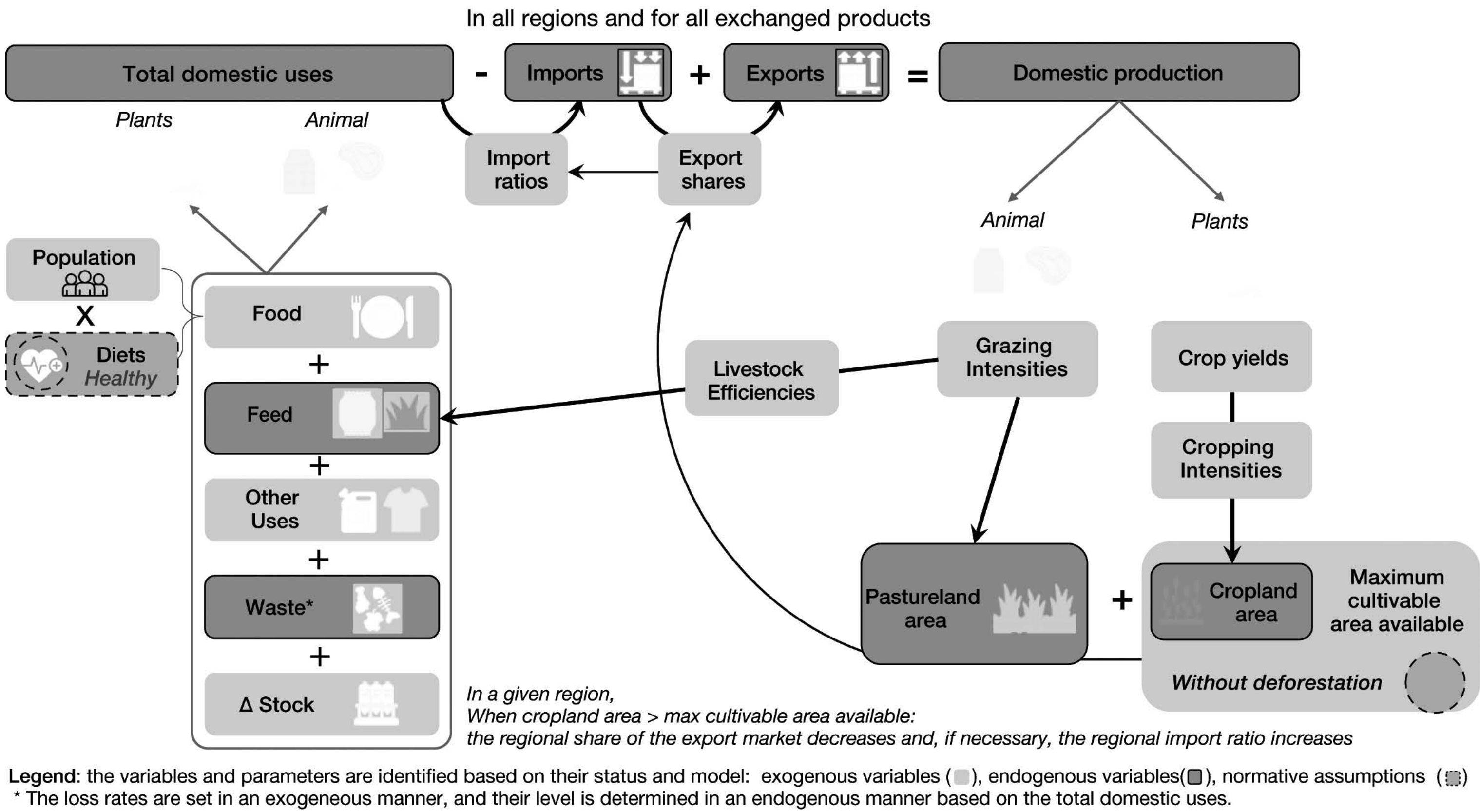

Figure 12.3. General functioning of the GlobAgri model.

Table 12.7. Assessment of the SISAE scenario.

Environmental flows assessed	Tools used
GHG balance taking direct emissions (enteric fermentation, livestock waste management, nitrous oxide emissions linked to the use of nitrogen fertilizers), indirect emissions (related to input production) and carbon sinks into account	MoSUT coupled with ClimAgri®
Water consumption for irrigation	MoSUT coupled with ClimAgri®
Energy consumption for agriculture and share of renewable energy	MoSUT coupled with ClimAgri®
Land use and land taking	MoSUT
Nitrogen balance	MoSUT coupled with ClimAgri®

Chapter 13

Possible futures for livestock farming and ownership by policy makers

Aurélie Wilfart, Olivier Mora and Sandrine Espagnol

⏩ Introduction: the role of foresight studies in the public policy cycle

We use the *policy cycle analysis method* to look more closely at the intricate relationship between foresight livestock farming studies and public policy so that the different points in time can be identified in public actions. Typically, a sequential approach to public policy would be to successively design, implement and evaluate a policy. This would constitute one full cycle. This process could then begin again, starting a new public policy cycle. Within this sequential approach, the public policy cycle is broken down into five stages: agenda-setting (to define priorities for action), policy formulation, decision-making (debate and deliberation), policy implementation and policy evaluation (Jacquot, 2019).

Foresight studies are mobilized from the very start of this cycle, specifically in the *agenda-setting* phase, at the moment in time when the public policy is being reconsidered in terms of its objectives, while drawing on the outcomes of previous policies (from the evaluation step). Thus, foresight analysis is key to defining the priorities in public policies as it can help reexamine and identify public problems, with a focus on the dynamics of future developments, interdependencies, emerging issues and possible disruptions.

This next section shows that foresight analysis also plays a key role in public policy *formulation*. As such, and in France, foresight studies, scenarios and quantified simulations are widely used to develop public *transition* policies. To do so, the problem to be dealt with would have already been identified by the public actor, and the goal of this step is then to formulate a public policy to address it. Scenarios and simulations stemming from foresight exercises are used to evaluate the potential impacts of the various assumptions and to look at how feasible the different transformations are, so as to have an action plan. Quantitative simulations of a scenario can be used to simultaneously make sure that the quantified objectives of the transition policies have been met, and because the scenarios themselves are based on a systemic approach, they can be used to make ensure consistency of the implemented strategies with public policies. Lastly, scenarios and their simulations represent an opportunity for public decision-makers to engage in *strategic conversations* with the stakeholders, with an aim to define novel issues for public action and to co-construct new action strategies.

Foresight analysis also plays a role in the *decision-making* phase by guiding the choices to be made, the deliberation process and decision-making. Foresight analysis helps practitioners better understand they choices they are faced with, as these analyses use the various possible outcomes and their implications to propose a wide diversity of possible futures together with a systemic view of future developments.

However, foresight exercises are but just one of the elements used to build public policies. Numerous factors and actors are involved in order for public issues to even be put on the agenda. Despite this, foresight studies are used to address public issues in various ways: during the agenda setting stage, by reformulating what could cause problems in the future (identifying future challenges); during the policy formulation stage, by anticipating the potential impacts of the action that could be undertaken; and during the deliberation and decision-making stage by highlighting the conditions of possibility and the challenges of normative transformations.

⏩ Livestock farming at the centre of numerous French government departments

In France, for the most part, livestock farming issues are addressed by two ministries: the Ministry of Agriculture, Food Sovereignty and Forestry, and the Ministry of Ecological Transition, Energy, Climate and Risk Prevention. Various departments within these two ministries were surveyed in 2024 to look at both if and how policymakers have adopted foresight studies as well as the possible futures of livestock farming in France.

1. The Emissions and Steering Office for the National Low Carbon Strategy (SNBC) at the Directorate General for Energy and Climate (DGEC). This office is in charge of developing the SNBC, reviewing it every five years, and helping to put it in place. Specifically, it models the various carbon-emitting and carbon sink sectors, in particular for agriculture, by assessing the greenhouse gas emission reduction trajectories needed to meet France's decarbonization objectives.

2. The Sustainable Agriculture and Food Office at the General Commission for Sustainable Development (GCSD). This office deals with issues relating to the development of practices that are more environmentally sustainable (especially organic farming and the development of Payments for Ecosystem Services – PES) as well as links to food and climate policies (e.g. co-steering France's National Strategy for Food, Nutrition and Climate (SNANC) and implementing the national anti-food waste label). It also contributes to the development of national strategies aimed at reconciling climate and agricultural objectives while encouraging a transition to more sustainable practices.

3. The Food Policy Office within the French General Directorate of Food (DGAL). This office coordinates the public policies related to food, by implementing the National Food Programme (PNA). It uses a systemic approach that takes the various sustainability challenges into consideration (economic, health, social and environmental) and it is pivotal in adapting food policies to environmental and health objectives.

4. The Directorate General of Economic and Environmental Performance of Enterprises (DGPE). This department, which includes the Meat and Animal Production Office and an Environmental Performance Officer, focuses on development in

territories and improving the environmental performance of agricultural enterprises. It reviews policies that affect the agri-food sector, specifically livestock farming, and how they adjust to climatic and economic requirements.

These departments are pivotal to the inclusion of foresight studies in public policies, guiding these policies toward agriculture and food that is more sustainable, while also taking into account climate, nutritional and economic objectives.

⏩ The main political actions concerning livestock farming in France

There are various public policies currently influencing the livestock sector in France. They aim to reduce greenhouse gas emissions and, more broadly, to transition to more environmentally friendly agricultural practices. Two main sectors stand out: the activity sector (including agriculture) and the food sector (Figure 13.1), each of which is structured around the definition of plans and strategies that are later implemented using various tools.

Ecological planning, launched by the government and steered by the General Secretariat for Ecological Planning (SGPE), monitors environmental issues and sets out to reach ambitious climate targets by incorporating tangible measures to reduce emissions by 2030. Another objective is to tackle the challenges of adapting to the impacts of climate change, safeguarding and restoring biodiversity, resource conservation and reducing pollution that has an impact on health. This involves providing farmers with financial support, including through accompanying measures and investment aid for adopting agricultural and livestock practices that are more sustainable, such as producing biogas from manures or the development of areas dedicated to protein-rich crops.

Four strategies and one complementary plan, linked to this comprehensive planning, were cited for their impact on livestock farming: the SNBC, the National Biodiversity Strategy (NBS), the National Strategy to Combat Imported Deforestation (NSID), the SNANC and the National Adaptation Plan to Climate Change.

The SNBC sets goals to reduce GHG emissions, especially in the agricultural sector, with an aim of achieving carbon neutrality by 2050 partly based on cross-ministerial and regional coordination efforts, in addition to public consultation mechanisms used to adjust decarbonization measures based on feedback received from the stakeholders. At this juncture, the reduction target set by the current SNBC 2 (National Low-Carbon Strategy 2) for agriculture is a -46% reduction in GHG emissions by 2050 compared to 2015. There are no quantifiable sub-targets regarding the reduction of emissions related to livestock farming (even though SNBC 2 mentions a 25% decrease in dairy cattle herds by 2050 compared to 2015 and a 33% decrease in non-dairy cattle herds by 2050 compared to 2015). However, the strategy does include specific related measures, such as increasing self-sufficiency in plant proteins used in animal feed, optimizing herd management practices, limiting excessive meat consumption and eating more pulses, fruits and vegetables. The next version of this strategy (SNBC 3) should provide details about the assumptions of change for livestock herds and the amount of organic production deployment. The SNBC, NBS and National Climate Change Action Plan provide specific support for grassland conservation and adapting livestock farming practices to the impacts of climate change, taking extreme weather conditions and animal transport conditions into consideration. The aim of NSID is to put an end to the import of forestry and agricultural products contributing to deforestation. With this in mind, NSID will support the implementation of the European Union Deforestation and Forest Degradation Regulation (EUDR) by improving the traceability of products having a link to deforestation (e.g. soybean meals used in animal feed in France but sourced from a third-party country). Lastly, the National Plant Proteins Strategy (SNPV) defines a comprehensive public policy framework meant to improve France's self-sufficiency in plant proteins, especially when used in animal feed.

Several tools can be used to help implement these strategies, such as the Common Agricultural Policy (CAP), the main economic instrument in Europe used to help support agriculture. CAP provides funding for sustainable practices, especially through eco-regimes that offer aids for conversion to organic farming and grassland maintenance. That said, the current CAP is deemed insufficient when it comes to promoting agroecological practices. Payments for Ecosystem Services (PES) are also economic instruments intended to compensate farmers for the ecosystem services they provide (biodiversity protection, carbon sequestration, etc.). The Plant Protein Plan offers financial support to help France reduce its dependence on imported plant proteins from third-party countries through research and innovation measures, by supporting investments in the material needed on field crop farms and by livestock farmers, by supporting the structuring of plant protein supply chains and downstream investments, and by helping promote the consumption of pulses among consumers.

To comply with the PNNS' recommendations and to reach the ecological planning targets, we need to change our diet. The National Nutrition and Health Strategy (SNANC) steers this change and defines the strategic directions of food policies by incorporating climate, nutrition and sustainability issues into food policies and encouraging more sustainable food and production practices as per public health and environmental recommendations. The PNA and PNNS are responsible for its implementation in operational terms. The PNA is broken down into three themes (social justice, combating food waste and food education) and two cross-cutting areas (institutional food services and regional projects). In addition to the SNANC, even if slightly outside its scope, there are also food sovereignty plans (developed per sector) that aim to make France more self-sufficient when it comes to food by increasing self-sufficiency and limiting imports, as well as the protein diversification strategy, which is a legal requirement for institutional food services that serve over 200 meals per day.

