



Fondation Charles Léopold Mayer
pour le Progrès de l'Homme

An agroecological Europe in 2050: multifunctional agriculture for healthy eating

Findings from the Ten Years For Agroecology (TYFA) modelling exercise

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AGROECOLOGY: AN AMBITIOUS AND SYSTEMIC PROJECT

Jointly addressing the challenges of sustainable food for Europeans, the preservation of biodiversity and natural resources and the fight against climate change requires a profound transition of our agricultural and food system. An agroecological project based on the phasing-out of pesticides and synthetic fertilizers, and the redeployment of extensive grasslands and landscape infrastructure would allow these issues to be addressed in a coherent manner.

AN ORIGINAL MODELLING OF THE EUROPEAN FOOD SYSTEM

The TYFA project explores the possibility of generalising such agroecology on a European scale by analysing the uses and needs of current and future agricultural production. An original quantitative model (TYFAm), linking on a systemic manner agricultural production, production methods and land use, makes it possible to analyse retrospectively the functioning of the European food system and to quantify an agroecological scenario by 2050 by testing the implications of different hypotheses.

PROSPECTS FOR A LESS PRODUCTIVE AGROECOLOGICAL SYSTEM

Europe's increasingly unbalanced and over-rich diets, particularly in animal products, contribute to the increase in obesity, diabetes and cardiovascular diseases. They are based on intensive, highly dependent agriculture: (i) synthetic pesticides and fertilizers—with proven health and environmental consequences; (ii) imports of vegetable proteins for animal feed—making Europe a net importer of agricultural land. A change in diet less rich in animal products thus opens up prospects for a transition to an agroecology not bound to maintain current yields, thus opening new fields for environmental management.

SUSTAINABLE FOOD FOR 530 MILLION EUROPEANS

The TYFA scenario is based on the widespread adoption of agroecology, the phasing-out of vegetable protein imports and the adoption of healthier diets by 2050. Despite an induced drop in production of 35% compared to 2010 (in Kcal), this scenario:

- provides healthy food for Europeans while maintaining export capacity;
- reduces Europe's global food footprint;
- leads to a 40% reduction in GHG emissions from the agricultural sector;
- regains biodiversity and conserves natural resources.

Further work is needed and underway on the socio-economic and policy implications of the TYFA scenario.

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AN AGRO-ECOLOGICAL EUROPE: A DESIRABLE, CREDIBLE OPTION TO ADDRESS FOOD AND ENVIRONMENTAL CHALLENGES

Social expectations regarding healthy diets, the protection of natural resources and biodiversity are becoming increasingly apparent at the European level. Effectively managing these expectations implies generalising an agro-ecological model, in other words one that uses no pesticides and maximises ecological processes. In Europe, this kind of agriculture is less productive on average, and is therefore considered incompatible with tackling other crucial challenges: producing enough for Europe and the world while developing bioeconomy sectors to combat climate change.

The TYFA project (Ten Years for Agroecology in Europe) addresses this apparent dilemma by examining how much feed/food/fuel and material the agricultural sector could and should produce to tackle, with equal priority, challenges associated with climate change, health, the protection of biodiversity and natural resources, and the provision of a sustainable and healthy diet to Europeans—without affecting global food security. Top scientific experts helped to build a quantitative model simulating the agricultural functioning of the European food system in order to examine the current situation and to develop an agro-ecological scenario for Europe in 2050. This is the first component of a foresight exercise that will successively deal with the socioeconomic challenges and the policy levers for an agro-ecological transition.

The current European food system is not sustainable

The European food system is often perceived as being highly productive. To its credit, we can consider the volumes produced, the structure of an agri-food industry capable of not only feeding more than 500 million Europeans, but also of contributing positively to the balance of trade, providing 4.2 million jobs in Europe. In addition, for the last 20 years, the efficiency of European agriculture has been improving in terms of greenhouse gases (-20% since 1990), due in particular to the concentration of livestock farming and to higher nitrogen use efficiency.

However, for several decades, these successes have produced more and more serious social and environmental impacts. In terms of health, diet-related diseases are growing at an alarming rate (diabetes, obesity, cardiovascular disease). Although we produce a lot in Europe, we also eat too much and our diets are unbalanced in relation to the nutritional recommendations of the European Food Safety Authority (EFSA) and the World Health Organization (WHO).¹ This is particularly

1. EFSA (2017b). EFSA Comprehensive European Food Consumption Database. European Food Safety Authority – <https://www.efsa.europa.eu/en/food-consumption/comprehensive-database>.

true for animal products (+60% animal proteins in relation to recommendations), which are themselves fed by a growing share of the crop production available in Europe—58% and 67% of, respectively, available cereals and oilseed/protein crops are used to feed livestock—the majority of the later being mostly imported from Latin America in the form of soybean meal.

The high productivity of land in Europe is also the result of the widespread use of chemical inputs – pesticides and synthetic fertilisers. The former are responsible for an increase in the prevalence of numerous diseases among farmers,² and there are strong concerns about their impact on our food, including drinking water. European agriculture is also threatening biodiversity, the loss of which is causing alarm. In the space of one generation, 20% of common birds have disappeared,³ and some regions are lamenting the loss of three quarters of all flying insects.⁴ This picture should also include the destruction of tropical forests, which we indirectly “import” through the soybean produced in South America. Natural resources are unquestionably changing.

These dynamics are the result of specialisation, concentration and intensification processes in farms. Farmers are engaged in competition to expand and to over-equip their farms, in an approach in which every agricultural advance consumes more and more energy and imported nutrients, and in a continuous race between pesticides and pests. Maintaining agricultural potential has a high financial and environmental cost and, more worryingly, seems to have no end.

Faced with these challenges, the dominant response is sustainable intensification, which seeks to “do more with less”, by using inputs and resources more efficiently. However, it is based on partial technical solutions, meaning that farm expansion, concentration and specialisation dynamics continue, and are a major cause of biodiversity loss and agricultural landscape degradation. This response also leaves other questions unanswered: will “using fewer” inputs be enough for biodiversity and natural resources? And for the quality of our food?

An ambitious and systemic approach to an agro-ecological agriculture

In TYFA, agroecology is approached as an innovation pathway in agricultural systems aimed at maximising the use of ecological processes in the functioning of agro-ecosystems, with a view to achieving sustainable food. On this basis, we propose hypotheses concerning every dimension of the agricultural and food system: fertility management, plant production, land use, animal production, non-food uses, and European diets. These hypotheses must be understood in the light of the balance sought when addressing issues relating to health, food security, the protection of natural resources and biodiversity, and climate mitigation.

In agricultural terms, these hypotheses translate into the need to promote optimum use of local resources—leading to a detailed management of nutrient flows at the territorial level—and a precautionary principle to stop the use of pesticides. The goal is to return to agro-ecosystems that make maximum use of soil life and legume symbiotic nitrogen fixation capacities (which are inhibited by mineral nitrogen fertiliser inputs). Fertility transfers between areas that provides nitrogen through leguminous crops, and areas that exports it (non-legume crops) occur through livestock manure. Unfertilised natural grasslands and the animals that enhance them play a key role in this nitrogen supply. Finally, agroecology as envisaged in TYFA is based on the significant development of agro-ecological infrastructures —hedges, trees, ponds, stony habitats favourable to insects—, to cover 10% of cultivated land, in addition to the extensive grasslands that are the main component of these infrastructures.

The shift to no-input agriculture with a high proportion of permanent extensive grasslands and other agro-ecological infrastructures thus makes it possible to directly address the restoration of biodiversity, the quality of natural resources and a reduction in greenhouse gas emissions.

However, this multifunctional ecological performance of agroecology is only possible because it is accompanied by a decline in production relative to the current situation. Indeed, the yield assumptions used in TYFA (based on organic agriculture references for Europe⁵) are 10 to 50% lower than current average yields depending on the crops, although future innovations should be considered in this field, which would help to adapt to the impacts of climate change, for example.

2. Inserm (2013). *Pesticides – Effets sur la santé – Synthèse et recommandations*. Paris, Expertise collective, 146 p.
3. Inger, R. *et al.* (2015). Common European birds are declining rapidly while less abundant species' numbers are rising. *Ecology letters*, 18 (1), 28-36.
4. Hallmann, C.A. *et al.* (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLOS ONE*, 12 (10).

5. Ponisio, L.C. *et al.* (2015). Diversification practices reduce organic to conventional yield gap. *Proc. R. Soc. B*, 282 (1799).

An agro-ecological Europe can meet balanced food requirements for 530 million Europeans by 2050

Can we therefore envisage the decline in production that would result from the generalisation of yields observed today in organic farming and still meet the needs of a population expected to reach almost 530 million people by 2050?

The answer is yes, and this is one of the key findings of the modelling and quantification process undertaken in TYFA. Based on a healthy diet, according to current nutritional recommendations (EFSA, WHO and PNNS), while retaining important cultural attributes such as the consumption of animal products and wine, the decline in production modelled in the scenario (-30% for plant products and -40% for animal products) is sufficient to feed Europeans, even when a high proportion of land is given over to agro-ecological infrastructures that do not directly produce, but contribute to the proper functioning of agro-ecosystems.

In particular, this diet contains fewer animal products (but those consumed are of better quality) and less sugar; on the other hand, it is higher in fibre and contains more—seasonal—fruit and vegetables. Overall, it is more nutritionally balanced and has absolute environmental quality if we consider the replacement of pesticides by beneficial organisms. It unquestionably marks a shift away from what we eat today, but this transformation is not necessarily on a vastly different scale from the changes occurring in this field between the post-war period and today.

Non-food uses of biomass are also considerably reduced in TYFA. In this respect, the scenario contrasts with other scenarios that rest on a highly productive bioeconomy to reduce the use of fossil fuel. The production of biofuels and natural gas (by anaerobic digestion) is indeed reduced to zero in 2050 compared to, respectively, 8,7 and 10,7 millions of toe in 2010—which however represents only 2 % of European energy consumption. Despite this, the TYFA scenario has the potential to reduce agricultural greenhouse gas emissions by 36% compared to 2010. This figure increases to 45% if the calculation of 2010 emissions includes those associated with “imported deforestation”, which disappear completely in TYFA with the suspension of plant proteins imports.

Moreover, the diversification of agricultural products and landscapes is an advantage of this scenario in terms of adaptation to climate change.

An agro-ecological Europe that contributes to global food security

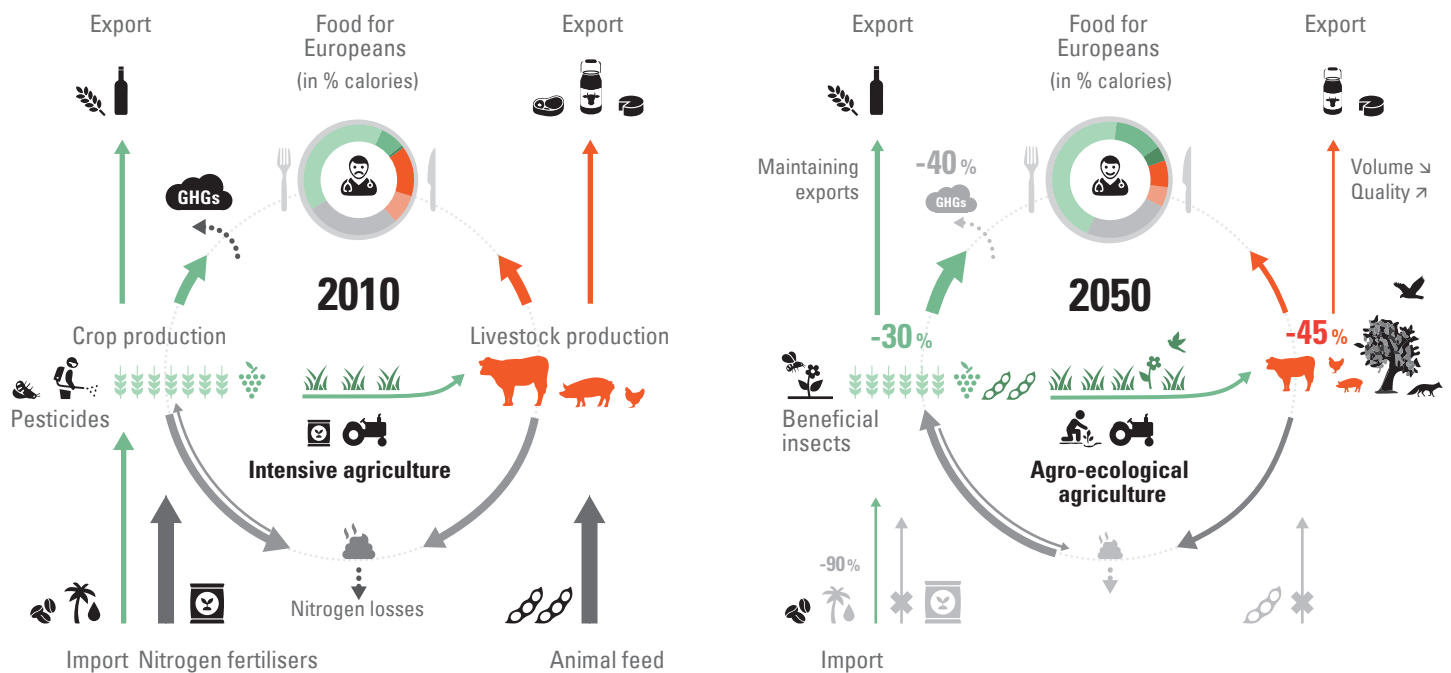
Although the benefits of TYFA are centred on Europe—the health of Europeans (especially agricultural producers) and of functional ecosystems and landscapes—global challenges are not sacrificed in the shift to an agro-ecological Europe, which, moreover, will not become self-sustaining in the process. In terms of food security, reducing the consumption and production of animal products, especially granivores, translates into reduced demand for cereals for this sector, freeing up a surplus of cereals comparable, in volume, to the net export-import balance of the last decade (6% of production). This quantity is not expected to “feed the world”—countries must first feed themselves—but at providing a reserve that can be used in case of food crises, especially in the Mediterranean zone. But the main contribution to food security consists in envisaging a more autonomous European agriculture, which stops importing almost 35 million hectares of soybean. For soybean exporting countries, this means lower deforestation pressure.

The agro-ecological Europe described in TYFA also frees up a share of production not directly consumed by Europeans, which can be used for export, in particular because of its quality, for dairy products (20% of production, just under half the 2010 amount) and wine.

Envisaging a transition to agroecology

The lessons from the TYFA scenario, summarised above, are based on the construction of a picture of agriculture and food in 2050. In this picture, the agro-ecological “European farm” is productive and very efficient in the use of scarce resources. This picture can be perfected and variations can be considered. Its function is not to impose a diet and an overall structure for agricultural production, but to inform the debate by demonstrating the feasibility and relevance of a different approach to integrate environmental and social challenges into agricultural production. The next stage of the process needs to address other economic and policy issues. The challenge appears in the very title of TYFA: “Ten Years” is the timescale needed not to achieve an entirely agro-ecological Europe by this time, but to launch a movement that makes this a feasible prospect by 2050. The goal of the analysis presented here is to show that this transition is not only desirable, but also credible. A debate and a new strategic area are opening; they will be political. ■

TYFA : A SCENARIO FOR AN AGRO-ECOLOGICAL EUROPE IN 2050

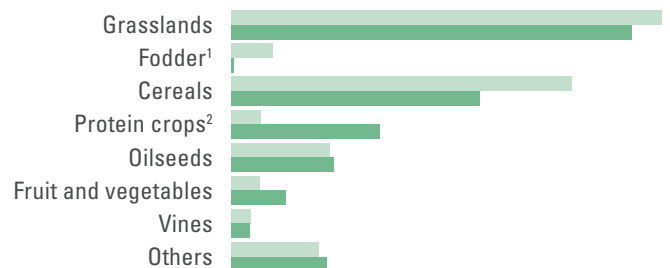


Productions

- Cereals and starchy foods
- Fruit and vegetables
- Protein crops (peas, lentils, etc.)
- Meat, eggs and fish
- Dairy products
- Others



Land use ● 2010 ● 2050



Grasslands

1: non protein; 2: grain and fodder

The TYFA scenario (Ten Years for Agroecology) is based on phasing out pesticides and synthetic fertilisers, redeploying natural grasslands and extending agro-ecological infrastructures (hedges, trees, ponds, stony habitats). It also envisages the generalisation of healthier diets containing fewer animal products and more fruit and vegetables. Despite a 35 % decline in production compared to 2010 (in kcal), this scenario meets the food needs of all Europeans while maintaining export capacity for cereals, dairy products and wine. It reduces agricultural sector greenhouse gas (GHG) emissions by 40 % compared to 2010, restores biodiversity and protects natural resources (soil life, water quality, more complex trophic chains).

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FOREWORD

This study presents the methodology and results of an agricultural modelling of the “European farm” of 2050, as part of a prospective research project entitled Ten Years for Agroecology (hereinafter referred to as TYFA). This project is based on two premises:

- in light of the environmental, socio-economic and human-health related challenges the European food system is facing,¹, agroecology constitute a credible and holistic response;
- achieving an agro-ecological Europe by 2050 means taking action now. In this context, the next 10 years will be critical in terms of engaging Europe in a real agro-ecological transition.

This study focuses on the coherence and credibility of such an agro-ecological scenario mainly from an agronomic point of view. Although it incorporates certain socio-economic and political aspects (concerning exports, production sobriety, or the very social framing of agricultural thinking), developments are underway in these areas and will be discussed at later stages of the process, based on the agricultural and ecological assumptions established in this first phase.

The assumptions underpinning this scenarios are radical. In terms of production: achieving protein self-sufficiency, halting imports of protein crops, phasing out pesticides and synthetic nitrogen—we will see that this latter assumption is undoubtedly the one that raises the most questions –, and giving a key role to extensive livestock systems, for biodiversity and nitrogen fertility management. In terms of consumption and dietary

changes: a significant reduction in animal protein (meat, fish and dairy products) on the one hand, and a sharp increase in fruit and vegetables on the other.

This set of assumptions echoes health expectations expressed by citizens and reported by civil society, in terms of not only nutrition, but also, more generally, exposure to active substances associated with the use of synthetic inputs. It also makes reference to alarming reports on biodiversity loss and climate change and, implicitly, to the increasing specialisation and simplification of agricultural landscapes.

These radical, original assumptions are put to the test within a rapidly evolving field of prospective agricultural research, which is explicitly geared towards testing the feasibility of scaling up technical options currently considered to be alternative, in particular organic agriculture (Van Grinsven *et al.*, 2015; Muller *et al.*, 2017; Billen *et al.*, 2018). This research illustrates the fact that the approach presented in this report: (i) is not isolated and is part of a global debate on the redesign of agricultural development models, (ii) belongs to a groundbreaking research effort and raises questions that remain to be explored, and (iii) proposes a specification of this prospective thinking at the regional levels (in the sense of the major biogeographic agricultural production zones).

Several approaches clearly echo the questions raised in the context of TYFA– at the French level (Solagro *et al.*, 2016; Billen *et al.*, 2018) or the global level (Schader *et al.*, 2015; Lassaletta *et al.*, 2016; Le Mouel *et al.*, 2016; Muller *et al.*, 2017). However, none of these directly address the challenges in the manner proposed by TYFA, which led us to develop an original approach in terms of both the framework and the methodology.

1. Although the study does not directly address animal well-being, the assumptions about livestock systems would also produce marked improvements in this area.

This study thus describes what an agro-ecological “European farm” (this concept will be discussed in more detail in the introduction) might be like in 2050, along with a typical European diet and Europe’s contribution to world agricultural markets. The radical nature of the assumptions used is intended to open a space for discussion within a debate that has gradually closed in around two ideas, which are widely accepted as self-evident, but which we believe need to be discussed: (i) it is essential to maintain a high production level in Europe to ensure food security; (ii) the environmental priority is improving efficiency in the use of inputs, without specifying the desirable level of these inputs—efficiency can be achieved without sobriety—or the impact on landscapes and land use, and thus on biodiversity.

In this respect, TYFA has to be understood as a prospective approach upstream of, and partly independent from, decision-making processes (Labbouz, 2014). Its goal is not to paint a picture of a “programme” to be conducted, but rather to envisage changes in order to fuel discussions that we believe contain blind spots in terms of human and environmental health and biodiversity—to mention only the biotechnical aspects.

In terms of methodology, every effort has been made to build the process on the most robust, explicit foundations possible—as reflected by this document, which aims to ensure transparency in the model assumptions and configuration. It should be noted that while we present a stabilised document here for presentation purposes, every assumption and every parameter has been tested, discussed and questioned. The assumptions are thus the result of numerous iterations and revisions inherent in the exploration of a complex system, in particular through discussions and exchanges with the researchers and experts to whom we presented earlier versions (Box 1).

Finally, although the results of this process provide a useful benchmark in debates on agriculture and food, they by no means conclude them. The questions they raise and the need for further research they reveal are proof of this. Our study is therefore just a pioneering step within a field of discussion and debate that must continue in the years to come.

Box 1: Discussing the agricultural basis of TYFA

The work presented in this report was the subject of a series of presentations to researchers, experts and actors involved at different levels in discussions on the possibilities and challenges of a transition of the European food system. Four workshops were organised between September 2017 and April 2018, including three in Paris with an audience largely composed of agronomists, and one in Brussels with a broader panel including civil society actors, social scientists (economics, law, political science) and think tanks. The goal of these meetings was to discuss the *framework* as well as the *methodology* proposed in order to develop the TYFA scenario.

Concerning the *framework*, the aim was more specifically to share views on the assumptions structuring TYFA and to ensure they were all justifiable—albeit eminently debatable in the scientific sense—in view of the state of knowledge, the current structure of debates and the existing regulatory framework.

Regarding the *methodology*, the content of the model and its architecture, as well as the translation of qualitative assumptions into quantifiable parameters, were scrutinised by the researchers convened. These exchanges led us in particular to repeatedly review the configuration of the hypotheses in TYFA and to completely rework the architecture of the model following the first workshop.

1. INTRODUCTION

1.1. An approach to agroecology centred on agronomy

This report presents the first findings of Ten Years for Agroecology in Europe (TYFA). As part of a political, economic and, indeed, social debate on the future of the European food system, this project questions the *styles of farming* (van der Ploeg, 1994) to be supported in order to achieve sustainable diets, according to the FAO definition of this term:

Diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources

In this context, the goal is therefore not only to feed Europeans with a balanced diet from a nutritional standpoint, limiting risks to health, but to do this with an agriculture which, through its very act of production, safeguards agro-ecosystem functioning. TYFA is based on the assumption that, in order to address biodiversity and climate change issues, a transformation of European patterns of production and consumption is inevitable. Adapting just the fringes of the current agricultural development model, whose environmental, health and social impacts have long been presented as the inevitable counterpart of its economic competitiveness, will not be enough. On the contrary, the goal is to envisage a multifunctional agricultural system that enables the production of food in and by landscapes with a rich biodiversity, while maintaining a production function, limiting greenhouse gas (GHG) emissions and drastically reducing health risks (for farmers and consumers alike) (Thérond *et al.*, 2017).

In order to consider this multifunctionality intrinsic to production, TYFA departs from the idea that agricultural models are “all alike” and that the

main challenge for public action is to ensure their coexistence. Based on numerous studies, especially on the sociology of innovation (van Mierlo *et al.*, 2017), TYFA considers on the contrary that the different agricultural models do not coexist peacefully in the territories, but are in fact competing for access to different factors of production (land, labour, capital, subsidies), especially due to their scarcity. From this perspective, the dominance of an innovation regime geared primarily towards the search for efficiency tends to reduce the alternative options (agroecology and organic agriculture, in particular) to niches (Barbier & Elzen, 2012; Meynard *et al.*, 2013b). In this context, TYFA develops a structured picture within which, at the European level, a transition process enables these niche systems to become dominant. In line with transition management studies (Rotmans *et al.*, 2001; Geels, 2005), the goal is thus to provide the public debate with a comparison of the sustainability of different transition scenarios in order to identify the levers and obstacles to achieving the scenario considered to be the most sustainable/desirable.

The bias towards agroecology in TYFA—which will be described in detail in sections 2 and 3—is based on the increasing evidence in recent years of the adverse environmental impacts of the majority of conventional agricultural systems. It should be noted that the concept of agroecology—whose origins date back to the early 20th century—is tackled here from a primarily agronomic perspective², as an approach that makes maximum use of ecological processes in order to redesign production systems and to radically reduce agricultural pressure on the environment (Gliessman, 2007).

2. Indeed, agroecology can be considered from three complementary angles (Wezel *et al.*, 2009): as a social movement (in reference to the Latin American social movements, in particular); as a field of investigation for agronomy; and as a set of practices with varying degrees of formalisation. It is the *agronomic* approach that will be taken here—see section 3 below for a more in-depth discussion of the agro-ecological approach adopted in this project.

In line with similar exercises (Van Grinsven *et al.*, 2015; Solagro *et al.*, 2016; Muller *et al.*, 2017), the TYFA project is a scenario exercise of the 2050 European agri-food system, whose objectives are threefold:

- identifying whether, and under which conditions (agricultural, socio-technical, social, political and economic), a large-scale agro-ecological transition would be possible and capable of meeting the environmental and public health challenges the European food system is currently facing;
- developing one or more plausible transition pathways (identifying the main levers and obstacles) leading to the picture thus painted...
- ... in order to use scientifically-based results to inform academic, political and social debates on the future of agriculture and the food system.

1.2. Agroecology and sustainable intensification

Although agroecology is becoming more visible in the European debate³, many actors prefer the idea of smart agriculture (EC, 2017) or sustainable intensification (Garnett *et al.*, 2013). According to their advocates, the advantage of these two approaches, which are almost synonymous in the European context, is that—at least in theory—they do not imply a decline in production, but instead do “better with less” by improving efficiency in the use of resources and inputs. This project has real agricultural foundations. We see, for example, that Europe has increased average nitrogen use efficiency over the last decade (Lassaletta *et al.*, 2014; Eurostat, 2017), thereby effectively doing “more with less” for this factor of production. But sustainable intensification is generally based on technical solutions that lead to an increased use of capital and to farm expansion and specialization, making it difficult to improve agricultural system performance in terms of biodiversity and landscapes (or integrates such issues as a component that is exogenous to production, in the context of land sparing or ecological compensation approaches—see the literature review recently published in Weltin *et al.*, 2018). It leaves other questions unanswered on the socio-economic level regarding the labour and capital intensity of agriculture or its economic resilience—especially if we consider the public funds that would need to be tapped in the new Common

Agricultural Policy (CAP) in order to accelerate this transition.

Conversely, agroecology has been presented by some as a set of constraints or sacrifices whose widespread implementation in Europe would result in lower yields, implying higher production costs that would jeopardise food security in Europe and, by extension, the rest of the world. Indeed, we believe that a decline in yields is the most plausible assumption associated with agroecology in Europe today, even though it is important to remember that agroecology is an innovation pathway, and that current technical references could be improved by research and innovation over the next 40 years. This cautious assumption of reduced yields, based on meta-analyses of organic agriculture (Ponisio *et al.*, 2015)—currently agriculture that uses no synthetic inputs –, underpins our study (see section 3). From this standpoint, the agro-ecological challenges facing Europe are very different from those in the tropical countries, or even the temperate countries practising relatively low-input agriculture: in these latter cases, unlike in Europe, agroecology could more plausibly lead to an *increase* in yields compared to their current level.

