SUSTAINABLE DEVELOPMENT & INTERNATIONAL RELATIONS

Agroecology and carbon neutrality in Europe by 2050: what are the issues?

Findings from the TYFA modelling exercise

Pierre-Marie Aubert, Marie-Hélène Schwoob (IDDRI), Xavier Poux (AScA, IDDRI)

The latest IPCC report[1] sets the objective of achieving carbon neutrality by 2050, 2070 at the latest. The sustainable intensification of agricultural production, in a land sparing logic, is most often considered as a necessary step to achieve this. In contrast, this *Study* questions the potential contribution of a more extensive agroecological food system (i.e. land sharing logic). It rests on a comparison of the TYFA (Ten Years For Agroecology in Europe) scenario with the agricultural component of recently published scenarios achieving carbon neutrality by 2050,[2] using a multi-criteria dashboard. The objective of climate mitigation is put in the broader perspective of transitioning towards a sustainable food system, taking into account the challenges of human health, conservation of natural resources and biodiversity, and adaptation to climate change. .

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

2 European Commission (2018). *A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*. European Climate Foundation (2018). *Net Zero By 2050: From Whether to How*.

KEY MESSAGES

The TYFA scenario is based on the generalisation of organic farming (abandoning synthetic pesticides and fertilizers), the extension of agroecological infrastructures and the adoption of healthy diets, to feed 530 million Europeans by 2050 (despite a 35% drop in production). It leads to a 40% reduction in GHG emissions (35% for direct non-CO_2 emissions), offers a potential for soil carbon sequestration of 159 $MtCO_2$eql/year until 2035, and a reduction of bioenergy production to zero. The scenario is thus not easily compatible with the objective of carbon neutrality, but offers many co-benefits: biodiversity, natural resources, adaptation, health.

A variant of TYFA, TYFA-GHG (for greenhouse gases) improves these performances with a view to achieving carbon neutrality, while conserving the core assumptions of the initial scenario. Emission reductions reach -47%, the sequestration potential is similar, and bioenergy production amounts to 189 TWh/year. TYFA-GHG is based on a greater reduction in bovine livestock (-34% compared to 2010, compared to -15% for TYFA) and the controlled development of anaerobic digestion using grassland grasses and animal manure as feedstock.

In contrast, carbon neutral scenarios rely on a land sparing approach: increases in agricultural yields enable to free up land that is either afforested to increase the biogenic sink or used to produce biomass energy. However, assumptions on yield increases seem very high (up to +30%) if one considers, on the one hand their recent stagnation in Europe (particularly for cereals) and, on the other hand, the potential impacts on biodiversity and soil health. Those impacts could indeed call into question the very productive capacity of agroecosystems and thus lead to lower yields rather than higher ones.

This *Study* proposes a framework for discussing scenarios designed with distinct perspectives. The aim is to ensure that political debates regarding decarbonisation pathways of the agricultural sector will (i) better integrate biodiversity and soil health issues (beyond a single carbon metric) in order to (ii) reconsider strategies based on land sharing and agroecology as credible ones.

STUDY

N°02
April
2019

EXECUTIVE SUMMARY

1. The mitigation potential of a multifunctional food system: from TYFA to TYFA-GHG

The TYFA scenario was developed to explore the conditions under which a generalisation of agroecology, based on more extensive and multifunctional agroecosystems, could be possible. It relies on a modelling tool simulating the functioning of the European food system in terms of basic biophysical constraints (nitrogen cycle, feed-food balance). The main assumptions tested in the scenario are: the generalisation of organic farming, the extension of agroecological infrastructure, the redeployment of permanent grasslands and the adoption of healthier diets (in particular less animal products and more fruit and vegetables). These hypotheses were defined in order to jointly address the key challenges the European food system is currently facing, including the increase in chronic non-communicable diseases associated with food, impacts on, and of, climate change on agricultural systems, biodiversity loss and the degradation of natural resources (soil, water).

Despite a 35% drop in production, the TYFA scenario would enable to feed 530 million Europeans more sustainably by 2050 while generating a surplus in cereals, dairy products and wine. It would also reduce direct and indirect GHG emissions by around -40% compared to 2010 (-35% for non-CO_2 direct emissions using the UNFCCC framework), and offer a soil carbon sequestration potential in arable land and grassland of 159 $MtCO_2$eql/year, at least up until 2035. Bioenergy production based on agricultural feedstock would however be reduced to zero, as almost all the land would be used for food production due to lower yields. Such characteristics (and in particular the fact that residual emissions of the agricultural sector would still amount to around 60 $MtCO_2$eql/year) make the TYFA scenario difficult to reconcile with the objective of carbon neutrality.