Within this framework, below, we give two examples of tools that have to do with the consumption of animal products. The first is the "EGAlim law" of 30 October 2018 that aims to balance business relationships in the agricultural and food sector, and to ensure healthy, sustainable and accessible food for all. This law was supplemented by the "Climate and Resilience Law" (law no. 2021-1104) which aims to combat climate change and strengthen the country's resilience to its impacts. It sets benchmarks for the sustainability and quality of the food supplied to catering facilities (at least 50% sustainable and high-quality products including 20% organic products, 60% sustainable and high-quality meat and fish, with the level raised to 100% in government-run, public-sector facilities and publicly owned catering companies). Under the EGAlim law, it is mandatory to offer a vegetarian menu (at least once a week in school

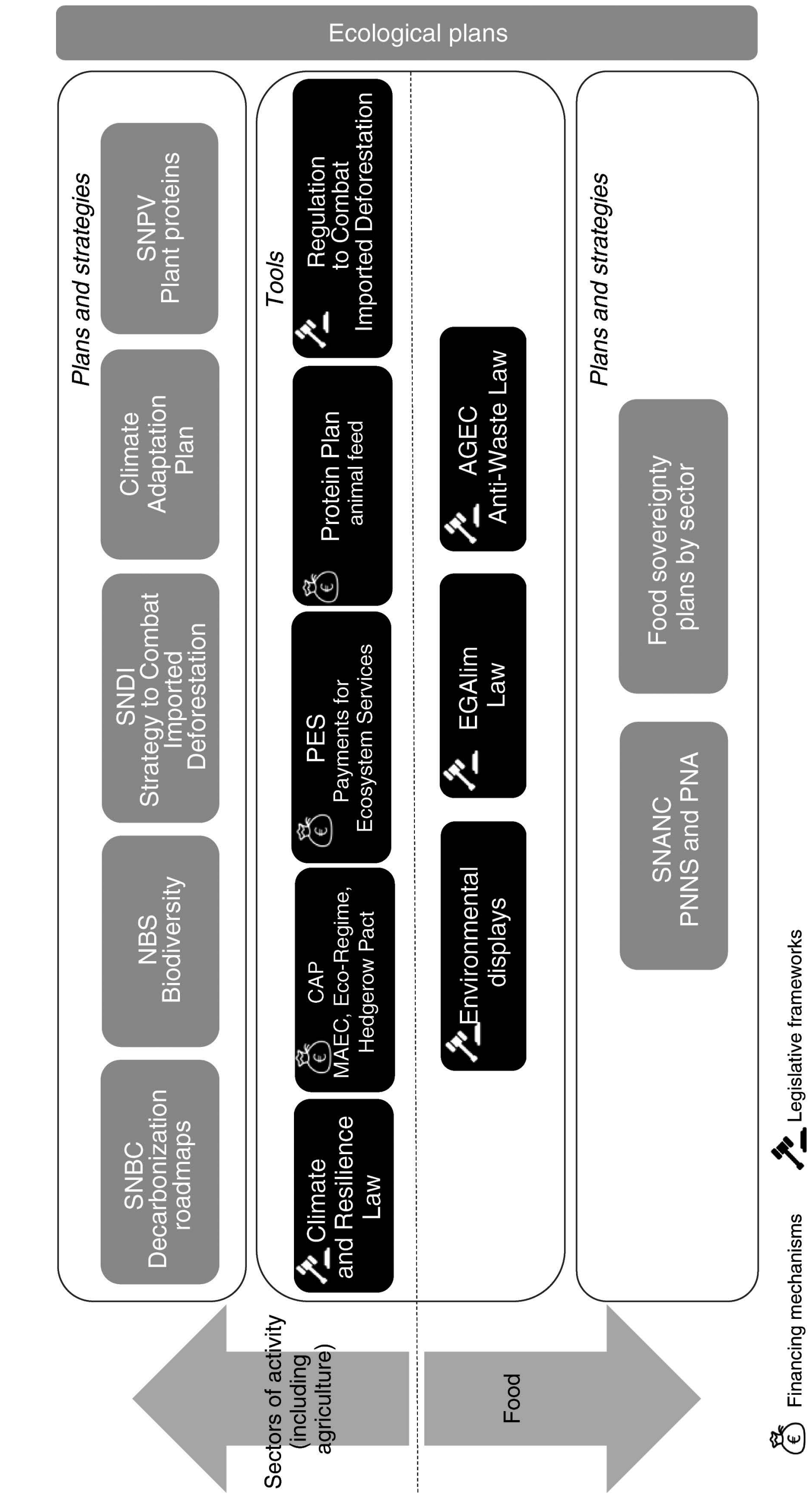

Figure 13.1. Summary of the main current and future public policies applied in France relating to livestock farming.

canteens, and a daily vegetarian option in government-run, public-sector facilities and publicly owned catering companies). Additionally, this law also encourages the consumption of plant-based proteins (e.g. with a multiyear action plan for protein diversification, mandatory for catering facilities serving more than 200 table settings per day). The second example is eco-labelling, which helps guide consumers toward more sustainable choices by providing them with clear information about the environmental impact of the food they are buying. These labels are also meant to provide producers with incentives to adopt more environmentally friendly practices.

These public policies are coordinated by different government sectors to make sure there is a coherent and integrated approach, supported by appropriate financing and regulations.

⏩ How are foresight studies used in French public policy?

The French government departments surveyed are aware of and consult several foresight studies to guide their sustainable agriculture and food strategies. The three most cited foresight studies were the Transition(s) 2050 scenarios from ADEME, Afterres 2050 from Solagro and TYFA from IDDRI. These scenarios are considered useful for imagining potential futures for French agriculture.

Foresight studies are used for strategy planning to compare different assumptions, assess different levers for action, assess the feasibility of policy measures and ultimately to develop and adjust public policies. They can be used early in the process, like in the SNBC, to compare the various hypotheses in critical areas such as changes in cattle herds, which may differ greatly depending on the scenario, ranging from a decrease by 60% to maintain a stable herd size. In this case, foresight studies serve as a point of reference to see what is workable and to fine-tune strategic choices based on the actual constraints within the agricultural sector and the emission reduction targets. Based on strategic choices and in addition to consulting the existing foresight studies, the SNBC creates and calculates its own scenarios using the MoSUT tool developed by Solagro, which is also used in the Afterres 2050 and Transition(s) 2050 foresight exercises. As part of the SNANC, the results of the scenarios built within the SNBC framework and PNNS guidelines were used, instead of directly using the foresight exercises. As such, the interviews conducted within the government departments surveyed highlighted that foresight exercises are specifically used to feed in-house and cross-ministerial discussions for the purpose of making sure that coherent strategic choices are made and to pinpoint the levers for action. Futurists (foresight experts) play a key role in this planning. Government departments consult the results of foresight exercises or define the drivers for new scenarios and may discuss certain details of the underlying models (especially the SNBC), but as they do not have access to the models they instead rely on the results.

The various different departments that were surveyed all underscored the importance of having foresight studies at different scales (regional, national, European) as they allow us to anticipate the future by imagining plausible scenarios at the scale of France and, consequently, they can be used to develop realistic and well-documented working hypotheses. In the SNBC, by calculating the achievable GHG reductions for a set of assumptions, it then becomes possible to envision the potential progress when it comes to effective GHG emission reduction. At the same time, it helps establish quantifiable targets within the strategy. By constructing specific scenarios for the SNBC, this helps ensure that the strategic choices stay in line with the overall emission reduction and carbon neutrality targets by the year 2050, while also taking stock of economic and social realities. When constructing a strategy, foresight scenarios are used to compare the impact of different levers for action or various changes (e.g. decreases in herd size or increases in pulse crops) to determine how feasible these measures are in terms of closing nutrient cycles, especially nitrogen, and to make sure that the trajectories envisaged stay on track so that carbon neutrality will be reached by 2050. The foresight scenarios mentioned previously in this chapter are also useful to setting up milestones: they describe the conditions needed to possibly reach the target. The scenario that shows that agroecological models can feed the population while also simultaneously preserving the environment is the TYFA scenario. As such, this scenario reinforces the vision held by government departments as it shows that sustainable agriculture is possible under certain conditions. The TYFA scenario is also commended for the fact that it puts forth multiple scenarios and therefore provides an overview of several possible trajectories, each with its own conditions. This makes it easier to initiate dialogue with the stakeholders, including economic actors, to identify appropriate levers for action and to make any necessary adjustments based on local realities. From a methodological perspective, the advantage of the previously mentioned foresight studies is that they use a systemic approach, and they are able to represent complex agricultural systems in relation to food. These studies also help to pinpoint the key drivers of these systems so that they can be improved and, in particular, so that the ecological transition is as smooth and consistent as possible. As a result, the surveyed departments all consider foresight studies to be valuable and useful tools for anticipating potential future changes and for preparing robust strategies, while at the same time remaining flexible in the face of the uncertainties and rapid changes in the overall context. Foresight analyses will continue to be used for this purpose, and it is felt that it will be especially useful to have new foresight studies to help guide future agricultural choices.

Even though these interviews highlighted many advantages, they also pointed out certain limitations, especially to do with methodology.

Some key drivers in the performance of the calculated scenarios are seen as not being well enough understood and therefore they are perceived as being inadequate for precisely clarifying the policy implementation. An example of this is the achievable levels of symbiotic nitrogen fixation in France, which is key to reducing the nitrogen imbalance and ensuring that crops have the nitrogen inputs required for production. The levels of symbiotic fixation depend on the number of pulses in crop rotations and the fixation rates per unit of yield. INRAE has been tasked with specifically studying this potential in the aim of understanding this issue better and determining what these drivers can be expected to do in future scenarios.

The interviews carried out underscored that foresight exercises insufficiently address socio-economic aspects. This is undoubtably true, as political ambition is not quite in sync with the levels of change proposed in the foresight studies due to supply chain issues. Some government departments may be frustrated with this lower level of ambition because it seems that not enough is being done on climate and biodiversity issues, and in providing targeted support for sustainable livestock farming.

Other departments emphasize the challenge of preserving the livestock sector together with pursuing strong environmental goals. The decline in livestock farming in France is a matter of concern regarding food sovereignty and safeguarding the ecosystem services that livestock farming provides (e.g. preserving permanent grasslands) as well as the socio-economic impacts.

Questions have been raised about the fact that the MoSUT model is almost exclusively used to construct foresight scenarios, because it is an unpublished model that has not been assessed by the scientific community and it is being used by a private design office, thereby creating a “black box” effect. At the time, it was decided to use this model for the Transition(s) 2050 scenarios and the SNBC given that no equivalent model existed in public research and development in France. That is not as much the case today, and therefore, some of the surveyed departments have suggested to also use other models, including more models stemming from public research, so that the methodology of the resulting scenarios will be more transparent (calculation methods, parameters, and emission factors used). That said, the idea is not to use these foresight scenarios in expert debates that are too technical as this could detract focus from the primary strategic goals. The best way to use foresight studies is to look at the weak signals and emerging trends they highlight, while keeping in mind that these possible projected futures may rapidly change depending on the economic or social context, e.g. as seen in recent world events (Covid-19, war in Ukraine, etc.).

Lastly, it should be remembered that the available modelling tools mostly focus on the production stage. For the moment, there are not as many tools that can be used to assess trends and changes in consumption patterns. Yet, food systems are every bit as complex and are highly impacted by the major uncertainties surrounding consumer behaviour and as a result, a comprehensive approach that includes these uncertainties should be used to assess the robustness of the results from these studies.

⏩ What about in other contexts elsewhere in the world?

To date, it has not been possible to thoroughly analyse the various government departments that have an influence on the future of livestock farming, the main political actions on livestock issues and/or, on a broader level, the use of foresight exercises to define public policies in other parts of the world. However, a number of reports and studies have shown that the contexts in Global South countries may differ quite significantly, in particular due to: i) diverse ministerial structures (e.g. Senegal has a Ministry of Livestock given its economic importance), ii) varying capacities of national research centres and other national institutions to be able to carry out foresight studies (as an example, INRAE in France has specific departments for foresight studies and supports public policy making, which is not the case for most national research centres in West Africa), and iii) quite different issues and challenges when it comes to livestock farming. In the introduction section of this book, we mention that the challenge in northern countries is to decrease the amount of animal products consumed and to support the agroecological transition of livestock farming systems, whereas the challenges in southern countries are quite different because there needs to be a substantial increase in animal production to meet public health and economic development purposes.

The use of foresight studies could also be used to help define major development plans internationally. For instance, the IFAD and World Bank draw on the scientific work carried out by the FAO, ILRI, and CIRAD to argue why it is important to support livestock development as a driver of economic growth and poverty reduction in rural areas (The World Bank, 2009). But again, based on our current understanding of how these development plans are built, we cannot say for certain that global foresight studies, such as Agrimonde-Terra, have been or are being used around the world.

General conclusion

Key points to remember

Jonathan Vayssières and Aurélie Wilfart

⏩ Thematic summary

The changes in eating habits, among other things, that we're seeing today will go hand-in-hand with changes seen around the world in terms of consumer expectations, climate change, the emergence of zoonotic diseases and other factors, the importance and types of livestock farming in different regions and agri-food systems. Foresight studies are needed to address the high degree of uncertainty facing the future of livestock farming and the complexity of the mechanisms involved.

The foresight studies presented in this book explore possible futures for livestock farming in various contexts (in both industrialised and developing countries) and at different scales (region, country, continent, world), mobilizing a wide variety of players and methods. Numerous conclusions can be drawn from these studies.