In this context, TYFA fundamentally questions the need to ensure yields remain close to the maximum potential of land and to condition the achievement of environmental and social objectives on this first objective. As a basis for this analysis, it will be useful to clarify the initial diagnosis: to what extent is the current productivist approach in European agriculture associated with a lack of overall sustainability (section 1)? Second, envisaging a decline in production raises the question of how far we can go without jeopardising Europe’s capacity to feed itself, or even to continue exporting. Relaxing the production constraint in the debate to make room for multifunctionality does not however imply being released from production imperatives. There is currently a dearth of research focusing on this issue specifically at the European level.

1.3. An analysis at the “European farm” level

In this report, the European Union of 28⁴ (hereinafter referred to as the EU-28) constitutes the unit of analysis. It is seen as a “black box”, without

3. With a specific adaptation in France, where agroecology has been included in article L.1 of the Rural and Maritime Fisheries code further to the bill on the Future of Agriculture, Food and Forestry of 2014.

4. Soon to be 27, but this does not fundamentally change the issue. The orders of magnitude are very similar with or without the United Kingdom, and the reasoning is applied in the same way.

direct considerations regarding its functioning or its internal heterogeneity, with two implications. First, only flows between Europe and the rest of the world are considered, with intra-European flows being transparent. Second, all reasoning is based on average values for the EU-28, whether for production (yields) or for consumption (diets). This “black box” constitutes the “European farm”, which we consider as a set of production systems that is coherent and organised (at the logistic, economic and political levels). Although this approach may appear contrary to the basic principles of agroecology, which is rooted in the territorial and local levels, we believe it is an essential prerequisite for participating in debates that tackle the issue at this level. Abandoning a niche approach implies first considering overall feasibility.

Reasoning at the European level also ensures a synthetic, systemic approach to two crucial aspects of the agri-food system: closing biogeochemical cycles (especially for nitrogen); and achieving balances between crop production and livestock production on the one hand, and between agricultural production in general and human food on the other.

In this sense, the question this report seeks to answer can be summarised as follows: is a generalisation of agroecology “feasible”, from both a dietary and a biogeochemical point of view? In other words, are the agricultural assumptions envisaged in TYFA capable of feeding all Europeans by 2050? Under which assumptions about their diets? And what are the consequences for the major biogeochemical cycles? An agro-ecological Europe that became a structural importer of food or nitrogen would indeed make little sense.

While this European-level approach thus appears essential from an agricultural viewpoint, it also proves necessary at the political level: this is the level at which the tools for an agro-ecological transition are found. The public policies involved—the Common Agricultural Policy, trade agreements (multilateral and bilateral)⁵, environmental policies—all fall largely within the remit of the European Union. However, in discussions on these policies, the idea of an entirely agro-ecological Europe is often considered as an overly optimistic or unrealistic assumption, especially in terms of food security. Participating in these debates in order to promote the agro-ecological option implies first making a structured analysis of the possibility of its generalisation.

This report thus provides the key elements of an agricultural and dietary qualification and quantification process. However, it does not exhaust the full range of questions raised by the idea of a large-scale agro-ecological transition. Instead, it should be seen as the foundation stone of a broader prospective exercise that will successively address issues concerning the regionalisation of the scenario (how could the macro picture painted here be adapted to reflect the diversity of soil and weather conditions, agricultural practices and dietary habits characterising the EU-28?), its economic impacts (what impacts could it have on farmers’ incomes and farm trajectories? And on sector dynamics and the cost of food?), and the social and public policy changes it would imply or require. These questions will be the subject of future analyses and publications, and the issues they raise are briefly outlined in part 5 of this study.

1.4. Modelling the European food system from an agro-ecological perspective

The quantification targeted in TYFA is based on an original modelling process at the European level. It links sustainable diet issues to production issues. The agro-ecological focus and problematisation we have presented led us to design a model that ensures discussions regarding agricultural and biotechnical assumptions are as transparent as possible. We thus clarified the linkages between:

(i) consumption and exports of certain strategic products. Although the quantitative analysis is central (overall food requirements approached in terms of their nutritional values), some more qualitative aspects will also be discussed: no pesticides in the production and processing system, high omega-3 content;

(ii) crop and livestock production methods, which can be associated with yield levels and nitrogen management⁶. Once again, quantification is central, but the parameters refer to some more qualitative assumptions that will be discussed in more detail later in the report;

(iii) land use, whose categories aim to reflect the specific challenges of agroecology: the importance of considering the different types of leguminous crops, grasslands and rangelands, and ecological focus areas. In this land use, we differentiate between crops and grasslands that supply nitrogen to the agro-ecosystem, and those that export it.

5. As shown in particular by tensions associated with the negotiation of the agricultural aspects of free trade agreements with Canada or MERCOSUR (see, for example, Hübner *et al.*, 2017; Harmann & Fritz, 2018).

6. The key role of phosphorus in maintaining the fertility of agricultural production systems has not been analysed at this stage of the model development. It will be dealt with in future developments.

The model resulting from this approach (herein-after referred to as TYFAM) is organised around five compartments between which material and energy flow, and which are connected systemically:

- *crop production*, resulting from a certain European *land use* (distributed between arable land, permanent crops, permanent grasslands and agro-ecological infrastructures: hedges, trees, ponds, stony habitats, sunken paths) and the associated *yields*;
- *livestock production*⁷, fed by a fraction of crop production, some of which may compete with human food (for example cereals), while the rest does not (grasslands and co-products);
- *demand for food*, which is the result of individual *eating habits* and a given level of *population growth in Europe* by 2050, and is covered by both European production and imported products⁸;
- *non-food/industrial demand* for biomass (energy and biomaterials), which can once again be covered by a mix of European production and imports;
- finally, the *nitrogen flows* associated with the functioning of and interactions between the first four compartments, which largely determine the level of soil fertility⁹. The analysis of these flows takes into account the different types of *inputs* (synthetic nitrogen, animal feed imports, symbiotic fixation, transfers by manure) and *exports* (livestock and crop production).

In the approach adopted—the EU-28 as the unit of analysis –, flows within the EU for each of these compartments are not analysed, unlike those between the EU and the rest of the world. Figure 1 provides a graphic representation of the logical structure of the model.

7. The more specific analysis of the *crop production* and *livestock production* compartments approaches the "European farm" as a production system (according to the definition of this term given by comparative agriculture, see Cochet *et al.*, 2007), which is itself organised into several animal or plant production systems, each with their own particular rationale. We will return to this later in the report (part 3).
8. It should be noted that we believe the TYFA assumptions are compatible with imports of non-substitutable tropical products: coffee, cocoa, tea—the level of which remains to be determined. But discussions regarding these products are not at the agricultural level (see section 3.6) and we will not go into detail here.
9. Other components of fertility clearly play a major role in the organisation of the system, especially phosphorus and, to a lesser extent, potassium. In an initial approach, we considered that nitrogen plays a more important role than phosphorus as a "command variable" for the different yields of the global system; we also have far more data on it. A closer analysis of phosphorus, similar to the one for nitrogen, will need to be conducted following this first version of the TYFA scenario.

The development of this model (whose organisation is presented in more detail in the annex entitled "Behind the scenes of TYFAM") aimed at addressing the key questions raised by a possible generalization of agroecology, as outlined in the introduction: within the "European farm", what level of production is compatible with the multifunctional assumptions associated with agroecology? Is this level of production sufficient to feed Europeans or to generate a surplus, and under which conditions in terms of their diets?

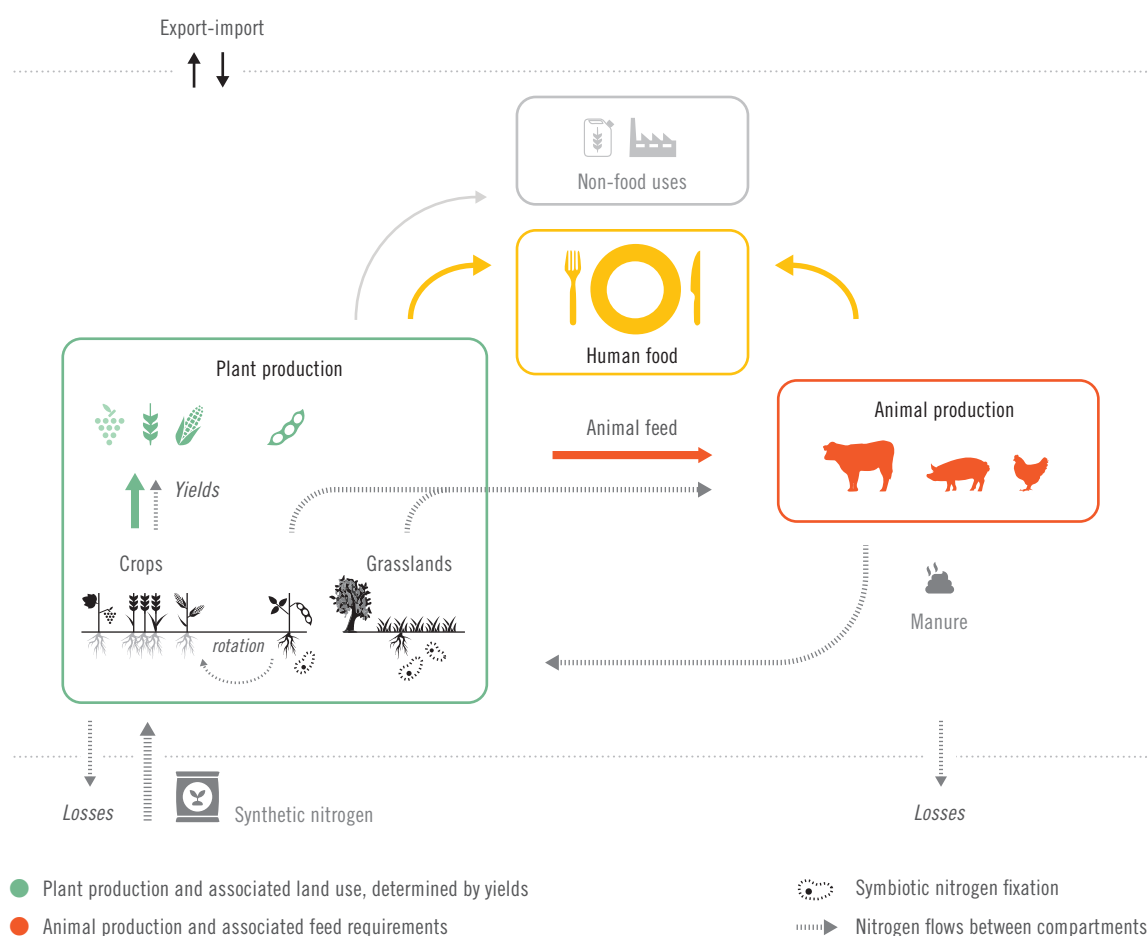
This report explains and justifies the *assumptions* we have made regarding what is meant by an agro-ecological Europe, and details the way in which we have *translated* these into parameters that can be used in the model.

1.5. The modelling process as a "common thread"

The overall structure of the model, as shown in Figure 1, enables us to organise the process according to four phases:

- a retrospective phase (part 2), consisting in characterising and analysing the development of the food system and the "European farm" in recent decades. This retrospective analysis has two key functions:
 - a descriptive, functional role, which involves identifying the way in which the model components are articulated (for instance, how, historically, production and consumption patterns can be compared). This function contributes to establishing the orders of magnitude for production, consumption, the quantities imported and exported, etc. Its goal is to ensure the structure of TYFAM actually enables us describe the current and past functioning of the food system and the "European farm";
 - the identification of challenges: retrospective analysis also enables us to examine the production-based approach of the "European farm" and its environmental impacts. On this basis, we can highlight the challenges facing agroecology in Europe. This part is not in itself an evaluation of the agricultural coherence and the environmental impact of the baseline scenario that pursues the current innovation pathway, but it indicates the main problems of unsustainability that past trends will raise should they continue.
- a phase involving the characterisation of the set of assumptions in the specific meaning this report gives to the idea of an agro-ecological Europe by 2050 (part 3). This part is built in reference to the conclusion of the previous

Figure 1. Logical structure of TYFAM: a simplified representation of the European food system



section: based on the (un)sustainability challenges highlighted by the analysis of the current system, which desirable characteristics can we associate with an agro-ecological project? Those qualitative assumptions are then translated into quantitative parameters for each of the six component of the model;

- a prospective phase, which tests the consequences of the agro-ecological assumptions at the European farm level; in other words, it identifies the modalities of the output variables according to those of the input variables (part 4). These modalities are compared to the current situation described in part 2;

- part 5 discusses these results and places them in the context of the key elements of the debate TYFA seeks to inform. The results are discussed with regard to existing prospective studies on agriculture and food and current public policy guidelines.

2. A RETROSPECTIVE ANALYSIS OF THE EUROPEAN FOOD SYSTEM: TRENDS AND CHALLENGES FOR AN AGRO-ECOLOGICAL TRANSITION

In this part, the current functioning of the European food system and its dynamics over the last 50 years are analysed through the prism of TYFAM. This retrospective analysis enables us to simultaneously examine the capacity of the model to reflect, from a functional viewpoint, the dynamics of the European farm, and to identify the main challenges facing an agro-ecological transition.

2.1. The data sources

The model was first calibrated on the year 2010, the last year for which we had comprehensive data for all of the dimensions of the model. A retrospective analysis of the period 1962-2010 was then conducted. Three main sources of data were used to inform different aspects of the model.

- For plant products and their uses, associated land use, and animal products, we combined the Eurostat and FAOSTAT data¹⁰. The Eurostat data was used to adjust the model to 2010, while the FAOSTAT data enabled us to trace the history of products and their uses since 1962. The import-export data for each product category was also obtained from these two databases. In order to make the model easy to manipulate, we grouped plant products into 44 categories and animal products into six major categories (milk, beef, etc.), within which we distinguish between herd structures (details of the content of each category are presented in the annex).
- For food consumption, two sources of data were again combined. The FAO “Food balance sheets” provide a record of food uses for each commodity in kg/person/year, in grams of protein/person/day, as well as in kcalories/person/day, for all 28 European Union Member States¹¹, from 1962

to 2010. However, this data does not take into account the levels of waste along the food chain and only covers apparent consumption. Consequently, data from food consumption surveys of more than 37 000 Europeans in 17 EU countries (France, Germany, Italy, United Kingdom, Austria, Finland, etc.), collected and published by the European Food Safety Authority (EFSA), was also used. This data lists consumption in grams of food per day and per category, whose correspondence with agricultural production categories is directly accessible (for example, between consumption of bread and production of wheat). An EU average was obtained by weighting the data by the population of the country surveyed, so as to reflect the relative weight of European eating habits (see Saulnier, 2017).

- Finally, nitrogen flows were examined based on data presented in the European Nitrogen Assessment (Leip *et al.*, 2011) and the Eurostat balance, in order to produce an apparent nitrogen balance covering only European cultivated land.

2.2. Excessively rich, unbalanced diets

TYFAM is based on matching *agricultural production available* and *actual dietary habits*, in particular so as to identify the coverage rate for European food requirements. This approach implies examining an “average” European diet according to the main categories of agricultural production. Such a diet was reconstructed using the above-mentioned EFSA database. This average approach does not reflect the different specificities at the regional level and within populations. However, it provides an essential framework for analysing the current and future challenges facing food in

10. Although the two databases do not always correspond exactly.

11. The principle is to reconstruct from 1962 onwards the

geographic area of the EU-28, bearing in mind that this political entity did not exist at the time.

terms of nutrition and agricultural production requirements.

Table 1. Average diet and rate of consumption of agricultural products

Product	Raw available 2010 (g/pax/ day)	« Apparent » intake (g/pax/ day)	Consumption ratio (intake/ available)
Cereals	355	278	78%
Oilseeds	76	34	45%
Fruit and vegetables	356	268	75%
Potatoes	303	116	38%
Sugar	103	36	35%
Legumes	7	5	75%
Meat	193	173	89%
Fish	38	27	73%
Dairy products	726	505	70%
Eggs	39	20	51%
Total	2 195	1 460	70%

Source: Own calculations, according to Eurostat and EFSA

The average diet obtained is presented in Table 1 by main categories of agricultural production. In the first phase, this average diet is compared with food available (in other words production - exports + imports). The consumption rate (the ratio between food consumed and food available) ranges between 35% for sugar and 89% for meat. The low level of these rates for oil, sugar and eggs suggests that some of the gap is the result of the difficulty accounting for product processing—for example, where oil is concerned, its use as cooking oil, and more generally due to the complex nature of the oilseeds and protein crop sector, for sugar in drinks, and for eggs in industry. However, for most products, the gaps observed largely result from food losses and waste along the food chain: field, post-harvest and home losses. On average, our calculations based on Eurostat and EFSA data (a consumption rate of 70%) converge with the estimates provided by the FAO High-Level Panel of Experts on Food Security (HLPE, 2014), which indicate a losses and waste rate of 30% of final European consumption. In the absence of more specific details on the determinants of the consumption to availability ratio, we considered these apparent consumption rates as “black boxes” that include hidden variables.

The reconstruction of this average diet also identifies today's key nutritional challenges with regard to EU recommendations. We considered two aspects: the need to cover nutritional requirements and the risks and benefits associated with the consumption of certain food groups (ANSES, 2016b).

In terms of nutritional requirements, and given the complexity of the subject, we considered only

macronutrients—proteins, lipids and fatty acids, carbohydrates and sugars –, fibre and calories. Micronutrients (vitamins and trace elements) were not taken into account at this stage, although their role in a healthy diet is just as essential. Based on the latest EFSA advice (EFSA, 2017a)¹², we used the following benchmarks (presented in Table 2): an average calorie requirement of 2 300 kcal/person, taking into consideration relevant recommendations for each age group and sex, for an average level of physical activity, and weighting these requirements by the current age pyramid; a protein requirement of 50 g/day/person¹³ - with a maximum of 35 g for animal protein; a carbohydrate requirement ranging between 45 and 60% of total calorie intake, with a proposed limit of 100 g/day for sugars; a lipid requirement ranging between 30 and 40% of calorie intake; and a satisfactory fibre intake of at least 30 g/day, but which should reach or exceed 100 g/day in order to have a positive effect on colorectal cancers.

These limits, expressed as nutrients and energy, were supplemented by the inclusion of the risks and benefits associated with the consumption of certain product groups, based on different scientific publications, as well as on ANSES, EFSA and WHO recommendations. From these, we derived an *upper safety limit* for red meat of 70 to 80 g/day, and for cured and processed meats of 25 g/day. It is also clear that eating more than 400 g of fruit and vegetables per day significantly reduces the risk of type II diabetes and cardiovascular diseases.

The main nutritional benchmarks derived from this analysis are presented in Table 2 and compared to the average diet previously calculated. The energy and nutrient content of the current diet was calculated based on the CIQUAL database provided by ANSES (ANSES, 2016a).

Although these figures should be viewed more as orders of magnitude than as strict values, our conclusions converge with other studies in this field (see, for example, Westhoek *et al.*, 2011; WWF & Friends of the Earth Europe, 2014): the average European diet is excessively rich and unbalanced. It is too high in calories, but especially in protein and sugar. It is also unbalanced, with the excessive calorie and protein intake compounded by a low consumption of fibre, which reflects in particular a lack of fruit and vegetables. The average consumption

12. Although these recommendations vary more specifically from one country to another, they all remain within the general framework provided by EFSA.

13. This figure corresponds to a requirement of 0.66 g/kg of body mass for an “average” individual weighing 75 kg (EFSA, 2017a, p. 24)—a value also given in Westhoek *et al.* (2011), or to a protein intake equivalent to 10% of the calorie intake for 2 300 kcal/day (ANSES, 2016b, p. 23).

of red meat is also almost double that of WHO recommendations.¹⁴

Table 2. “Average” European diet in 2010 compared to the nutritional benchmarks used

	Nutritional benchmarks	Consumption in 2010	Gap
Total calorie intake (kcal/day)	2 300	2 606	113%
Protein (g/day)	50	100	200%
Including: upper limit for animal protein (g/day)	35	56	165%
Including: upper limit for red meat (g/day)	70	120	171%
Carbohydrates (kcal/day)	950-1400	1350	OK
Including: upper limit for sugars (g/day)	100	360	360%
Lipids (kcal/day)	690-920	760	OK
Including: recommended ratio between $\Omega 6 / \Omega 3$	3-8	> 10	To be reduced
Fibre (g/day): satisfactory intake vs minimum intake (colorectal cancer)	30-100	27	To be increased
Fruit and vegetables (g/day)	400	268	67%

Source: EFSA, 2013 ; 2017 ; ANSES, 2016 ; OMS

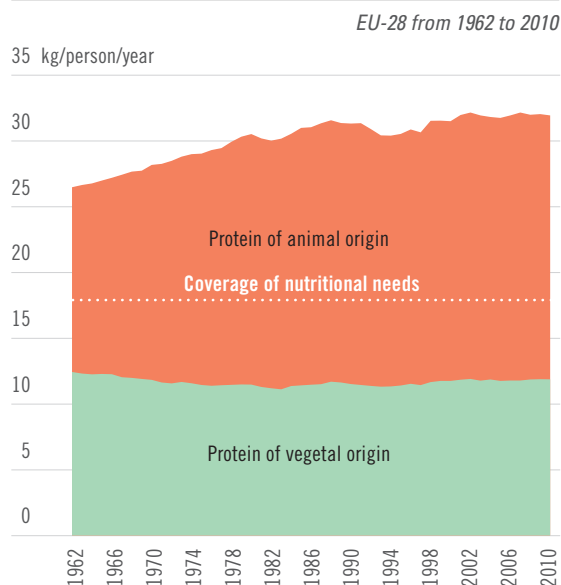
This diet has evolved gradually from the 1960s until today, although the majority of changes took place between 1960 and 1990: a progressive increase in the intake of calories and protein (especially animal protein: +42% for the period, Figure 2), vegetable oils (+83%), a reduction in staple foods (Cereals and potatoes: -12%)—see Figure 3. Moreover, the consumption of meat and animal products has also undergone significant qualitative changes, with a rapid increase in the consumption of white meat and a gradual decline in that of red meat (Figure 4). The apparent consumption of fruit and vegetables has remained very stable over the period.

Today, this diet has significant, well-documented impacts on health. The changes described above have thus gone hand-in-hand with an increase in obesity rates in Europe (Blundell *et al.*, 2017, p. 31-32) as well as in the prevalence of cardiovascular diseases and type II diabetes (Mozaffarian, 2016). Although the determinants of these disorders are eminently multifactorial and it is therefore almost impossible to establish linear causal relationships, diets that are unbalanced and excessively rich, such as those of Europeans today, are clearly factors in their onset or aggravation¹⁵.

14. Salt does not appear in this analysis, which focuses on calories and nutrients, but there is also too much of it in our diet.

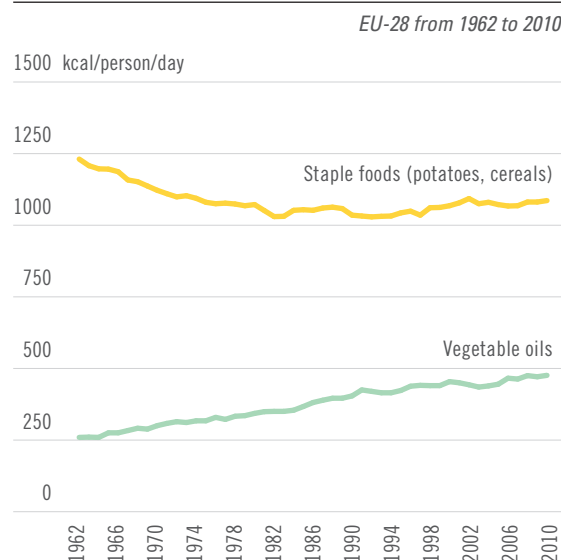
15. On another level—we will come back to this in

Figure 2. Annual protein consumption



Source: author, according to FAOstat.

Figure 3. Apparent consumption of vegetable oils and staple foods (potatoes, cereals)

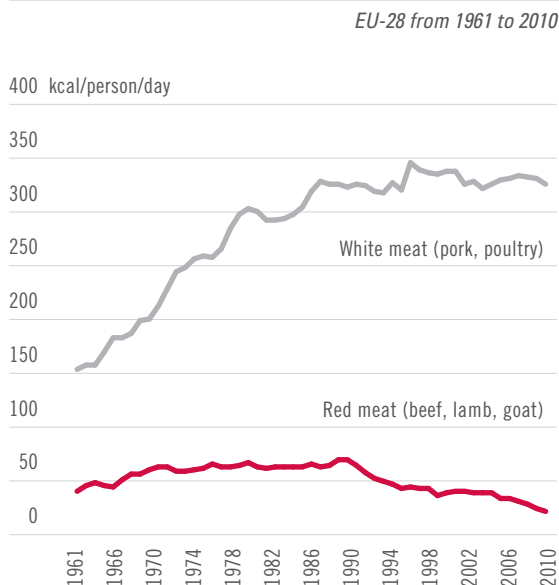


Source: author, according to FAOSTAT.

Changes in food consumption are also strongly correlated with those in production, as shown in the following section. We will show in particular that the increase in livestock production that has accompanied these changes in consumption is primarily

part 3—the presence of pesticides in food, including in water consumed, is also a major food risk factor with established effects on certain types of diabetes and neurological diseases, and other suspected effects on certain types of cancer (Inserm, 2013)

Figure 4. Apparent consumption of white and red meat



Source: author, according to FAOSTAT.

based on the intensification of livestock farming, which is itself dependent on plant protein imports from the American continent. One of the key consequences of these changes is that the European food system is now a *net* importer of agricultural land (von Witzke & Noleppa, 2010); in other words, as things stand, it is the world that feeds Europe rather than the other way round, as is often claimed (see following sections, 2.3 and 2.5).

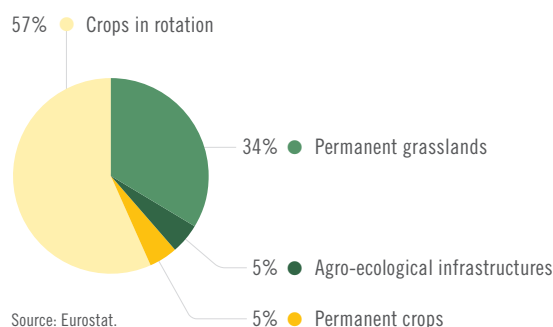
2.3. Crop production and land use: intensification and specialisation

In TYFAM, land use and crop production are approached according to four major compartments: crops in rotation (including temporary grasslands and vegetable crops), permanent crops (vines, orchards, etc.); permanent grasslands; and other agro-ecological infrastructures (hedges, sunken paths, wetlands, grass strips, etc.). In 2010, these four compartments covered a utilised agricultural area (UAA) of 177 million ha, or 43% of the total EU area (Figure 5).

At 57% of UAA, crops in rotation largely dominate the agricultural landscape. Within this category, cereals hold a key position (60%), alongside oilseed crops (12%) (see Figure 6).

This domination has gradually increased over recent decades, to the detriment in particular of protein crops (peas, faba beans, lupins, etc.), but also of the overall share of permanent grasslands

Figure 5. Use of European UAA in 2010



Source: Eurostat.

in European cultivated land (-14% in area between 1962 and 2010 at the EU-28 level). These are the most visible consequences of a threefold dynamic involving the intensification, specialisation and concentration of European production systems (Stoate *et al.*, 2001; Stoate *et al.*, 2009).

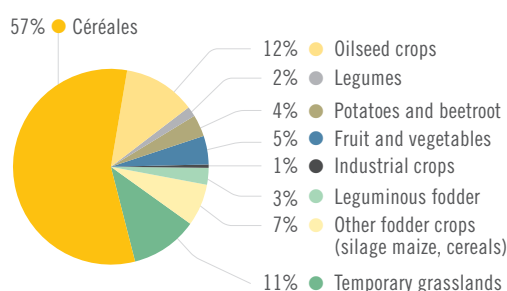
First, intensification has been achieved by acting simultaneously on land and labour productivity. In terms of land, varietal improvement has been associated with a significant increase in the level of inputs used in cropping systems (Stoate *et al.*, 2001). The use of synthetic fertilisers and pesticides (fungicides, insecticides, herbicides) thus radically increased over the decades until the 1990s.