To explore the possible contribution of an agroecological Europe to this objective, a variant of the scenario, TYFA-GHG, has been developed. It borrows some assumptions from scenarios that are more climate performance-oriented from the outset than TYFA, while maintaining the latter's fundamentals in terms of biodiversity and natural resource management. In a nutshell, the controlled and limited development of anaerobic digestion using grassland grasses (and animal manure) allows for a greater reduction in cattle numbers compared to 2010 (-34% compared to -15% for TYFA) while maintaining the area under permanent grassland. Thus, 18% of the biomass of grasslands and 50% of animal manure are used as feedstock for biogas production. The relatively larger decrease in the cattle population explains the significant improvement in TYFA-GHG' GHG balance (-47% compared to -35% for non CO_2 direct emissions), while the development of anaerobic digestion allows for a bioenergy production of 189 TWh. Potential negative impacts of such a development on soil and water quality (in particular through digestate spreading) and the diversity of cropping systems (associated to scale effects given the important investment costs), although difficult to quantify in a prospective manner, can be significant. These two aspects led us not to consider a more substantial development of anaerobic digestion, based for example on cover crops or on a larger fraction of grassland, although the latter would have made it possible to further reduce the cattle population. Without being able to set a precise limit from which the scenario would switch to a bioenergy logic that would change the very nature of the agroecology envisaged, it should be recalled that scale changes the very structure of the sector: TYFA-GHG is not a justification in principle for anaerobic digestion development, but the exploration of a variant that has its interest only at the scale where it is envisaged.

In order to understand the mitigation implications of TYFA/TYFA-GHG, and to compare them with the agricultural component of recently published carbon-neutral scenarios, a comparative framework has been developed. It provides a basis for a more general discussion on transformation pathways towards a sustainable food system (including the objective of carbon neutrality).

2. A "dashboard" for a multidimensional approach to the decarbonation of the food system

Following the methodology developed in the Deep decarbonisation Pathways project,[1] we propose a "dashboard" structured around three themes: drivers of change; emission structure; co-benefits and trade-offs. For each theme, a limited number of indicators allow to make explicit the choices, hypotheses and results of each scenario and thus to compare them systematically. **Table 1** illustrates the approach adopted and presents selected indicators for each theme.

This dashboard must be understood in a dynamic perspective: beyond a static comparison between scenarios whose objective would be to define which would be the «best», its objective is to engage a discussion between approaches that are characterized by different starting points, and which have tended–so far–to ignore each other. The objective is to identify in this way the "no regrets" options and the trade-offs to be considered, being as explicit as possible as to their consequences on one or other of the dimensions considered.

TABLE 1. A dashboard for a multidimensional approach to the decarbonation of the European food system

Themes	EU LTS	NZ 2050	TYFA
Drivers – Human diets (caloric intake, ratio animal / vegetal proteins, ratio ruminant/monogastric meat) – Yields – Carbon efficiency (kg CO_2eql/tons) – Land use change – Food waste and losses (in % of the production) – Trade balance (in tons)			
Mitgation – Emissions reduction – Carbon sequestration : (i) agricultural soils ; (ii) forest ecosystems – Fossil carbon substitution : energy production from agricultural feedstock			
Co-benefits and trade-offs – Biodiversity and natural resources (area under natural/extensive grasslands, share of agroecological infrastructures, pesticides/synthetic fertilizers uses) – Human health – Climate change adaptation (level of diversification of farming systems)			

Note: EU LTS = scenarios belonging to the Long Term Strategy of the European Union; NZ 2050 = net-zero scenarios developed by the European Climate Foundation.

3. Two "families" of scenarios with different starting points

The scenarios analysed first rest on two different logics.

Those proposed under the European Union's long-term strategy (EU LTS) and the Net Zero 2050 study (NZ 2050) seek primarily to achieve a deep decarbonisation of the whole economy. They rely on yields increases through the intensification of agricultural systems and (secondarily) on changes in diets (less animal products, especially ruminants). The objective is to free up agricultural land to either afforest it—and thus increase the biogenic sink—or use it to produce bioenergy. In this land sparing approach, increases in yields (for both animal and cropping systems) play a central role. The productivity gains envisaged are based on the adoption of technologies that are deemed to also limit (or even reduce) the environmental impacts of agricultural systems, in a context where these same impacts are today very significant.

The TYFA/TYFA-GHG scenarios were constructed in order to test the credibility of a generalisation of agroecology on a European scale. They consider changes towards more thrifty diets and more extensive animal and plant production systems as key (and complementary) levers to meet the challenges of natural resources management (soil and water), biodiversity conservation and human health. In such a land sharing approach, the extensification of farming systems makes it possible to simultaneously *reduce* total GHG emissions—although the level of carbon efficiency of production is only slightly improving—and *restore* natural resources and biodiversity.

The characteristics of the food systems resulting from these two approaches are logically quite distinct. While TYFA's compatibility with the objective of carbon neutrality is questionable, the scenario addresses many of the key issues the European food system is now facing.