Trade-offs need to be prioritized or facilitated for a multitude of reasons: there is not just one but multiple food, environmental and socio-economic issues facing livestock farming, these issues have varying degrees of importance depending on the context and it can be quite difficult to address all these issues simultaneously.

Livestock dynamics are different in different regions. Based on differing demographics and food eating habits, the trend is to move toward fewer herds and farmers in industrialized countries and, conversely, toward growing the livestock sector in developing countries. As such, these dynamics will have a significant impact on how these regions operate and their sustainability factors.

Often, changes in livestock numbers are strongly connected with changes in livestock farming systems. Foresight studies show that there is a general need to transition toward so-called "more sustainable" agroecological livestock systems. These systems are more ecologically intensive in developing countries as they adapted to specific aspects within the territories and the changes to come, while simultaneously accounting for the complex interactions between agriculture, food, and society.

Numerous levers can be used to respond to these needs for change by reducing the negative impacts of livestock farming and increasing the services it provides to ecosystems and human societies. Specifically, these levers include a change in livestock farming practices, the animal species and breeds raised, the number of animals, the spatial distribution of livestock farms and their integration in landscapes and, on a broader level, their contribution to the circularity of agri-food systems by, among other things, providing organic fertilizer to the soil and better using uncultivated land and co-products from crops and the agro-industry.

⏩ Methodological summary

There is a clear need to objectively assess the impacts that changes in livestock farming will have on territories and agri-food systems and therefore, to that end, this book offers a set of recommendations on how to combine and better integrate foresight analysis, modelling and multicriteria scenario assessment. This is not an easy task since, more often than not, foresight studies are qualitative approaches whereas modelling and assessment are mostly based on quantitative methods. Also, the fact that there is a wide range of foresight, modelling and assessment methods means that their combined use may be more difficult. This is why this book provides a framework to help choose the best coupling approaches depending on the methods used.

Foresight studies can be conducted for numerous varied reasons, ranging from exploratory (e.g. describing the range of possibilities) to normative reasons (e.g. reducing the carbon footprint, conflict resolution), and they may be based on various intermediary objects. Scenario-based methods are especially helpful for dealing with the uncertainty associated with future trajectories in complex systems. The method that uses morphological charts to explore plausible combinations of assumptions seems especially suitable for proposing a wide spectrum of robust and easily modelled scenarios.

There is also a wide spectrum of modelling and assessment methods. These assessments may be qualitative or quantitative, with one criterion or several criteria, aggregated or not, etc. Specifically, they may use numerical simulation models upstream to convert scenarios into quantitative data that can then be used in the assessments. These models can be static or dynamic, empirical or mechanistic, non-spatialized or spatially explicit, and so forth. At present, most of the models used to assess foresight scenarios are static and focus more on "matter balances". Integrative approaches combining spatial, dynamic, multicriteria and agent-based methods are still not very widely used in foresight exercises because they can be quite tricky to manage and often require a significant amount of data. Nevertheless, integrative approaches offer promising prospects for representing the functioning and dynamics of livestock farming areas and agri-food systems.

There are many advantages to combining foresight and modelling-assessment approaches. For instance, information produced by one method can be used by the other, and vice versa. Foresight analysis is usually carried out prior to modelling-assessment and produces a set of scenarios that can be modelled and assessed. Additionally, the method based on scenarios and morphological charts describes the structural and dynamic dimensions of the studied system and also examines the causal links and potential interactions between the various components, in multiple plausible configurations. Because of this, foresight analysis provides very valuable information that can be used to develop simulation models and define assumptions for the assessment. Other times, assessments are conducted before the foresight analysis and in this situation, they become important in identifying and prioritizing the issues that need to be addressed in the foresight studies.

In all cases, the availability of the information and data needed for foresight analysis, modelling and assessment is a major factor in the choice of which methodology to employ. As one might expect, the availability of these two important components changes based on the context and sometimes can be a limiting factor (e.g. in developing countries), which means that the methods used in these three approaches need to be adjusted so that they are suitable for the situation. One way to do this is to reduce the granularity of models and assessments; another is to mobilize qualitative methods that make more use of local know-how and expert knowledge.

⏩ Functional summary

Given the importance and wide array of challenges ahead, this book clearly underscores that we need to have appropriate and ambitious public policies that will focus on livestock farming as a lever for territorial development and sustainability.

From a theoretical point of view, foresight analyses and the modelling-assessment of scenarios have an important part in shaping these policies. Referring back to the public policy cycle (design, implementation and evaluation), foresight is very useful in the design phase, especially in three key stages: i) in the agenda-setting stage, foresight analysis can be used to (re-)examine and identify public issues, focusing on the dynamics of future changes, interdependencies, emerging issues and potential disruptions; ii) in the policy formulation stage, scenarios and the simulation-assessment of scenarios stemming from foresight analysis can help anticipate the possible ramifications of the various assumptions and determine the feasibility of various transformations so to construct an action strategy. Quantitative scenario assessments help make sure transition policies are meeting their targets; iii) lastly, in the decision-making stage, foresight analysis puts forth several different possible futures and provides a systemic view of future developments, and as such provides valuable information that can be used in deliberations and to make choices.

In practice, however, foresight experts often report that scenarios are underused or not used in a timely manner in policies. Our survey in the French government departments dealing with livestock farming matters shows that policymakers are aware of some of the national and European foresight studies and consult them to construct transition policies in France. This is not always the case in the rest of the world, where their availability varies. For instance, there are fewer foresight studies in developing countries mostly because national organizations have a lower capacity to conduct foresight studies and to produce robust and suitable simulation and assessment models. Foresight studies can also be used to define broad development plans around the world, such as is already done by the FAD and World Bank, which use scientific research to argue why it is important to support livestock farming as it drives economic growth and poverty reduction in rural areas.

Be that as it may, this book does not delve too deeply into analysing how public decision-makers have adopted these foresight studies and their impact on major policy directions at the national, regional, and global scales. This is something that is worthy of further study. If a retrospective analysis of this type were to be carried out one day, it would be quite useful as it would help researchers suggest methods and scientific findings that are easier to use by public policy actors. This means that livestock farming will be able to fully play its role in the transition to more sustainable agri-food systems.

Bibliographic references

Ademe, 2016. Pertes et gaspillages alimentaires : l'état des lieux et leur gestion par étapes de la chaîne alimentaire. Rapport d'étude, disponible en ligne : https://www.actu-environnement.com/media/pdf/news-26873-pertes-gaspillage-alim-ademe.pdf

Ademe, Réthoré O., Hugrel C., Palluau M., Bleu Safran, Audard G., Osset P., Solinnen, 2020. Guide d'aide à la sélection des méthodes d'évaluation environnementale, 53 p., available online: https://www.valobat.fr/wp-content/uploads/2025/02/guide-aide-choix-methodes_evaluation-rapport-vf.pdf

Afssa, 2007. "Apport en protéines : consommation, qualité, besoins et recommandations", https://www.anses.fr/fr/system/files/NUT-Ra-Proteines.pdf

Alary V., Duteurtre G., Faye B., 2011. Élevages et sociétés : les rôles multiples de l'élevage dans les pays tropicaux, *in* Coulon J.-B., Lecomte P., Boval M., Perez J.-M. (eds), Numéro spécial, élevage en régions chaudes. *INRA Productions Animales*, 24 (1), 145-156, https://doi.org/10.20870/productions-animales.2011.24.1.3246

Alexandratos N., Bruinsma J., 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working Paper 12-03. Rome (Italie), Food and Agriculture Organization.

Allen M. R., Lynch J., Cain M., Frame D., 2022. *Climate metrics for ruminants*. Oxford, Oxford Martin Programme on Climate Pollutants, 4 p.

Allen M. R., Shine K. P., Fuglestvedt J. S., Millar R. J., Cain M., Frame D. J., Macey A. H., 2018. A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science*, 1 (1), 16, https://doi.org/10.1038/s41612-018-0026-8

Altieri M. A., Funes-Monzote F. R., Petersen P., 2011. Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. *Agronomy for Sustainable Development*, 32 (1), 1-13, https://doi.org/10.1007/s13593-011-0065-6

Amanatidou E., Butter M., Carabias V., Könnölä T., Leis M., Saritas O., Könnölä T., Leis M., Saritas O., Petra Schaper-Rinkel P., Van Rij V., 2012. On concepts and methods in horizon scanning: Lessons from initiating policy dialogues on emerging issues. *Science and Public Policy*, 39 (2), 208-221, https://doi.org/10.1093/scipol/scs017

Amer M., Daim T. U., Jetter A., 2013. A review of scenario planning. *Futures*, 46, 23-40.

An L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling*, 229, 25-36, https://doi.org/10.1016/j.ecolmodel.2011.07.010

Anglade J., Billen G., Garnier J., 2015. Relationships for estimating N_2 fixation in legumes: incidence for N balance of legume-based cropping systems in Europe. *Ecosphere*, 6 (3), 1-24, https://doi.org/10.1890/ES14-00353.1

Anses, 2016a. Composition nutritionnelle des aliments Table Ciqual version 2016. Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail – https://pro.anses.fr/tableciqual/

Anses, 2016b. Actualisation des repères du PNNS : révision des repères de consommations alimentaires. Avis de l'Anses. Maison Alfort, Agence nationale de la sécurité sanitaire, alimentation, environnement, travail, 82 p.

Aubert P.-M., Gardin B., Alliot C., 2021. *Vers une transition juste des systèmes alimentaires, enjeux et leviers politiques pour la France*. Paris, Iddri-Basic, 76 p., https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Rapport/rapport%20SNBC%20agri%20FR_1.pdf

Aubert P.-M., Schwoob M.-H., Poux X., 2019. *Agroecology and carbon neutrality in europe by 2050: what are the issues? Findings from the Tyfa modelling exercise*. Paris, Iddri Study.

Bailly J.-P., 2005. Prospective territoriale et action publique. *Futuribles*, 314, 53-67.

Bajzelj B., Richards K. S., Allwood J. M., Smith P., Dennis J. S., Curmi E., Gilligan C. A., 2014. Importance of food-demand management for climate mitigation. *Nature Climate Change*, 4, 924-929.

Barbier C., Couturier C., Dumas P., Kesse-Guyot E., Baudry J., Pharabod I., Pourouchottamin P., Toilier F., 2022. *Prospective du système alimentaire et de son empreinte énergétique et carbone*. Paris, CIRED, https://www.centre-cired.fr/wp-content/uploads/2022/09/Publication_SISAE.pdf

Barbier C., Couturier C., Pourouchottamin P., Cayla J.-M., Sylvestre M., Pharabod I., 2019. *L'empreinte énergétique et carbone de l'alimentation en France*. Paris, Iddri, 24 p.

Barbieri P., Pellerin S., Seufert V., Smith L., Ramankutty N., Nesme T., 2021. Global option space for organic agriculture is delimited by nitrogen availability. *Nature Food*, 2 (5), 363-372, https://doi.org/10.1038/s43016-021-00276-y

Bareha Y., Affès R., Buffet J., Girault R. 2021. « SYS-Metha : Outil de prédiction des flux d'azote et de carbone sur les filières de méthanisation et des propriétés des digestats », https://doi.org/10.15454/U4S6OF, Recherche Data Gouv, V1.

Bareille F., Boussard H., Thenail C., 2022. Productive ecosystem services and collective management: Lessons from a realistic landscape model. *Ecological Economics*, 169, https://doi.org/10.1016/j.ecolecon.2019.106482

Barlagne C., Diman J.-L., Galan M.-B., Hoton C., Mora O., Noglotte T., Ozier-Lafontaine H., Vinglassalon A., 2016. Étude prospective : L'agriculture guadeloupéenne à l'horizon 2040. Rapport final d'exécution. Inra, 250 p. https://hal.inrae.fr/hal-02800576

Barré R., 2005. Intervention au séminaire Concepts et Méthodes de la Prospective, « Figures de la prospective », Observatoire international de prospective régionale.

Béné C., Oosterveer P., Lamotte L., Brouwer I. D., de Haan S., Prager S. D., Talsma E. F., Khoury C. K., 2019. When food systems meet sustainability – Current narratives and implications for actions. *World Development*, 113, 116-130, https://doi.org/10.1016/j.worlddev.2018.08.011

Bengtsson J., Bullock J. M., Egoh B., Everson C., Everson T., O'Connor T., O'Farrell P., Smith H., Lindborg R. 2019. Grasslands – more important for ecosystem services than you might think. *Ecosphere*, 10 (2), e02582, https://doi.org/10.1002/ecs2.2582

Benjaminsen T. A., Ba B., 2018. Why do pastoralists in Mali join jihadist groups? A political ecological explanation. *Journal of Peasant Studies*, 46, 1-20.

Benton T. G., Vickery J. A., Wilson J. D., 2003. Farmland biodiversity: is habitat heterogeneity the key?. *Trends in Ecology and Evolution*, 18 (4), 182-188, https://doi.org/10.1016/S0169-5347(03)00011-9

Berre D., Blancard S., Boussemart J.-P., Leleu H., Tillard E., 2014. Finding the right compromise between productivity and environmental efficiency on high input tropical dairy farms: A case study. *Journal of Environmental Management*, 146, 235-244, https://doi.org/10.1016/j.jenvman.2014.07.008

Bignal E., 2000. The environmental impact of dairy production in the EU – practical options for the improvement of the environmental impact. European Commission (DGXI) CEAS, 1179.