Since then, the level has stabilised for pesticides, and has decreased moderately for synthetic fertilisers over the last decade (Lassaletta *et al.*, 2016). On this aspect, the assumption made by advocates of sustainable intensification is that the use of new technologies, and in particular progress in plant improvement and genetics, associated with precision agriculture, will enable a sharp decrease in the level of inputs in the coming years¹⁶. The increase in labour productivity is intrinsically linked to the development of agricultural mechanisation, which continues today with the arrival of robotics on farms.

Second, the specialisation of production systems has occurred on two levels.

- At the most general level, livestock and crop production systems have been gradually decoupled, which has resulted *spatially* in the creation of areas specialising in crop production on the one hand—within which permanent grasslands have progressively disappeared—and in livestock production on the other (Dumont *et al.*, 2016). Although there are still many areas in which livestock and crop production systems coexist, this territorial specialisation has had a

¹⁶. Meanwhile, current levels of input use, despite some improvement, are already having serious environmental and health impacts, which we will describe in more detail in part 3.

Figure 6. Crops' share on arable land in the European Union

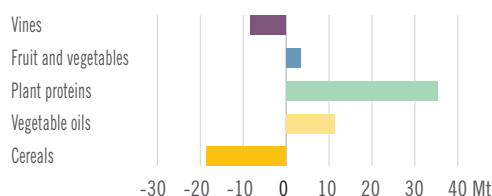
Source: Eurostat.

major impact on biodiversity—largely linked to the disappearance of permanent grasslands (see section 3.4.2)—as well as on the closing of fertility cycles, and more specifically that of nitrogen (this point will be addressed in greater detail in section 2.6).

- At the more specific level of crop production systems, specialisation has taken the form of a simplification and shortening of crop rotations around cereals—especially wheat and maize, according to soil and weather conditions—and oilseed crops, especially rapeseed. This simplification of systems, which has been well documented for central and northern France (e.g. Schott *et al.*, 2010; Meynard *et al.*, 2013a), has gone hand in hand with an increase in the use of synthetic inputs. The reduction in the share of protein crops in cropland has increased synthetic nitrogen requirements by limiting symbiotic fixation possibilities, whereas the simplification and shortening of rotations have resulted in growing exposure of crops to pests (insects and fungus) and weeds. Such systems are now characterised by a very specific form of socio-technical lock-in, which makes any alternative developments extremely complex (see section 5 on the initial analysis of tools for the transition).

The environmental impacts of these changes have been massive (for an overview of field crops, see in particular Stoate *et al.*, 2001; Stoate *et al.*, 2009). They concern simultaneously biodiversity (Pe'er *et al.*, 2014)—in connection with the disappearance and intensification of permanent grasslands (Pärtel *et al.*, 2005; Plachter & Hampicke, 2010), the use of pesticides (Geiger *et al.*, 2010; Beketov *et al.*, 2013; Pisa *et al.*, 2015), and greenhouse gas emissions (EEA, 2015, pp. 33-39)—and soil degradation (e.g. Stoate *et al.*, 2009; Creamer *et al.*, 2010).

On the other hand, these changes have resulted in a significant increase in total crop production, intended for four main purposes: food for Europeans;

Figure 7. Import/export balance for EU food products in 2010

Source: Eurostat.

animal feed (within the EU-28); industrial uses (biomaterials and biofuels); and exports to other countries.

Exports became a key market for European production in the early 1990s, after the European markets became saturated, especially for cereals¹⁷. This dynamic has enabled Europe to become, since 2013, the world's leading agri-exporter in value, with a positive annual balance of almost 20 billion euros (DG AGRI, 2017), or approximately 5% of the total value of production. This global leadership is based on exports of high value added products (wine and spirits, infant formula, highly processed agri-food products and, to a lesser extent, cereals). It is coupled with massive imports, in volume, of plant proteins (for 68% of EU consumption) and oils (44% of EU consumption) (Figure 7). The former are mostly used for animal feed, and the latter for biofuel production and human food. Expressed in agricultural land equivalent, this situation makes the European Union a net importer of agricultural land, at almost 35 million ha (von Witzke & Noleppa, 2010), in other words just over 20% of its utilised agricultural area. **Figure 7.**

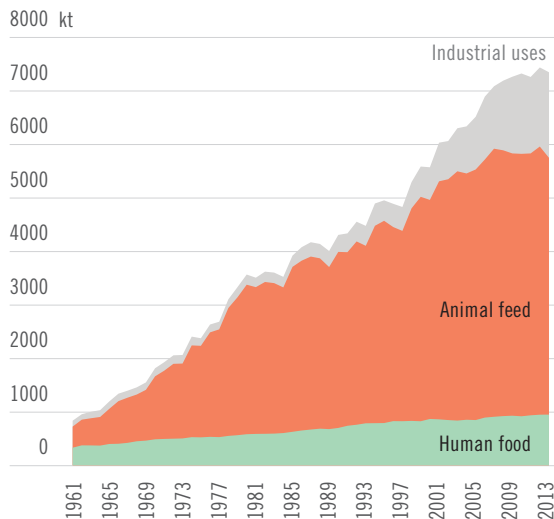
The uses of crop production available within the EU (after trade, in other words production - exports + imports) have changed considerably. In 2010, these uses were distributed as follows: 58% of cereals and 67% of oilseed crops available were used for animal feed, whereas industrial uses stood at around 15% for the latter, concentrated on just a few crops (90% of rapeseed oil and 45% of palm oil, mainly for biofuels) (Eurostat, 2017).

The predominant use of crop production for animal feed and, to a lesser extent, for industry, is nevertheless the result of a historical process, as shown in Figure 8. In the following paragraphs, we will briefly analyse recent developments in industrial uses, especially for biofuels (2.4). We will then look in more detail (2.5) at what we believe constitutes

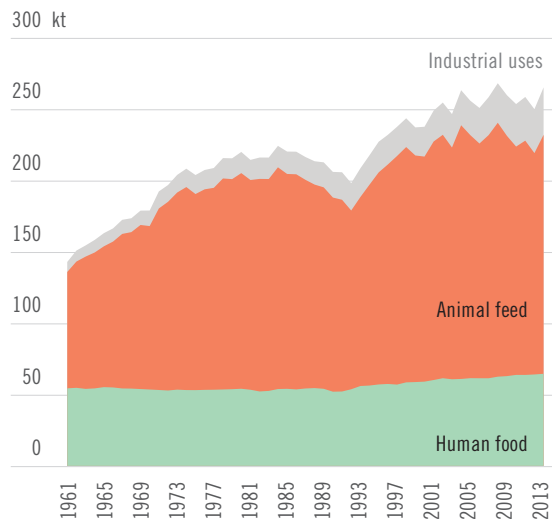
17. Using different instruments, especially the Common Agricultural Policy, the European Union has clearly made exports a key component of its agricultural development strategy (see, for example, EC, 2017).

Figure 8. Changes in uses of oilseed crops and cereals in Europe

8.a. Oilseeds, EU, 1961-2013



8.b. Cereals, EU, 1961-2013



Source: author, according to FAOstat.

the key feature of agricultural modernisation in the late 20th century, namely changes to animal production systems characterised by a type of “cerealisation” of livestock farming (Poux, 2004, p. 7). This has resulted in continued growth in the share of crop production used for animal feed, and, as a corollary, in protein imports.

2.4. Industrial uses: biofuels and bioeconomics

We distinguish between two major industrial uses of crop production: bioenergy on the one hand, and plant insulation, textiles, bioplastics and biopolymers on the other hand. In TYFAM, these uses are aggregated and, in its present form, the model does not enable a detailed configuration of the correspondence between biomass production and its different industrial uses. However, the following paragraphs propose a brief retrospective of these uses from 1990 to 2010. We will refer to this when we present the TYFA scenario assumptions regarding bioeconomics in part 3 of this report.

Biofuel production developed in Europe through two channels: first-generation biofuels, from the 1990s onwards; and the production of biogas by anaerobic digestion using different substrates in the 2000s, especially maize.

The development of first-generation biofuels was stimulated by several EU regulations, from the industrial set-aside system to the mandatory

blending of biofuels with petrol and diesel, which helped to reduce the cost of biomass supply and to finance the development of a sizeable industrial system. Four fifths of biofuels produced in Europe are biodiesel (from oilseed crops). Just over half of their production is dependent on biomass produced in Europe, and the rest on imported biomass. In absolute value, the volume of biomass produced in Europe for biodiesel production almost tripled between 2005 and 2010 (Transport & Environment, 2017), corresponding to a 40% increase in EU oilseed cultivation areas, or almost 11 million ha—just over 6% of the EU’s UAA (FAOSTAT, 2018).

Biogas production by anaerobic digestion can be based on any organic substrate. Further to various regulatory changes (especially price support for producers), biogas production was strongly encouraged in Germany, which in the space of a few years became Europe’s largest producer (more than 50% of European production). With 6 300 biogas plants running on agricultural feedstock, agricultural production used for anaerobic digestion—primarily maize—accounted in 2011 for almost 7% of Germany’s UAA (or just under 1% of the EU’s UAA), with significant environmental impacts (expansion of monoculture areas and impacts on soil fertility, nitrate pollution) (Herrmann, 2013).

Finally, the share of crop production used to produce biomaterials is relatively poorly documented in the 2010 situation; according to Eurostat, it accounted for just under 600 000 ha, or less than 0.5% of the EU’s UAA.

2.5. The intensification of livestock production

In TYFAM, livestock production is primarily distributed between monogastric and ruminant animals, then in more detail, within each of these categories, between dairy cattle, beef cattle and sheep/goats (grouped together) for ruminants, and between pigs and chickens for monogastric animals (with the exception of horses and donkeys). Total livestock and its productivity per animal (in meat, milk and eggs) are constrained and partly determined by the quantity and quality of feed available. One key aspect of the modelling process in TYFAM is therefore matching animal feed (from crop production and any trade, imports or exports) and livestock production.

Feed requirements for monogastric and ruminant animals are different. The former consume cereals and protein crops, whose production is (i) in competition with human food production, and (ii) potentially decoupled, in spatial terms, from livestock production areas themselves. The latter consume grass and green grain and, to a lesser extent, cereals and protein crops in the form of concentrates. The level of competition between ruminant feed and human food is lower than for monogastric animals, and the possibility of decoupling livestock production and crop production is also lower for ruminants than for monogastric animals.

European livestock in 2010 stood at 133 million livestock units (LU), just over half of which were ruminants (48% cattle and 8% sheep), and the rest monogastric animals (16% poultry and 28% pigs).

Table 3. Correspondence between feed available and consumed in 2010

Type of food	Quantity available (Mt)	Quantity required (Mt)	Rate of consumption (%)
Permanent grasslands	300 000 (estimated)	171 964	57%
Fodder in rotation	184 887	152 073	82%
Compound feed (Cereals + proteins)	187 244	181 594	97%
Total	672 130	505 631	75%

Source: authors, according to Hou *et al.* (2016) and Eurostat (2017)

The estimation of average feed requirements by livestock type (based on Hou *et al.*, 2016) and of feed availability (based on Eurostat data) enabled us to match livestock production and crop production in the 2010 situation. This indicates that almost 75% of available animal feed is consumed, with significant differences between feed types. Thus, cereal/plant protein compound feed is almost fully consumed. On the contrary, the proportion of grass from

grasslands actually consumed by cattle appears far lower, ranging from 50 to 60% (see Table 3).

The livestock thus fed annually produces 134 million tonnes of milk, 6.3 million tonnes of eggs and 56 million tonnes of meat (measured in whole carcass mass). Between 1960 and 2010, three aspects marked changes in production.

First, the intensification of production levels per livestock unit tripled meat production and significantly increased the production of eggs (+62%) and milk (+27%), while at the same time livestock numbers increased moderately for monogastric animals, and even decreased for ruminants. This intensification was achieved by acting simultaneously on two levers: genetics and feed. The different selection techniques associated with the possibility of ever greater control over the environment of animals led to the gradual replacement of a variety of local breeds with ultra-specialised, productive breeds. These changes were accompanied by an increase in the proportion of concentrates in animal feed, resulting for ruminants in a drastic reduction in grass consumption—which itself explains the significant reduction in permanent grasslands mentioned previously.

The increase in production was closely correlated with that of the consumption of animal protein in our diets (+42% increase in apparent consumption of animal protein between 1960 and 2010). However, these changes have not been clear-cut. For example, while the production of red meat has remained almost constant over the period, that of white meat has literally exploded (+200%) in line with the changes in eating habits described in section 2.2.

It is also partly linked to an increasingly export-oriented strategy. Thus, while the export-import balance for animal products in the European Union increased moderately from the 1960s to the 1980s, before hovering around a stable value (4 to 6% of production for meat, 8 to 10% for milk), trade between the EU and other countries has intensified in terms of both imports and exports. The *balance* of 6% of meat production exported is thus explained by an export share of production standing at 40%, whereas the equivalent of 35% is imported.

All of the changes observed in each of the food system compartments—food, crop production/land use and livestock production—have also resulted in a fundamental reconfiguration of the nitrogen cycle. We will discuss this point in the following paragraph.

2.6. The opening of the nitrogen cycle and its consequences

There are several approaches to calculating the nitrogen balance, each with different problems (Oenema *et al.*, 2003). TYFAM tackles nitrogen flows at the level of cultivated land (crops in rotation and permanent crops) rather than across the whole of the European farm, since the agricultural significance of a balance on such a scale is low. An analysis of the inputs and outputs to the cultivated land produces an *apparent* balance, consistent with the nitrogen requirements of crops, which also enables us to assess the surplus level and the efficiency of inputs. This approach is inspired by the one developed by Lassaletta *et al.* (2014), except that we have not taken into account atmospheric depositions, which represent around 10% of inputs, depending on the model used. In this context, four types of *inputs* to cultivated land are considered:

- synthetic mineral nitrogen;
- symbiotic fixation by legumes in rotation;
- organic fertiliser, from managed manure, which is equated with nitrogen excreted in buildings (everything for granivores, a fraction depending on the stocking rate for herbivores). These inputs depend on the nitrogen contained in crops used for animal feed;
- compost from composting of green waste produced outside cultivated land.

Net exports from cultivated land are equivalent to the nitrogen content of all crops harvested, picked or mown, whatever their use. For each crop, the quantity of nitrogen exported depends on the yield and its protein content, according to a relationship explained in the annex (Behind the scenes of TYFAM).

Table 4. Structure of the nitrogen balance for the European farm in 2014 and overall comparison with 2010

	Outputs (t N)	Outputs (t N)	Ratio inputs / outputs
TOTAL 2014	24 564 119	16 068 471	153%
Synthetic fertilisers (45% inputs)	11 053 854		
Manure (38% inputs)	9 334 365		
Symbiotic fixation (6% inputs)	1 473 847		
Atmospheric position (8% inputs)	1 965 130		
Others (3% inputs)	736 924		
TOTAL 2010 (in comparison)	23 834 249	14 988 204	159%

Source: Eurostat (2018)

In the approach adopted here, which focuses on cultivated land, nitrogen fixed in permanent grasslands—which contain a large proportion of legumes—is not recognised as such¹⁸. Permanent grasslands are in fact considered as an autonomous black box capable of feeding herbivores, whose recoverable waste is found on cultivated land (see list below of inputs considered). Moreover, atmospheric flows (deposition and volatilisation) and leaching are not directly considered by the model in its present form.

In view of the data available, it has not been possible to *recalculate* the 2010 nitrogen balance according to the TYFAM methodology, which will only be applied to the calculation of the 2050 situation. However, every year the European Commission establishes an EU-wide nitrogen balance. This balance considers all of the EU's UAA, including grasslands, and counts as inputs fertilisers, all animal waste, atmospheric inputs and estimated symbiotic fixation. Circular economy inputs (sewage sludge, urban compost, etc.) are poorly understood and considered negligible. Outputs include all exported crop production (food and feed) (Eurostat, Eurostat metadata, 2018). This balance constitutes an agri-environmental indicator. It is not intended to explain a given agricultural performance (coverage of needs) or environmental performance (accurate estimation of losses per compartment); it approaches the global efficiency of the European farm in a simplified way, enabling monitoring over time.

The latest detailed values of this nitrogen balance are available for the year 2014. We can compare this year with 2010, which we have selected as a reference for aggregate data on inputs and outputs (data available for this year); the orders of magnitude are very similar.

Our analysis of this balance does not go into detail about the different items and their significance in relation to the agro-ecosystem functioning. Instead, the goal is to highlight a number of key observations:

- overall, inputs still exceed outputs by almost 50%, despite efforts to manage both mineral and organic fertilisation;
- the very important role synthetic nitrogen fertilisers play in inputs;
- a significant production of manure and slurry in inputs, consistent with high levels of feed production and soybean imports;
- minority symbiotic fixation, with the low level of this item—whose detailed calculation remains to be explored—explained by the low

¹⁸. Despite accounting for half of all nitrogen fixed by symbiosis in Europe in 2009 (Baddeley, *et al.*, 2013).

proportion of legumes in rotation and by grassland fertilisation, which reduces their fraction in the balance of species present.

This nitrogen balance for the cultivated land can also be compared with the broader dynamics of the nitrogen cycle within the European food system. The key observations made above should thus be viewed in relation to the progressive opening of the nitrogen cycle that has characterised the European situation for a century (Sutton & Billen, 2011, TS 5 and TS 6). This opening of the nitrogen cycle is itself a consequence of the gradual disconnection of crop and livestock systems at the European level (see section 2.3), which has resulted in a massive input of reactive nitrogen to the European food system through two main sources:

- plant protein imports for animal feed, which, as we have seen, increased tenfold between 1961 and 2010;
- and the increase in mineral fertilisation, as the possibilities for nitrogen transfer from grassland areas capable of capturing atmospheric nitrogen to crops systems have gradually diminished with territorial specialisation¹⁹.

The nitrogen inputs from these two sources thus increased by around 20% between 1970 and 2010. Although these additional inputs of nitrogen enabled significant productivity gains per hectare by removing one of the main production limiting factors, the ensuing opening of the nitrogen cycle is not without consequences. The European Nitrogen Assessment (ENA) thus estimates that between 1970 and 2010, nitrogen emissions (per hectare of UAA) in different forms (atmospheric and leaching) increased by 20 to 30% (Sutton *et al.*, 2011). These emissions are now in the atmosphere, in surface water, the oceans and groundwater, posing major challenges for the environment and health—in a context in which agricultural nitrogen use accounts for 70% of all uses at the European level. The resulting widespread eutrophication causes the loss of species, due in particular to the excessive development of nitrophilous species, which in aquatic environments can lead to anoxia, with its own cascading consequences (Billen *et al.*, 2011). Overall, excess nitrogen impacts water and air quality, produces greenhouse gas emissions, disturbs land and aquatic ecosystems and their biodiversity, and alters soil life.

2.7. Partial conclusion: the challenges of the agro-ecological transition in TYFA

The contemporary dynamics of the European food system are far removed from an agro-ecological approach, the goal of which is to maximise the use of ecosystem dynamics in order to foster agricultural system performance in terms of both production and the environment. The changes that have marked this system have clearly had a series of impacts acknowledged as positive in the context of post-World War II economic development, including an increase in food production to address growing demand and the structuring of an economically powerful sector that generates foreign exchange through its export capacities. On the other hand, the environmental and health impacts have become increasingly visible, while the social benefits are ambiguous, with jobs being created at the expense of others. It is thus necessary to call into question this low environmental and social sustainability of the food system. If we consider in particular the role pesticides play in the functioning of the system and their impacts on biodiversity and health, and the importance of excess nitrogen that contributes to anoxia in the oceans and seas (Billen *et al.*, 2011), we see that there is an urgent need to change the functioning of the system as a whole.

Although this is not an original finding, the detailed description of each of the compartments of the current food system and the linkages between them through the prism of TYFA_m provides informed insights for rethinking this food system from an agro-ecological perspective. The characterisation of the structural relationships between the approach to crop production, imports, livestock production, consumption and exports enables us to clearly set out the challenges of changing the system. More specifically, one of the objectives thus consists in moving away from the combination of “we eat too much and badly” and “we produce a lot and badly”, in order to develop a scenario in which “we eat enough and well” and “we produce what we need”. The next part identifies for each of the components of the food system analysed by TYFA_m assumptions that are consistent with this approach. In the final phase, these assumptions will enable us to configure the TYFA_m model in order to simulate the functioning of an agro-ecological European food system and, ultimately, to test its coherence, robustness and relevance (part 4).

19. The decline in the proportion of protein crops in cultivated land, and thus in symbiotic fixation possibilities, has also contributed to an increase in mineral nitrogen use in cropping systems.

3. TOWARDS AN AGRO-ECOLOGICAL EUROPE: PRINCIPLES AND APPLICATION TO THE CONFIGURATION OF TYFA^m

3.1. A situated and coherent approach to agroecology

The concept of agroecology was first defined in the early 20th century from an essentially technical viewpoint, which it has retained to this day. The idea consists in applying the concepts and principles of scientific ecology to the management of agro-ecosystems, taking account in particular of biogeochemical flows and the functional interactions between organisms at the level of complex agro-ecosystems (Gliessman, 2007). This vision is in line with our approach of agroecology as an innovation pathway. Other approaches developed from this basis, rooted in the field of scientific research, in the social movements—agroecology then became a holistic concept in which the technical, political, and even philosophical aspects are interconnected –, or more specifically, in the field of agricultural practices around various networks of actors on the ground (Wezel *et al.*, 2009). A number of approaches thus coexist within different national and cultural contexts. Without seeking to cover every aspect of the discussion as to what exactly constitutes agroecology, the goal here is therefore to provide the framework for TYFA.

In this study, we concentrate on the technical aspects (agroecology as an agricultural innovation pathway), while keeping in mind that these aspects have consequences for, or are conditioned by, all of the economic, social and political dimensions of the food system to which an agro-ecological Europe contributes. Or, in other words, that the adoption of agro-ecological practices on a large scale as described in this study implies fundamental economic, political and social changes²⁰. Although these aspects will not be

discussed directly here, they will be the subject of further work within the TYFA framework. The framework we use as a starting point is the one developed by the Interdisciplinary Agroecology Research Group (GIRAF) (Stassart *et al.*, 2012), whose key principles are presented in Box 2.

Box 2. The agricultural principles of agroecology as proposed by GIRAF and adopted in TYFA²¹

Since the definition of agroecology is broad, the concept can be approached by considering the principles that guide researchers, practitioners and social actors in the field of agroecology. The following list, which should not be seen as a fixed framework, clarifies these.

- Recycling biomass, optimising and closing nutrient cycles
- Improving soil condition, especially its organic matter content and biological activity
- Reducing dependence on external synthetic inputs
- Minimising resource losses (solar radiation, soil, water, air) by managing the micro-climate, increasing soil cover, harvesting rainwater, etc.
- Enhancing and preserving the genetic diversity of crops and livestock
- Strengthening positive interactions between the different elements of agro-ecosystems, by (re-)connecting crop and livestock production, designing agroforestry systems, using push-and-pull strategies for pest control
- Integrating biodiversity protection as an element of food production

that the adoption of integrated pest management practices, based on more diverse and complex crop rotations, had never taken off in California in the 1980s, despite their biotechnical efficiency, since the advisory systems and sectors in place were ill-adapted to such changes. Research by Jean-Marc Meynard and his team on the need for coupled innovations between agricultural production systems and food processing systems confirms this point (Meynard *et al.*, 2017).

21. The principles proposed by GIRAF that do not directly concern agricultural aspects production are not included in this box.

20. This aspect was highlighted in the late 1980s by Altieri (1989) in the American context. He showed in particular

- Integrating short- and long-term considerations into decision-making
- Aiming for optimum yields rather than maximum yields
- Promoting value and adaptability

Although this GIRAF framework establishes a “sphere of possibilities” inspired by a strong sustainability approach (Godard, 1994)²²—and thus, implicitly, a “sphere of impossibilities” for agroecology—, this sphere remains vast. For example, it leaves open the question of the degree of mobilisation of external inputs (fertilisers and pesticides). TYFA therefore adapts this framework in order to balance the challenges for health, biodiversity protection—which is too often excluded from the debate on agriculture—and climate change; the latter is becoming increasingly prominent in the policy debate (for example in EC, 2017), with a very strong tendency to override all other dimensions.

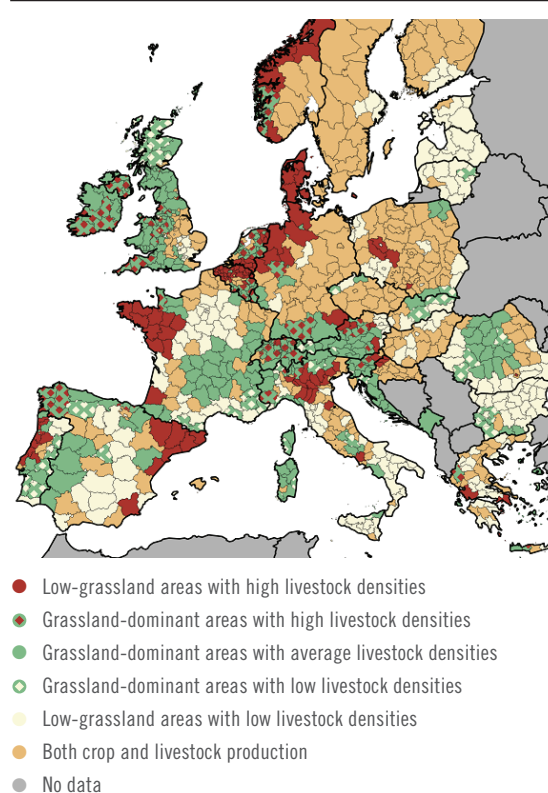
The set of assumptions described in the following paragraphs should be considered in the light of the “macro” level to which it applies. These assumptions must enable the configuration of TYFAM in order to simulate the functioning of an agro-ecological Europe, and therefore concern the five compartments of the model: fertility management and nitrogen cycle; crop production and land use; livestock production; industrial uses; and food. From this perspective, we define a comprehensive conceptual framework, while recognising that many aspects could be described in more detail.

3.2. Nitrogen management: closing fertility cycles at the territorial level

Underpinning an agro-ecological system is the idea of closing nutrient cycles at the lowest possible territorial level. This principle provides a solid foundation for configuring the “nitrogen flow” component of TYFAM, while having significant consequences for the other components of the European food system, which we will describe in the following sections. Building on the retrospective presented above (see section 2.6), two key assumptions emerge regarding the nitrogen cycle. These can be linked, in one way or another, to the need to *reconnect livestock production and crop production*.

The first assumption concerns restoring EU protein self-sufficiency associated with *halting plant*

Figure 9. Typology of European agricultural territories, according to the role of livestock production



Source: Scientific appraisal, Roles, impacts and services provided by European livestock production (Dumont *et al.*, 2016).

protein imports.²³ Over and above the benefits in terms of nitrogen, halting plant protein imports will also drastically reduce the level of *imported tropical deforestation* in the European Union, which is associated with substantial biodiversity loss and GHG emissions. In 2008, plant protein imports for animal feed accounted for 44% of imported deforestation in the EU, primarily soybean from Latin America (EC, 2013, p. 30-31).