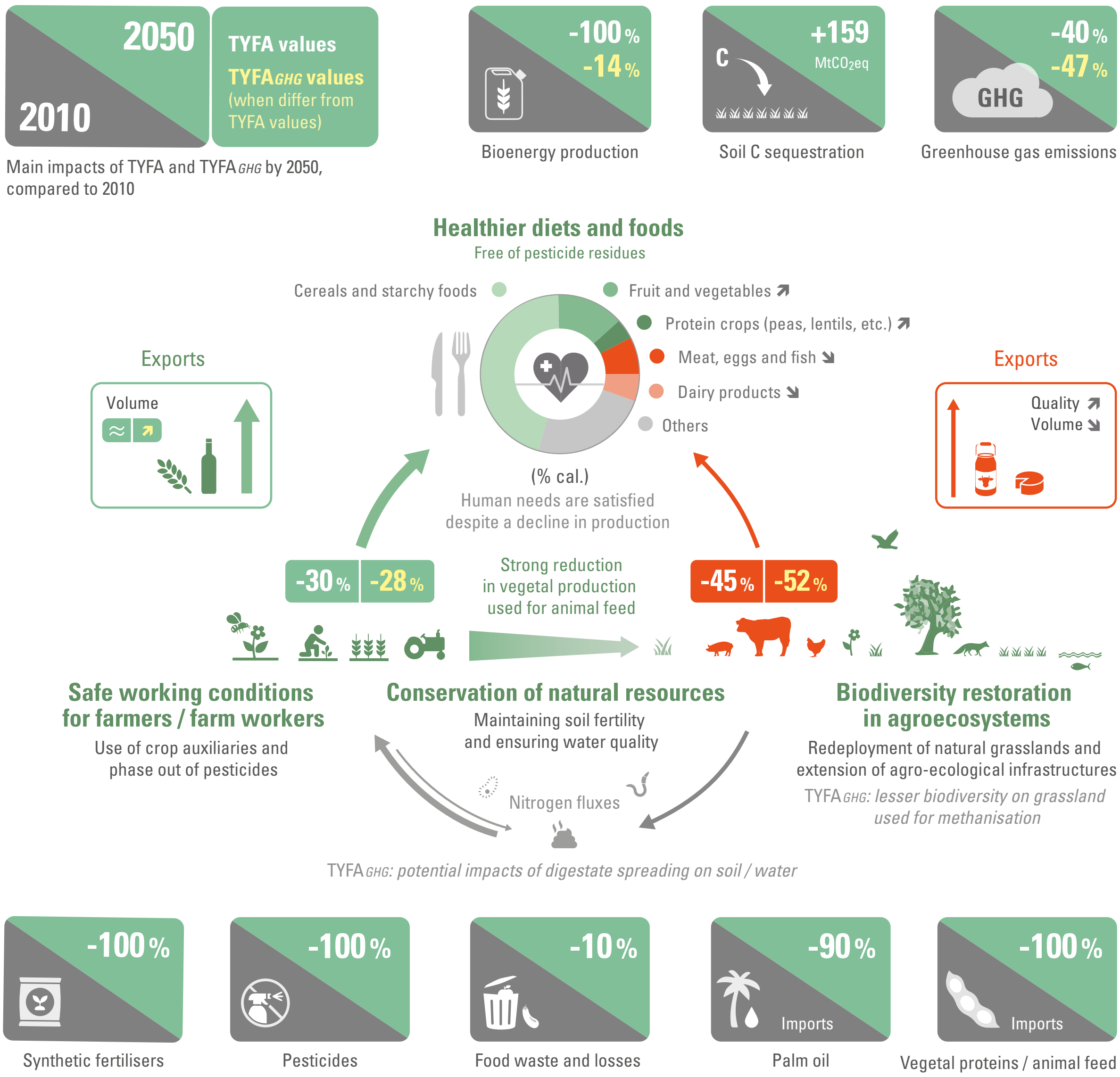
- In terms of human health, the phasing out of pesticides simultaneously provides safer working conditions for farmers, who are the first to be affected by pesticide use, and healthier food.[2] The envisioned dietary changes, that go beyond simply reducing total and animal calories in order to reduce emissions, but also consider increasing fruit and vegetables consumption and reducing sugar, would also improve consumer health.
- In terms of biodiversity, the extension of agroecological infrastructures—which represent 10% of arable land in 2050—combined with the redeployment of natural grasslands and the abandonment of pesticides and synthetic fertilizers, ensure in TYFA/TYFA-GHG a real recovery of biodiversity through the redeployment of food webs at all

1 Waisman, H. *et al.*, (2019). A pathway design framework for national low greenhouse gas emission development strategies. *Nature Climate Change*, 9 (4), 261-268.

2 While the positive effects on human health of a diet free of pesticide residues are difficult to demonstrate today, several recent studies provide arguments that are increasingly difficult to ignore. See notably Baudry, J. *et al.* (2018). Association of Frequency of Organic Food Consumption With Cancer Risk. Findings From the NutriNet-Sante - Prospective Cohort Study. *JAMA Internal Medicine*, 10 ; Johansson, E. *et al.* (2014). Contribution of Organically Grown Crops to Human Health. 11 (4), 3870.