Billen G., Aguilera E., Einarsson R., Garnier J., Gingrich S., Grizzetti B., Lassaletta L., Le Noë J., Sanz-Cobena A., 2021. Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity. *One Earth*, 4 (6), 839-850, https://doi.org/10.1016/j.oneear.2021.05.008

Billen G., Lassaletta L., Garnier J., 2014. A biogeochemical view of the global agro-food system: Nitrogen flows associated with protein production, consumption and trade. *Global Food Security*, 3, 209-219, https://doi.org/10.1016/j.gfs.2014.08.003

Blanfort V., Vayssières J., Assouma M. H., Plassin S., Poccard-Chapuis R., 2019. Landsharing for climat smart lanscapes in dry and humid tropical livestock areas, in 5th Global Science Conference on Climate-Smart Agriculture, Bali, Indonesia, October 8-10, poster, 1 p.

Bocquier F., Benoit M., Laignel G., Dedieu B., Cournut S., Fiorelli C., Jouven M., Moulin C. H., Aubron C., Lurette A., Lapeyronie P., Hassoun P., Meuret M., Agreil C., Napoléone M., Hoste H., Friggens N., Tichit M., Gonzalez-Garcia E., Hazard D., François D., Pellicer-Rubio M.-T., Guillouet P., Boissard K., Fabre-Nys C., Teyssier J., Tournadre H., Mihaud M., Malpaux B., Chemineau P., Bodin L., Prache S., Bouix J., Barillet F., Boutonnet J.-P., Chia E., Lasseur J., Étienne M., Gibon A., Choisis J.-P., Labatut J., Paoli J. C., Santucci P.-M., 2011. Innovations et performances environnementales en production caprine et ovine : Expertise élevage-environnement à l'Inra. *Innovations agronomiques*, 12, 29-52, https://doi.org/10.17180/h30x-fy29

Bommel P., Becu N., Le Page C., Bousquet F., 2016. Cormas: an agent-based simulation platform for coupling human decisions with computerized dynamics, in Kaneda T., Kanegae H., Toyoda Y., Rizzi P., *Simulation and gaming in the network society*. Singapore, Springer.

Bordeaux C., 2015. L'alimentation des volailles en agriculture biologique. Itab, IBB, Chambres d'agriculture, Inra, Itavi, 68 p.

Börjeson L., Höjer M., Dreborg K. H., Ekvall T., Finnveden G., 2006. Scenario types and techniques: towards a user's guide. *Futures*, 38 (7), 723-739.

Bots P. W. G., Daalen C. E., 2008. Participatory model construction and model use in natural resource management: A framework for reflection. *Systemic Practice and Action Research*, 21 (6), 389-407, https://doi.or/10.1007/s11213-008-9108-6

Boulay A.-M., Drastig K., Amanullah, Chapagain A., Charlon V., Civit B., Decamillis C., De Souza M., Hess T., Hoekstra A. Y. Ibidhi R., Lathuillière M. J., Manzardo A., McAllister T., Morales R. A., Motoshita M., Palhares J. C. P., Pirlo G., Ridoutt B., Russo V., Pfister S., 2021. Building consensus on water use assessment of livestock production systems and supply chains: Outcome and recommendations from the FAO LEAP Partnership. *Ecological Indicators*, 124, 107391.

Bourgoin J., Corniaux C., Touré L., Cesaro J. D., 2018. Atlas des dynamiques observées dans le bassin de collecte de la Laiterie du Berger. Cirad, 32 p.

Bousquet F., Le Page C., 2004. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling*, 176 (3-4), 313-332.

Bouvarel I., Pottiez E., Magdelaine P., Seguin F., Conan S., Pineau C., Dennery G., Landrault M., Riffard C., Guyot M., 2013. Avibio : des systèmes durables pour dynamiser l'AVIculture BIOlogique. *Innovations agronomiques*, 30, 13-25.

Bouwman A. F., Van der Hoek K. W., Eickhout B., Soenario I., 2005. Exploring changes in world ruminant production systems. *Agricultural Systems*, 84 (2), 121-153.

Brisson N., Gate P., Gouache D., Charmet G., Oury F.-X., Huard F., 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research*, 119 (1), 201-212.

Buendia E., Tanabe K., Kranjc A., Baasansuren J., Fukuda M., Ngarize S., Osako A., Pyrozhenko Y., Shermanau P., Federici S., 2019. 2019 Refinement to the 2006 IPCC Guidelines for national greenhouse gas inventories. Geneva, IPCC.

Calvar C., 2015. Quoi de neuf en élevage de porcs biologiques ? Le point sur la filière, la règlementation, la conduite d'élevage et les résultats de la recherche. Rennes, Chambres d'agriculture de Bretagne – Pôle porcs, 12 p.

Caron P., Reig E., Roep D., Hediger W., Le Cotty T., Barthélemy D., Hadyńska A., Hadyński J., Oostindie H. A., Sabourin E., 2008. Multifunctionality: refocusing a spreading, loose and fashionable concept for looking at sustainability?. *International Journal of Agricultural Resources, Governance and Ecology*, 7 (4/5), 301-318.

Catarino R., Therond O., Berthomier J., Miara M., Mérot E., Misslin R., Vanhove P., Villerd J., Angevin F., 2021. Fostering local crop-livestock integration via legume exchanges using an innovative integrated assessment and modelling approach based on the Maelia platform. *Agricultural Systems*, 189, https://doi.org/10.1016/j.agsy.2021.103066

CE, 2018. A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. Brussels, European Commission / In depth analysis in support of the Commission Communication COM (2018) 773, 291 p.

CE, 2020. Farm to Fork Strategy. For a fair, healthy and environmentally-friendly food system. Brussels, European Union, 22 p.

Cesaro J.-D., Vall E., Gaye M., Müller J. P., Diaw A., Ickowicz A., 2020. Estimation spatialisée du potentiel laitier autour de Richard-Toll et scénarios d'évolution des systèmes de collecte. Cirad, 10 p.

Chateauraynaud F., 2013. Regard analytique sur l'activité visionnaire, *in* Bourg D., Joly P.-B., Kaufmann A. (eds), *Du risque à la menace. Penser la catastrophe*. Paris, Presses universitaires de France, p. 287-309, https://doi.org/10.3917/puf.bourg.2013.02.0287

Chevassus-Au-Louis B., Génard M., Glaszmann J.-C., Habib R., Houllier F., Lancelot R., Malézieux E., Muchnik J., 2009. L'intégration, art ou science ? Colloque international Inra-Cirad. Partenariats, Innovation, Agriculture (p. 132-157), Paris, FRA (2008-06-03).

Clark M. A., Domingo N. G. G., Colgan K., Thakrar S.K., Tilman D., Lynch J., Azevedo I. L., Hill J. D., 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science*, 370, 705-708.

Cnued, 1992. Agenda 21. An action plan for the next century. United Nations Conference on Environment and Development, New York.

Collectif Commod, 2005. La modélisation comme outil d'accompagnement. *Natures Sciences Sociétés*, 13, 165-168.

Constantin J., Willaume M., Murgue C., Lacroix B., Therond O., 2015. The soil-crop models STICS and AqYield predict yield and soil water content for irrigated crops equally well with limited data. *Agricultural and Forest Meteorology*, 206, 55-68.

Cordell D., Schmid-Neset S., White J.-O., 2009. Preferred future phosphorus scenarios: A framework for meeting long-term phosphorus needs for global food demand, in Ashley K. I., Mavinic D., Koch F. (eds), International conference on nutrient recovery from wastewater streams: May 10-13, 2009, the Westin Bayshore Hotel and Resort, Vancouver, British Columbia, Canada. IWA Publishing.

Cordova-Pozo K., Rouwette E. A., 2023. Types of scenario planning and their effectiveness: A review of reviews. *Futures*, 149, 103153.

Cork S., Alexandra C., Alvarez-Romero J. G., Bennett E. M., Berbés-Blázquez M., Bohensky E., Bok B., Costanza R., Hashimoto S., Hill R., Inayatullah S., Kok K., Kuiper J. J., Moglia M., Pereira L., Peterson G., Weeks R., Wyborn C., 2023. Exploring alternative futures in the Anthropocene. *Annual Review of Environment and Resources*, 48 (1), 25-54.

Corniaux C., Alary V., Gautier D., Duteurtre G., 2012. Producteur laitier en Afrique de l'Ouest : une modernité rêvée par les techniciens à l'épreuve du terrain. *Autrepart*, 3, 17-36.

Corniaux C., Ancey V., Touré I., Camara A., Cesaro J.-D., 2016. Pastoral mobility, from a Sahelian to a sub-regional issue, *in* Pesche D., Losch B., Imbernon J. (eds), *A new emerging rural world. An overview of rural change in Africa, Atlas for the Nepad rural futures programme*. Second edition, Montpellier, Cirad, 76 p.

Corniaux C., Thébaud B., Gautier D., 2012. La mobilité commerciale du bétail entre le Sahel et les pays côtiers : L'avenir du convoyage à pied. *Nomadic Peoples*, 16, 6-25, https://doi.org/10.3167/np.2012.160203

Couturier C., Charru M., Doublet S., Pointereau P., 2016. Le scénario Afterres 2050 version 2016. Toulouse, Solagro, 93 p.

Crippa M., Solazzo E., Guizzardi D., Monforti-Ferrario F., Tubiello F. N., Leip A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2 (3), 198-209.

Cumming G. S., Olsson P., Chapin F. S., Holling C. S., 2013. Resilience, experimentation, and scale mismatches in social-ecological landscapes. *Landscape Ecology*, 28 (6), 1139-1150, https://doi.org/10.1007/s10980-012-9725-4

Cuypers D., Geerken T., Gorissen L., Lust A., Peters G., Karstensen J., Prieler S., Fischer G., Hizsnyik E., Van Velthuizen H., 2013. The impact of EU consumption on deforestation: Comprehensive analysis of the impact of EU consumption on deforestation. Brussels, European Commission – DG Environment, 108 p.

D'Ottavio P., Francioni M., Trozzo L., Sedić E., Budimir K., Avanzolini P., Trombetta M. F., Porqueddu C., Santilocchi R., Toderi M., 2018. Trends and approaches in the analysis of ecosystem services provided by grazing systems: A review. *Grass and Forage Science*, 73 (1), 15-25.

Dainese M., Martin E. A., Aizen M. A., Albrecht M., Bartomeus I., Bommarco R., Carvalheiro L. G., Chaplin-Kramer R., Gagic V., Garibaldi L. A., 2019. A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances*, 5 (10), 13.

Daley C. A., Abbott A., Doyle P. S., Nader G. A., Larson S., 2010. A review of fatty acid profiles and antioxidant content in grass-fed and grain-fed beef. *Nutrition Journal*, 9 (1), 10.

de Vries M., de Boer I. J. M., 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science*, 128, 1-11.

Degenne P., Lo Seen D., 2016. Ocelet: Simulating processes of landscape changes using interaction graphs. *SoftwareX*, 5, 89-95.

Delanoue E., Roguet C., 2015. Acceptabilité sociale de l'élevage en France : recensement et analyse des principales controverses à partir des regards croisés de différents acteurs. *INRAE Productions Animales*, 28 (1), 39-50.

Delay E., Müller J. P., Cesaro J.-D., Valls-Fox H., Ickowicz A., 2021. Empowering a model for improved multi-actor discussions: case study from Dairy production in Sahelian agro-pastoral systems, in 1st conference Gama Days 2021, June.

Delgado C. L., 2003. Rising consumption of meat and milk in developing countries has created a new food revolution. *Journal of Nutrition*, 133 (11), 3907S-3910S.

Dibari C., Pulina A., Argenti G., Aglietti C., Bindi M., Moriondo M., Mula L., Pasqui M., Seddaiu G., Roggero P. P., 2021. Climate change impacts on the Alpine, Continental and Mediterranean grassland systems of Italy: A review. *Italian Journal of Agronomy*, 16 (3).

Dobereiner J., De-Polli H., 1980. Diazotrophic rhizocoenoses – Nitrogen fixation. *Proceedings of the Phytochemical Society of Europe symposium*, 18, 301-344.

Dourmad J.-Y., Guilbaud T., Tichit M., Bonaudo T., 2019. Les productions animales dans la bioéconomie. *INRAE Productions Animales*, 32 (2), 205-220.

Durance P., Godet M., 2010. Scenario building: Uses and abuses. *Technological Forecasting and Social Change*, 77 (9), 88-92.

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 ?. *Agronomie, Environnement and Sociétés*, 11 (1).

Duru M., Therond O., Fares M., 2015. Designing agroecological transitions: A review. *Agronomy for Sustainable Development*, 35 (4), 1237-1257.

ECF, 2018. Net Zero By 2050: From Whether to How. Brussels, European Climate Foundation – Climact, 66 p.

EEA, FOEN, 2020. Is Europe living within the limits of our planet? An assessment of Europe's environmental footprints in relation to planetary boundaries. Luxembourg, Federal Office of the Environment/European Environmental Agency, 61 p.

Efsa, 2017. Efsa Comprehensive European Food Consumption Database. European Food Safety Authority – https://www.efsa.europa.eu/en/food-consumption/comprehensive-database

Eglin T., Martin É., Martin S., Trévisiol A., Mousset J., Doublet S., Galsomiès L., 2016. Climagri: A computer tool and participatory approach to design mitigation strategies of air pollutant and GHG emissions due to agriculture at a territorial level. *Pollution atmosphérique*, 203-207.

Einarsson R., Sanz-Cobena A., Aguilera E., Billen G., Garnier J., van Grinsven H. J., Lassaletta L., 2021. Crop production and nitrogen use in European cropland and grassland 1961-2019. *Scientific Data*, 8 (1), 288.