The second assumption concerns the substitution of synthetic mineral nitrogen inputs in the agricultural system by two main channels in order to close the nitrogen cycle at the territorial level: symbiotic fixation by legumes—which in turn implies significantly increasing the proportion of legumes in cropland; and nitrogen transfers enabled by ruminant livestock production, from temporary and permanent grasslands and, more generally, the *saltus* (Poux *et al.*, 2010), up to the cultivated area. This aspect implies in turn the reintroduction of grasslands in highly specialised areas where cropland dominate, in order to enable nitrogen transfers and

22. In short, the idea of strong sustainability refers to an approach to sustainable development in which environmental sustainability takes precedence over the two other pillars of sustainability.

23. Here, we are taking literally the most recent policy announcements on this issue, at the French or EU level (European Parliament, 2018).

that ruminant farming remains at a sufficient level across all European territories. The difficulty of re-deploying livestock production and grasslands in field crop areas should not be underestimated if we continue in a similar socio-economic context. However, it should be stressed that highly specialised field crop areas are far from dominating the EU's UAA, as shown in Figure 9.

We clearly see the extremely systemic nature of this second assumption. Indeed, it has huge implications for land use and crop production, which we cover in section 3.3, as well as for livestock production, which we describe in greater detail in section 3.4.

3.3. Extensive crop production in a diversified agricultural landscape

An agro-ecological system is fundamentally based on its capacity to maintain a high level of biodiversity, not only for the intrinsic value of this biodiversity, but also for the services it provides in terms of agro-ecosystem functioning. A high level of biodiversity in an agro-ecosystem depends on two pillars, according to which our assumptions are made (Gonthier *et al.*, 2014): the extensification of practices at the plot level, which, supported by the re-diversification of crop rotations, radically reduces the direct environmental impact of agricultural practices; and a heterogeneous landscape structure, leaving room for elements of semi-natural vegetation and a vertical layering of crops through the introduction of wood elements.

3.3.1. The extensification of practices at the plot level

Phasing out pesticides: ecosystem consequences

In TYFA, the extensification of practices at the plot level primarily relies on phasing out pesticides—insecticides, herbicides and fungicides—whose environmental impacts are now well documented (IPBES, 2016; Delaunay *et al.*, 2017). Associated with synthetic fertilisers and progress in genetics, the arrival of pesticides has in fact been one of the agricultural pillars of the intensification of crop production over the last few decades (Stoate *et al.*, 2001). The assumption of their phase-out in TYFA therefore has structural and systemic consequences for crop production as a whole. Before describing these different challenges, we will briefly discuss the diversity and scale of impacts currently attributed to pesticides.

In terms of biodiversity, the effects of a large number of molecules on ecosystems are now well documented for most taxons—including those not

directly targeted by the molecule in question (Geiger *et al.*, 2010; Pelosi *et al.*, 2014; Pisa *et al.*, 2015; Woodcock *et al.*, 2016)—and it has now been shown that their ecosystem impacts go well beyond their point of application due to transport through air and water (Beketov *et al.*, 2013). The endless race between the introduction of pesticides and the emergence of resistance “requiring” new molecules is also an important challenge.

Moreover, the impacts of pesticides on human health can no longer be ignored.

- The effects on the health of agricultural workers are known for around ten serious diseases or functional disorders (leukaemia, non-Hodgkin lymphoma, myeloma, prostate cancer, Parkinson's disease and Alzheimer's, cognitive and fertility disorders, foetal malformations and childhood leukaemia) and suspected for four others (INSERM, 2013).
- Where consumers are concerned, traces of pesticides (in particular organochlorines, organophosphates and pyrethroids) are found in almost all subjects at different doses, and in more than 50% of all food products consumed. Between 2005 and 2008, exposure of French consumers to the 400 molecules authorised in Europe was chronic for 7 of them, acute for 17, and for 59 of the substances in question, additional monitoring was required, since the risks were considered high (Afsset & ORP, 2010). The demonstration of direct effects on consumer health through food and the identification of causal relationships nevertheless remains the exception, leading the monitoring agencies (EFSA in Europe, WHO at the global level) to exercise caution in their recommendations regarding the possible impact of a category of pesticides. It is nevertheless worth noting that in its latest collective appraisal, INSERM insists on the difficulty of detecting direct effects using the assessment methods currently available, highlighting in particular three important limitations (INSERM, 2013, p. 117):
 - only active ingredients are tested, whereas adjuvants can change the degree of hazard of a molecule;
 - failure to account for cocktail effects—although these are beginning to be documented (e.g. Lukowicz *et al.*, 2018);
 - failure to account for the effects of metabolites resulting from the degradation of parent molecules and their accumulation in the medium to long term.

In this context, the determination of the “right dose” of pesticides, without environmental and/or health impacts, is almost impossible (unlike nitrogen, for example), especially since the very notion

of a dose and its hazardousness is open to discussion and cannot be assessed simply in g/ha. TYFA adopts an assumption inspired by the precautionary principle (Godard, 2005): if the goal is overall human and environmental health (this is the One Health concept, see Lebov *et al.*, 2017), the total phase-out of pesticide use is the most robust assumption to be tested in the first instance. Any intermediate solution, which could be justified on levels other than the environment and health, appears extremely difficult to justify on the ecosystem level.

In this respect, it should be noted that the TYFA approach does not engage in the debate that distinguishes pesticide use from the presence/absence of residues in food, including water. Even if these residues are effectively absent from what we eat—or non-detectable or non-verifiable, which is not the same thing –, they are nevertheless present in our environment and have impacts on biodiversity. The potential long-term adverse impacts on endocrine systems and on the microbiota (a concept that refers to the whole microbial system connecting the microbiology of our intestinal system to that of our environment and of the animals and plants we eat) is one more reason for applying a precautionary approach.

The phase-out of synthetic fertilisers associated with that of pesticides

The assumption regarding the phase-out of pesticides leads us to also envisage that of synthetic fertilisers. Historically, the rapid development of fertilisers and pesticides was concurrent, even if small amounts of synthetic fertilisers were used from the beginning of the 20th century in “state-of-the-art” European farms, which also used the first synthetic pesticides (copper sulphate).

This assumption is justified if we consider in particular that, in the current context, the use of mineral nitrogen²⁴ at high levels fosters the development of fungal diseases and weeds in plots, which in turn require their management through the use of pesticides. In addition, it is associated with plant varieties whose great yields are only attained when pesticides and growth regulators are used (one emblematic example being lodging in wheat). It thus appears agronomically difficult to maintain the current level of synthetic nitrogen use without pesticides.

While it is probably possible to use Nitrogen in moderation with a low impact on the environment

and biodiversity, three reasons prompted us to adopt as the first TYFA assumption the total phase-out of synthetic/mineral nitrogen use.

(i) The combination of this assumption and the phase-out of pesticides corresponds first to the core of the standards for organic agriculture: we can therefore refer to established agricultural references in order to configure our model. On the other hand, there are no references regarding pesticide-free systems that use moderate levels of synthetic nitrogen.

(ii) Next, research on planetary boundaries clearly indicates that human use of nitrogen resources—and the environmental losses it generates—far exceeds the possibilities of our planet (Rockström *et al.*, 2009), especially in the case of the agricultural/food sector (De Vries *et al.*, 2013; Campbell *et al.*, 2017): faced with the challenge of significantly reducing the use of synthetic nitrogen, its phase-out is unquestionably the most robust assumption.

(iii) Finally, the health and environmental impacts of nitrogen application can be very serious:

- in terms of health, poorly managed nitrogen use contributes to nitrate loading of drinking water, which primarily affects the most sensitive populations (pregnant women, elderly people, children) (Sutton *et al.*, 2011);
- in terms of biodiversity, excess nitrogen in the environment can be expressed at low levels. Thus, grassland fertilised with 50 units of mineral nitrogen will suffer a significant loss of flora, and especially of legumes (which are disadvantaged compared to grasses at such doses) (Klimek *et al.*, 2007; Vertès *et al.*, 2010). Moreover, even at very low doses, mineral nitrogen losses from cultivated areas contribute to the eutrophication of aquatic environments, which calls for ambitious action (Billen *et al.*, 2011);
- finally, nitrogen application to arable land is one of the main factors in agricultural sector greenhouse gas (GHG) emissions, producing just over a third of emissions. Phasing out synthetic fertilisers can only lead to the development of low-nitrogen systems (which rely solely on organic nitrogen and symbiotic fixation by legumes), in which emissions levels will be significantly reduced.

Overall, the radical nature of the assumption for synthetic nitrogen expresses a framework that aims to ensure the robust integration of ecosystem issues. Associated with the assumption on pesticide phase-out, it has significant impacts on the organisation of cropping systems (yields, complexity of rotations, diversity of crops) and on their interfaces with livestock systems.

24. The ecosystem impact is linked more to the mineral form of nitrogen than to its origin (synthetic). A nitrate form of nitrogen obtained by anaerobic digestion, for example, will have the same direct impact, even if its energy and GHG balance is of course far better.

Organisation and yields of cropping systems in TYFA: organic agriculture as a model

Configuring the shift to organic agriculture envisaged in TYFA thus requires analysis of two key aspects of organic systems: the issue of fertility and associated yields, and that of pests and parasites.

Regarding yields and fertility, the simultaneous phase-out of synthetic fertilisers and plant protein imports leads us to consider a system in which any nitrogen inputs are the result of symbiotic fixation: either directly through legumes (the proportion of which necessarily increases, see section 4.2) in cropland, or through nitrogen transfers by ruminants from permanent grasslands to cropland. This is one of the main coherence tests for TYFA: is the scenario “tenable” in terms of nitrogen²⁵? Under which conditions regarding the yields expected?

The yield values used to configure TYFAm are based on the meta-analysis by Ponisio *et al.* (2015), which develops and confirms two similar, older meta-analyses (Badgley *et al.*, 2007; Seufert *et al.*, 2012) focusing on the yield gaps between conventional systems and organic systems. Of more than 1,000 systems analysed in 105 different studies, 429 are in Europe. The European values were extracted from the database associated with the study and an average yield gap was calculated for each type of crop available. For oilseeds and protein crops, for which the meta-analysis by Ponisio *et al.*, (2017) gives only an aggregate value, we have detailed the values per crop type based on complementary studies compiled by Guyomar *et al.*, (2013) (Table 5).

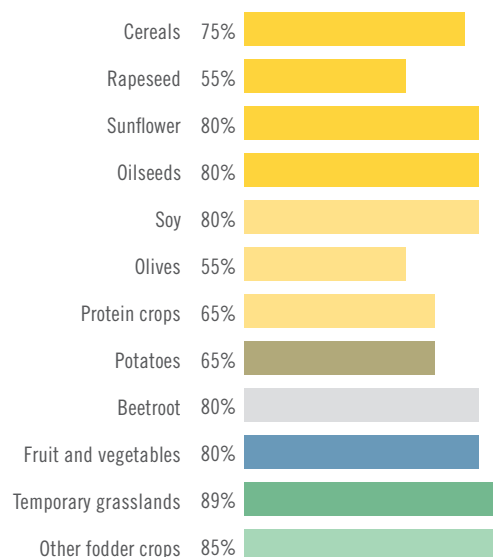
Table 5. Yield gaps for oilseed crops and leguminous crops between organic and conventional agriculture and yield retained for the TYFA scenario

	Yield Ponisio <i>et al.</i>	Yield guyomar <i>et al.</i> 2013	Yield retained in TYFA
Rapeseed		59%	55%
Sunflower	55%	80%	80%
Olives		n.d.	55%
Other oilseeds		n.d.	80%
Soybean		80%	80%
Other leguminous crops	64%	Féverole 49% Pois 57%	65%

Source: Ponisio *et al.* (2015) et Guyomar (2013). Les ratios ont été établis sur la base des rendements AB et agriculture conventionnelle établis par Agreste en 2011 et 2012.

25. The issue of phosphorus is also crucial under the assumption of a shift to organic agriculture in a context in which, as things stand, organic farms depend heavily on transfers of phosphorus from conventional farms (Nowak *et al.*, 2013). As explained previously, in its present form, TYFAm is unable to examine this issue at this stage.

Figure 10. Yield gaps between TYFA 2050 and 2010 yields



Source: Ponisio *et al.* (2015), values for Europe.

The reduction in yields for organic plots is in the order of -25% for cereals, between -20 and -45% for oilseeds and protein crops, and -5 to -20% for fruit and vegetables. It is presented graphically in Figure 10.

The assumptions we use for yields are therefore cautious, for at least two reasons. First, they do not include the potential effects of agro-ecological innovation over the next 30 years between now and 2050. But the shift to a 100% agro-ecological system could be accompanied by a massive redirection of research and development resources towards agroecology, which currently only receives a small proportion (Vanloqueren & Baret, 2009). Moreover, Ponisio *et al.* (2015) show that the yield gaps between organic and conventional systems can be halved by the adoption of agro-ecological practices, such as crop rotations and mixed cropping, which are central to the TYFA assumptions regarding crop production (Cereals + protein crops and/or agroforestry). Bretagnolle *et al.* (2018) also indicate the importance of pollination, associated with organic agriculture, in the development of yields, especially for oilseeds and protein crops.

As for the criticisms raised by different authors (Connor, 2008; De Ponti *et al.*, 2012; Connor, 2013) that the organic yields observed in these meta-analyses cannot be generalised, since they do not take account of nitrogen transfers between different parts of the world (and especially from Latin America through the intensive production of soybean, which

is subsequently transformed into animal feed, then converted by livestock metabolism to manure, before being applied to crops), these criticisms do not apply to TYFA, since the scenario assumes the suspension of plant protein imports. The challenge is clearly to succeed in closing the nitrogen cycle in this context (see part 4.3).

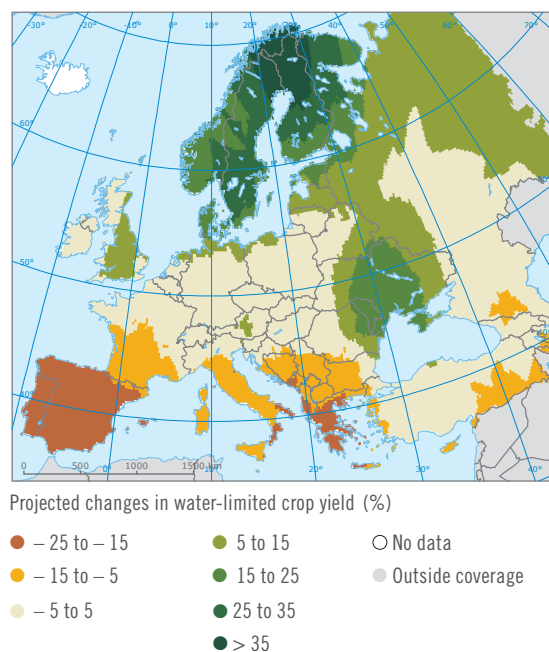
A second important aspect of organic agriculture cropping systems concerns the management of parasites (insects and fungus) and weeds. It should first be noted that TYFA is based on the assumption of restoring the diversity and complexity of crop rotations and crop types consistent with organic agriculture (Barbieri *et al.*, 2017). From this perspective, the ratio between the different types of crops—cereals, oilseeds, fodder legumes or seed crops and temporary grasslands—is evolving significantly towards a decline in the proportion of cereals in rotations. Wheat continues to dominate the cereals category, but other secondary, hardier cereals (oats, rye, triticale) are reappearing in rotations to limit the risks of disease and to improve weed control. Rotations have generally been lengthened to 6, 7 or even 8 to 10 years. This increased complexity of rotations, associated with the heterogeneity of landscape structures in TYFA, is a robust element fostering biological control of parasites and weed reduction (Barbieri, 2001; Winqvist *et al.*, 2011; Veres *et al.*, 2013; Muneret *et al.*, 2018).

Downstream of production, phasing out fungicides raises the question of the prevalence of mycotoxins in food products, and thus of the risk to consumer health. A meta-analysis conducted within the framework of a report by AFSSA in the early 2000s nevertheless shows that, for the main categories of products concerned (Cereals, milk, apples), the mycotoxin levels in organic agriculture are not significantly different from those recorded in conventional agriculture. Indeed, although organic agriculture standards prohibit the use of synthetic fungicide treatments, they promote cropping practices that help to limit mycotoxin contamination (AFSSA, 2003, p. 95).

Finally, let us clarify two aspects of TYFA in reference to organic agriculture:

- although our reasoning leads us to consider organic agriculture as a logical component of agroecology, it was not a presupposition: pesticide phase-out seems to us to be the most robust option for health and biodiversity, but the total phase-out of mineral nitrogen seems less fundamental in this respect, even if it is a legible assumption on a socio-political level (organic agriculture is now an established reference);
- this assumption of synthetic nitrogen phase-out can be justified retrospectively, once the TYFA model has confirmed the assumption that

Figure 11. Map of projected impact of climate change on yields in 2050



Source: EEA, 2017.

symbiotic nitrogen fixation in the EU (without imports of mineral or extra-EU nitrogen) is at a sufficient level to cover plant outputs²⁶, with the yield assumptions used. But, as we shall see, this assumption remains “tense”, and an alternative, envisaging a moderate use of synthetic nitrogen (the conditions and impacts of which remain to be specified) does not seem to us to question the whole approach to agroecology adopted in TYFA.

Taking account of the impacts of climate change on yields

The 2050 time horizon means the impacts of climate change must be taken into account in the model.

At the quantitative level, existing models indicate different results concerning yield differences under the effects of climate change (Lavalle *et al.*, 2009; Wilcox & Makowski, 2014; EEA, 2017; Hart *et al.*, 2017). Some indicate reductions when water stress outweighs other parameters, while others indicate increases when the CO₂ fertilisation effect is taken into account. More generally, we note difficulty in anticipating an overall change in yields at the level of the “European farm”, due to the significant variations in climate change at this level, as shown in Figure 11.

26. We will return to this point in more detail later in the document.

At the European level, sharply reduced yields are expected in the Mediterranean regions, whereas increases are expected in northern Europe, with the middle zone remaining within current yield values.

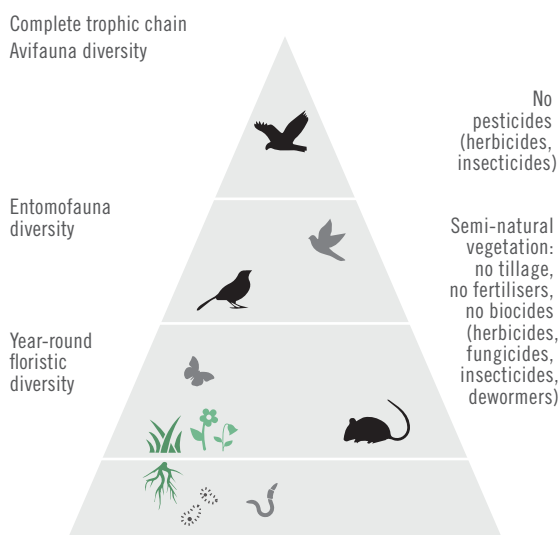
The combination of uncertainty in model conclusions (which is itself the result of uncertainty surrounding the models and their parameters) and the geographical variability leads us to adopt as a key default assumption the same yields for 2050 as in organic agriculture today. The yields retained are those calculated using Ponisio *et al.*'s data (2015, see Figure 10). This assumes that gains linked to agro-ecological innovation over the next few decades will only just offset losses linked to climate change. That said, although our central assumption on yields is conservative, we will discuss the sensitivity of our model to the variability of these yields. Considering that there are just as many arguments for a reduction as for an increase in yields, we will integrate upward or downward assumptions in the second phase (see section 4.4.2).

On a more qualitative level, TYFA takes into account the key role of the management of soil and production systems in adaptation to climate change. The main factor that could result in a reduction in yields under the effect of climate change is linked to increased water stress. On this point, we believe our agricultural assumptions can limit the risks, through high inputs of organic matter and favourable practices—for example a drastic reduction in dewormer inputs –, and thus a soil structure likely to increase the available water capacity. Reducing yields and fertilisation also limits crop vulnerability to drying conditions.

As regards irrigation, it seems difficult to avoid in areas identified as the most sensitive, especially in the Mediterranean regions. Although our model does not enable a quantification of irrigation at this stage, our agricultural assumptions can nevertheless reduce global demand for water by acting on three parameters:

- changes in rotations (with, in particular, less use of grain and silage maize). TYFA leads to the development of fruit and vegetable crops across Europe, which fosters local, more rainfed, and seasonal production. This assumption results in a form of de-specialisation in the Mediterranean regions, which are major users of water to irrigate these crops;
- a reduction in crop yields, which in turn reduces water “requirements” to achieve the desired yield;
- the extensification of grazing livestock, enabling the mobilisation of hardy breeds that are more likely to eat more woody fodder, suited to drier climates.

Figure 12. Semi-natural habitats and trophic chains



3.3.2. A more diverse agricultural landscape

The challenges of spatial heterogeneity

The homogenisation of agricultural landscapes, associated with the threefold process of specialisation, intensification and concentration from the 1960s to the present day, has had huge impacts on the biological diversity of agro-ecosystems. Insect, bird and plant populations and diversity have thus collapsed over this period. Hallmann *et al.* (2017) indicate, for example, a 75% loss of insect biomass in protected areas in Germany over the last 30 years. Inger *et al.* (2015) make similar observations for birds at the European level, with common bird populations dropping by more than 20% over the last 30 years. These studies clearly point to the ecosystem effects (the loss of insects leads to that of birds) and the responsibility of agricultural practices in the changes observed.

Restoring a high level of diversity and abundance, comparable to the 1960s, therefore implies, conversely, returning to a certain level of extensiveness and heterogeneity in landscapes—which is expressed in terms of composition (the landscape is composed of a mosaic of different spaces) and structure (the form and size of these spaces are themselves heterogeneous) (Fahrig *et al.*, 2011). From this perspective, all forms of semi-natural vegetation (SNV)—permanent grasslands, hedges, ponds, stone walls, sunken paths—play a crucial role in three respects, for both immobile and mobile species: (i) as sources of food; (ii) as stable habitats for reproduction; and (iii) as a form of territorial connectivity (Benton *et al.*, 2003; Le Roux *et al.*, 2008).

The presence of SNV thus simultaneously increases the number of taxons and the complexity of trophic chains, as illustrated by the very simplified chain presented in Figure 12.

The key role of SNV in this “equation” is based on two fundamental principles: maintaining permanent cover—hence no tillage—and using no inputs, which disturb trophic functions or destroy organisms (biocides of all types)²⁷. It is generally held that maintaining 20 to 30% of the UAA under semi-natural vegetation is sufficient to support a variety of species at the landscape level (Le Roux *et al.*, 2008). This SNV percentage is not the only answer to a high level of biodiversity, and harvest plants²⁸, for example, develop in cultivated areas—provided there are few fertilisers and no herbicides. But considering SNV as the matrix for biological richness is the most robust approach in terms of biodiversity.

An agro-ecological food system must thus make it possible to increase the share of semi-natural vegetation in the agrarian landscape. The heart of this semi-natural vegetation is made up of grasslands and extensive rangelands (see following paragraph), combined with linear or isolated agro-ecological infrastructures (AEIs) that strengthen certain ecological functions providing food and shelter for species. According to the statistics available, in 2010 these infrastructures accounted for 5% of the UAA (see section 2.3).

We assume that increasing the share of AEIs to 10% of the area under cultivated land (excluding grassland) in 2050 is consistent with contributing to a high level of biological diversity. At a level of detail not applied in this document, it should be noted that hedges and trees are not a universal response when it comes to biodiversity; some bird species need open spaces. Biodiversity calls for a range of landscapes and AEI combinations.

Maintaining extensive permanent grasslands

All forms of SNV play a role in the development of an agro-ecological system. Natural grasslands²⁹ nevertheless have a special place in several respects. First, they are the main category of SNV (34% of the EU’s UAA, compared to 5% for the other AEIs); and many other types of SNV are also

associated with them, either directly or indirectly: hedges, wetlands, trees. Although some types of biodiversity associated with agriculture can be developed independently of natural grasslands (for instance, through agroforestry in cultivated areas without inputs and with a complex plot layout), in terms of diversity, they will never replace those that have built up over the centuries in grassland areas.

Indeed, and this is the second point, extensive grasslands play a decisive role for European biodiversity. Although their existence depends at present on pastoral practices, and thus on humans, they developed as a natural habitat under the effect of the mega-herbivores and natural fires over several million years (Pärtel *et al.*, 2005). They contain a remarkable species diversity (79 species of vascular plants have been recorded in just 1 m² in some parts of central Europe, for example); just over a quarter of habitats of European importance under the EU regulation are thus associated with grassland ecosystems, the majority of which are currently in poor condition due to inappropriate pastoral practices (Halada *et al.*, 2011).

A third aspect makes grasslands a key component of TYFA: their role in fertility management. In a permanent grassland that is managed extensively, the share of legumes stabilises at between 25 and 40%, enabling atmospheric nitrogen fixation that can vary from 150 and up to 250 kg/ha/year (Vertès *et al.*, 2010). Ruminant production on these grasslands then enables nitrogen transfer from the grasslands to cropland, resulting in a net input of nitrogen³⁰ into the system. The share of nitrogen entering the cropping system in this manner thus plays a decisive role in the TYFA scenario, and will be described in detail in section 4.3.

The importance given to grasslands is therefore approached in TYFA through its association with extensive ruminant production (primarily cattle). This has direct implications for the scenario assumptions regarding livestock systems (see section 3.4), and diets (see section 3.6). First, on a quantitative level, the conservation of grasslands implies maintaining a cattle population large enough to ensure they remain open. This in turn implies a sufficient consumption of the associated

27. In addition to pesticides used on crops, we can also mention dewormers which, when found in manure, can seriously disturb beneficial soil organisms and thereby have systemic impacts.

28. Harvest plants are annual plants that germinate preferably in autumn or winter and are found in cereal fields after harvesting: cornflowers, poppies, etc.

29. In this section, we refer to a “broad” definition of grasslands—from grasses to woody species. They are all open spaces used by herbivores. By extension, we can include grazed sparsely wooded areas. See Box 3 for more details.

30. Total nitrogen outputs from the livestock grazing these permanent grasslands can be estimated at between 65 kg (heifers) and 170 kg (productive dairy cows) (Peyraud *et al.*, 2012), excluding returns. We assume at this stage that grasslands are also able to play a role in the mobilisation of alternative sources of phosphorus, through deep root growth in the bedrock. This assumption—and its importance for maintaining fertility in the system as a whole—will need to be tested during future developments of the model and the scenario.