TYFA AND TYFA GHG

POTENTIAL FOR CLIMATE MITIGATION AND CO-BENEFITS OF AN AGROECOLOGICAL EUROPE



The TYFA scenario is based on abandoning pesticides and synthetic fertilisers, redeploying natural grasslands and extending agro-ecological infrastructures (hedges, trees, ponds and stony habitats). It also relies on the generalisation of healthy diets with fewer animal products and more fruit and vegetables, generating important benefits in terms of biodiversity and natural resources conservation, human health and adaptation capacity. From a climate mitigation perspective, this scenario has a potential for GHG reduction comparable to that of most scenarios currently under discussion at the EU level: –40% (considering direct and indirect, CO_2 and non CO_2), compared to 2010. The potential for soil carbon sequestration is also important (up to 159 $MtCO_2eq$/year in the initial phase), but given the reduction in yields, there is no potential for bioenergy production. TYFA-GHG was developed to improve the climate performances of TFYA without modifying its overall philosophy. Based on a greater reduction in bovine livestock (-34% compared to 2010 compared to -15% for TYFA) and the controlled development of methanisation from grassland grasses and animal manure, emission are reduced up to -47%, the soil C sequestration potential is similar, and 189 TWh/year of bioenergy can be produced.

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scales, from soil to landscape. In combination with continuous soil cover through the development of intermediate crops, TYFA/TYFA-GHG should also leads to healthier soils and water body status to be achieved simultaneously.

— Finally, the significant rediversification of plant systems, the reconnection of crop and livestock systems and the improvement of soil health are key aspects that would contribute to increase the adaptation capacity of the agricultural sector to climate change impacts: increased water stress, emergence of new parasites/diseases, irregular rainfall.

In contrast, the mitigation potential of the EU LTS and NZ 2050 scenarios are, by construction, very high: their net annual sequestration potential (allowing to offsett residual emissions from other sectors) ranges from 83 to 489 $MtCO_{2eql}$. On the other hand, these scenarios are not always explicit on how they plan to address other sustainability issues of the food system, while their negative impacts could potentially be significant.

— In terms of biodiversity, the drastic reduction in the share of agroecological infrastructure considered as "non-productive", as well as in the area under natural grasslands (up to -53% of non-productive areas in EU-LTS, -91% of grasslands in NZ 2050), will not be without effects given the major role that semi-natural vegetation plays for European biodiversity. Besides that, no details are given on the use of pesticides. Given the assumptions of yield increases, these uses could at best slightly reduce if we consider technological progress, at worst increase to maintain yields in the face of new resistance and pathogens. The consequences in terms of biodiversity will be important in both cases.

— Similarly, the use of synthetic fertilizers is not questioned, nor are the high levels of territorial specialisation and the imbalances in the nutrient cycles that accompany them. This could result in potentially further degradation of soil life and organic matter content, as well as impacts on surface and groundwater bodies.

— Finally, the issue of the resilience of agroecosystems and production systems is only quickly touched upon; here again, the priority given to yields increases and the poor consideration for farming systems rediversification appear to difficult to combine with an increase in their adaptive capacities.

These limitations can be explained in part for methodological reasons: couplings between climate models and biodiversity models are still in their infancy,[3] and potential impacts of scenarios on soil life /soil structure are difficult to quantify using single / univocal indicators. But they also reflect an implicit hierarchy, as they *de facto* lead to consider the climate issue as the priority over others.

It is however the very realism of some of the land sparing scenarios here analyzed that can be questioned in this respect, given the importance yields increases play therein. The trend towards stagnation in European yields, particularly in cereals, indeed shows that this assumption is by no way not self-evident. Considering in addition the potential impacts of most scenarios on soil life, and on biodiversity in the broad sense, as well as the low capacity of the resulting agricultural systems to adapt to climate change, it is the very productive potential of agroecosystems that, in the medium or long term, could be called into question, leading in return not to an increase in yields but to their decline. Beyond the question of the hierarchy of objectives between climate and biodiversity, it is the very strategy of climate change mitigation, based on land sparing, that would become ineffective.

4. Conclusion: structuring the discussion beyond climate issues

This *Study* shows that if the potential contribution of an agroecological Europe to the objective of decarbonization is not immediately compatible with the objective of neutrality, it appears substantial and above all provides credible solutions to the other challenges the current European food system is facing.

These same issues—biodiversity, natural resources, human health—have thus to be better considered when developing and discussing climate-focused scenarios for the agricultural sector. This is all the more so since, as time goes by, the possibility of identifying and implementing trajectories considering together all the sustainable development goals is increasingly challenging and is likely to lead us to the necessity to make choices. These should be based on the most transparent possible discussion of the implications of different options. The dashboard logic used here is particularly important in this respect.

3 Leclere D. *et al* (2018). Towards pathways bending the curve of terrestrial biodiversity trends within the 21st century.

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INTRODUCTION

Human-induced climate change has become one of the most pressing issue human societies have to deal/cope with. According to the latest IPCC report (Masson-Delmotte *et al.*, 2018), carbon neutrality should be reached by no later that 2060-2070 if we want to keep global warming below 1.5°C, and by 2100 at the latest to keep it below 2°C. It is now increasingly acknowledged that the food, agricultural and land sector will play a key role in achieving this goal, by simultaneously (i) *reducing its emissions*, (ii) *increasing carbon removal* and (iii) *providing biomass* for fossil C substitution for energy and material production. This report explores the extent to which a large-scale agroecological transition that would build on the principles of organic agriculture—hence on a *land sharing* strategy—could combine those three approaches to contribute to climate mitigation in the European context. It does so by making explicit the climate implication of an agroecological scenario for Europe presented elsewhere, the Ten Years For Agroecology in Europe scenario (hereafter referred to as TYFA) (Poux & Aubert, 2018). One of the specificities of this scenario is to grant equal importance to several key issues associated to the food, agricultural and land sector. Alongside climate change, TYFA aims at addressing biodiversity conservation (both within and outside Europe); natural resources preservation (and in particular water and soils); food security and human health issues, associated to both diets and exposure to agricultural chemicals; and adaptation capacity at the farm and landscape levels.