Eurostat, 2017. Agriculture and environment – pollution risks, http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agriculture_and_environment_-_pollution_risks

Eurostat, 2018. Agri-environmental indicator – gross nitrogen balance, http://ec.europa.eu/eurostat/statisticsexplained/index.php/Agri-environmental_indicator_-_gross_nitrogen_balance - Analysis_at_EU_level

FAO, 2018.World livestock: Transforming the livestock sector through Sustainable Development Goals. Rome (Italie), 222 p.

FAO, 2011. Global food losses and food waste – Extent, causes and prevention, Rome (Italie), Food and Agriculture Organization of the United Nations, 38 p.

FAO, 2022. The state of world fisheries and aquaculture 2022: towards blue transformation, Rome (Italie), Food and Agriculture Organization of the United Nations, 266 p.

FAO, 2023. Pathways towards lower emissions – A global assessment of the greenhouse gas emissions and mitigation options from livestock agri-food systems. Rome (Italie), Food and Agriculture Organization of the United Nations, 77 p.

FAO, PNUE, OMS et OMSA, 2023. Plan d'action conjoint « Une seule santé » (2022-2026). Travailler ensemble pour des êtres humains, des animaux, des végétaux et un environnement en bonne santé. Rome (Italie), 100 p, https://doi.org/10.4060/cc2289fr

Faucon M.-P., Houben D., Reynoird J.-P., Mercadal-Dulaurent A.-M., Armand R., Lambers H., 2015. Chapter Two – Advances and perspectives to improve the phosphorus availability in cropping systems for agroecological phosphorus management, in Sparks D. L. (ed.), *Advances in Agronomy, Academic Press*, 134, 51-79, https://doi.org/10.1016/bs.agron.2015.06.003

Foley J. A., Ramankutty N., Brauman K. A, Cassidy E. S., Gerber J. S., Johnston M., Mueller N. D., O'Connell C., Ray D. K., West P. C., Balzer C., Bennett E. M., Carpenter S. R., Hill J., Monfreda C., Polasky S., Rockström J., Sheehan J., Siebert S., Tilman D., Zaks D. P. M., 2011. Solutions for a cultivated planet. *Nature*, 478, 337-342.

Frehner A., Muller A., Schader C., De Boer I. J. M., Van Zanten H. H., 2020. Methodological choices drive differences in environmentally-friendly dietary solutions. *Global Food Security*, 24, 100333.

Galang E. I. N. E., Bennett E. M., Hickey G. M., Baird J., Harvey B., Sherren K., 2025. Participatory scenario planning: A social learning approach to build systems thinking and trust for sustainable environmental governance. *Environmental Science and Policy*, 164, 103997.

Garibaldi L. A., Oddi F. J., Miguez F. E., Bartomeus I., Orr M. C., Jobbágy E. G., Kremen C., Schulte L. A., Hughes A. C., Bagnato C., 2020. Working landscapes need at least 20% native habitat. *Conservation Letters*, e12773, 10 p.

Gascuel-Odoux C., Aurousseau P., Cordier M.-O., Durand P., Garcia F., Masson V., Salmon-Monviola J., Tortrat F., Trepos R., 2009. A decision-oriented model to evaluate the effect of land use and agricultural management on herbicide contamination in stream water. *Environmental Modelling and Software*, 24, 1433-1446.

Gattinger A., Muller A., Haeni M., Skinner C., Fliessbach A., Buchmann N., Mäder P., Stolze M., Smith P., Scialabba N. E.-H., 2012. Enhanced top soil carbon stocks under organic farming. *Proceedings of the National Academy of Sciences*, 109 (44), 18226-18231.

Giec, 2006. Lignes directrices 2006 du Giec pour les inventaires nationaux de gaz à effet de serre, https://www.ipcc-nggip. iges.or.jp/public/2006gl/french/index.html

Gliessman S. R., 2007. *Agroecology: the Ecology of Sustainable Food Systems*. New York, Taylor and Francis.

Godet M., 2007 (reissue). *Manuel de prospective stratégique*. Third edition. Tomes 1 et 2. Paris, Dunod.

Godet M., 2000. The art of scenarios and strategic planning: tools and pitfalls. *Technological Forecasting and Social Change*, 65 (1), 3-22.

Godfray H. C. J., Beddington J. R., Crute I. R., Haddad L., Lawrence D., Muir J. F., Pretty J., Robinson S., Thomas S. M., Toulmin C., 2010. Food security: The challenge of feeding 9 billion people. *Science*, 327 (5967), 812-816.

Gonin A., Gautier D., 2015. Shift in herders' territorialities from regional to local scale: The political ecology of pastoral herding in Western Burkina Faso. *Pastoralism*, 5, 1-12.

Govoni C., Chiarelli D. D., Rulli M. C., 2024. A global dataset of the national green and blue water footprint of livestock feeds. *Scientific Data*, 11, 1419, https://doi.org/10.1038/s41597-024-04264-2

Green R. E., Cornell S. J., Scharlemann J. P. W., Balmford A., 2005. Farming and the fate of wild nature. *Science*, 307 (5709), 550-555.

Griffon M., 2010. *Pour des agricultures écologiquement intensives*. La Tour-d'Aigues, Éditions de l'Aube, 144 p.

Grillot M., Guerrin F., Gaudou B., Masse D., Vayssières J., 2018a. Multi-level analysis of nutrient cycling within agro-sylvo-pastoral landscapes in West Africa using an agent-based model. *Environmental Modelling and Software*, 107, 267-280.

Grillot M., Vayssières J., Guerrin F., Lecomte P., 2018b. Modélisation conceptuelle de la gestion adaptative de la biomasse face à l'aléa climatique en système agro-sylvo-pastoral. *Cahiers Agricultures*, 180048, 1-9.

Grimm V., Railsback S. F., 2005. *Individual-based modeling and ecology*. Princeton, Princeton University Press, 448 p.

Guitouni A., Martel J.-M., 1998. Tentative guidelines to help choosing an appropriate MCDA method. *European Journal of Operational Research*, 109 (2), 501-521.

Gupta B., Zurek M., Woodhill J., Ingram J., 2025. *Food systems of the future: A synthesis of food system drivers and recent scenario studies*. Oxford (United Kingdom), Foresight4Food.

Guyomard H. (ed.), 2013. *Vers des agricultures à hautes performances*. Volume 1. Analyse des performances de l'agriculture biologique. Paris, Inra, 368 p.

Halada L., Evans D., Romão C., Petersen J.-E., 2011. Which habitats of European importance depend on agricultural practices?. *Biodiversity and Conservation*, 20 (11), 2365-2378.

Hamilton S. H., Elsawah S., Guillaume J. H., Jakeman A. J., Pierce S. A., 2015. Integrated assessment and modelling: Overview and synthesis of salient dimensions. *Environmental Modelling and Software*, 64, 215-229, https://doi.org/10.1016/j.envsoft.2014.12.005

Herrero M., Havlík P., Valin H., Notenbaert A., Rufino M. C., Thornton P. K., Blümmel M., Weiss F., Grace D., Obersteiner M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences*, 110 (52), 20888-20893.

Hervieu B., 2002a. La multifonctionnalité de l'agriculture : genèse et fondement d'une nouvelle approche conceptuelle de l'activité agricole. *Cahiers Agricultures*, 11, 415-419.

Hervieu B., 2002b. La multifonctionnalité : un cadre conceptuel pour une nouvelle organisation de la recherche sur les herbages et les systèmes d'élevage. *Fourrages*, 20, 219-226.

Heurgon E., 2006. Territoires en question(s), territoires en devenir. Essai de prospective du présent. *Territoires 2030*, nº 3, 9 p.

HLPE, 2014. Food losses and waste in the context of sustainable food systems. High level panel of expert of the committee on World food security, 116 p.

Hou Y., Bai Z., Lesschen J. P., Staritsky I. G., Sikirica N., Ma L., Velthof G. L., Oenema O., 2016. Feed use and nitrogen excretion of livestock in EU-27. *Agriculture, Ecosystems and Environment*, 218, 232-244.

Huang J., Tichit M., Poulot M., Darly S., Li S., Petit C., Aubry C., 2015. Comparative review of multifunctionality and ecosystem services in sustainable agriculture. *Journal of Environmental Management*, 149, 138-147.

Hubert B., Ison, R., 2011. Institutionalising understandings: From resource sufficiency to functional integrity, in Kammili T., Hubert B., Tourrand J.-F. (eds), *A paradigm shift in livestock management: From resource sufficiency to functional integrity*. Avignon (France), Hohhot's Workshop.

Huyghe C., De Vliegher A., van Gils B., Peeters A., 2014. *Grasslands and herbivore production in Europe and Effects of common policies*. Versailles, éditions Quæ.

Ickowicz A., Blanfort V., Forman S., Hubert B., Lasseur J., Marguerat C., Tourrand J.-F., Velasco G., Wedderburn L., 2018. Why and how address multifunctionality of pastoral farming systems?, in Blanfort V., Lasseur J. (eds), Multifunctionality of pastoralism: linking global and local strategies through shared visions and methods. International Rangeland Congress Workshop 2016. GASL Montpellier 127 p.

Ickowicz A., Hubert B., Blanchard M., Blanfort V., Cesaro J.-D., Diaw A., Lasseur J., Thi Thanh Huyen L., Li L., Mauricio R. M., Cangussu M., Müller J.-P., Quiroga Mendiola M., Quiroga Roger J., Vera T. A., Ulambayar T., Wedderburn L., 2022. Multifunctionality and diversity of livestock grazing systems for sustainable food systems throughout the world: Are there learning opportunities for Europe?. *Grass and Forage Science*, 77 (4), 282-294, https://doi.org/10.1111/gfs.12588

Ilri, IUCN, FAO, WWF, Unep and ILC, 2021. Rangelands Atlas. Nairobi Kenya. Ilri, 42 p.

Inosys, 2014. Des systèmes ovins confortés par la réforme de la Pac. Octobre 2014, https://idele.fr/inosys-reseaux-elevage/publications/detail-article?tx_atolidelecontenus_publicationdetail%5Baction%5D=showArticle&tx_atolidelecontenus_publicationdetail%5Bcontroller%5D=Detail&tx_atolidelecontenus_publicationdetail%5Bpublication%5D=8037&cHash=a2a3390cf43405234ac6531d247ddb3b

Isa, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework. EN Isa 14040. Geneva (Switzerland), International Organization for Standardization.

Jacquot S., 2019. L'approche séquentielle, *in* Boussaguet L., Jacquot S., Ravinet P. (eds), *Dictionnaire des politiques publiques*. Paris, Presses de Sciences Po, p. 81-87.

Jahel C., Bourgeois R., Bourgoin J., Daré W., Lattre-Gasquet M. (de), Delay E., Dumas P., Le Page C., Piraux M., Prudhomme R., 2023. The future of social-ecological systems at the crossroads of quantitative and qualitative methods. *Technological Forecasting and Social Change*, 193, 122624, https://doi.org/10.1016/j.techfore.2023.122624

Jakeman A. J., Letcher R. A., Norton J. P., 2006. Ten iterative steps in development and evaluation of environmental models. *Environmental Modelling and Software*, 21, 602-614.

Jeffrey D., 1988. Mineral nutrients and the soil environment, in Jones M. B., Lazenby A. (eds), *The Grass Crop*. London, New York, Springer, p. 179-204.

Jetter A. J., Kok K., 2014. Fuzzy cognitive maps for futures studies – A methodological assessment of concepts and methods. *Futures*, 61, 45-57.

Jeuffroy M.-H., Biarnes V., Cohan J.-P., Corre-Hellou G., Gastal F., Jouffret P., Justes E., Landé N., Louarn G., Plantureux S., 2015. Performances agronomiques et gestion des légumineuses dans les systèmes de productions végétales, in Schneider A., Huyghe C. (eds), *Les légumineuses pour des systèmes agricoles et alimentaires durables*. Versailles, éditions Quæ, p. 139-224.

Jouvenel H. (de), 1999. La démarche prospective. Un bref guide méthodologique. *Futuribles*, 247, 47-68.

Julhia L., Barzman M., Belmin R., Pailly O., Mora O., Casabianca F., Beretti H., Bénaouf G., Curk F., Donati M., Mancel J.-P., Fazi P. S., Marcadal V., Sainte-Beuve D., Welschinger B., Froelicher Y., 2018. Prospect'Agrum Prospective pour la mobilisation des ressources génétiques et la compétitivité des filières structurées autour de labels de qualité : cas de l'agrumiculture Corse à l'horizon 2030. [Rapport de recherche] Inra, 68 p. ⟨hal-03232237⟩.

Jurjanz S., Roinsard A., 2014. Valorisation de l'herbe par des truies plein-air. *Alteragri*, 125, 25-28, mai-juin.

Karlsson J. O., Carlsson G., Lindberg M., Sjunnestrand T., Röös E., 2018. Designing a future food vision for the Nordics through a participatory modeling approach. *Agronomy for Sustainable Development*, 38 (6), 59.

Karlsson J. O., Röös E., 2019. Resource-efficient use of land and animals – Environmental impacts of food systems based on organic cropping and avoided food-feed competition. *Land Use Policy*, 85, 63-72.

Kauko K., Palmroos P., 2014. The Delphi method in forecasting financial markets. An experimental study. *International Journal of Forecasting*, 30 (2), 313-327.

Kizeková M., Hopkins A., Kanianska R., Makovníková J., Pollák Š., Pálka B., 2018. Changes in the area of permanent grassland and its implications for the provision of bioenergy: Slovakia as a case study. *Grass and Forage Science*, 73 (1), 218-232.