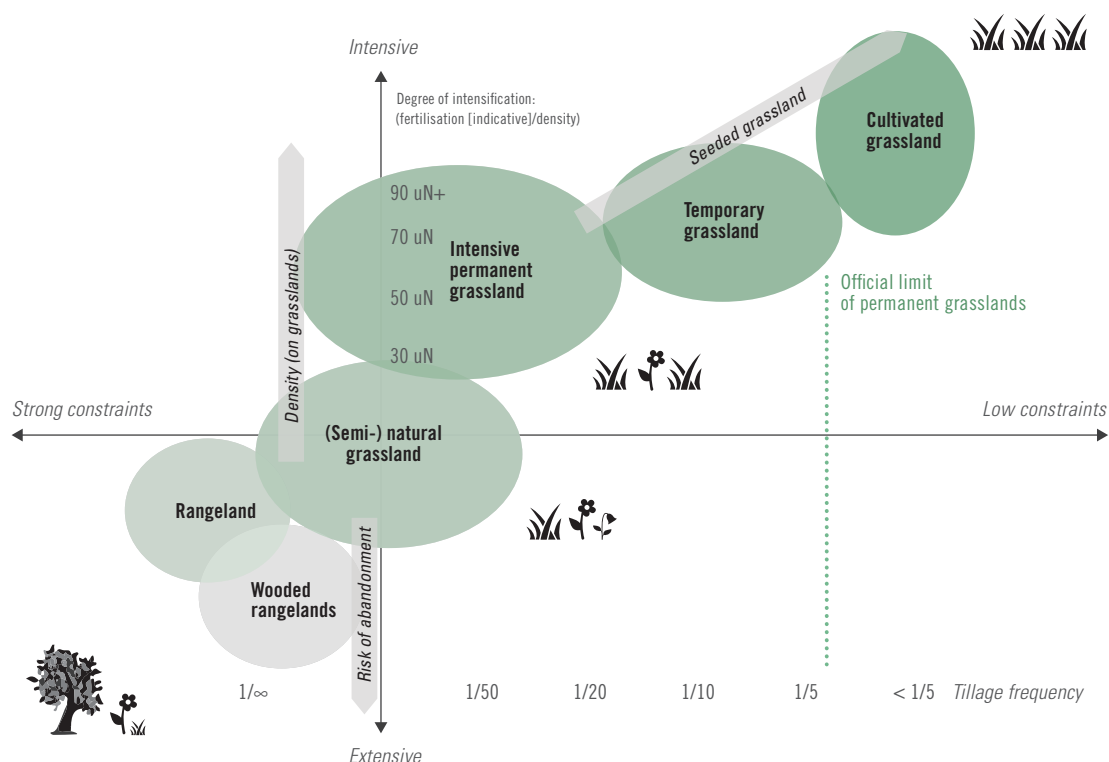
products (milk and meat). Next, on a qualitative level, the omega-3 content of milk and meat from ruminants is more than doubled by grass feeding as opposed to maize silage (Couvreur *et al.*, 2006). The health benefits are considerable—especially for cardiovascular health (Gebauer *et al.*, 2006)—, in a context in which omega-3 consumption in Europe is, *on average*, less than half the recommended amount.

Finally, the maintenance of grasslands can be discussed in terms of their potential contribution to soil carbon storage—in the order of 0.7 tC/ha/year (Soussana & Lemaire, 2014)—although this is a particularly sensitive issue. In a context in which climate change is becoming the main environmental challenge, the majority of existing scenarios tend to compare these sequestration opportunities—which are, moreover, time limited and highly reversible—with the emissions associated with maintaining a large cattle population. The conclusion that emerges almost systematically from this is that it is far more interesting, purely from the viewpoint of emissions, to radically reduce cattle numbers, to intensify remaining herds for milk production, and to replace whatever possible for meat production with monogastric animals, considered to be more

efficient³¹ (Westhoek *et al.*, 2014; Garnett *et al.*, 2017; Rööß *et al.*, 2017). Such an approach automatically results in a reduction in permanent grassland areas, which are either tilled in order to be cultivated or afforested in order to store carbon. Both cases entail a major loss of biodiversity, even afforestation, which significantly reduces the level of biodiversity, especially if the wood is also intended as an energy crop. The possibility of bringing nitrogen into the system through transfers to cultivated areas disappears, and the omega-3 content of food products also diminishes. Overall, the “climate-centric” approach to agriculture-environment relations—and in particular grasslands and cattle production—that has gained prominence does not lend itself to considering these different dimensions. Conversely, the TYFA assumptions are multifunctional from the outset, and give equal priority and ambition to

31. As a rule, monogastric animals require only a third of the amount of plant protein fed to ruminants to produce the same amount of protein. GHG emissions per kg of animal products are also two to three times lower (at least in appearance—we will come back to this) for monogastric animals than for ruminants, mainly as a result of methane emissions caused by enteric fermentation in ruminants (Bellarby *et al.*, 2013).

Figure 13. The different types of grasslands in temperate contexts



Source: adapted from Poux *et al.* (2010).

biodiversity conservation, climate mitigation and nutritional challenges.

Box 3. The different types of grassland and semi natural vegetation, and their contribution to biodiversity

The concept of a grassland is less clear than it might seem. In ecology, it is an open habitat dominated by grasses. But the statistical definition of a grassland in the CAP includes rangelands and spaces that may be rich in woody species, with a series of debates and mechanisms for the inclusion or non-inclusion of these spaces in the agricultural area, the principle being the reality of their use for grazing. In discussions concerning biodiversity, the species richness of a grassland—whether dominated by grasses or not - refers to two key criteria: the frequency of tillage (this criteria being the only one under the CAP, for example) and the intensity of management (not included in the CAP or statistical studies). Grasslands that are regularly tilled can be regarded as grass crops and must be fertilised if the proportion of legumes is too low. They are of little interest for biodiversity (even with legumes when the number of species is limited). On the other hand, long term, unfertilised and especially untreated grasslands/rangelands can be considered as semi-natural habitats and will be rich in biodiversity. Some permanent grasslands, when fertilised and/or overseeded, also lose species richness. Between these two poles is a spectrum of practices ranging from temporary grasslands (in the statistical sense: with a tillage frequency of less than five years) to “long-term” temporary grasslands (tilled every 8 to 10 years). The figure 13 proposes a typology of the different kinds of “grasslands” (and rangelands with or without woody species).

Table 6. Technical bibliographic references used to configure livestock systems

Livestock sector	References used for livestock system	General references used (typologies)
Dairy cattle	(Barataud <i>et al.</i> , 2015)2015 (Coquil <i>et al.</i> , 2014)	(CEAS & EFNCP, 2000) (Solagro <i>et al.</i> , 2016)
	(Réseaux d'élevage <i>et al.</i> , 2005)	(Devun & Guinot, 2012) (Pflimlin <i>et al.</i> , 2006)
Beef cattle	(Chambres d'agriculture <i>et al.</i> , 2014)	(Pflimlin, 2013)
Sheep	(Tchakérian & Bataille, 2014)	(Poux <i>et al.</i> , 2006)2006
Pigs	(Jurjan & Roinsard, 2014)	Not mobilised for granivores
	(Calvar)	
Poultry	(Bordeaux, 2015)	
Laying hens	(Bouvarel <i>et al.</i> , 2013)	

Source: authors

3.4. Livestock production: a redesign linked to crop extensification

3.4.1. Limiting food-feed competition by reducing livestock numbers

In TYFA, the assumptions regarding yield reductions associated with the shift to organic agriculture lead to an overall reduction in crop production and, consequently, in livestock production. Feeding Europeans properly while maintaining a surplus that can potentially be exported thus implies restoring flexibility by rethinking the relationships between agriculture and food. In a context in which almost 60% of cereals and 70% of oilseeds available in Europe are used to feed animals, one of the main margins used in TYFA consists in limiting competition between animal feed and human food. From this perspective, ruminants are of special interest in relation to monogastric animals. Where livestock is concerned, TYFA is thus built on a dual approach:

- the de-intensification / extensification of ruminant production limits the use of concentrates (Cereals and protein crops), while maintaining grasslands and producing omega-3 rich products with acknowledged nutritional benefits. This de-intensification results in a reduction in livestock numbers;
- monogastric numbers (pigs and poultry) are reduced and productivity per animal diminishes, in order to minimise food-feed competition. In this context, monogastric animals act as a “adjustment variable”: the livestock population of monogastric is established in our model by the quantity of feed that remains available for them, depending on the other assumptions made for other compartments of the model.

Table 6 indicates the references used to characterise the different livestock systems. Two types of sources were identified:

1. functional descriptions of individual production systems, engaged in organic agriculture and/or extensive livestock production (first column). These descriptions identify a type of herd management (and therefore an age structure) and associated feed requirements;

2. European statistics and typological studies (second column) to verify orders of magnitude for feed and the use of space and density for herbivore systems (in order to place the reference production systems in a broader statistical sample).

The livestock systems resulting from this approach and from these references are presented in more detail in the following paragraphs.

3.4.2. Ruminants to enhance grasslands and foster biodiversity

Different herbivore systems are envisaged in TYFA. They all maximise the use of extensive grasslands in line with an approach based on non-competition between animal feed and human food. The efficiency of these systems is low if we just look at energy (the conversion of solar energy into plant then animal biomass), but it becomes high if we consider that they make use of what humans cannot eat. The extensive grassland approach implies changing breeds and performance criteria. Physical productivity (the quantity of meat or milk per animal) becomes secondary, in favour of criteria such as hardiness and the ability to eat fodder resources containing more woody species that are available over a longer period. In some cases, herd management may imply grazing animals learning to valorize semi-natural ecosystems. In more detail, several systems are mobilised.

Milk and the co-production of meat

The core of European livestock production remains dairy production, which covers the largest surface area if we include the co-production of meat driven by milk. Two typical dairy systems are modelled and configured in TYFAM (based on CEAS & EFNCP, 2000; Pflimlin *et al.*, 2006; Devun & Guinot, 2012; Pflimlin, 2013):

- a grass-fed system, in which the majority of fodder resources come from permanent grasslands, with an average level of productivity per cow of 5 000 kg of milk/year. This type of system typically corresponds to medium- and high-altitude mountain areas and to a density of 0.9 LU/ha³²;
- a mixed system, in which permanent grasslands are combined with other fodder resources: temporary grasslands, cereals and legumes (alfalfa, clover). The average production level is 7 000 kg of milk/year. In TYFA, this system can be developed anywhere in Europe where agricultural conditions are wet enough, with production levels that vary according to potential. The average density is 1.1 LU/ha (Coquil *et al.*, 2014; Solagro *et al.*, 2016).

Compared to current dairy systems, those in TYFA rely on the use of extensive grassland, which results in specific herd management and structure:

- by a longer lifespan in animals—between 9 (mixed) and 11 years (grass-fed)—and an age at

first freshening raised to 3 years (compared to 2 in current, more intensive systems);

- a direct consequence of this extensification of management is the reduction in replacement rates (which fall to 12.5% or 17%, depending on the management type), with replacement heifers that calve at 3 years;
- a second consequence is the higher relative share of slaughter cattle, heifers not intended for replacement and all males.
- These animals for slaughter are the third system associated with dairy production. Once again, the rationale is to maximise the use of grass in meat production. The modelling of this system is therefore inspired by grass-dominant finishing systems in the Cantal department (Chambres d'Agriculture *et al.*, 2014), from which we take the following characteristics:
 - dual-purpose breeds, suitable for both dairy production and meat production;
 - primarily grass-fed systems—with a smaller proportion of maize and hay from temporary grasslands—which lengthens the production cycle to 34 months. The density is 1 LU/ha.

Two approaches are combined concerning the management of herds in terms of time and space for the three systems: an approach that optimises time spent in barns to recover as much manageable nitrogen as possible; and an approach that fosters pastoralism (which may also involve grouping animals at night and in the morning). The assumptions regarding time spent indoors and outdoors are indicated in Table 14 (section 4.3). These times constitute an important parameter for nitrogen management (Barataud *et al.*, 2015).

It should be noted that in order to simplify the model, we have assimilated the approach to sheep and goat dairy production with that of the cattle sector. In particular, the relative intensification approach—feed supplements required to produce milk—is found in the three species. At the scale at which we work, we assume that this simplification does not question our reasoning.

The other meat ruminant systems

The assumptions regarding milk consumption and exports (which we present in section 3.6), combined with those on the management of systems that we have just described, correspond to the use of 60% of permanent grassland areas in 2010 and to a level of meat production from dairy herds of 23 g/day/person, compared to 173 g/day/person (all species combined) in 2010. There is therefore scope for producing meat on grasslands, in order to maintain them in 2050. Two systems are considered from this perspective:

32. Densities are estimated on the basis of a fodder requirement expressed in t DM/animal divided by assumptions regarding grassland productivity (4.5 t DM in 2050 compared to 5 t DM in 2010).

- a beef cattle system, whose overall approach is similar to the one associated with milk (finishing at 34 months enabling maximum use of grass), with an average density of 0.9-1 LU/ha;
- a sheep system, corresponding to an extensive pastoral approach, with an average density of 0.4 LU/ha (Poux *et al.*, 2006).

3.4.3. Monogastric animals as “decision variables”

The level of development of monogastric animals—pigs and poultry—can be understood implicitly in relation to a use of the UAA that gives first priority to the production of crops directly consumed by humans, and second priority to grass production—with a minimal consumption of compound feed. The production of monogastric livestock is therefore in third place in the model construction process, especially as it does not bring any nitrogen into the cultivated ecosystem: monogastric animals transfer nitrogen from symbiotic fixation by legumes on cropland to other crops on the same land; while nonetheless producing food in the process!

The three monogastric systems—pigs, broiler chickens, laying hens—are described in less detail in technical and management terms than herbivore systems. What we seek to characterise here is the metabolism of these systems: what they produce in quantities of meat (carcass and net) or eggs, what type of feed they consume—distinguishing between feed for energy and feed for protein –, and what they produce in terms of nitrogen. The unit of analysis is the breeding female, to which we attribute a progeny (number of piglets, chicks or chickens, etc.) producing a quantity of products, and consuming a quantity of feed. The technical performances (prolificacy, weight, etc.) are those observed in organic agriculture systems in Brittany.³³

Where feed is concerned, the model is based on real rations in organic systems using European products (Cereals and especially proteins: peas, or even alfalfa instead of soybean) (Bouvarel *et al.*, 2013; Jurjanz & Roinsard, 2014; Bordeaux, 2015; Calvar, 2015). The rations take account of the different types of feed according to age and production cycles, and include oil cakes co-produced by the oil-seed and protein crop sectors for human use. Where nitrogen is concerned, we assume that all of the nitrogen produced in the systems is manageable.

In the monogastric systems modelled, it is considered that the feed is produced on farms or supplied

through feed value chains, following established rations. This approach disregards other ways of feeding these animals which, being omnivorous, can adapt to a wide variety of resources. Besides the possibility to use rangelands for pig production, whose quantitative impact is most probably marginal at the European level, a circular economy approach can potentially provide some very significant leeway. Basing feed requirements on standard rations leaves the majority of nitrogen contained in oil cakes of all kinds (rapeseed, sunflower, soybean, olive, etc.) unused³⁴, not to mention the use of whey. Energy is therefore the limiting factor for producing other granivores, but in this field there are many sources, ranging from beet pulp to a variety of co-products produced by food systems and the recycling of human food “waste”.

Estimating these sources is a field of research in its own right, and goes beyond the current framework of the study. A significant development of this production of granivorous “recyclers” would be an interesting alternative to explore, not so much to increase human consumption of animal protein—which is not the dietary priority –, but to reduce pressure on agricultural land and to contribute to nitrogen transfers (see, for example, EC, 2018). Overall, we adopt the indicative assumption of an “additional” production of monogastric livestock enabled by the use of these co-products corresponding to 1/6 of total production. This value results from assumptions regarding the nitrogen available in oil cakes (but this is not the limiting factor), but it refers especially to the fact that animal protein requirements for human food are largely covered by ruminant production.

3.5. Reducing industrial and energy uses

The bioeconomy is considered as an important component of the transition to a low-carbon society. Its development must make it possible to replace fossil carbon from oil and coal with biomass-derived renewable carbon, for the production of both energy and materials (bioplastics, textiles, construction). From this perspective, a proportion of agricultural production must be gradually directed (or redirected) towards industrial units (bio refineries or biogas plants) that can process them. In addition to its climate

33. This may seem like a strong assumption, but it corresponds to the idea that by 2050, farmers all over Europe will have technical expertise comparable to what is seen in this type of agricultural system. The aim is not to export the current “Breton (industrial) model”, but to generalise a kind of technical support in organic agriculture.

34. A rapid calculation based on oil cakes available/consumed in the model indicates that only 15% of the nitrogen available is necessary for the production of granivores in TYFA in 2050, due to the significant reduction in populations.

benefits—because it limits the use of fossil fuels –, the bioeconomy is often presented as a response to the challenges of re-diversifying agricultural systems, which have been simplified to the extreme. It is indeed deemed to provide new prospects for using crops that have been abandoned or are seldom used in certain production areas (linen, hemp, other protein crops). The development of these new sectors can also create jobs in rural areas, and thus appears as a potential response to the current challenges in many rural parts of Europe (see Colona & Valceschini, 2017). Although so far the production of energy and materials from biomass has generally been in direct competition with human food (with the exception of forest products), the emergence of second and third generation refineries using crop residues (straw, etc.) and microalgae is intended to address this issue in the short or medium term.

These different qualities, and the prospect of decoupling from food production, thus make the agricultural bioeconomy—and, more specifically, its energy component—an important part of many prospective scenarios in this field. Despite these promises, TYFA approaches the bioeconomy from a critical perspective. It assumes that the share of biomass used for energy purposes (natural gas by anaerobic digestion and biofuels) is reduced to zero, and that industrial crops (linen, hemp, etc.) are maintained at 2010 levels. We believe these assumptions are justified in view of the scale effects linked to the development of industrial facilities for the agricultural bioeconomy³⁵. Experience over the last 20 years in this field—concerning in particular biofuels in France (Schott *et al.*, 2010) and anaerobic digestion in Germany (Emmann *et al.*, 2013)—has shown that the development of these installations has resulted in the simplification of cropping systems in their supply area, whereas an agro-ecological approach requires, on the contrary, greater diversification. The investment represented by these installations means their profitability is in fact dependent on a critical size, below which the investment costs can no longer be covered by the operational profits, and therefore on the need to source their raw materials within a limited distance. Although the development of small-scale biorefineries (Bruins & Sanders, 2012) or community biogas plants (ADEME, 2010; Couturier, 2014) has been proposed as a possible response to these questions, assuming their generalisation against the argument of economies of scale is, in our view, difficult.

The possibility of using anaerobic digestion in the context of the TYFA scenario was a critical issue

when evaluating its GHG emissions (see section 4.4). Indeed, a biogas plant is able to “digest” all types of biomass in order to transform them into biogas and reactive nitrogen, which can be used as an equivalent to mineral nitrogen. From this viewpoint, a biogas plant can be considered as an effective substitute for a herd of cattle: it can simultaneously use grasslands (by digesting the grass they produce), and therefore maintain their associated biodiversity, and ensure nitrogen transfers from the *saltus* to cropland, while radically reducing GHG emissions, since biogas plants do not produce methane from enteric fermentation (Couturier, 2014). However, in the scenario in its present form, we have initially chosen not to use anaerobic digestion for two main reasons: the economic approach mentioned above, and the fact that the nitrogen produced in this way is in mineral form, and therefore has the same impacts as synthetic nitrogen. This approach to anaerobic digestion is a key discussion point in TYFA³⁶.

3.6. Sustainable diets for an agro-ecological system

To be coherent, the definition of a sustainable diet must take account of all the dimensions covered by the definition proposed by FAO:

“Sustainable diets are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources.” (FAO, 2010, *Sustainable Diets and Biodiversity*).

Four dimensions are generally considered: nutritional, cultural, economic and environmental (adapted from Johnston *et al.*, 2014). Until recently, dietary recommendations were made at the national level by combining nutritional and cultural elements, and relatively less attention was given to the two other aspects. In line with EFSA (2010), these recommendations are based on a balance between, first, the need to cover nutritional requirements while avoiding the risks and maximising the benefits associated with the consumption of certain

35. The situation is different for the anaerobic digestion of urban waste.

36. On the other hand, another circular economy sector is present in TYFA, consisting in recycling organic flows for animal feed (recycling urban “waste”) and for the management of nutrient flows (nitrogen and phosphorus). We will return to this in section 4.3.

food groups and, second, the need to not stray too far from existing eating habits in order to ensure people adopt the recommendations.

Over the last 10 years, different studies have sought to simultaneously address three or four of the dimensions of a sustainable diet (nutritional, cultural, environmental and economic) in order to propose diets at the national or European levels. These result in a relatively broad range of proposals, as shown in Table 7 presenting the daily consumption values proposed in these studies for different food groups.

In this first version of the TYFA scenario, based primarily on agro-environmental considerations, the economic aspects have not been taken into account and the cultural aspects have been considered at the European level, taking no account of infra-regional/national specificities. The definition of an “average” sustainable diet for the whole of Europe, in line with

the agro-ecological principles presented above, is built on the combination of three dimensions: nutritional benchmarks (as presented in section 2.2); a departure from existing eating habits (as a proxy of the cultural dimension); and environmental challenges (biodiversity, land use, and climate change). The outcome is presented in Table 8. Like other components of TYFA, this 2050 diet proves compatible with the nutritional criteria used, without suggesting that it is the only one possible.

From a cultural viewpoint, the diet was constructed from the “average” food matrix rebuilt for 2010 (Figure 14); although it involves certain changes, in particular for proteins (a reduction in animal proteins and an increase in plant proteins), sugar (a significant reduction), and fruit and vegetables (a much higher proportion), these changes are comparable in scope to those that occurred between 1962 and 1990 for meat and vegetable oils (see section 2.2).

Table 7. Assumptions regarding consumption for several food groups in a number of studies similar to TYFA (European or national level)

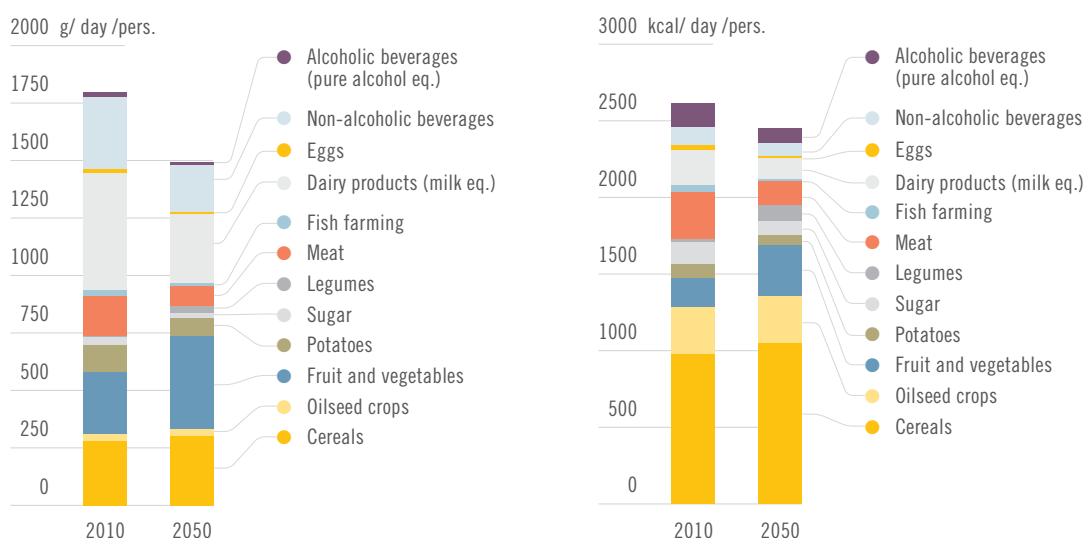
Food category	Recommendation range (g/pax/day)	References used
Cereals	240-380	(Westhoek <i>et al.</i> , 2014 ; WWF & Friends of the Earth Europe, 2014 ; WWF, 2017)
Legumes	4-90	(Mithril <i>et al.</i> , 2012 ; van Dooren <i>et al.</i> , 2014 ; Westhoek <i>et al.</i> , 2014)
Meat (white and red combined)	30-150	(van Dooren <i>et al.</i> , 2014 ; Westhoek <i>et al.</i> , 2014 ; WWF & Friends of the Earth Europe, 2014 ; ANSES, 2016b ; Solagro <i>et al.</i> , 2016 ; WWF UK, 2017)
Milk and dairy products	300-450	(Mithril <i>et al.</i> , 2012 ; van Dooren <i>et al.</i> , 2014 ; ANSES, 2016b)
Eggs	11-29	(Mithril <i>et al.</i> , 2012 ; van Dooren <i>et al.</i> , 2014 ; Westhoek <i>et al.</i> , 2014 ; WWF & Friends of the Earth Europe, 2014 ; Solagro <i>et al.</i> , 2016)
Vegetables	200-300	(van Dooren <i>et al.</i> , 2014 ; WWF & Friends of the Earth Europe, 2014)
Fruit	200-277	(Mithril <i>et al.</i> , 2012 ; van Dooren <i>et al.</i> , 2014 ; WWF & Friends of the Earth Europe, 2014)
Potatoes	25-350	(Mithril <i>et al.</i> , 2012 ; van Dooren <i>et al.</i> , 2014 ; WWF & Friends of the Earth Europe, 2014)

Sources: compilation of different studies, cited in the Table

Table 8. The diet proposed in TYFA

Consumption and intake	total	Energy	Protein	Carbohydrates	Lipid	Sugar	Fibre
	g/day	Kcal	g/day	g/day	g/day	g/day	g/day
Cereals	300	1 047	32	197	9	6	21
Oilseeds	34	306	0	0	34	0	0
Fruit and vegetables	400	331	11	23	18	19	11
Potatoes	80	65	2	13	0	1	1
Sugar	23	92	0	23	0	23	0
Legumes	30	100	8	15	0	0	2
Meat	92	165	17	0	17	0	0
Fish from fisheries	10	16	2	0	1	0	0
Dairy products	300	137	4	0	0	0	0
Eggs	10	14	1	0	0	0	0
Sweetened beverages	204	79	1	16	0	16	1
Alcoholic beverages	14	101	0	20	0	20	0
Total with beverages		2 265	82	286	82	64	36
Total without beverages		2 445	83	323	82	100	37

Source: TYFA_m

Figure 14. Assumptions regarding diets in TYFA and comparison with the 2010 diet

Source: TYFam for 2050 and (EFSA, 2017a) for 2010.

Table 9. Detail of the composition of meat consumption, comparison 2010-2050

In g/day	2010	2050 / TYFA	Δ 2050/2010
Beef	32	31	-3%
Pork	88	36	-60%
Poultry	58	20	-66%
Lamb/goat	5	5	=

Source: authors

Table 10. Positioning of the TYFA diet compared to 2010 and to the main nutritional benchmarks used

	Benchmarks	2010	2050 / TYFA	Gap 2010-TYFA
Total calorie intake (kcal/day)	2 300	2 606	2 445	- 6%
Proteins (g/day)	50	100	83	- 17%
<i>Including: upper limit for animal protein (g/day)</i>	35	58	29	- 50%
<i>Including: upper limit for red meat (g/day of meat)</i>	70	120	67	- 44%
Carbohydrates (kcal/day)	950-1 400	1 350	1340	=
<i>Including: upper limit for sugar (g/day)</i>	100	360	100	- 72%
Lipids (kcal/day)	690-920	760	760	=
<i>Including: recommended ratio between Ω6 / Ω3</i>	3-8	> 10	n.d.	n.d.
Fibres (g/day) : satisfactory intake vs minimum intake (colorectal cancer)	30-100	27	37	+ 37%
Fruit and vegetables (g/day) : recommended intake	400	268	400	+ 50%

Source: authors, according to TYFam and (ANSES, 2016b; EFSA, 2017a)

Finally, on the environmental level, three criteria were taken into account: land use; the need to introduce symbiotic nitrogen; and the need to maintain grasslands in order to conserve biodiversity. These three criteria led us to (i) give an important share to legumes in order to simultaneously maximise nitrogen provision to crops and protein intake in feed; (ii) minimise the share of monogastric animals in meat

consumption, since cereal-based feed for these animals is in direct competition with human food; (iii) ensure the level of consumption of products of bovine origin (milk and meat) remains sufficient to enable maximum use of permanent grasslands. In this respect, the assumptions regarding diets in TYFA differ from those generally adopted in similar exercises: the share of red meat is higher than that of white

meat, this being the only way to preserve permanent grasslands without anaerobic digestion (Table 9).

The definition of this average diet then enables us to estimate the demand for raw products by 2050, based on three parameters: (i) population growth, for which we have used the Eurostat assumption of a population of 528 million people in 2050; (ii) the usage coefficients for each product (for example, 98% of a tonne of cereals produced can be directly used as feed, compared to 15% for a tonne of sugar beet); (iii) and the level of waste. With regard to the latter point, we adopted a very cautious assumption of a 10% improvement: we continue to lose 90% of what is lost today. This choice, which can be adjusted, is justified by the idea of concentrating the analysis at this stage on the agricultural conditions of the transition to agroecology, rather than on the social conditions.