This contribution comes at a moment where a broad consensus seems to emerge on the idea that *land sparing* strategies (Phalan, 2018) are best suited to address climate issues and reach carbon neutrality, while neither threatening European/world food security, nor destroying remaining rich biodiversity areas. While this land sparing strategies have mainly been defended considering situations under the tropics (and notably with regard to deforestation), it has naturally been transposed to Europe. Indeed, in most scenarios currently discussed at the European Union (EU) or Member State (MS) levels (Schulte *et al.*, 2013 ; Bryngelsson *et al.*, 2016 ; EC, 2018 ; Lóránt & Allen, 2019), sustainably intensifying food production in a climate efficient way (both animal and vegetal production) is considered as a prerequisite to spare land that can, in turn, be used either for afforestation or bioenergy production—implying in some cases important land use changes within the European territory. In such a perspective, (i) emissions reduction *per kg of food produced* comes together with (ii) *greater sequestration potential* (through afforestation) and/or (iii) *biomass production for energy* (through the development of bioenergy crops). Other trade-offs and benefits associated to the key issues highlighted above—biodiversity and natural resources conservation, adaptation, human health—are rarely accounted for in such land sparing scenarios. Yet, to give but one example, the biodiversity implications of an agricultural intensification that would continue to rely on pesticides and mineral fertilizers can be questioned, as it can even impact agricultural production itself—e.g. through a continuing loss of pollinators (Sponsler *et al.*, 2019) or auxiliaries/insects (Sánchez-Bayo & Wyckhuys, 2019). Other recent works have also shown that the land use changes associated to the above mentioned approaches—leading in most cases to the conversion of large areas of grasslands into bioenergy crops—imply huge trade-offs with biodiversity that are nothing but negligible (Heck *et al.*, 2018 ; Hof *et al.*, 2018).

In this context, this report intends to take a broader perspective on the question of climate mitigation in the agricultural and land sector to analyse the implications of the TYFA scenario, a land sharing inspired scenario for Europe. In doing so, it follows and deepens, at the sectoral level, the efforts undertaken in the last IPCC special report to relate climate mitigation pathways to a broader set of sustainable development objectives (Roy *et al.*, 2018)—including adaptation.

The main results of the report are threefold.

- First, it shows that an agroecological approach to climate mitigation, based on organic agriculture and the generalisation of healthier diets for Europeans, would reach a similar or even higher level of emissions reduction than most scenarios currently discussed at the EU or MS levels.
- Second, this would come together with important co-benefits in terms of biodiversity, natural resources

conservation, human health and climate adaptation that seems potentially higher than that of existing scenarios, for which these issues are largely ignored.

— Third, the potential for both carbon sequestration/carbon removal and bioenergy/biomaterial production of TYFA appears however much lower than for land-sparing inspired scenarios, maximizing the carbon balance. This last result brings us to discuss in conclusion the conditions under which carbon neutrality could be compatible with an agroecological Europe.

The report is divided into three main parts. In a first part, the foundations of the TYFA scenario are briefly outlined—the reader interested for more details can consult the full TYFA report (Poux & Aubert, 2018). The rationale for a variant of the scenario is also presented. In a second part, the potential of emissions reduction, carbon removal and fossil substitution of the TYFA scenario and its variant are presented, while in the third part, associated co-benefits are discussed. A fourth and last part compares TYFA and TYFA-GHG with a series of climate-mitigation scenarios that have recently been discussed at the EU level, using a "dashboard" approach as the one recently proposed by Waismann *et al.* (2019). The ClimAgri® calculator and how we parameterized it to assess emissions reduction potentials of the TYFA scenarios between 2050 and 2010 are presented in annex to this document (section 7.2).

1. A SCENARIO FOR A EUROPEAN AGROECOLOGICAL TRANSITION

Published in September 2018, the TYFA scenario has been developed to test the extent to which a large-scale agroecological transition in Europe could be a plausible answer to the pressing environmental and societal challenges the European food system is facing. It shows that a generalissation of agroecology, understood broadly as the combination of the principles of organic agriculture with the redeployment of natural grasslands and the extension of agroecological infrastructures (hedges, trees, ponds and stony habitats) could feed 530 millions of European citizens by 2050 under the conditions of significant changes in diets (see section 1.2 for more details). To make the implications of such a scenario for climate mitigation explicit, this section briefly presents the model on which the scenario rests, its main hypothesis, the variant that has been developed to better address climate issues (hereafter referred to as TYFA-GHG), and the main outcomes of the two scenarios developed (TYFA and TYFA-GHG).