Kleinpeter V., Lo Seen D., Degenne P., Lurette A., Wassenaar T., Vayssières J., 2024. A stakeholder decision and road-network-based deterministic model to simulate material flows in regional scale industrial symbiosis networks. *Journal of Cleaner Production*, 434, 139778.

Kok K., van Vliet M., Bärlund I., Dubel A., Sendzimir J., 2011. Combining participative backcasting and exploratory scenario development: Experiences from the SCENES project. *Technological Forecasting and Social Change*, 78 (5), 835-851, https://doi.org/10.1016/j.techfore.2011.01.004

Krätli S., Toulmin, C., 2020. Farmer-herder conflict in Sub-Saharan Africa? A research paper for AFD, Research Report, IIED: London, UK, 2020; ISBN 978-1-78431-828-4. Disponible en ligne : http://pubs.iied.org/10208IIED.

Kremen C., Iles A., Bacon C., 2012. Diversified farming systems: an agroecological, systems-based alternative to modern industrial agriculture. *Ecology and Society*, 17 (4), 44.

Lacroix D., Mora O., Menthière N. (de), Bethinger A., 2021. *La montée du niveau de la mer d'ici 2100 : Scénarios et conséquences*. Versailles, éditions Quæ, collection « Matière à débattre et décider », 128 p.

Lairez J., Feschet P., 2016. Chapitre 5 – Choisir une méthode d'évaluation, *in* Lairez J., Feschet P., Aubin J., Bopckstaller C., Bouvarel I. (eds). *Agriculture et développement durable*. Versailles, éditions Quæ and Éducagri éditions, 129-168.

Lairez J., Feschet P., Aubin J., Bockstaller C., Bouvarel I., 2016. *Agriculture et développement durable : Guide pour l'évaluation multicritère*. Dijon, Éducagri éditions.

Lamine C., 2012. Changer de systèmes : une analyse des transitions vers l'agriculture biologique à l'échelle des systèmes agri-alimentaires territoriaux. *Terrain et Travaux*, (1) 20, 139-156.

Le Berre S., 2013. Gouverner les territoires par la prospective stratégique ? Une comparaison Bretagne / Pays-de-Galles. Congrès de l'Association française de science politique, Paris, 32 p.

Le Mouël C., Forslund A., 2017. How can we feed the world in 2050? A review of the responses from global scenario studies. *European Review of Agricultural Economics*, 44 (4), 541-591.

Le Mouël C., Dumas P., Manceron S., Forslund A., Marajo-Petitzon E., 2018a. The GlobAgriAgrimonde-Terra database and model, in Le Mouël C., Lattre-Gasquet M. (de), Mora O. (eds), *Land use and food security in 2050: a narrow road. Agrimonde-Terra*. Versailles, éditions Quæ, p. 28-36.

Le Mouël C., Lattre-Gasquet D., Mora O., 2018b. *Agrimonde Terra -Land use and food security in 2050: a narrow road*. Versailles, éditions Quæ, 400 p., https://doi.org/10.35690/978-2-7592-2880-5

Lebourgeois V., Dupuy S., Vintrou É., Ameline M., Butler S., Bégué A., 2017. A combined random forest and Obia classification scheme for mapping smallholder agriculture at different nomenclature levels using multisource data (simulated Sentinel-2 time series, VHRS and DEM). *Remote Sensing*, 9 (3), 259.

Lenton T. M., 2013. Environmental tipping points. *Annual Review of Environment and Resources*, 38 (1), 1-29.

Lescourret F., Magda D., Richard G., Adam-Blondon A.-F., Bardy M., Baudry, J., Doussan I., Dumont B., Lefèvre F., Litrico I., Martin-Clouaire R., Montuelle B., Pellerin S., Plantegenest M., Tancoigne E., Thomas A., Guyomard H., Soussana J.-F., 2015. A social-ecological approach to managing multiple agro-ecosystem services. *Current Opinion in Environmental Sustainability*, 14, 68-75.

Lin B. B., 2011. Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience*, 61 (3), 183-193.

Loiseau E., Aissani L., Le Féon S., Laurent F., Cerceau J., Sala S., Roux P., 2018. Territorial life cycle assessment (LCA): What exactly is it about? A proposal towards using a common terminology and a research agenda. *Journal of Cleaner Production*, 176, 474-485.

Loiseau E., Roux P., Junqua G., Maurel P., Bellon-Maurel V., 2014. Implementation of an adapted LCA framework to environmental assessment of a territory: important learning points from a French Mediterranean case study. *Journal of Cleaner Production*, 80, 17-29.

Loiseau E., Salou T., Roux P., 2022. Chapter 9 – Territorial Life Cycle Assessment, in Teodosiu C., Fiore S., Almudena Hospido A. (eds), *Assessing progress towards sustainability*. S. l., Elsevier, p. 161-188, https://doi.org/10.1016/B978-0-323-85851-9.00011-0

Loiseau P., Louault F., Le Roux X., Bardy M., 2005. Does extensification of rich grasslands alter the C and N cycles, directly or via species composition?. *Basic and Applied Ecology*, 6 (3), 275-287.

Lopez-Ridaura S., 2005. Multi-scale sustainability evaluation: a framework for the derivation and quantification of indicators for natural resource management systems, PhD thesis. Wageningen, The Netherlands, Wageningen University.

Lóránt A., Allen B., 2019. Net-zero agriculture in 2050: how to get there? Brussels, Report by the Institute for European Environmental Policy, 41 p.

Lynch J., Cain M., Frame D., 2021. Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO_2-emitting sectors. *Frontiers in Sustainable Food Systems*, 4.

Mäder P., Edenhofer S., Boller T., Wiemken A., Niggli U., 2000. Arbuscular mycorrhizae in a long-term field trial comparing low-input (organic, biological) and high-input (conventional) farming systems in a crop rotation. *Biology and Fertility of Soils*, 31 (2), 150-156.

Magruk A., 2020. Uncertainties, knowledge, and futures in foresight studies – A case of the industry 4.0. *Foresight and STI Governance*, 14 (4), 20-33, https://doi.org/10.17323/2500-2597.2020.4.20.33

Maier H. R., Guillaume J. H., van Delden H., Riddell G. A., Haasnoot M., Kwakkel J. J., 2016. An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together?. *Environmental Modelling and Software*, 81, 154-164.

Malézieux E., 2012. Designing cropping systems from nature. *Agronomy for Sustainable. Development*, 32 (1), 15-29

Manson S. M., Sun S., Bonsal D., 2012. Agent-based modeling and complexity, in Heppenstall A. J., Crooks A. T., See L. M., Batty M. (eds), *Agent-based models of geographical systems*. Dordrecht, Springer Netherlands, p. 125-139.

Martin G., Moraine M., Ryschawy J., Magne M.-A., Asai M., Sarthou J.-P., Duru M., Therond O., 2016. Crop-livestock integration beyond the farm level: a review. *Agronomy for Sustainable Development*, 36 (3), 53.

Martin M., Eglin T., Bardy M., 2015. Stockage de carbone dans les sols de grandes cultures : méthodes de comptabilisation à différentes échelles, *in* Bourges B., Broc J.-S., Gourdon T. (eds), *Empreinte carbone : évaluer et agir*. Paris, Presses des Mines, collection « Développement durable ».

McGinnis M. D., Ostrom E., 2014. Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society*, 19, https://doi.org/10.5751/ES-06387-190230

Mekonnen M. M., Hoekstra A. Y., 2012. A global assessment of the water footprint of farm animal products. *Ecosystems*, 15 (3), 401-415.

Mendez M. A., Popkin B. M., 2004. Globalization, urbanization and nutritional change in the developing world. eJADE – *Electronic Journal of Agricultural and Development Economics*, 1, 220-241.

Mercandalli S., Losch B., 2018. Une Afrique rurale en mouvement. Dynamiques et facteurs des migrations au sud du Sahara. Rome (Italy), FAO ; Montpellier (France), Cirad, 60 p.

Mermet L. (ed.), 2005. *Étudier des écologies futures. Un chantier ouvert pour les recherches prospectives environnementales*. Bruxelles, P.I.E.-Peter Lang, série « EcoPolis », 411 p.

Mermet L., 2009. Extending the perimeter of reflexive debate on futures research: An open framework. *Futures*, 41 (2), 105-115.

Miles I., Keenan M., 2002. *Practical guide to regional foresight in the UK*. Luxembourg, European Communities, 132 p.

Millennium Ecosystem Assessment (MA), 2005. *Ecosystems and human well-being: synthesis*. Washington DC, Island Press, 155 p.

Miller R., 2007. Futures literacy: a hybrid strategic scenario method. *Futures*, 39 (4), 341-362.

Miller V., Reedy J., Cudhea F., Zhang J., Shi P., Erndt-Marino J., Coates J., Micha R., Webb P., Mozaffarian D. *et al.*, 2022. Global, regional, and national consumption of animal-source foods between 1990 and 2018: findings from the Global Dietary Database. *The Lancet Planetary Health*, 6 (3), e243-e256.

Misslin R., Clivot H., Levavasseur F., Villerd J., Soulié J.-C., Houot S., Therond O., 2022. Integrated assessment and modeling of regional recycling of organic waste. *Journal of Cleaner Production*, 369, https://doi.org/10.1016/j.jclepro.2022.134725

Moine A., 2006. Le territoire comme un système complexe : un concept opératoire pour l'aménagement et la géographie. *L'Espace géographique*, 115, https://doi.org/10.3917/ eg.352.0115

Monfreda C., Ramankutty N., Foley J. A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, 22 (1).

Moore F. C., Lobell D. B., 2015. The fingerprint of climate trends on European crop yields. *Proceedings of the National Academy of Sciences*, 112 (9), 2670.

Mora O., Banos V., 2014. La forêt des Landes de Gascogne : vecteur de liens ?. *VertigO : La revue électronique en sciences de l'environnement*, 14 (1), 23 p.

Mora O., Banos V., Carnus J.-M., Régolini M., 2012. Quel avenir pour le Massif des Landes de Gascogne à l'horizon 2050 ?. Rapport de la prospective. Inra, 290 p.

Mora O., Berne J.-A., Drouet J.-L., Le Mouël C., Meunier C., Forslund A., Kieffer V., Paresys L., 2023. European Chemical Pesticide-Free Agriculture in 2050. Foresight Report. INRAE, Depe, 643 p. ⟨hal-04231124⟩.

Mora O., Le Mouël C., Lattre-Gasquet M. (de), Donnars C., Dumas P., Réchauchère O., Brunelle T., Manceron S., Marajo-Petitzon E., Moreau C., Barzman M., Forslund A., Marty P., 2020. Exploring the future of land use and food security: A new set of global scenarios. *PLOS One*, 15 (7), https://doi.org/10.1371/journal.pone.0235597

Mottet A., Bicksler A., Lucantoni D., De Rosa F., Scherf B., Scopel E., López-Ridaura S., Gemmil-Herren B., Bezner Kerr R., Sourisseau J.-M., Petersen P., Chotte J.-L., Loconto A., Tittonell P., 2020. Assessing transitions to sustainable agricultural and food systems: A tool for agroecology performance evaluation (Tape). *Frontiers in Sustainable Food Systems*, 4.

Mottet A., de Haan C., Falcucci A., Tempio G., Opio C., Gerber P., 2017. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security*, 14, 1-18.

Mottet A., Teillard F., Boettcher P., De' Besi G., Besbes B., 2018. Review: Domestic herbivores and food security: current contribution, trends and challenges for a sustainable development. FAO. *Animal*, 12 (s2), 188-198, http://dx.doi.org/doi:10.1017/S1751731118002215

Muneret L., Mitchell M., Seufert V., Aviron S., Djoudi E.A., Pétillon J., Plantegenest M., Thiéry D., Rusch A., 2018. Evidence that organic farming promotes pest control. *Nature Sustainability*, 1 (7), 361.

Nassauer J. I., Opdam P., 2008. Design in science: extending the landscape ecology paradigm. *Landscape Ecology*, 23 (6), 633-644, https://doi.org/10.1007/s10980-008-9226-7

Pahl-Wostl C., 2007. Transitions towards adaptive management of water facing climate and global change. *Water Resources Management*, 21, 49-62.

Paillard S., Treyer S., Dorin B. (eds), 2010. *Agrimonde. Scénarios et défis pour nourrir le monde en 2050.* Versailles, éditions Quæ, 296 p.

Parrott L., Meyer W. S., 2012. Future landscapes: Managing within complexity. *Frontiers in Ecology and the Environment*, 10, 382-389, https://doi.org/10.1890/110082

Pärtel M., Bruun H. H., Sammul M., 2005. Biodiversity in temperate European grasslands: origin and conservation. *Grassland Science in Europe*, 10, 1-14.

Peeters A., 2009. Importance, evolution, environmental impact and future challenges of grasslands and grassland-based systems in Europe. *Grassland Science in Europe*, 55 (3), 113-125.

Pellerin M., 2021. Listening to herders in West Africa and the Sahel: What future for pastoralism in the face of insecurity and its impacts? Report Réseau Billital Maroobé: Rome (Italie), 163 p. Disponible en ligne : https://www.maroobe.com/index.php/publications/rapports

Pellerin S., Bamière L., Angers D., Béline F., Benoît M., Butault J.-P., Chenu C., Colnenne-David C., De Cara S., Delame N., Doreau M., Dupraz P., Faverdin P., Garcia-Launay F., Hassouna M., Hénault C., Jeuffroy M. H., Klumpp K., Metay A., Moran D., Recous S., Samson E., Savini I., Pardon L., 2013. Quelle contribution de l'agriculture française à la réduction des émissions de gaz à effet de serre ?. Potentiel d'atténuation et coût de dix actions techniques. Inra, France.