3.7. Summary of key assumptions

Figure 15 summarises all of the key assumptions used to configure TYFAM for the development of the scenario. These are to be considered as a whole rather than individually.

Figure 15. Main assumptions of the TYFA scenario

- 1 Fertility management at the territorial level that depends on:
 - The suspension of soybean/plant protein imports
 - The reintroduction of legumes into crop rotations
 - The re-territorialisation of livestock systems in cropland areas
- 2 The phase-out of synthetic pesticides and the extensification of crop production - all year soil cover: organic agriculture as a reference
 
- 3 The redeployment of natural grasslands across the European territory and the development of agro-ecological infrastructures to cover 10% of cropland
 
- 4 The extensification of livestock production (ruminants and granivores) and the limitation of feed/food competition, resulting in a significant reduction in granivore numbers and a moderate reduction in herbivore numbers
 
- 5 The adoption of healthier, more balanced diets according to nutritional recommendations
 - A reduction in the consumption of animal products and an increase in plant proteins
 - An increase in fruit and vegetables
- 6 Priority to human food, then animal feed, then non-food uses
 

Source: authors.

4. THE AGRO-ECOLOGICAL EUROPE OF 2050 IN THE TYFA SCENARIO: RESULTS AND KEY FINDINGS

The set of parameters defined in the previous section enables us to simulate the functioning of an entirely agro-ecological European food system. This fourth and final section highlights the key findings of this simulation on four interdependent levels: (i) agricultural production, the evolution of diets and agricultural exchanges; (ii) land use changes resulting from this scenario; (iii) the nitrogen balance and fertility management; and (iv) the broader environmental impacts of the scenario (GHG emissions and biodiversity impacts). A final subsection analyses the sensitivity of these simulations to alternative assumptions in order to test the robustness of the model and the framework proposed.

4.1. Production, exchanges and diets in 2050

The first key finding of TYFA is that agricultural production (crop production + livestock production) under the assumptions set out in section 3 is sufficient to meet European demand for food in 2050, despite a significant decline in total production (-30% in kcal equivalent, see Figure 16 and Figure 18). This result is achieved by the widespread adoption of a lower calorie, more plant-based, and therefore less agriculturally intensive diet.

The satisfaction of these needs also entails a certain amount of leeway. Indeed, only 92% of the UAA (including 52 million ha of natural grasslands and 10 million ha of agro-ecological infrastructures) is required to meet the needs of Europeans with the diet proposed. The remaining 8% of the UAA (or just under 16 million ha) is allocated according to two objectives: maintaining permanent grasslands, and maintaining export capacity for cereals to the Mediterranean countries.

Maintaining almost the same proportion of natural grasslands as in 2010 (58 million ha in TYFA

2050 compared to 60 million in 2010) is achieved by increasing dairy herds. This generates a surplus of dairy products corresponding to 20% of dairy production, which can be exported, providing benefits in terms of both biodiversity and the balance of trade³⁷. Moreover, this dairy production, which is more grass-fed and extensive in 2050 than in 2010, no longer imports soybean or other proteins.

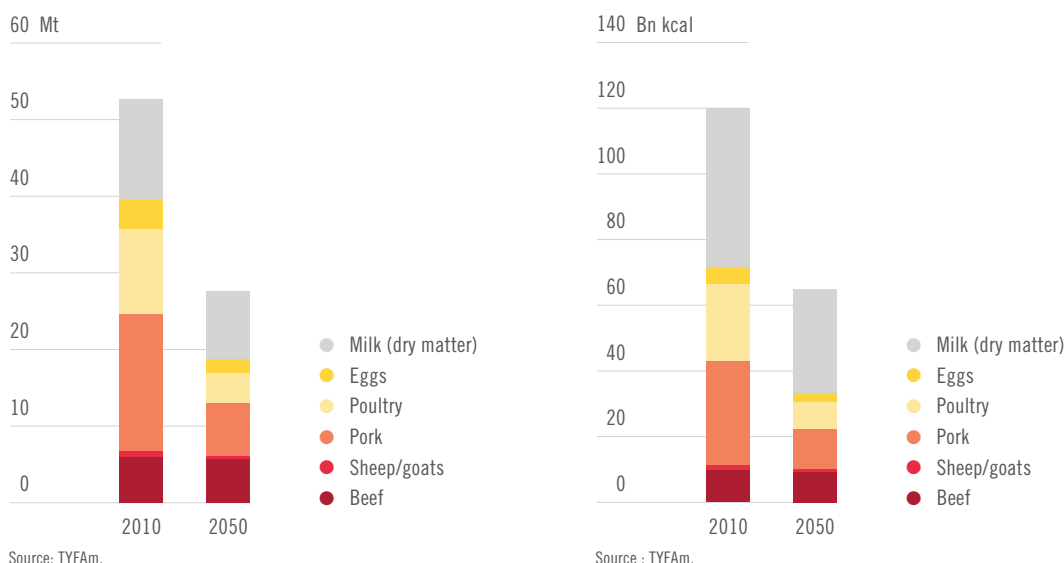
The rest of the UAA not used directly to meet European food requirements is allocated to cereals. Indeed, the reduction in granivore production combined with the extensification of ruminant production substantially reduces domestic demand for cereals and therefore maintains export capacity in cereals, with the primary outlet for these crops in 2010 being animal feed. The entirety of this “additional” production is assumed to be wheat, for two reasons: on an economic level, this cereal being the most widely traded at present and the most conducive to achieving food security objectives; and on an agricultural level, in order to maintain a balance between wheat and the other coarse cereals in rotations similar to those currently observed in organic agriculture (see section 4.2.2). Overall, the scenario maintains a wheat surplus in the order of 12 million tonnes, comparable to the average import-export balance of the EU-28 in the 2000s.

4.1.1. Changes in livestock production

The TYFA assumptions have major impacts on livestock production. Three assumptions are more particularly key: (i) an overall reduction in consumption and exports of animal products; (ii) a relatively higher share of herbivores in animal protein supply; and (iii) the extensification of

37. In principle, this grassland conservation objective could also be achieved by exporting meat from grass-fed ruminants. But this assumption is less robust on the economic level: European meat does not have the advantage of its dairy products in international trade, and it generates less added value.

Figure 16. Evolution of livestock production between 2010 and 2050, in tonnes (dry matter for milk) and in kcal



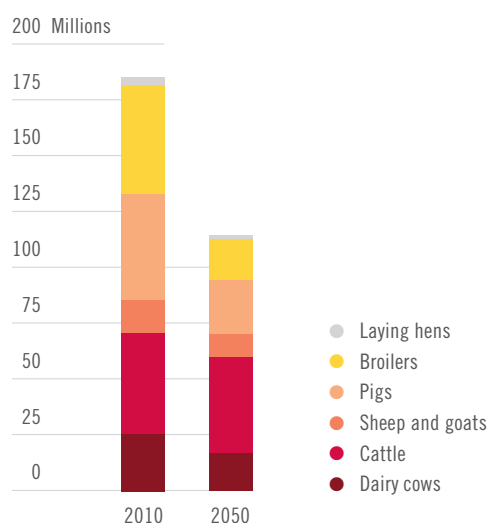
livestock production, which results in a decline in the number of animals that is not proportional to the decline in production.

Livestock production declines by approximately 40% in tonnage and in calories, largely due to the decline in the production of granivores and of pigs in particular, but also of dairy products (~31% between 2010 and 2050). The reduction in granivore herds is also amplified by the return to a zero trade balance for these products—which in 2010 stood at respectively 10% and 3% of production for pigs and poultry). On the other hand, this assumption of a zero trade balance limit the reduction in sheep and goat herds, as the equivalent of 18% of consumption was imported in 2010, compared to 0 in 2050.

The level of beef production is maintained at a similar level by 2050 through the extensification of grass-fed dairy production. Two factors are combined, the second of which is critical in the equation:

- the lower productivity per unit for cows requires more animals in order to produce the same amount of milk (5 500 kg/DC/year on average in TYFA, compared to 6 400 kg/DC/year in 2010);
- changes in dairy herd management associated with the increase in the number of lactations induces: (i) a reduction in the proportion of heifers for replacement (which falls from a third to a quarter) and thus, automatically, an increase in heifers for fattening; (ii) a higher number of animals (heifers and calves) produced in the life-cycle of a dairy cow, per kilo of milk produced. Overall, the ratio of “dairy beef per kilo of milk produced” increases due to the increase in dairy progeny.

Figure 17. Changes in livestock numbers between 2010 and 2050

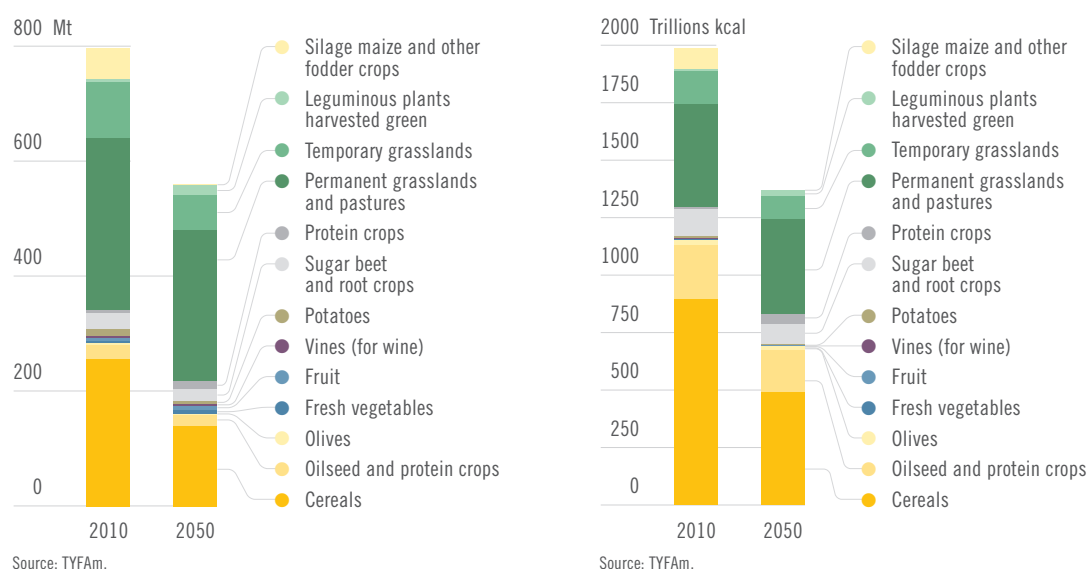


N.B.: the “Cattle” category includes all cattle, excluding dairy cows, including suckler cows (which represent 4.5 million heads in 2050 compared to 17 million for dairy cows).

Source: TYFAM.

Overall, maintaining a certain production and therefore consumption of beef is largely the result of the assumptions regarding the conservation of grassland areas and the extensification of the associated dairy production. The fact that this dairy beef production³⁸ in 2050 corresponds to the 2010 level of consumption is a coincidence, not a

38. Including when counting exports.

Figure 18. Changes in crop production in the “European farm” between 2010 and 2050 in Mt and kcal

structural assumption of the diet. The large amount of beef available reduces the amount of meat to be provided by granivores, to remain within the limits of guidelines on animal proteins.

4.1.2. The evolution of crop production

The evolution of crop production is to be viewed in the context of the respective changes in human consumption (food) and animal consumption (feed)—which accounts for the larger part of volume. This animal consumption itself depends on the assumptions regarding livestock systems, in particular the use of fodder resources from temporary and permanent grasslands, as well as those regarding yields from these grasslands. The shift towards more grass-fed ruminant production reduces the use of grain maize and, consequently, of crop proteins (imported soybean or others).

Figure 18 summarises changes in production, expressed in tonnes of dry matter and in energy.

4.2. Land use associated with production

4.2.1. Land use changes that mainly concern arable land

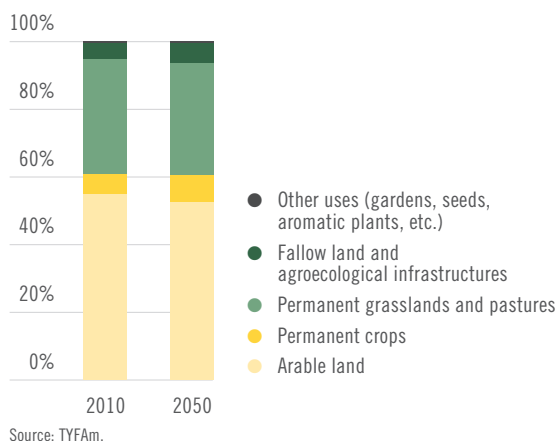
Land use at the level of the European farm follows logically from the crop production levels (food and feed) described above, as well as from yield assumptions. The areas utilised are calculated crop by crop, taking account of the different uses.

The uses presented above in a very analytical manner can be grouped into broad land use categories, as shown in Figure 19.

These broad categories (arable land, permanent crops, permanent grasslands and rangelands, non-productive land) only change slightly. The fraction of permanent grasslands is assumed to remain unchanged. Land under permanent crops increases by 30% (as a result of the increase in fruit consumption) to the detriment of arable land, but at the level of the European farm, since these crops account for only 6% of the UAA, these changes do not fundamentally alter land use per broad category. It is worth noting the special case of the “fallow land and ecological infrastructures” category, whose ecological function changes between 2010 and 2050. In 2010, this land has an “ecological compensation” rationale in a largely intensive agrarian environment.

In 2050, all agricultural land is managed extensively based on a variety of crops and types of land use, along with extensive grasslands that play a key role in the ecological structure. The ecological infrastructures of 2050 thus complete an agricultural approach that ensures levels of ordinary biodiversity that are already far higher than those seen today, in order to provide ecosystem services that the agricultural approach alone could never achieve. Their significant presence in the UAA—assuming 10% of arable land and permanent crops—reflects an environmental ambition that impacts land use. In practice, some of this land could have a pastoral function and be added to the “permanent grasslands” and “rangelands” categories.

Figure 19. Evolution of agricultural land use by broad category



The main changes of land use are thus in arable land (see Figure 20).

We note a reduction in the fraction of cereals in favour of protein crops and legumes harvested green (alfalfa, clover), which together account for a quarter of arable land. Silage maize declines with the grass-fed approach to dairy production. Temporary grasslands also decline, but to a lesser extent. This latter finding may seem surprising given that these grasslands are currently associated with organic livestock production. This is explained by the fact that in 2050, these temporary grasslands compete with permanent grasslands to provide hay/forage.

In cereal cropland, the assumptions used in TYFAM result in a reduction in the fraction of wheat and an increase in hardier cereals such as oats or cereal mixes (Figure 21). But these assumptions are not the most significant in the model in the sense that, at the scale of this analysis, the different cereals are generally interchangeable in use, with the exception of wheat and durum wheat for human consumption and malting barley.

4.2.2. An analysis in terms of changes in land use categories and rotations

The reasoning in TYFAM focuses on the “European farm” level, and the land use described in the previous section stems conceptually from the sum of different regional situations. Without proposing a detailed analysis, this section addresses two issues enabling us to link the reasoning at the global level to regional situations that will need to be taken into account in the next part of the process.

In terms of broad categories of land use

Two points emerge on this issue. First, although the increase in permanent crops does not appear

Figure 20. Evolution of overall crops' share in arable land

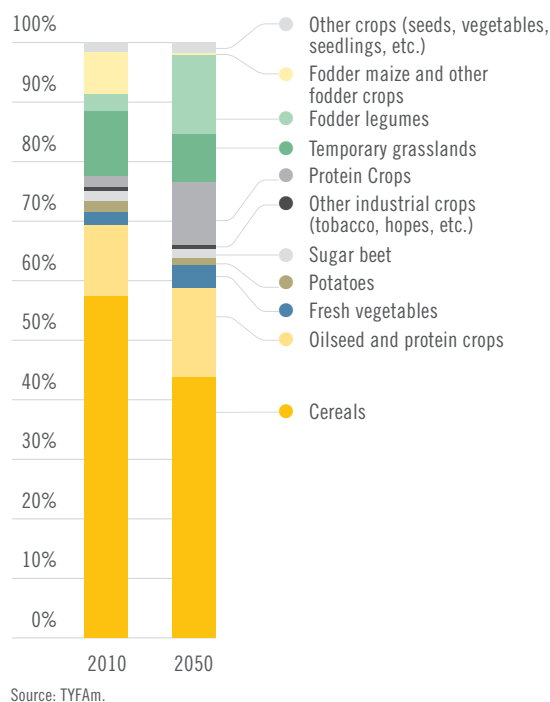
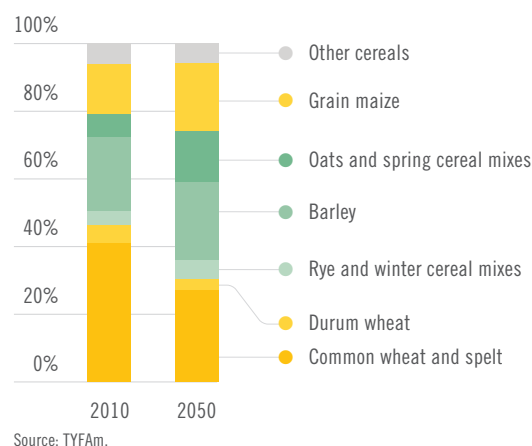


Figure 21. Indicative evolution of the composition of cereal cropland



as the most problematic aspect—it is easier to envisage turning arable land into permanent crops than vice versa, because of soils and slopes, in particular—it can lead to significant changes in some regions, especially in the Mediterranean. The underlying logic consists in better distributing fruit crops across Europe to reduce regional specialisation. This could entail moving Mediterranean tree

crops that are currently irrigated (especially citrus fruits) further north, into rainfed systems; and re-balancing Mediterranean cropland through an increase in grasslands, rangelands and dry arable crops.

Second, one of the key aspects of TYFA involves mobilising permanent grasslands for biodiversity conservation reasons, but also for nitrogen transfer, which implies redeploying these grasslands (and therefore the associated herbivore production) in areas currently used for field crops. Given that the area of permanent grassland remain quasi constant in 2050 (compared to 2010), some grasslands located in grass-dominant areas will have to be tilled and sowed, to offset the reintroduction of grasslands in areas that are currently in predominantly arable regions. This diversification in specialised grassland regions also has agricultural, zootechnical and environmental advantages. The challenges of quantifying such category changes at the regional level will need to be specified during a future phase in which the assumptions will be regionalised, but this analysis produces a conceptual distinction between three categories of permanent grassland:

- those that are necessarily grass-dominant and constitute the “core” whose function will not change;
- those that are currently in grass-dominant areas, but which could be turned into arable land; these grasslands may correspond to those declared as permanent in the 2010 statistics for public policy reasons, but which are actually successive temporary grasslands, and/or to areas that were recently cultivated (within the last 50 years);
- the new permanent grasslands in 2050, reclaimed from arable land³⁹.

In terms of rotations

The reasoning in TYFA_m is based on agricultural product requirements for human food and animal feed, the sum of which defines an average crop rotation system at the European level. This raises the question of the coherence of this system with plausible rotations on arable land (permanent crops, grasslands and rangelands not being concerned by rotations). In other words, is the average rotation on the arable fraction of the UAA agronomically consistent and compatible with organic agriculture cropping systems?

Barbieri *et al.* (2017) identify different characteristics of rotations in organic agriculture

(OA) compared to those in conventional agriculture. Their conclusions are presented for an analysis at the global level, but the data for Europe correspond and the following points can be highlighted:

- rotations in OA are longer and more diverse than conventional rotations;
- they associate primary cereals (common and durum wheat, maize) and coarse cereals (barley, oats, rye, triticale, spelt, etc.), protein crops, oilseed crops, industrial crops and temporary grasslands. Intercropping are much more developed in these rotations, especially for fertility management reasons;
- the share of legumes is high (input of nitrogen into the system), as is that of temporary grasslands (contribution to weed management).

The results of TYFA_m converge with the points above, with the notable exception of the role of temporary grasslands, which are “replaced” by legumes harvested green that can be equated with artificial grasslands. These then play the same agricultural role as temporary grasslands in terms of weed management, but contribute to nitrogen inputs through symbiotic fixation.

Beyond this overall agriculture coherence of arable land use in TYFA 2050, we analysed its coherence in terms of crop rotations. Contrary to conventional agriculture, where access to chemicals makes less necessary to think in terms of prophylactic measures or closing nutrient cycles, agro-ecological rotations require a combination of cropping patterns that are agriculturally coherent in terms of the management of fertility, diseases and weeds. Consequently, organic rotations generally combine several succession planting patterns—some of which include legumes (in multi-annual cropping or relay cropping, especially for fertility reasons). In these patterns, straw cereals follow the break crops (non-straw cereal crops considered to be a “good” option before planting cereals) or multi-annual fodder legumes.

The average rotation in TYFA_m 2050 can be interpreted coherently as the combination of the following patterns (from (a) to (e)) at respectively 24%, 21%, 18%, 31% and 7% of cropland.

a) Break crop (BC)—wheat; b) BC—wheat—coarse cereal; c) Temporary grassland—temporary grassland—maize-wheat; d) Fodder legume (3 years)—wheat-(coarse cereal)—“BC”/annual fodder—wheat; e) Maize-maize-wheat.

We can thus explain the whole arable land use (break crops, temporary and artificial grasslands and cereals) with rotations consistent with an agro-ecological approach.

39. It is worth remembering that in these arable regions, ecological infrastructures are added to permanent grasslands.

Table 11. Key characteristics of crops share used for crop rotation analysis

	2010	2050
% Cereals/arable	57%	45%
% Pulse crops/legumes	5%	25%
% Spring crops	29%	28%
Wheat+corn (main cereals)/Total cereals	56%	52%
Temporary grassland / arable land	11%	8%
Temporary grassland+green legumes/arable	14%	20%

Source: TYFAM

4.3. The nitrogen balance: 2050 results and points of comparison

4.3.1. Calculating the 2050 nitrogen balance

As indicated in section 2, TYFAM enables us to produce the nitrogen balance for *cultivated land*. In the TYFA 2050 scenario, there are three types of inputs:

- synthetic mineral nitrogen (whose default value is 0);
- organic fertiliser from managed manure, which is equated with nitrogen excreted in buildings (everything for granivores, a fraction depending on the grazing time vs stable time for herbivores). These inputs vary according to the nitrogen contained in crops used for animal feed;
- symbiotic fixation by legumes directly in rotations.

Outputs from cropland are equivalent to the nitrogen content of all crops harvested, picked or mown, whether for human food, animal feed or industrial uses. The share of nitrogen exported by crops is of course dependent on yields according to a linear relationship presented in the annex (Anglade *et al.*, 2015).

Producing a input-output balance makes it possible to test a *necessary condition* for an adequate supply of nitrogen for crops—a condition that is obviously not sufficient. Here, the default reasoning is: a negative balance for inputs from European legumes alone (since proteins are no longer imported for animal feed) would indicate that the assumption that “we can do without nitrogen fertilisers” is not valid. A positive balance means that the assumption is valid on the whole, but that it must be tested at finer levels than Europe, and especially the territorial level—which is not possible with the current version of TYFAM.

Outputs by crops

Table 12 indicates nitrogen outputs by crops. Net nitrogen outputs away from the cultivated land ecosystem stand at just over 10.5 million tonnes at the European level. It should be noted that as regards permanent grasslands and rangelands—non-fertilised and used extensively in TYFAM –, we consider that net outputs occur through livestock production, and that the spontaneous presence of legumes supply enough nitrogen to these (see footnote 31).

Inputs from legumes in rotation

Table 13 summarises nitrogen inputs by legumes in rotation⁴⁰.

Inputs from livestock waste (manure)

Nitrogen inputs from waste, in the form of manure, depend on herd structure and, for herbivores, on the time spent in barns corresponding to the production of manageable nitrogen. Table 14 indicates calculation methods for dairy herds: dairy cows, dairy progeny and dairy beef animals (heifers and finished dairy calves).

Without going into detail in the main report, the reasoning is similar for the other animal products, with an assumption of total nitrogen recovery for granivore production. On the basis of this reasoning and calculation, Table 15 indicates the production of available nitrogen by livestock.

40. Note that permanent crops export just under 377 kt of nitrogen, or less than 4% of the total nitrogen output: inputs in rotations are therefore central to the nitrogen issue.

Table 12. Nitrogen outputs by crops

Crop	Area (ha)	Yield (tonnes/ha)	% nitrogen in output share (including straw)	Total nitrogen output
Common wheat and spelt	10 956 266	4.20	1.88%	866 968
Durum wheat	1 399 662	2.46	2.35%	80 757
Rye and winter cereal mixes	2 284 501	2.45	1.75%	97 973
Barley	9 297 821	3.28	1.70%	518 819
Oats and spring cereal mixes	6 196 589	2.17	1.80%	241 757
Grain maize	8 153 085	5.39	1.20%	527 725
Other cereals	2 082 299	1.41	1.50%	44 015
Rice	389 441	5.13	1.20%	23 968
Rapeseed	5 294 674	1.60	2.90%	244 999
Sunflower	5 792 496	1.48	2.40%	205 091
Soybean	2 464 995	2.28	5.50%	308 975
Other oilseed crops	328 049	2.15	2.50%	17 601
Olives	5 367 051	0.62	2%	66 476
Fresh vegetables	3 632 208	16.76	0.2%	121 739
Fruit	2 879 324	9.82	0.18%	50 869
Nuts	1 545 633	2.00	3.00%	92 738
Citrus fruits	947 040	8.03	0.18%	13 696
Cultivated mushrooms	50 951	64.00	0.18%	5 870
Vines (for wine)	3 006 597	5.59	0.73%	126 770
Potatoes	1 059 441	20.30	3.40%	731 093
Sugar beet	1 411 739	54.36	1.10%	844 162
Pulses (grain protein crops)	9 761 372	1.57	3.50%	535 991
Temporary grasslands	7 569 685	8.10	2.50%	1 532 861
Fodder legumes	12 203 016	8.88	3%	3 251 442
Grain maize	458 654	11.21	1.15%	59 105
Total nitrogen output				10 611 459

Source: TYFAM

Table 13. Nitrogen inputs to cropland through symbiotic fixation by legumes in rotation

Crop	Production (in tonnes)	Nitrogen fixed = f(production) (t _N /t _{product})	Total nitrogen fixed
Soybean	2 464 995	0.059	145 193
Legumes	9 761 372	0.059	574 966
Temporary grasslands (net input from below ground)	7 569 685	0.102	775 253
Fodder legumes	12 203 016	0.341	4 165 925
Legumes in intercropping*	26 221 944	0.05	2 581 392
TOTAL N fixed by N fixing crops in rotations			8 242 730

Source: TYFAM. *These intercropped legumes are assumed to account for 100% of all intercropping, which covers all land under spring crops ("0 bare soil"). Their estimated yield is 2 t DM/ha (Anglade, Billen, & Garnier, 2015).