1.1. Modelling an agroecological Europe: the analytical framework

While the term agroecology actually encompasses different meanings,[1] it is tackled here from a primarily agronomic perspective, 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). Without seeking to cover every aspect of the discussion as to what exactly constitutes agroecology, TYFA thus concentrates on the technical aspects, while keeping in mind that these aspects have consequences for, and are conditioned by, all of the economic, social and political dimensions of the food system to which an agroecological Europe contributes.

The development and the quantification of the TYFA scenario were based on an original modelling process of the European food system, which enabled us to answer to the following questions (see section 1.4): is a generalisation of agroecology "feasible", from both a dietary and a biogeochemical point of view? Under which assumptions about diets? With which consequences for biogeochemical cycles?

In the perspective adopted, the European Union of 28[2] (hereinafter referred to as the EU-28) constitutes the unit of analysis. It is seen as a "black box", without direct consideration 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 the 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). This approach appeared essential from a policy perspective: this is indeed the level at which most public policies involved in an agroecological transition—the Common Agricultural Policy, trade agreements (multilateral and bilateral),[3] environmental policies—are negotiated.

The model itself (hereinafter referred to as TYFA*m*) is organised around five compartments between which material and energy flow, and which are connected systemically:

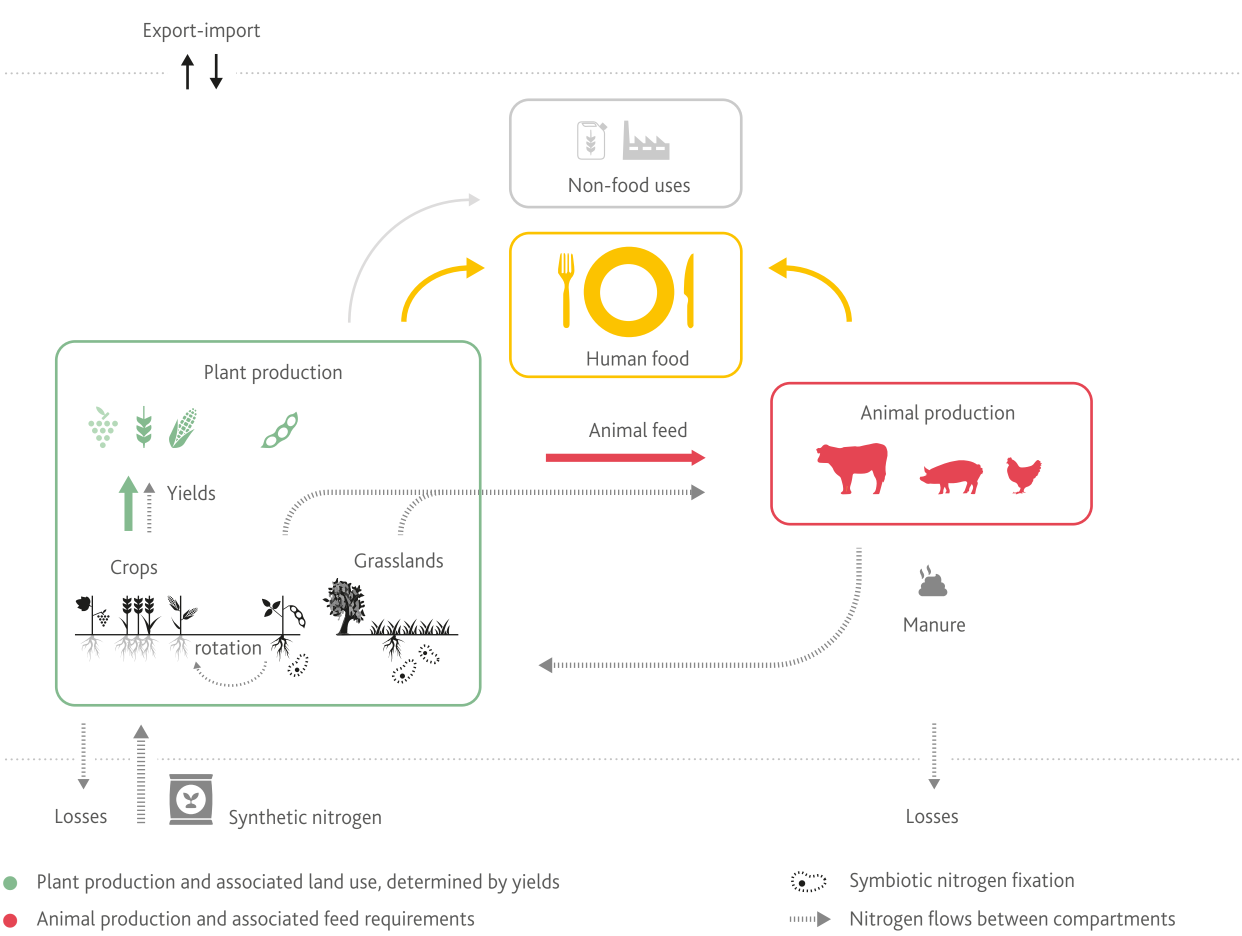
— *Crop production*, resulting from a certain European *land use* (distributed between arable land, permanent crops, permanent grasslands and agroecological infrastructures: hedges, trees, ponds, stony habitats, sunken paths) and the associated *yields*;

1 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 for a more in-depth discussion of the agroecological approach adopted in this project.