Pellerin S., Bamière L., Launay C., Martin R., Schiavo M., Angers D., Augusto L., Balesdent J., Basile-Doelsch I., Bellassen V., Cardinael R., Cécillon L., Ceschia E., Chenu C., Constantin J., Darroussin J., Delacote P., Delame N., Gastal F., Gilbert D., Graux A. I., Guenet B., Houot S., Klumpp K., Letort E., Litrico I., Martin M., Menasseri S., Mézière D., Morvan T., Mosnier C., Roger-Estrade J., Saint-André L., Sierra J., Therond O., Viaud V., Grateau R., Le Perchec S., Réchauchère O., 2019. Stocker du carbone dans les sols français. Quel potentiel au regard de l'objectif 4 pour 1 000 et à quel coût ?. Synthèse du rapport d'étude, Inra, 114 p.

Pica-Ciamarra U., Baker D., Morgan N., Ly C., Nouala S., 2013. Investir dans l'élevage en Afrique : Perspectives commerciales pour 2030-2050. Washington, DC, World Bank, http://hdl.handle.net/10986/17866

Pointereau P., Coulon F., Doxa A., Jiguet F., Paracchini M. L., 2010. Location of HVN farmland area in France and links between changes in High nature value farmland areas and changes in birds' population. JRC/Solagro, http://agrienv.jrc.ec.europa.eu

Ponisio L. C., M'Gonigle L. K., Mace K. C., Palomino J., de Valpine P., Kremen C., 2015. Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences*, 282 (1799), 20141396.

Popkin B. M., 1993. Nutritional Patterns and Transitions. Population Development. *Review*, 19 (1), 138-157.

Popkin B. M., 2006. Global nutrition dynamics: the world is shifting rapidly toward a diet linked with noncommunicable diseases. *American Journal of Clinical Nutrition*, 84 (2), 289-298.

Popp A., Calvin K., Fujimori S., Havlik P., Humpenöder F., Stehfest E. Bodirsky B. L., Dietrich J. P., Doelmann J. C., Gusti M., Hasegawa T., Kyle P., Obersteiner M., Tabeau A., Takahashi K., Valin H., Waldhoff S., Weindl I., Wise M., Kriegler E., van Vuuren D. P., 2017. Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, 42, 331-345.

Pörtner H. O., Scholes R.J., Agard J., Archer E., Arneth A., Bai X., Barnes D., Burrows M., Chan L., Cheung W. L., Diamond S., Donatti C., Duarte C., Eisenhauer N., Foden W., Gasalla M. A., Handa C., Hickler T., Hoegh-Guldberg O., Ichii K., Jacob U., Insarov G., Kiessling W., Leadley P., Leemans R., Levin L., Lim M., Maharaj S., Managi S., Marquet P. A., McElwee P., Midgley G., Oberdorff T., Obura D., Osman E., Pandit R., Pascual U., Pires A. P. F., Popp A., Reyes-García V., Sankaran M., Settele J., Shin Y. J., Sintayehu D. W., Smith P., Steiner N., Strassburg B., Sukumar R., Trisos C., Val A. L., Wu J., Aldrian E., Parmesan C., Pichs-Madruga R., Roberts D. C., Rogers A. D., Díaz S., Fischer M., Hashimoto S., Lavorel S., Wu N., Ngo H. T., 2021. IPBES-IPCC co-sponsored workshop report on biodiversity and climate change; IPBES and IPCC, 28 p, https://doi.org/10.5281/zenodo.4782538

Poux X., Aubert P.-M., 2018. Ten Years for Agroecology in Europe: a multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (Tyfa) modelling exercise. Paris, Iddri, https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Etude/201809-ST0918EN-TYFA.pdf, 73 p.

Raimbault P., Kaminski G., Desaulty C., Jolivet A. C., Gadon C., Tomezak S., Pierre H., Mauler C., Garriga A., Ferran C., Montet-Lattes F., Guyard A., Herrero E., Lemaire M., Vujkovic N., Pons C., Louart C., Périé P., Fuentes S., 2020. Bien manger : un défi au-delà de nos assiettes. Toulouse, France, Université fédérale de Toulouse Midi-Pyrénées, dossier Exploreur, 43.

Ramirez R., Wilkinson A., 2014. Rethinking the 2×2 scenario method: Grid or frames?. *Technological Forecasting and Social Change*, 86, 254-264.

Rangé C., Magnani S., Ancey V., 2020. « Pastoralisme » et « insécurité » en Afrique de l'Ouest. *Revue internationale des études du développement*. Paris, Institut d'études du développement de la Sorbonne, p. 115-150.

Raworth K., 2017. A Doughnut for the Anthropocene: humanity's compass in the 21st century. *The Lancet Planetary Health*, 1 (2), e48-e49.

Ray D. K., Ramankutty N., Mueller N. D., West P. C., Foley J. A., 2012. Recent patterns of crop yield growth and stagnation. *Nature Communications*, 3 (1), 1293, https://doi.org/10.1038/ncomms2296

Reganold J. P., Watcher J. M., 2016. Organic agriculture in the twenty-first century. *Nature Plants*, 8 p, https://doi.org/10.1038/nplants.2015.221

Ritchey T., 2011. Modeling alternative futures with general morphological analysis. *World Future Review*, 3 (1), 83-94.

Robinson T. P., Thornton P. K., Franceschini G., Kruska R. L., Chiozza F., Notenbaert A., Cecchi G., Herrero M., Epprecht M., Fritz S., You L., Conchedda G., See L., 2011. Global livestock production systems. Rome, Food and Agriculture Organization of the United Nations (FAO) and International Livestock Research Institute (Ilri), 152 p.

Rockström J., Steffen W., Noone K., Persson Å., Chapin F. S. III, Lambin E., Lenton T. M., Scheffer M., Folke C., Schellnhuber H. J., Nykvist B., De Wit C. A., Hughes T., van der Leeuw S., Rodhe H., Sörlin S., Snyder P. K., Costanza R., Svedin U., Falkenmark M., Karlberg L., Corell R. W., Fabry V. J., Hansen J., Walker B., Liverman D., Richardson K., Crutzen P., Foley J. A., 2009. A safe operating space for humanity. *Nature*, 461, 472-475, https://doi.org/10.1038/461472a

Röös E., Patel M., Spångberg J., Carlsson G., Rydhmer L., 2016. Limiting livestock production to pasture and by-products in a search for sustainable diets. *Food Policy*, 58, 1-13, https://doi.org/10.1016/j.foodpol.2015.10.008

Roper M., Gupta V., 2016. Enhancing non-symbiotic N_2 fixation in agriculture. *The Open Agriculture Journal*, 10 (1), https://doi.org/10.2174/1874331501610010007

Roux A., Dhôte J.-F. (coord.), Achat D., Bastick C., Colin A., Bailly A., Bastien J.-C., Berthelot A., Bréda N., Caurla S., Carnus J.-M., Gardiner B., Jactel H., Leban J.-M., Lobianco A., Loustau D., Meredieu C., Marçais B., Martel S., Moisy C., Pâques L., Picart Deshors D., Rigolot E., Saint-André L., Schmitt B., 2017. Quel rôle pour les forêts et la filière forêt-bois françaises dans l'atténuation du changement climatique ? Une étude des freins et leviers forestiers à l'horizon 2050. Rapport d'étude pour le ministère de l'Agriculture et de l'Alimentation, Inra et IGN, 101 p. + 230 p. (annexes).

Russeil V., Lo Seen D., Broust F., Bonin M., Praene J.-P., 2023. Food and electricity self-sufficiency trade-offs in Reunion Island: Modelling land-use change scenarios with stakeholders. *Land Use Policy*, 132, 106784.

Ryschawy J., Martin G., Moraine M., Duru M., Therond O., 2017. Designing crop-livestock integration at different levels: Toward new agroecological models?. *Nutrient Cycling in Agroecosystems*, 108 (1), 5-20.

Sandström V., Chrysafi A., Lamminen M., Troell M., Jalava M., Piipponen J., Siebert S., Van Hal O., Virkki V., Kummu M., 2022. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. *Nature Food*, 3 (9), 729-740.

Schils R. L. M., Bufe C., Rhymer C. M., Francksen R. M., Klaus V. H., Abdalla M., Milazzo F., Lellei-Kovács E., ten Berge H., Bertora C., 2022. Permanent grasslands in Europe: Land use change and intensification decrease their multifunctionality. *Agriculture, Ecosystems and Environment*, 330, https://doi.org/10.1016/j.agee.2022.107891

Schils R., Olesen J. E., Kersebaum K.-C., Rijk B., Oberforster M., Kalyada V., Khitrykau M., Gobin A., Kirchev H., Manolova V., 2018. Cereal yield gaps across Europe. *European Journal of Agronomy*, 101, 109-120, https://doi.org/10.1016/j.eja.2018.09.003

Searchinger T. D., Zionts J., Wirsenius S., Beringer T., Dumas P., 2021. A pathway to carbon neutral agriculture in Denmark. Washington, World Resources Institute, 166 p.

Searchinger T., Waite R., Hanson C., Ranganathan J., Dumas P., Matthews E., 2018. Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050. WRR Synthesis Report, 564 p.

Simoncini R., Ring I., Sandström C., Albert C., Kasymov U., Arlettaz R. 2019. Constraints and opportunities for mainstreaming biodiversity and ecosystem services in the EU's Common Agricultural Policy: Insights from the IPBES assessment for Europe and Central Asia. *Land Use Policy*, 88, 104099.

Smit H. J., Metzger M. J., Ewert F., 2008. Spatial distribution of grassland productivity and land use in Europe. *Agricultural Systems*, 98 (3), 208-219, https://doi.org/10.1016/j.agsy.2008.07.004

Smith L. C., Haddad L., 2015. Reducing child undernutrition: past drivers and priorities for the post-MDG era. *World Development*, 68, 180-204, https://doi.org/10.1016/j.worlddev.2014.11.014

Smith P., Haberl H., Popp A., Erb K. H., Lauk C., Harper R. Tubiello F. N., de Siqueira Pinto A., Jafari M., Sohi S., Masera O., Böttcher H., Berndes G., Bustamante M., Ahammad H., Clark H., Dong H., Elsiddig E. A., Mbow C., Ravindranath N. H., Rice C. W., Robledo Abad C., Romanovskaya A., Sperling F., Herrero M., House J. I., Rose S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals?. *Global Change Biology*, 19(8), 2285-2302, https://doi.org/10.1111/gcb.12160

Sourisseau J.-M., Bélières J.-F., Bourgeois R., Soumaré M., Rasolofo P., Guengant J.-P., Bougnoux N., 2017. Penser ensemble l'avenir d'un territoire. Diagnostic et prospective territoriale au Mali et à Madagascar (études de l'Agence française de développement AFD). Paris (France), AFD. Disponible en ligne : https://www.afd.fr/index.php/fr/penser-ensemble-avenir-territoire, 179 p.

Soussana J.-F., Lemaire G., 2014. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecosystems and Environment*, 190, 9-17, https://doi.org/10.1016/j.agee.2013.10.012

Spaniol M. J., Rowland N. J., 2019. Defining scenario. *Futures and Foresight Science*, 1 (1), e3, https://onlinelibrary.wiley.com/doi/full/10.1002/ffo2.3

Spielman D. J., Ekboir J., Davis K., 2009. The art and science of innovation systems inquiry: Applications to Sub-Saharan African agriculture. *Technology in Society*, 31, 399-405. https://doi.org/10.1016/j.techsoc.2009.10.004

Spohr C., 2009. Vers une prospective territoriale post-Grenelle de l'environnement : Questions et modes d'emploi. Commissariat général au développement durable. *Études et documents*, nº 12, 54 p.

Springmann M., Clark M., Mason-D'Croz D., Wiebe K., Bodirsky B. L., Lassaletta L., De Vries W., Vermeulen S. J., Herrero M., Carlson K. M., 2018. Options for keeping the food system within environmental limits. *Nature*, 562 (7728), 519-525, https://doi.org/10.1038/s41586-018-0594-0

Springmann M., Godfray H. C. J., Rayner M., Scarborough P., 2016. Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, 113 (15), 4146-4151, https://doi.org/10.1073/pnas.1523119113

Springmann M., Wiebe K., Mason-D'Croz D., Sulser T. B., Rayner M., Scarborough P., 2018. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *The Lancet Planetary Health*, 2 (10), e451-e461.

Stehfest E., Bouwman L., van Vuuren D. P., den Elzen M. G. J., Eickhout B., Kabat P., 2009. Climate benefits of changing diet. *Climatic Change*, 95 (1-2), 83-102, https://doi.org/10.1007/s10584-008-9534-6

Steinfeld H., Gerber P., Wassenaar T., Castel V., Rosales M., de Haan C., 2006. Livestock's Long Shadow. Environmental Issues and Options. LEAD initiative. Rome (Italie), FAO, 390 p.

Swinburn B. A., Sacks G., Hall K. D., McPherson K., Finegood D. T., Moodie M. L., Gortmaker S. L., 2011. The global obesity pandemic: shaped by global drivers and local environments. *The Lancet*, 378, 804-814.