Table 14. Calculation of nitrogen production potentially available for crops—examples of herds associated with dairy production

	Nb of heads	N product / head (kg/head) (CORPEN data)	% grazing time	N available / head	Total nitrogen (in tons)
Dairy production					
No. dairy cows	17 239 256	85	25%	64	1 085 156
no. heifers 0-1 years	2 657 719	25	50%	13	33 221
no. heifers 1-2 years	2 657 719	42	50%	21	55 812
no. heifers 2-3 years	2 657 719	72	50%	36	95 678
Meat production					
No. dairy cows	2 154 907				
Heifers:					
no. heifers 0-1 years	5 961 909	25	50%	13	74 524
no. heifers 1-2 years	5 961 909	42	50%	21	125 200
no. heifers 2-3 years	5 961 909	72	30%	50	300 480
Males for meat production					
no. males 0-1 years	8 619 628	25	50%	13	107 745
no. males 1-2 years	8 619 628	42	50%	21	181 012
no. males 2-3 years	8 619 628	72	30%	50	434 429
Total net available N for crops (t)					2 225 655

Source: TYFAM

Table 15. Nitrogen potentially available for crops through transfers from livestock waste

Available N from manure	t N
From dairy sector and induced meat production	2 225 655
From meat-beef sector	451 704
From hens	89 979
From pigs	331 441
From broilers	126 030
From sheep and goat	102 029
Total	3 326 837

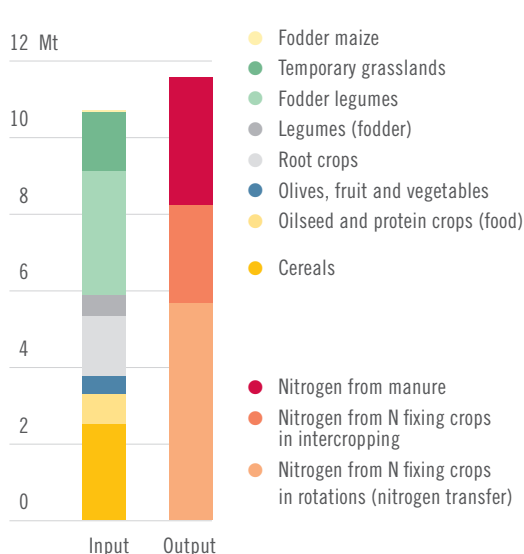
Source: TYFAM

The distribution of nitrogen sources shows the prevalence of herbivores in this contribution, which is consistent with the general assumptions regarding the conservation of permanent grasslands combined with moderation in the consumption of animal proteins.

A balance around an equilibrium in 2050—elements for discussion

Figure 22 summarises the components of the balance. The balance indicates a very slight surplus, with an input/output ratio (before integration of additional sources, see below) of 109%. Under the assumptions made, and at the European level, nitrogen available for crops could therefore theoretically cover what leaves the cropland ecosystem in terms of the material balance, but at the cost of radical improvements in nitrogen use methods and loss limitation.

Figure 22. Nitrogen balance in TYFA 2050



Source: TYFAM.

4.3.2. Elements of comparison and discussion

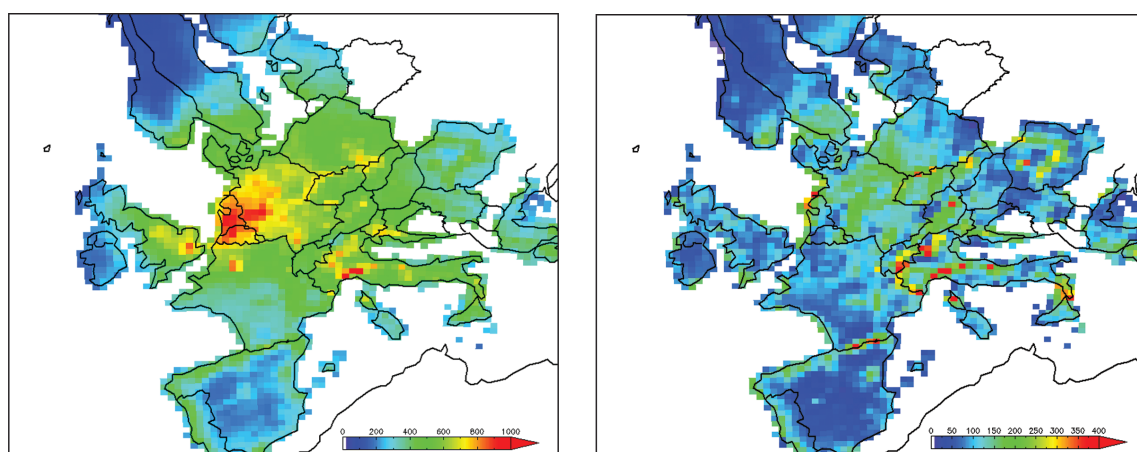
Interpretation of the nitrogen balance at the global level

The studies that come closest to the balance produced in TYFAM are those conducted by Lassal-etta, Billen and Garnier (2014; 2016). Their balance is also centred on cultivated land, with the inclusion of inputs from synthetic fertilisation, manure

Table 16. Comparison of nitrogen balances at the European level, 2010 and 2050 (million tonnes of N)

	European Nitrogen Assessment				Lassaletta <i>et al.</i> 2016		TYFAM	
	Integrator	IDEAg	MITERRA	IMAGE	2009	2050	2050	2050
Reference year	2000	2002	2000	2002	2009	2050	2050	2050
Biological fixation	1.3	1	0.8	1.4	1.7		8.2	8.2
Manure	10.3	8.8	10.4	9.8	3.5	n.d.	3.3 (fumier maniable seul)	5.3 (fumier seul)
Synthetic fertilisers	11.5	11.4	11.3	11.3	9		0	0
Atmospheric depositions	2.7	2.1	2	2.8	1.2		n.d.	n.d.
TOTAL	25.8	23.3	24.5	25.3	15.4	4.2	11.5	13.5
Removal by crops	15.4	12.5	11.3	13.5	9	3.8	10.6	10.6
Inputs/outputs (without atm. deposition.)	150%	170%	199%	167%	158%	111%	109%	128%
N efficiency (without atm. deposition)	67%	59%	50%	60%	63%	90%	92%	78%

Source: de Vries *et al.* (2011, p. 324); Lassaletta *et al.* (2016); TYFAM

Figure 23. Spatialisation of atmospheric nitrogen deposition (all types)

Source: Simpson (2011b). The map on the left is the result of the aggregation of seven models; the one on the right indicates the variability of results. The scale is in kg/ha.

(usable fraction, as in TYFAM), symbiotic inputs and, unlike TYFAM, atmospheric deposition.

Over and above the value expressed in a few percentage points, the conclusion that emerges is one of an extremely tight nitrogen balance, which could be workable. This result cannot be interpreted in an unequivocal, definitive manner, especially as there is significant uncertainty. We will return to this discussion on the margins of uncertainty as part of a comparison between approaches adopted at the European level.

The paper by Lassaletta *et al.* (2016) also includes a 2050 scenario called the Self-Sufficiency Equitable Diet, which is relatively similar in its assumptions to TYFA and can thus serve as a reference for our 2050 discussion. Chapter 15 of the European Nitrogen Assessment (ENA) (de Vries *et al.*, 2011) also proposes a comparison of European nitrogen balances based

on different models, which identifies the different approaches used. Table 16 proposes an overall comparison of the balances available, compared with TYFAM estimates for 2050⁴¹.

The comparison between the nitrogen balances for the different categories (inputs and outputs) in studies that evaluate the current situation and, on a prospective level, between the scenario by Lassaletta *et al.* (2016) and TYFA, points to two conclusions:

41. The nitrogen balance produced by Eurostat at the European level that we drew on in section 2 could also have been used here. However, it does not distinguish the share of manageable nitrogen in animal waste, which is likely to be transferred to the cropland ecosystem. Moreover, outputs include permanent grasslands (Eurostat, 2013, 2018), unlike the balances presented here, which focus on cropland.

- An overall convergence in the estimation of nitrogen efficiency at the European level (between 50 and 67% in the current situation), but with highly variable results. Table 16 thus highlights the importance of the perimeters and parameters to consider in the comparison of balances. The balances studied in the ENA include all nitrogen excretion in animals, whereas Lassaletta and TYFA only count nitrogen actually available for cultivated land. The Integrator model includes outputs from grasslands, unlike the others. Overall, the significance and comparison of results is not to the nearest percentage point, given the high sensitivity to data and assumptions. Naturally, this also applies to TYFAm.
- Nitrogen use efficiency (NUE in what follows) in TYFA is very high (92% if we include only nitrogen from manure available on cropland, just under 80% if we include all nitrogen, as in the models discussed by the ENA and Eurostat). These high values clearly reflect challenges in nitrogen management and, if we compare them to the current situation, to a paradigm shift in relation to a situation in which nitrogen is widely available. The assumption is that the scarcity of nitrogen in TYFA implies high efficiency for a resource that becomes scarce. On this basis, nitrogen efficiency is comparable to the level proposed by Lassaletta *et al.* (2016).

Additional sources of nitrogen: atmospheric deposition and the circular economy

The high tension surrounding nitrogen efficiency leads us to discuss the additional sources likely to “ease” the balance. The first of these sources is atmospheric nitrogen, which is not included in our model, but which partly reduces this pressure with total inputs that can amount to almost 10 kg of nitrogen/ha in temperate continental regions (Simpson *et al.*, 2011a). Figure 23 indicates the spatial variability of these depositions, which may nevertheless change by 2050, since they are also dependent on inputs volatilised in the atmosphere, particularly through nitrogen fertilisers, which disappear in TYFA. Atmospheric depositions could thus represent up to 1 million tonnes (compared to 1.2 to 2.8 million tonnes at present, depending on the model), with a low value being the most plausible assumption.

A second source is the recovery of urban effluents from wastewater treatment plants (WWTPs). Recent research by Esculier *et al.* (2018) in metropolitan Paris along with analyses conducted at the EU-27 level at the request of DG Environment on the reuse of WWTP sludge in agriculture (Salado *et al.*, 2008) enable a rough evaluation of this source of nitrogen. Five parameters need to be considered,

for which the two aforementioned studies enable us to make assumptions regarding the current situation, as well as the future:

- The European population in 2050, estimated in TYFA at 528 million people (Eurostat projection).
- Average per capita nitrogen excretion, which depends on diet. In the case of metropolitan Paris, Esculier *et al.* estimated the average annual excretion entering the water treatment system at 4.7 kg N/person/year. Given the reduction in protein consumption projected in TYFA (-17%), an excretion level of 3.9 kg N/person/year can be applied for 2050.
- The collection rate for wastewater in treatment plants (WWTP): this was estimated at 40% on average in 2005 for the EU as a whole (Salado *et al.*, 2008); given the percentage of the population currently living in urban areas in the EU (72%) and the development of water treatment infrastructure, an assumption of 70 or even 80% would be realistic.
- The nitrogen recovery rate in WWTP sludge: according to Esculier *et al.* (2018), almost 90% of the nitrogen passing through WWTPs is either volatilised or lost through infiltration in water bodies. Thus, the proportion of nitrogen actually recoverable in the form of sludge is currently no more than 10%. We assume that this proportion could triple by 2050 under the combined effect of technical progress and nitrogen scarcity.
- The utilisation rate of this sludge as agricultural fertiliser. In the different scenarios proposed to DG Environment, Salado *et al.* (2008) estimate that in 2020, the utilisation rate of WWTP sludge as agricultural fertiliser could be 45%, climbing to 60% in 2030 and 70% in 2050.

On this basis, we arrive at a theoretical nitrogen availability in the order of 345 000 tonnes, or less than 5% of outputs by crops. At the European level, these figures are low, but if we consider the geography of the regions likely to require these resources (those that currently specialise in cereal production) and of cities, this source can become significant⁴².

A third alternative source of nitrogen (and phosphorus) lies in the livestock processing industry. A rapid estimation of nitrogen contained in bones—the “fifth quarter” of the meat sector—gives a figure of 160 000 tonnes of nitrogen, but we will not present the method here. As with urban effluents, this source can be an important

42. This recovery of WWTP sludge is all the more necessary in the context of closing the phosphorus cycle, which could even be its main justification.

supplement in a territorial approach to nitrogen management. In addition to this direct agricultural use, another area should be considered that we have not sought to quantify in TYFAm: zootechnical recovery (meat and bone meal, whey, etc.). This available nitrogen could be used to feed additional granivores to those included in our model. These products could be exported, as with “additional” dairy products in order to make use of grasslands (see section 4.1). They would provide a supplementary input of nitrogen that is relatively easy to territorialise.

Overall, 1.5 million tonnes of additional nitrogen could thus be added to the TYFA balance, based on cautious assumptions for each category. The difference in the overall balance is significant: the input/output ratio (considering only cropland) increases from 109 to 116%, which gives a NUE of 87%. This value is clearly still high, above the values observed empirically, but it substantially relieves the pressure.

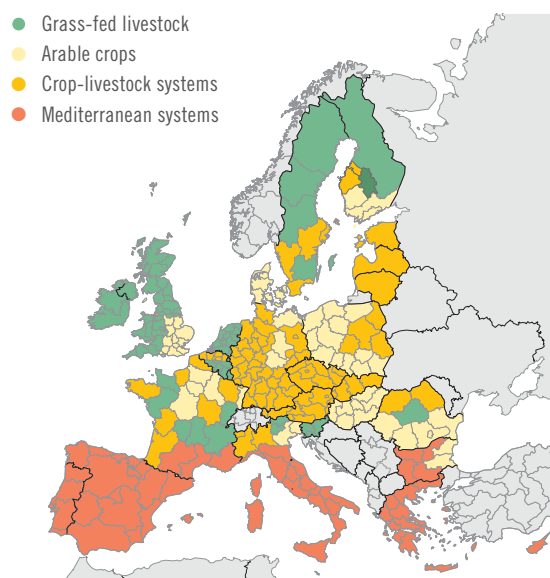
The challenges of nitrogen management at the territorial level

The shift from a global approach to nitrogen to one of actual nitrogen supply for crops implies to adopt a territorial perspective. Two aspects are essential in this respect: (i) the contribution of legumes, combined with (ii) nitrogen transfers through livestock. To avoid transferring manure over long distances, which is not economically viable, we need to consider:

- the presence of legumes in all cropping systems within European agricultural systems (see section 4.2.2). These legumes should vary (soybean, peas, lentils, etc. for grain; alfalfa, clover, sainfoin, etc. for fodder or intercropping) from one region to another according to agronomic characteristics, but they will be systematically required, including in intercropping;
- a new distribution of herbivore production, allowing for the presence of permanent and temporary grasslands in a majority of agricultural systems. Indeed, although granivore production contributes to the nitrogen balance through its capacity to efficiently use cereal proteins, it only recycles nitrogen flows at the territorial level⁴³. Net inputs to the system are mostly from permanent grasslands and green manure in intermediate crops.

43. Only legumes needed to feed granivores are grown: the nitrogen balance is therefore at best neutral, with an output exactly equivalent to proteins in meat (negligible in relation to nitrogen excreted to cover physiological requirements).

Figure 24. Map of dominant production systems (OTEX) in the EU-27 regions in 2012



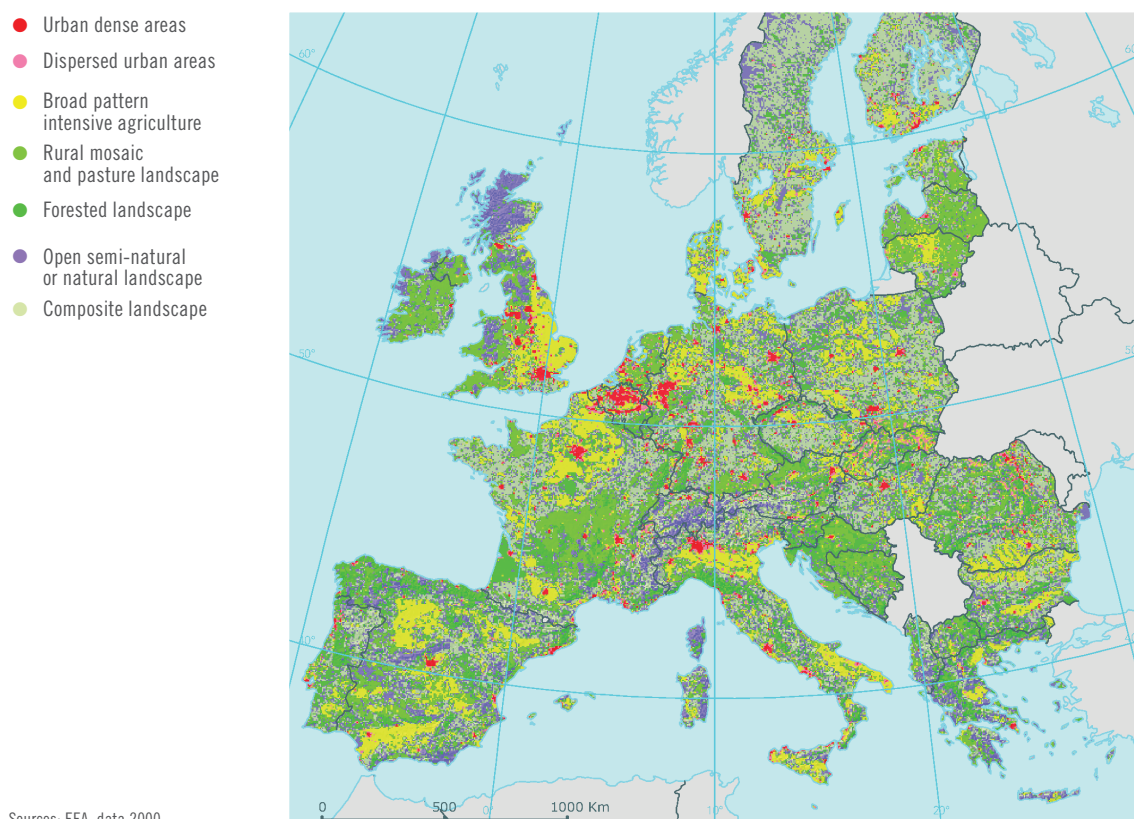
Source: FADN 2012.

Nitrogen management in TYFA thus implies the redeployment of grasslands in cropland regions (which is in any case considered desirable for biodiversity reasons, see section 3) and, in parallel, a “despecialisation” of grassland areas towards mixed systems⁴⁴. One alternative, which still exists in the Mediterranean regions, involves nitrogen transfers through transhumance in regions that are nevertheless dominated by cropland (for example, Castilla y León in Spain). The regionalisation of TYFA is a task that lies ahead, which will enable us to more accurately examine the feasibility of the scenario from the viewpoint of nitrogen availability, but Figures 24 and 25 illustrate three points to clarify the feasibility of this dual dynamic of redeploying grasslands and de-specialising field crop areas.

- The temperate regions of Europe (outside the Mediterranean zone) that are highly specialised in field crop production are in fact the exception. They include the Île-de-France region in France as well as some parts of Germany and Hungary: elsewhere, a permanent grassland threshold of 8 to 15%, or even 15 to 24%, is more common.
- In the Mediterranean regions, where permanent grasslands are uncommon, certain forms of semi-natural vegetation exist, making it possible to envisage complementarities through

44. It should also be noted that feed produced in Europe can circulate more easily than manure, and therefore gives a map of granivore production that is less constrained than the one for herbivores. In other words, the distribution of granivores can act as an adjustment variable in a geographic approach to nitrogen.

Figure 25. Map of dominant types of land use in the EU-27 regions



transhumance (but the share of manageable nitrogen then needs to be clarified).

- Conversely, regions truly specialising in grass-fed livestock are in the minority (the British Isles and the Massif Central region in France) and have agricultural potential for a partial return to cropland.

The redeployment of mixed crop-livestock production systems at the territorial level (Moraine *et al.*, 2016) throughout Europe is therefore not always as difficult to imagine as in the most field crop specialised regions, which are the ones that come to mind when this issue is raised. In these regions, the constraint of a return to livestock production can be minimised, if not removed, by increasing the share of legumes in rotations and by mobilising alternative sources of nitrogen.

Conclusion regarding the nitrogen balance in TYFA: can we do without synthetic fertilisers?

The foregoing elements highlight real tension regarding nitrogen management as well as the high sensitivity of results to the calculation assumptions—we will return to this aspect in section 4.5.3 on model sensitivity tests. They nevertheless

provide the opportunity to discuss the possible phase-out of synthetic fertilisers—and thus the use of organic agriculture references, in both yield assumptions and crop management principles.

The nitrogen use efficiency level calculated for the TYFA scenario may seem too high in relation to existing references. However, the possibility of mobilising alternative sources of nitrogen, but also of making better use of symbiotic fixation potential—which is not well understood at present⁴⁵—holds promise for removing this constraint, at least partially.

This is why, in this first version of the scenario, we maintain the assumption of the non-use of synthetic fertilisers, since it ultimately seems to us to be more heuristic: the constraint is high, it may not be sustainable, but it raises a host of questions regarding nitrogen management that can only be beneficial to the environment.

Should the refinement of our assumptions lead to the conclusion that synthetic fertilisers must be used, we do not believe this would question the

45. In particular, synthetic nitrogen inputs into the environment inhibit these symbioses; their phase-out, on the other hand, would be likely to strengthen them.

whole agronomic approach adopted in TYFA. These fertilisers would be used sparingly, according to yield objectives that would ultimately be similar to the targets set.

4.4. A balance between GHG mitigation and biodiversity⁴⁶

4.4.1. GHG emissions reduction potential in TYFA

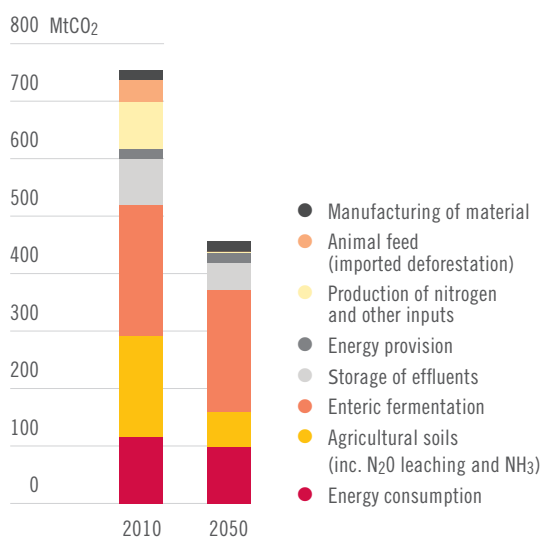
The impact of the TYFA scenario on GHG emissions was estimated by combining TYFAm with ClimAgri® (ADEME *et al.*, 2011). The ClimAgri model was developed to evaluate GHG emissions (NO₂, CH₄, CO₂) linked to agricultural practices in a given territory. To do so, it calculates the energy used for production in the territory, also taking into account energy consumption associated with the production of inputs; and the GHG emissions associated with crop and livestock practices. ClimAgri was initially developed to focus on territorial systems, but can be configured at any level, including the European level. The evaluation of GHG emissions with ClimAgri combines two types of data:

- data concerning vegetal and animal production: the organisation of cropland and the share of each crop in total surface area (the proportion of land used for organic agriculture, integrated agriculture, agroforestry, etc.); herd numbers and management for each livestock category (dairy cattle, meat cattle, sheep, goats, pigs and chickens);
- configuration data which, based on agricultural practices, can be used to estimate the level of GHG emissions for each type of production. This data concerns, for example, the level of fertilisation for each type of crop, the average power of greenhouses and the average energy mix used to heat them (natural gas, fuel oil, electricity or coal), tractor operating time/ha for each type of crop in order to estimate fuel expenditure, the time animals spend in housing and free ranging in order to estimate the proportion of manure to be stored and the amount produced in fields for each livestock system, and the respective share of the different manure management systems, etc.

The evaluation of GHG emissions reduction potential in the TYFA scenario involved three phases.

46. Here we only elaborate on the impacts on climate change and biodiversity, which are the most difficult to characterise, but the development of agroecology will also have major positive impacts on the quality of water resources and the sustainable management of soils (microbial activity, preventing soil erosion through permanent cover).

Figure 26. GHG emissions reduction potential in the TYFA scenario compared to 2010



Source: TYFAm.

In the first phase, ClimAgri was configured based on 2010 data provided by Eurostat, to recalculate the GHG balance for the European farm in 2010. In the second phase, the agricultural assumptions applied in TYFA, as outlined in part 3 of the report, served to reconfigure ClimAgri in order to establish the GHG balance of the European farm in 2050 in the TYFA scenario. The 2010 and 2050 GHG balances were then compared so as to estimate the abatement potential of the TYFA scenario.

The evaluation of the 2010 level of emissions with ClimAgri proved to be an essential first step in estimating the abatement potential of the TYFA scenario compared to 2010. Indeed, the scope applied by ClimAgri to evaluate agricultural sector emissions is broader than the one used by Eurostat in its contribution to the accounting system of the United Nations Framework Convention on Climate Change (UNFCCC), including in particular a high level of indirect emissions for TYFA.

ClimAgri thus identifies four types of direct emissions (very high correspondence with UNFCCC accounting):

- emissions from energy consumption;
- emissions linked to soil management, and in particular the use of nitrogen fertilisers;
- emissions linked to manure management;
- emissions from enteric fermentation in ruminants.

In addition to direct emissions, ClimAgri includes all indirect emissions associated with one or other of the four categories below, producing a more accurate picture of real agricultural sector impacts:

- the provision of energy;
- the production of fertilisers and other inputs;
- the production of animal feed;
- the manufacturing of material.

The recalculation of the 2010 GHG balance with ClimAgri is comparable to the 2010 Eurostat balance for direct emissions, which confirms the robustness of the configuration process carried out at the European level, based on *average* data for all of the Member States. The ClimAgri values are higher than those calculated by Eurostat for each category, with different explanations in each case. For energy consumption, the difference stems primarily from the fact that the Eurostat emissions figures tend to systematically underestimate the surface areas under heated greenhouses, which account for more than 50% of emissions for this category.

Where enteric fermentation is concerned, the difference arises from the calculation methodology: Eurostat uses the basic methodology of the Intergovernmental Panel on Climate Change (IPCC), which unequivocally allocates an identical level of emissions to every head of cattle of 140 kg of CH₄ per year, whereas ClimAgri works in more detail by adapting the emissions level to the ration.

Regarding manure, the difference is due to the difficulty of correctly allocating waste in ClimAgri according to its management method (slurry, manure, bedding, etc.). Indeed, the management method has a significant impact on emissions levels. This allocation was determined by experts and will need to be reworked in future versions of the scenario.

Finally, for emissions linked to soil, the relatively smaller difference observed is explained by the fact that the estimation and calculation methods for the main category—nitrogen application—are equivalent in both approaches (the same quantity of nitrogen is considered in both cases, and the same emission coefficient applied).

Under the assumptions made in TYFA, the overall reduction in emissions could be as much as 36% in total, distributed between direct and indirect emissions (see Table 18 and Figure 26). Moreover, in view of the fact that TYFA is based on the suspension of plant protein imports, a large proportion of which were from deforested land in Latin America in 2010 (Cuypers *et al.*, 2013), the GHG emissions reduction potential in TYFA 2050 could reach or even exceed -40%.