Taillandier P., Grignard A., Gaudou B., Drogoul A., 2014. Des données géographiques à la simulation à base d'agents : application de la plate-forme Gama. Cybergeo. *European Journal of Geography*, Systèmes, Modélisation, Géostatistiques, document 671, https://doi.org/10.4000/cybergeo.26263

Taillandier P., Vo D. A., Amouroux E., Drogoul, A., 2012. Gama: a simulation platform that integrates geographical information data, agent-based modeling and multi-scale control. In: Principles and Practice of Multi-Agent Systems: 13th International Conference, Prima 2010, Kolkata, India, November 12-15, 2010, Revised Selected Papers 13 (p. 242-258). Springer Berlin Heidelberg.

The World Bank, 2009. Minding the stock: bringing public policy to bear on livestock sector development. World Bank Group, Washington, DC, 74 p., http://documents.worldbank.org/curated/en/573701468329065723/Minding-the-stock-bringing-public-policy-to-bear-on-livestock-sector-development

Therond O., Belhouchette H., Janssen S., Louhichi K., Ewert F., Bergez J.-E., Wery J., Heckelei T., Alkan Olsson J., Leenhardt D., Van Ittersum M., 2009. Methodology to translate policy assessment problems into scenarios: the example of the SEAMLESS integrated framework. Environmental Science and Policy, 12 (5), 619-630, https://doi.org/10.1016/j.envsci.2009.01.013

Therond O., Sibertin-Blanc C., Balestrat M., Gaudou B., Hong Y., Louail T., Nguyen V. B., Panzoli D., Sanchez-Perez J. M., Sauvage S., Taillandier P., Vavasseur M., Mazzega P., 2014. Integrated modelling of social-ecological systems: The Maelia high-resolution multi-agent platform to deal with water scarcity problems, in Ames D. P., Quinn N. W. T., Rizzoli A. E. (eds), 7th International Congress on Environmental Modelling and Software (iEMSs), San Diego, CA, États-Unis, 8 p.

Thornton P. K., Herrero M., 2014. Climate change adaptation in mixed crop–livestock systems in developing countries. *Global Food Security*, 3, 99-107.

Tilman D., Balzer C., Hill J., Befort B. L., 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, 108 (50), 260-264.

Tilman D., Clark M., 2014. Global diets link environmental sustainability and human health. *Nature*, 515, 518-522.

Tribouillois H., Constantin J., Casal L., Villerd J., Therond O., 2022. Introducing and expanding cover crops at the watershed scale: impact on water flows. *Agriculture, Ecosystems and Environment*, 337, https://doi.org/10.1016/j.agee.2022.108050

Tribouillois H., Constantin J., Guillon B., Willaume M., Aubriond G., Fontained A., Hauprich P., Kerveillant P., Laurent F., Therond O., 2020. AqYield-N: A simple model to predict nitrogen leaching from crop fields. *Agricultural and Forest Meteorology*, 284, 107890, https://doi.org/10.1016/j.agrformet.2019.107890

Tribouillois H., Constantin J., Willaume M., Brut A., Ceschia E., Tallec T., Beaudoin N., Therond O., 2018. Predicting water balance of wheat and crop rotations with a simple model: AqYield. *Agricultural and Forest Meteorology*, 262, 412-422, https://doi:10.1016/j.agrformet.2018.07.026

Van Dijk M., Meijerink G. W., 2014. A review of global food security scenario and assessment studies: Results, gaps and research priorities. *Global Food Security*, 3 (3-4), 227-238.

Van Vuuren D. P., Kok M. T., Girod B., Lucas P. L., de Vries B., 2012. Scenarios in global environmental assessments: key characteristics and lessons for future use. *Global Environmental Change*, 22 (4), 884-895.

Van Zanten H. H. E., Mollenhorst H., Klootwijk C. W., Van Middelaar C. E., De Boer I. J. M., 2015. Global food supply: land use efficiency of livestock systems. *The International Journal of Life Cycle Assessment*, 21, 747-758.

Van der Ploeg J. D., 2008. The new peasantries: Struggles for autonomy and sustainability in an era of empire and globalization. London, Earthscan, 356 p.

Van Ittersum M., Ewert F., Heckelei T., Wery J., Alkan Olsson J., Andersen E., Bezlepkina I., Brouwer F., Donatelli M., Flichman G., Olsson L., Rizzoli A., van der Wal T., Wien J. E., Wolf J., 2008. Integrated assessment of agricultural systems – a component-based framework for the European Union (Seamless). *Agricultural Systems*, 96, 150-165.

Van Kernebeek H. R., Oosting S. J., Van Ittersum M. K., Bikker P., De Boer I. J., 2016. Saving land to feed a growing population: consequences for consumption of crop and livestock products. *The International Journal of Life Cycle Assessment*, 21 (5), 677-687.

van Selm B., Frehner A., de Boer I. J. M., Van Hal O., Hijbeek R., Van Ittersum M. K., Talsma E. F., Lesschen J. P., Hendriks C. M., Herrero M., 2022. Circularity in animal production requires a change in the EAT-Lancet diet in Europe. *Nature Food*, 3 (1), 66-73.

Van Zanten H. H. E., Herrero M., Van Hal O., Röös E., Muller A., Garnett T., Gerber P. J., Schader C., De Boer I. J., 2018. Defining a land boundary for sustainable livestock consumption. *Global Change Biology*, 24 (9), 4185-4194.

Van Zanten H. H. E., Meerburg B., Bikker P., Bikker P., Herrero M., De Boer I. J. M., 2016. Opinion paper: The role of livestock in a sustainable diet: a land-use perspective. *Animal*, 10 (4), 547-549.

Vayssières J., 2021. Modélisation intégrée et pluri-niveaux des stock-flux de matière et d'énergie dans les systèmes agricoles pour l'évaluation multicritère et l'accompagnement de transitions en élevage. Habilitation à diriger des recherches, université de Montpellier, école doctorale Gaia, 122 p.

Vayssières J., Guerrin F., Paillat J.-M., Lecomte P., 2009. Gamede: A global activity model for evaluating the sustainability of dairy enterprises. Part I – Whole-farm dynamic model. *Agricultural Systems*, 101, 128-138.

Vayssières J., Thévenot A., Acosta I., Vigne M., Tillard E., 2019. A participatory, territory-rooted and change-oriented approach to assess the multicriteria contribution of an agri-food value chain to sustainable development. *Indonesian Journal of Life Cycle Assessment and Sustainability*, 3 (1), 43-63.

Vertes F., Jeuffroy M.-H., Louarn G., Voisin A.-S., Justes E., 2015. Légumineuses et prairies temporaires : des fournitures d'azote pour les rotations. *Fourrages*, 223, 221-232.

Voinov A., Bousquet F., 2010. Modelling with stakeholders. *Environmental Modelling and Software*, 25 (11), 1268-1281, https://doi.org/10.1016/j.envsoft.2010.03.007

Walker D. H., 2002. Decision support, learning and rural resource management. *Agricultural Systems*, 73, 113-127.

Wezel A., Bellon S., Doré T., Francis C., Vallod D., David C., 2009. Agroecology as a science, a movement and a practice. A review. *Agronomy for Sustainable Development*, 29, 503-515.

WHO, 2007. Protein and amino acid requirements in human nutrition. WHO Technical Report Series, vol 935. World Health Organization, Geneva, Switzerland.

Wiebe K., Zurek M., Lord S., Brzezina N., Gabrielyan G., Libertini J., Loch A., Thapa-Parajuli R., Vervoort J., Westhoek H., 2018. Scenario development and foresight analysis: exploring options to inform choices. *Annual Review of Environment and Resources*, 43 (1), 545-570.

Wiek A., Iwaniec D., 2014. Quality criteria for visions and visioning in sustainability science. *Sustainability Science*, 9, 497-512.

Wiesmeier M., Hübner R., Kögel-Knabner I., 2015. Stagnating crop yields: An overlooked risk for the carbon balance of agricultural soils?. *Science of The Total Environment*, 536, 1045-1051.

Wilkinson J., 2011. Re-defining efficiency of feed use by livestock. *Animal*, 5 (7), 1014-1022.

Willett W., Rockström J., Loken B., Springmann M., Lang T., Vermeulen S., Garnett T., Tilman D., DeClerck F., Wood A., Jonell M., Clark M., GordonL. J., Fanzo J., Hawkes C., Zurayk R., Rivera J. A., De Vries W, Sibanda L. M., Afshin A., Chaudhary A., Herrero M., Agustina R., Branca F., Lartey A., Fan S., Crona B., Fox E., Bignet V., Troell M., Lindahl T, Singh S., Cornell S. E., Reddy K. S., Narain S., Nishtar S., Murray C. J. L., 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393 (10170), 447-492.

Wirsenius S., Azar C., Berndes G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030?. *Agricultural Systems*, 103 (9), 621-638.

World Health Organization/Food and Agriculture Organization, 2003. Diet, nutrition and the prevention of chronic diseases: report of a joint WHO/FAO expert consultation. WHO Technical Report Series 916. WHO, Geneva, 160 p.

World Population Prospects, 2015. The 2015 Revision.

Wu J., 2013. Landscape sustainability science: Ecosystem services and human well-being in changing landscapes. *Landscape Ecology*, 28 (6), 999-1023, https://doi.org/10.1007/s10980-013-9894-9

Zhai F. Y., Du S. F., Wang Z. H., Zhang J. G., Du W. W., Popkin B. M., 2014. Dynamics of the Chinese diet and the role of urbanicity, 1991-2011. *Obesity Reviews*, 15, 16-26.

Zurek M. B., Henrichs T., 2007. Linking scenarios across geographical scales in international environmental assessments. *Technological Forecasting and Social Change*, 74 (8), 1282-1295.

Zurek M., Hebinck A., Selomane O., 2021. Looking across diverse food system futures: Implications for climate change and the environment. *Q Open*, 1 (1), qoaa001, https://doi.org/10.1093/qopen/qoaa001

Abbreviations and units

ABEA: Breton association of agri-food businesses

ACCT: AgriClimateChangeTool

ADEME: The French Agency for Ecological Transition (formerly the French Environment and Energy Management Agency)

CAP: Common Agricultural Policy

Cirad: French agricultural research and cooperation organization working for the sustainable development of tropical and Mediterranean regions

CM: Conceptual model

CN: Carbon neutrality

CRAB: Regional Chamber of Agriculture of Brittany

CS: cropping system

DC: dairy cow

DGAL: French general directorate of food

DGEC: Directorate general for energy and climate

DGPE: Directorate General of Economic and Environmental Performance of Enterprises

DIP: multi-stakeholder dairy innovation platform

ECOWAS: Economic Community of West African States

GCSD: General Commission for Sustainable Development

GHG: greenhouse gas, expressed in kilograms of carbon dioxide equivalents (CO_2 eq kg)

GIS: geographic information system

GWP 100: global warming potential over the next 100 years

h: hour

ha: hectare

IAM: integrated assessment and modelling

IDDRI: Institute for Sustainable Development and International Relations

IFIP: French Pork and Pig Institute

IGN: National Institute of Geographic and Forest Information

ILRI: international livestock research institute

INCA: Individual national study of food consumption in France

INRAE: French National Research Institute for Agriculture, Food and Environment

IPBES: Intergovernmental science-policy platform on biodiversity and ecosystem services

IPCC: Intergovernmental panel on climate change

km: kilometre

kg: kilogram

LCA: life cycle analysis

Maec: CAP agri-environmental and climate measures

MAS: multi-agent system
MF(A): multifactorial (approach)
MCA: multicriteria assessment
Mha: millions of hectares
MoSUT: systemic model of land use
NBS: National Biodiversity Strategy
OECD: Organisation for Economic Co-operation and Development
PCAET: Territorial Climate-Air-Energy Plan
PES: payments for ecosystem services
PG: permanent grasslands
PNA: French national food plan
PNACC: French National Adaptation Plan for Climate Change
PNNS: French National Nutrition and Health Program
PNRI: French National Plan for research and innovation
RMT MAELE: Macro-Livestock-Environment (MAELE) Joint Technology Network (RMT)
SAE: socio-agroeosystem
SDG: Sustainable development goals
SFEC: French Energy-Climate Strategy
SGPE: General Secretariat for Ecological Planning
SNANC: French National Strategy for Food, Nutrition and Climate
SNBC: National low carbon strategy
SNDI: National Strategy to Combat Imported Deforestation
SNPV: French National Plant Protein Strategy
TFI: Treatment frequency index
TME: Trace metal element
TYFA: Ten Years for Agroecology in Europe
TU: biomass transformation unit
UAA: usable agricultural area (in %)
UNFCCC: United Nations Framework Convention on Climate Change
WWF: World Wide Fund for Nature

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The global food system is facing three major challenges: providing food security, protecting the environment and improving human health. These challenges place livestock farming at a crossroads. However, changes in diets, population growth and changes in the agricultural landscape vary depending on the regions of the world. These dynamics raise questions about the role of livestock farming in territories, the types of farming, its impacts and the services it can provide. How can we anticipate these changes and assess their consequences?

This book presents several different foresight studies that were carried out in different contexts (Global North and Global South) and at different scales (from local to global). It examines the connection between qualitative (joint) scenario building methods and quantitative modelling and assessment approaches. This work also explores the time sequence for the foresight–modelling–assessment cycle, identifying key variables, using data and the role stakeholders play in this whole process, especially when it comes to using these results to make decisions.

This book is based on work arising from the Research School that was organized by INRAE and CIRAD within the framework of the Macro-Livestock-Environment Joint Technology Network (RMT MAELE). The target audience is the scientific community engaged in interdisciplinary approaches. It will also be of interest to anyone working with agriculture, the environment and food, as well as to persons working in the field of sustainable agricultural development.

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