The possibilities for reducing GHG emissions in the TYFA scenario are related first to the low

Table 17. Agricultural sector direct emissions in 2010: comparison ClimAgri/Eurostat data

ClimAgri 2010		Eurostat 2010		Δ
	Mt eq. CO ₂		Mt eq. CO ₂	
Direct GHG emissions	599.65	Direct GHG emissions	496.64	21%
<i>energy consumption</i>	115.51	<i>energy consumption</i>	84.88	36%
<i>agricultural soils</i>	174.73	<i>agricultural soils</i>	156.12	12%
<i>enteric fermentation</i>	229.48	<i>enteric fermentation</i>	189.74	21%
<i>storage of effluents</i>	79.93	<i>storage of effluents</i>	65.90	21%

Sources : Eurostat (2017), TYFAm et ClimAgri

Table 18. Comparison of emissions from the European farm in 2010 and 2050 in the TYFA scenario

Category of emissions (in Mt CO ₂ e)	2010	2050	Variation
Direct GHG emissions	599.65	419.12	-30%
<i>energy consumption</i>	115.51	99.29	-14%
<i>agricultural soils (inc. N₂O leaching and NH₃)</i>	174.73	59.98	-66%
<i>enteric fermentation</i>	229.48	211.56	-8%
<i>storage of effluents</i>	79.93	48.29	-40%
Indirect GHG emissions	154.62	36.90	-76%
<i>energy provision</i>	16.54	16.86	2%
<i>production of nitrogen and other inputs</i>	81.23	1.88	-98%
<i>animal feed (imported deforestation)</i>	40.00	0.00	-100%
<i>manufacturing of material</i>	16.85	18.16	8%
Gross emissions balance (with soybean imports)	754.27	456.02	-40%
Gross emissions balance (without soybean imports)	714.27	456.02	-36%

Table 19. Indicators of determinants of biodiversity in TYFA 2050 vs. 2010 situation

Indicateur	2010	TYFA 2050
Proportion of UAA under organic agriculture	5,4% (2010) ; 6,2% (2016)	100%
Proportion of UAA under high nature value farming	40% (2012)*	~100%
Consumption of synthetic fertilisers	11 Mt N, corresponding to 75 kg Mineral N/ha (2015)	0
Consumption of synthetic fertilisers	380 kt of active substances, of which 40% fungicides (including copper sulphate)	0
Overall nitrogen balance (expressed in terms of coverage of requirements in cropland)	150 to 180% (according to calculation method - see section 4.3)	109 to 128%
Level of diversification (our calculation):		
<i>proportion of the main crop in arable land</i>	20% (wheat)	11% (legumes harvested green)
<i>proportion of the 4 main crops in arable land</i>	50%	40%
Proportion of AELs in arable land	8% (highly variable quality for biodiversity)	10% (high interest for biodiversity)
Proportion of fodder areas (grasslands) under extensive grazing (density < 1 LU/ha)	23% (2007)**	> 75% (estimation)

Sources: Eurostat for 2010, unless otherwise indicated; TYFAm for 2050. *European Environment Agency: <https://www.eea.europa.eu/data-and-maps/indicators/agriculture-area-under-management-practices/agriculture-area-under-management-practices-2>. **Eurostat, cited by Huyghe *et al.* (2014).

Table 20. Summary of impacts on biodiversity in TYFA 2050 vs. 2010 situation

		2010	2050
Soil life	Nitrogen	-	+
	Biocides	--	++
		Alteration of soil microbiota.	Recovery of microbiota.
Cultivated crops	Crop diversification	±	++
	Azote	-	++
	Biocides	--	++
		Loss of plant diversity (harvest plants) and insects. Pollinators in decline.	Recovery of plant diversity and microfauna.
Grasslands and rangelands	Nitrogen	-	++
	Density	±	+
			Legumes encourage pollinators
Landscapes	Plot size	±	+
	IAE	±	++
	Landscape diversity	-	++
		Loss of emerging biodiversity. Decline in microfauna and mesofauna (birds, mammals, amphibians, etc.).	Recreation des chaînes trophiques et des habitats variés favorables à la faune.
Summary		Alteration of most of the biodiversity framework through the loss of plant and animal species at the lowest trophic levels. Conservation in endangered enclaves.	Recreation of trophic chains and habitats conducive to species protection.

Source: authors. The signs “-”/“+” etc. summarise the impact, negative or positive, on biodiversity.

nitrogen levels in the scenario: lower levels of N₂O linked to the application of fertilisers in direct emissions, and the virtual elimination of emissions associated with the production of inputs.

Emissions reductions in energy consumption are obtained by marginally reducing the proportion of heated greenhouses in the TYFA scenario (-10%), taking account of assumptions regarding the relocation of production to areas with the most suitable soil and climate conditions.

In terms of the storage of effluents, the reductions stem from (i) the decline in the overall volume of manure, with the reduction in cattle numbers and, even more so in pig and poultry numbers, and (ii) the widespread adoption of soft farmyard manure management systems.

The emissions reductions associated with the suspension of soybean imports from Latin America

were calculated as follows: in 2010, the EU imported the equivalent of 30 million tonnes of soybean cakes from Brazil and Argentina, for which, in an “average” scenario, we can estimate that 30% are derived from deforestation or the conversion of savannas (Weiss & Leip, 2012). The level of GHG emissions from this soybean production can be estimated based on research by Castanheira & Freire, 2013; Raucci *et al.*, 2015; and Maciel *et al.*, 2016. This level is largely dependent on the density and quality of the forests converted. In the context of this report, we assume a relatively cautious emissions level of 4.5 kg of CO₂/kg of soybean produced, corresponding to a low value derived from the different studies cited (which give values ranging from 3 to 18 kg of CO₂/kg of soybean).

Sustaining a large cattle population, whose role in maintaining grasslands for biodiversity and in

nitrogen transfers from the *saltus* to cropland is decisive in TYFA, results in a moderate reduction in emissions associated with enteric fermentation.

Overall, the GHG emissions reduction potential in TYFA is comparable to, or even greater than, the potential in other scenarios presented at the European level, such as the European Commission's Roadmap 2050 (Höglund-Isaksson *et al.*, 2012) or the EcAMPA 2 study (Perez-Dominguez *et al.*, 2016)⁴⁷. By giving the same priority to biodiversity, human health, and climate mitigation issues, the agri-food system in the TYFA scenario nevertheless appears very different from the one outlined in the above-mentioned studies: the role of grasslands and semi-natural vegetation, changes in livestock numbers (especially ruminants), the level of intensity of production, but also the diet, are all very different. The role of technology also differs fundamentally from one scenario to another: where TYFA takes no technological gambles and, in many respects, can even be qualified as a low-tech scenario, EcAMPA 2 and Roadmap 2050 are largely based on efficiency gains associated with technological progress and the reduction in cattle populations.

In this regard, TYFA is very similar in design to the Afterres scenario developed in France, which estimates GHG emissions reduction potential at -54% (Solagro *et al.*, 2016). Although some of the leverage available is very similar, in particular changes in food consumption⁴⁸, Afterres focuses more clearly on climate issues and makes different choices, especially in relation to ruminant populations. The following section describes the impacts of TYFA on biodiversity.

4.4.2. Impacts on biodiversity in TYFA

Evaluating the impacts on biodiversity—or the potential to improve biodiversity—of a prospective scenario may at first seem complex. Unlike climate change, for which a single indicator organises the whole debate (the level of GHG emissions expressed in tonnes of CO₂ equivalent), there is no such equivalent for biodiversity. However, a prospective and partially quantitative evaluation remains relevant and possible. Here, we propose

using the IRENA indicators (Indicator Reporting on the Integration of Environmental Concerns into Agriculture Policy) developed by the European Environment Agency (EEA, 2005) in 2005. Of the 42 indicators developed by the EEA, six were used in the context of this report, since they identify pressure on biodiversity. To these indicators (the first six in Table 19), we have added those concerning the proportion of agro-ecological infrastructures and of extensive livestock production.

The interpretation of the impact of TYFA on biodiversity is largely redundant with the discussion on the assumptions, since these are made according to biodiversity recovery and conservation objectives at the European level, in a context in which current trends are highly problematic. Without reiterating this discussion here, in Table 20 we propose an evaluative summary, which highlights the paradigm targeted.

4.5. Sensitivity tests for the scenario and alternative assumptions

Table 21 presents the results when alternative assumptions are applied to the model, testing the sensitivity of results to the model input assumptions and configuration.

The output variables to which we compare the alternatives are: the percentage of UAA (2010 reference), the surface area under permanent grasslands, the nitrogen input/output ratio, the total cattle population, total LUs, and the calorific value of the ration. Several areas are tested, which we review. The exercise is analytical, proceeding assumption by assumption, with all other things being equal, knowing that the assumptions can be combined.

4.5.1. Sensitivity to the level of production - yields

This area is tested considering a uniform decline in yields of -60% compared to 2010 (production assumption: PA1). This would reflect, in particular, a severe climate change impact, to which agroecology in TYFA would be unable to adapt (this situation would then need to be compared to that of smart agriculture in 2050 for example, by testing the alternative adaptation capacities).

This reduction leads to pressure on agricultural land: 10% of UAA is “lacking” to provide the food and feed needed for the assumptions tested in TYFA⁴⁹. This figure does not question the overall approach; but it calls for a detailed reconsideration

47. By including only emissions linked to soil, enteric fermentation and manure management, and by comparing these with 2010 emissions, Roadmap 2050 indicates a reduction potential for the agricultural sector of -22% in 2050, and the EcAMPA 2 study a potential of -25% in 2030, compared to -34% for TYFA with identical scope (only direct emissions and without energy consumption).

48. As regards the impact of changes in eating habits on emissions levels across Europe, we can also refer to the research by Westhoek *et al.* (2014). However, they do not propose a detailed description of changes in agricultural systems, contrary to Afterres and TYFA.

49. The nitrogen input/output ratio improves, but this indicator is secondary in the discussion on this variant.

Table 21. Model sensitivity to alternative assumptions (shown by figures in bold)

Thema	Hypothesis	% SAU used	Permanent meadows	inputs/ outputs N	Cattle herd (M head)	TOTAL UGB all species	Kcal (with beverage)
References	European farm 2010	100%	60 Mha	150-180%*	88	186 M	2 606
	Basic assumptions TYFA 2050	100%	58 Mha	109%	78	115 M	2 445
Production	PA1 - Crop yields: -60% of 2010 yields (except grasslands -10%)	109%	n.d.	108%	n.d.	n.d.	n.d.
Diet	FA1: 0 animal protein (vegan)Food	46%	0 Mha	60%	0	0 M	2 317
	FA2: 50% of milk and beef, pork, and chicken compared to 2010	90%	41 Mha	103%	50	114 M	2 437
Nitrogen	NA1: nitrogen carryover provision -30% or +30%	100%	58 Mha	85%-130%	78	115 M	2 445
	NA2: utilisation coefficient manure - 30%	100%	58 Mha	100%	78	115 M	2 445
	NA3: utilisation coefficient manure + 20%	100%	58 Mha	115%	78	115 M	2 445
	NA4: 30% of ecological areas using green fertiliser (or 3% of cropland)	100%	58 Mha	115%	78	115 M	2 445

Source: TYFAm. *The balance varies according to the calculation methods—see section 4.3.

of the allocation of land and the priority given to (a) relative export levels for cereals and dairy products, and (b) food balances in the 2050 diet. This is what is indicated by “n.d.”—not-determined—in Table 21. New detailed assumptions and simulations are required.

The following tests, on nitrogen, suggest that the reduction in ruminant numbers does not immediately emerge as the best option if the goal is to retain the assumption of the non-use of synthetic nitrogen fertilisers.

It should be noted that nitrogen scarcity leads us not to consider the symmetric assumption of yields higher than those taken from Ponisio *et al.* (2015).

4.5.2. Sensitivity to the level of human food

Two alternative assumptions are tested in this area:

- FA1 corresponds to a “vegan” assumption, in which there is no longer any livestock production. Animal proteins are replaced by plant proteins, taking into account an agricultural constraint: legumes cover at most 30% of arable land. This option uses only 46% of the UAA, but nitrogen inputs (by symbiotic fixation in cropland alone) correspond to only 60% of outputs, implicitly highlighting the contribution of livestock to nitrogen supply in agro-ecosystems. Permanent grasslands also disappear, at least for livestock production uses. This assumption could be taken further on an agronomic level (alternative sources of nitrogen transfer, use of permanent grasslands for anaerobic digestion);
- FA2 corresponds to an assumption in which herbivore production is not a priority: the decline in the consumption of animal products is -50%

compared to 2010, and is identical for milk, beef, pork and chicken. In this assumption, we retain 20% exports of milk produced. This variant reduces the grassland area to just over 40 million ha (-1/3 compared to 2010), uses only 90% of the UAA, and gives an input/output ratio of 103%.

4.5.3. Sensitivity to the nitrogen balance level

As mentioned above, this is one of the most sensitive areas of the model. Four broad sets of alternative assumptions are tested:

- NA1 corresponds to a variation of $\pm 30\%$ around the average values for nitrogen fixation by legumes, considering the high variability of the factors explaining this fixation (soil, climate, soil biology, practices, yields) and the uncertainty surrounding measurements, especially below the root zone. This variation range of $\pm 30\%$ corresponds to a variation in the N input/output ratio of $\pm 20\%$ around the balance (from 85 to 130%). This parameter is therefore extremely sensitive in the model outputs. It should be noted that the increasing scarcity of nitrogen in the European agricultural environment is a factor that could foster natural symbiotic fixation, since nitrogen inputs inhibit this activity;
- in NA2, lower values for the actual use of manure, at -30%, considering that the assumptions adopted are overly optimistic. The impact on the nitrogen balance is a 10% reduction at the European level;
- NA3 envisages a symmetric assumption, in which the capacity to use manure that has now become valuable improves. A 20% improvement for this factor results in an 8% increase in the European nitrogen balance;

- finally, NA4 envisages an assumption in which nitrogen has become very limiting, and green fertiliser practices are thus extended over a third of ecological focus areas—which are themselves assumed to account for 10% of arable land—in order to return all nitrogen produced by legumes to cropland (we assume a net fixation of 200 kg of N/year). This assumption results in an improvement of just over 10% in the input/output ratio, which increases to 115%.

Overall, the tests for nitrogen reveal high model sensitivity to alternative assumptions. In particular, the assumptions consisting in increasing inputs in relation to outputs suggest plausible opportunities, or which at least need to be explored, retaining the assumption of phasing out synthetic nitrogen fertilisers.

In any case, as already stated in the TYFA founding assumptions, the issue of the origin of nitrogen—wholly organic or synthetic—may not be as

as important as the other assumptions regarding food, pesticide phase-out, and the emphasis placed on biodiversity management in agro-ecosystems. It increases the coherence of the set of assumptions, but it is possible to cover plant requirements that would be inadequately covered by organic nitrogen alone—at the yield levels tested—by using synthetic nitrogen sparingly in cropland. Based on a “zero synthetic nitrogen” assumption, which needs to be clarified at the regional level, our approach enables us to consider potential requirements for this fertiliser, not on the basis of a maximum or optimum yield, but by estimating what the “European farm” needs to produce in order to properly feed its population, to export what is socially acceptable, and to protect its continental and marine environment. Our model suggests that it is difficult to envisage average yields lower than those assumed in our assumptions and for which nitrogen would be a limiting factor.

5. CONCLUSIONS AND OUTLOOK

5.1. A pioneering modelling process

In the introduction to this document, we insisted on the pioneering and radical nature of this process. This aspect is reflected in the content of the assumptions, but also in the modelling approach used, to which we return in this conclusion.

One of the objectives of TYF*Am* is to examine the issue of biodiversity, which is often neglected in public debates informed by models based solely on a quantification of nitrogen fluxes or on a characterisation of different types of land use that does not always indicate their management intensity. Admittedly, models that identify increases in nitrogen or pesticide doses and explain grassland ploughing tell us something about biodiversity. But, conversely, from the perspective of biodiversity recovery, halving the frequency of pesticide applications may be “a step in the right direction”, but will give no specific indications about the final impacts to be expected on habitats and species, even in very general terms. Likewise, considering only grassland areas tells us little about their habitats. What is needed is to better qualify the types of areas used for agricultural production, which can be done only very imperfectly by “flux” models alone.

On the other hand, at the level at which we situate the debate, it is not possible to have a comprehensive approach taking into account landscape organisation issues, or specific practices such as dates of crop operations, etc.

In this context, TYF*Am* aims for an “intermediate level of complexity”, to use the insightful expression of one of the discussants of this exercise. The system-based approach central to TYF*Am* is aimed at identifying conceptual issues that explain the overall metabolism of the “European farm” and can also be linked to land use types and

However, in spite of the advances we have just described, some important agronomic and biotechnical areas remain to be explored for the analysis of the sustainability of the agricultural system described in TYF*A*:

- closing the phosphorus cycle, a subject frequently broached in the context of generalising organic agriculture, but more generally for the future of all types of agriculture. The question is not limited to just one aspect of organic agriculture standards (the non-use of synthetic phosphate fertilisers), but concerns the sustainability of phosphorus resources themselves, and this issue is not specific to agroecology;
- water management, which requires a more spatialised analysis than the one conducted;
- with a view to this spatialisation, one important development for TYF*Am* will involve efforts to regionalise the assumptions, in particular to refine our understanding of the closing of nutrient cycles and water management, which ultimately occurs at the territorial level.

These issues all need to be further analysed, but we assume that the conceptual approach adopted in TYF*Am*, based on a more detailed characterisation of production systems, opens up opportunities to do so.

5.2. Changes that are plausible, desirable and comparable in scope to others in the past

One of the key conclusions of TYF*A* concerns the agronomic and biotechnical plausibility, at the level of analysis applied, of the set of assumptions tested. The scenario thus shows that there is potential for phasing out pesticides while maintaining export capacity comparable to the current situation and, above all, while importing far less. It is possible to take an ambitious approach to biodiversity involving extensive herbivore systems and diversified cropping systems without synthetic inputs, while simultaneously reducing GHG emissions. The issue of nitrogen is more uncertain, despite an initial analysis that does not indicate the impossibility of closing the nitrogen cycle. However, as already discussed, we do not

believe it requires as radical an approach as pesticides, and there are many areas that require further exploration on this issue, whether improving the efficiency of symbiotic nitrogen throughout the cycle or considering a prudent use of synthetic fertilisers.

The key condition for ensuring a scenario of this type functions concerns changes in diets. Although the changes envisaged are substantial, they also respond to public health challenges and to widely expressed social expectations regarding healthier diets.

It is clear that TYFA presents a utopia. This is an essential dimension of any prospective approach and a heuristic engine. Our goal was to inform this utopia by establishing an archetypal, ideal vision for 2050. As we will see in the following section, the consequences and the conditions for the feasibility of this scenario need to be explored. So the question remains: this picture is certainly desirable in many regards, but is it not so ideal as to be unattainable? We clearly do not have the answer to this question, but we believe it is important to highlight two points:

- in the past, the project for the modernisation of agriculture and food that emerged in the post-war period seemed just as utopian. The technical, economic and socio-cultural changes that occurred in just 30 years (1950-1980) were of the same order of magnitude as those envisaged here. And many actors had serious doubts about the possibility of embarking on this project, which also had its opponents in the economic and political sphere. In other words, we are intellectually justified in considering a radical change, even if it is clear that the future will not be a repeat of what happened in the post-war period;
- although we have clearly identified the lock-ins that make the project proposed in TYFA a difficult one, there are also forces at work that suggest the lines may shift. The TYFA assumptions do not come from a social and political vacuum: they stem from a broader social movement that questions the use of pesticides; is concerned about dietary health; and is simultaneously worried about climate change, animal well-being and more recently perhaps (but very clearly in our opinion), the disappearance of insects and birds, etc. Opposite these sometimes contradictory expectations are unsatisfactory answers. For the last 25 years, for example, the CAP has been continuously “reformed” around environmental and... budgetary issues (conventional or “smart” agriculture is expensive). A response based on technical efficiency alone is not convincing. The lock-ins are therefore

substantial, but so is pressure to remove them and, for many, there are mechanisms at work that we feel are significant: meat consumption is declining due more to changes in consumer expectations than to price signals alone, distributors are promoting transparency on organic and high quality products, and some producers are experimenting and already implementing the systems that we have mobilised in TYFA_m. We will not go into detail in this conclusion, as this area would merit a separate analysis. The state of the environment is such that this is now an urgent matter and we return here to what we said at the very beginning of this document: 10 years are needed, not to achieve an entirely agro-ecological Europe in this timeframe, but to launch a movement that will make this a credible prospect.

5.3. Outlook for TYFA: socio-economic and political implications and pathways

This report has presented the agricultural basis for the TYFA scenario. It demonstrates the *technical* feasibility of an agro-ecological transition as envisaged by the set of assumptions proposed in part 3. However, it raises just as many questions as it answers: by demonstrating the biotechnical plausibility (in agricultural and dietary terms) of a radical transformation of our food system, it in turn questions the socio-economic implications, political conditions and possible pathways for such a transformation. While the goal is clearly not to address these questions in this conclusion, since they will themselves warrant considerable efforts in the months and years to come, we will nevertheless briefly outline them here.

On the socio-economic level, we believe four questions are central:

1. What are the implications of TYFA for producer income? Answering this question implies examining not only the way in which production chains and systems could (or should) change in order to be consistent with the *overall* agricultural picture painted here, but also their economic consequences. For example: under which conditions will the assumptions regarding agricultural practices, which will—at least initially—lead to an increase in production costs, not cause a drop in income for producers, who are already at rock bottom?
2. What are the implications for consumer food prices? Here, one of the most important questions concerns economic access to food. Indeed, it seems the increase in production costs mentioned above will inevitably result in a similar increase in

consumer prices in order to maintain a decent income for producers. In this case, what will become of the poorest households and their capacity to feed themselves properly?

3. Does the TYFA scenario create or destroy jobs? How can the sectors and territories reconfigure themselves in the context of TYFA, and with what impacts on employment?

4. How will the social and political challenges be addressed collectively and coherently? Many of the justifications for TYFA are currently considered as externalities of production (environment, health). Internalising multifunctionality issues associated with production is the key policy challenge for TYFA and calls for a reconsideration of the social and political contract for agriculture.

Together, these questions refer to a problem that can be expressed in terms of a “just transition”: how can we make the agro-ecological transition desirable

and as fair as possible from a social/societal viewpoint? Answering this question implies examining in detail the *political* changes required for this transition. Although many public policy sectors are concerned with TYFA, we believe five in particular deserve special attention since, together, they shape the field of possibilities for the transition: trade and intra-EU competition policies (because competition with the rest of the world is problematic); food policy (because it is important to guide dietary behaviours); agricultural policy (because it is necessary to rethink the distribution of public money); and environmental and health policies (because these issues need to be internalised in agricultural and trade policies). Aligning these five policy areas is obviously not easy; this is the challenge of establishing a common *food* policy, as called for by the International Panel of Experts on Sustainable Food Systems (IPES-Food), for example. ■

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ANNEX

BEHIND-THE-SCENES OF TYFAM: MODEL CONFIGURATION AND ORGANISATION

The logical structure of the model

Through its logical structure, TYFAM is a biomass balance model; it resembles other models developed over the last 10 years as part of similar prospective exercises: Agribiom (Paillard *et al.*, 2010), GlobAgri (Le Mouel *et al.*, 2016), and SOL (Schader *et al.*, 2015; Muller *et al.*, 2017).

The input variables concern demand for food (according to an average European diet) and the imported/exported fractions for the different products. These variables establish a level of “demand” for physical production of different products (Cereals, fruit, etc.), using assumptions regarding how to translate a consumption demand into a production demand (taking account of usage and loss coefficients in particular).

The output variables are land use, crop and livestock production, and the nitrogen balance. For these variables, TYFA rests on three basic balances⁵⁰:

On crop production:

Sum of uses (human food, animal feed, seed, industry) * loss coeff. = production + imports - exports + Δ stock

On livestock production:

Sum of feed available ≥ livestock feed requirements

On nitrogen:

Sum of inputs to cropland > sum of outputs

References for nitrogen

References for symbiotic fixation

Symbiotic nitrogen fixation processes are particularly complex and depend on numerous parameters: soils (type, physicochemical composition), climate, varieties, and mineral nitrogen management. Measurements of symbiotic nitrogen fixation by legumes thus give a wide range of values, in particular concerning the underground parts, which are poorly documented (Thiebeau *et al.*, 2010;

Liu *et al.*, 2011; Anglade *et al.*, 2015; Vertes *et al.*, 2015). Although at this stage of the model configuration we use average values, it is important to be aware that variability around the medians is high: the model sensitivity to this parameter is therefore potentially high. It should also be noted that as the usage of mineral nitrogen or nitrogen from manure is reduced, so the symbiotic fixation level naturally increases (Vertes *et al.*, 2015): in other words, the set of agricultural assumptions in TYFA (in which nitrogen becomes scarce) are in principle relatively consistent with high fixation values.

These studies, and in particular those by Anglade *et al.* (2015), constitute a baseline for TYFAM, derived from a meta-analysis of nitrogen fixation values found in the literature at the European level. These statistical analyses show a very high correlation between legume yields and total aerial nitrogen fixation:

$$N_{\text{fixed biologically in aerial parts}} = a \times \text{yield}^t \\ (\text{t MS}) + b^{51}$$

with noted values a and b that depend on crops

Moreover, these authors have compiled data that can be used to estimate the proportion of nitrogen fixed in the underground parts and to establish a coefficient for total nitrogen fixation (aerial + underground). This coefficient (BG factor) depends on the physiognomy of crops (root system in relation to aerial parts) and varies between 1.3 (relatively few underground parts, annual legumes) and 1.7 (perennial legumes: clover and alfalfa, for example).

These parameters can be used to estimate total nitrogen fixation and, by deducting outputs from aerial parts harvested (grain or fodder), we can estimate the net fraction of nitrogen remaining in cropping systems (underground fraction and aerial fraction not exported).

Table 22 only includes symbiotic inputs. In the overall calculation of the balance, we deduct outputs for grain protein and fodder legumes (3% of the yield in DM, according to the COMIFER tables). For temporary grasslands, in the absence of a similar reference for output coefficient according to yield, we consider that all aerial parts are exported, and that all that remains in cropping systems is the

50. Since the model was developed on an Excel® platform without automated calculations, these balances are verified and obtained by successive iterations, by changing the set of input assumptions. The assumptions presented in part 3 of this report are those obtained from a set of iterations.

51. The correlation coefficients R² have high values, between 0.62 and 0.83.

underground fraction, estimated at 37% of total nitrogen fixed (Anglade *et al.*, 2015): here, the inputs are therefore net of outputs. For legumes in intercropping, used as green fertiliser, all of the nitrogen fixed can be used in cropping systems.

Nitrogen references for livestock

For nitrogen production per animal, we have used the values established by CORPEN, per LU and species type. The interministerial circular of 19 August 2004 specifies that the “quantity of spreadable nitrogen determined according to the CORPEN references already takes account of losses of nitrogen compounds occurring in housing and during storage of average duration”; the nitrogen quantities are therefore usable for crops (volatilisation losses are found in the GHG balance).

Table 23 summarises the assumptions regarding time spent free ranging and in housing (manageable nitrogen) for the different livestock systems.

The values adopted reflect two approaches with opposite outcomes: priority to the use of nitrogen provided by manure (hence a high proportion of time spent in housing for dairy cows and “heavy” fattened animals), and a pastoral approach. It should be noted that housing cows at night concentrates the nitrogen collected, since animals excrete more nitrogen in the first morning urine (Farrugia & Simon, 1994).

TYFA assumes that all waste is used in the form of manure. The model integrates this assumption into straw cereal exports (according to quantities of straw required per animal).

Table 22. Symbiotic fixation values used in TYFA m as inputs to cropping systems

Crop	Example studied in (Anglade, Billen, & Garnier, 2015)	Yield (t/ha) (Ponisio LC, 2015)	N fixed in shoots (α rdt+ β) (kg/ha)	BG factor	N total (kg/ha)	Average value used for TYFA m (kg/ha)
Grain protein	Lentils, faba beans, peas	1.57 - 2.28	34-51	1.3-1.4	43-68	58
Fodder legumes	Alfalfa, clover	8.9	180-240	1.7	300-380	340
Legumes in temporary grasslands (non-fertilise)	Clover (30 % of temporary grassland)	8.9 (fraction clover)	72 (30% clover)	1.7	122 (30% clover)	45 (corresponds to 37% of underground N)
Legumes in intercropping (green fertiliser)	Clover	2			100	100

Table 23. Assumptions regarding time spent in housing for animals

Type of animal	Time 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.
Other animals (granivores)	100%	Housing

Source: our expertise in the absence of accessible references

An agroecological Europe in 2050: multifunctional agriculture for healthy eating

Findings from the Ten Years For Agroecology (TYFA)
modelling exercise

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