2 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.

3 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).

FIGURE 1. Logical structure of TYFAm: a simplified representation of the European food system



— *Livestock production,*[4] 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 products[5];
— *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 fertility.[6] 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 (as mentioned above). **Figure 1** provides a graphic representation of the logical structure of the model.

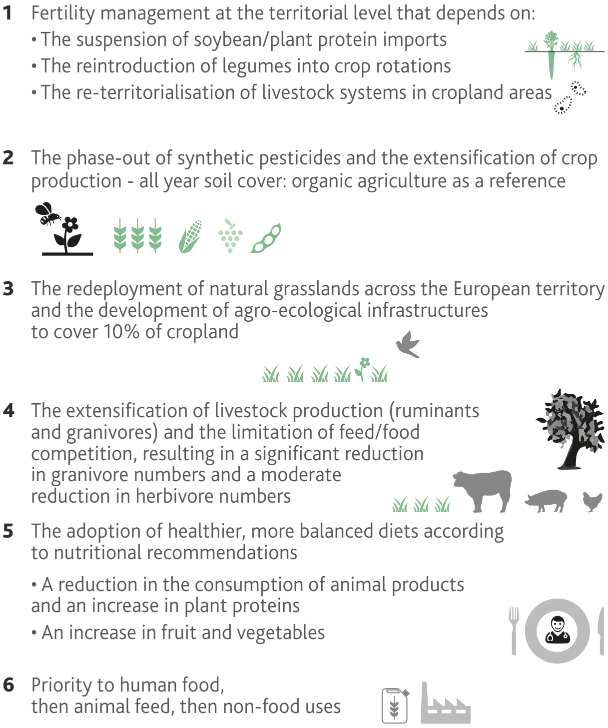
For each of those five compartments, specific assumptions were made to parametrize the model and *test* the coherence and the plausibility of the scenarios from a quantitative point of view. Those hypotheses are described in section 1.2.

4 The more specific analysis of the *crop production* and *livestock production* compartments considers 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.

5 It should be noted that we believe that the TYFA assumptions are compatible with imports of non-substitutable tropical products: coffee, cocoa, tea—the level of which remains to be determined.

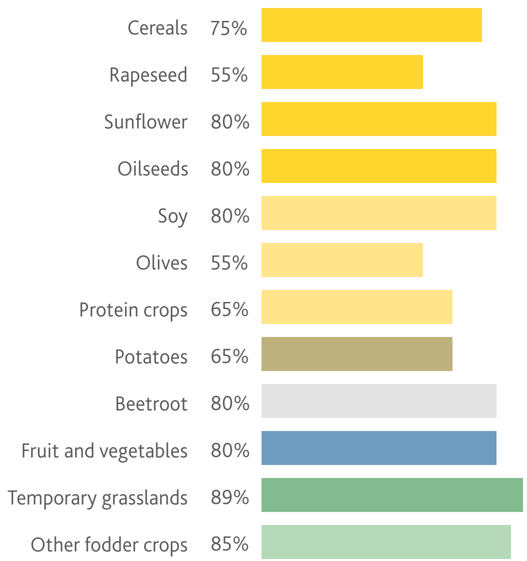
6 Other components of fertility clearly play a major role in the organisation of the system, especially phosphorus and, to a lesser extent, potassium. In an initial approach, we considered that nitrogen plays a more important role than phosphorus as a "command variable" for the different yields of the 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.

FIGURE 2. The main assumptions of the TYFA scenario



Source: authors.

FIGURE 3. Yield gap between TYFA 2050 and 2010



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

1.2. The tested hypotheses for an agroecological Europe

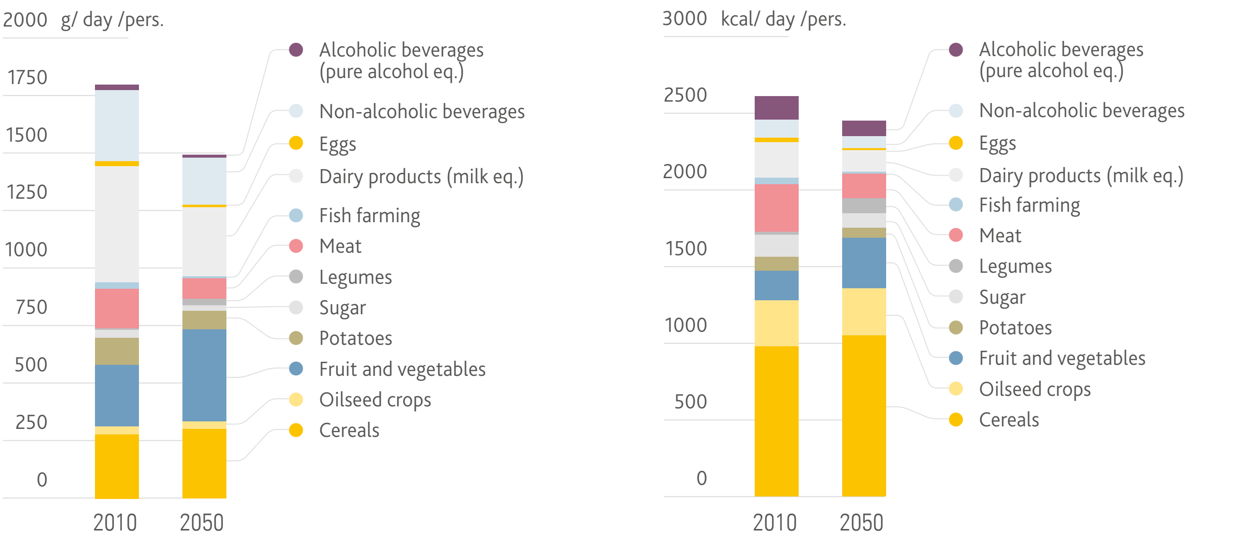
The framework that was used as a starting point for TYFA is the one developed by the Interdisciplinary Agroecology Research Group (GIRAF) (Stassart *et al.*, 2012), whose key principles are:

— 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;
— Aiming for optimum yields rather than maximum yields;

Although this GIRAF framework establishes a "sphere of possibilities" inspired by a strong sustainability approach (Godard, 1994), this sphere remains vast. For example, it leaves open the question of the degree of mobilisation of external inputs such as fertilisers and pesticides. TYFA therefore adapts this framework in order to balance the challenges for health, biodiversity protection and climate change. The set of assumptions made in TYFA are only quickly recalled in the following paragraphs and graphically represented in **Figure 2** (readers interested in their justification shall consult the full TYFA report (Poux & Aubert, 2018). These assumptions concern the five compartments of the model: fertility management and nitrogen cycle; crop production and land use; livestock production; industrial uses; and food.

— Nitrogen cycle and management: closing fertility cycles at the finest territorial level possible, which depends on:
  • The phase-out of soybean/plant protein imports;
  • The reintroduction of legumes into crop rotations;
  • The re-territorialisation of livestock systems in cropland areas;
— Crop production and land use: extensifying crop production in a re-diversified agricultural landscape, a two-level approach:
  • An extensification of crop production at the plot level that relies on the phasing-out of both pesticides and synthetic fertilizers, taking organic agriculture as a reference (most notably for yields—which are given in **Figure 3**);
  • A more diverse agricultural landscape that relies on a greater spatial heterogeneity, on the extension of semi natural vegetations (agroecological infrastructures) to 10% of the cropland area, and the redeployment of natural/permanent grasslands across the European territory;
— Livestock production: extensifying livestock production (both ruminants and granivores) and limiting the feed/food competition, which results in a significant reduction in granivore numbers and a moderate reduction in herbivorous numbers—the number of which has been calculated

FIGURE 4. Assumptions regarding diets in TYFA and comparison with the 2010 diet



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

to enable the maintaining of the European area under permanent and natural grasslands at a similar level in 2050 compared to 2010;

— Human diets: adoption of healthier and more balanced diets according to nutritional recommendations (see the resulting diet in **Figure 4**):
  - A reduction in the consumption of animal products and an increase in plant proteins. Following the hypothesis made on ruminant livestock, the reduction in meat consumption is higher for monogastric meat than for ruminant one;
  - An increase in fruit and vegetables consumption;

— Priority to human food, then animal feed, then non-food uses. In the TYFA scenario, this results in the total phase-out of bioenergy crops, neither under the form of biofuel nor that of biogas. The production of biomaterial from agricultural production is however kept constant.

Seen from a climate mitigation perspective, two of the above hypotheses are contrary to what should be done if climate change was the unique focus:

— Only slightly decreasing the amount of ruminant livestock and giving them a relatively higher importance in the diet than to monogastric (pork and poultry), which are however more climate efficient;

— And reducing to 0 the contribution of the agricultural sector to bioenergy production, while reaching carbon neutrality supposes in general a greater contribution of the agricultural sector to the production of renewable energy.

The first hypothesis on the priority given to ruminant livestock stemmed from the idea that while not optimal from a climate mitigation point of view, ruminants and the permanent grassland they allow to maintain play key roles for fertility transfer at the territorial level (Ryschawy *et al.*, 2012 ; Dumont *et al.*, 2018) and for biodiversity & natural resources conservation (Minns *et al.*, 2001 ; Pärtel *et al.*, 2005 ; Vertès *et al.*, 2010 ; Habel *et al.*, 2013). The size of the bovine herd was thus adjusted to ensure the maintaining of natural grasslands across Europe while decreasing the overall level of grazing intensity to around 1 LU/ha, while this average conceptually covers a variety of situations context dependant (see Poux & Aubert, 2018, p. 39-40 for a full description of livestock systems under TYFA). The objective is threefold: (1) to keep the European area under natural grassland constant by 2050, for more than 25% of all habitats and species the EU is committed to conserve as per the 1992 Habitat Directive and the Convention on Biological Diversity are associated with grasslands; (2) to ensure a better management of those grasslands, most of them being currently badly managed with regard to their conservation status (Halada *et al.*, 2011); (3) to decrease the demand for animal feed by priorising livestock production based on left-over (Schader *et al.*, 2015) rather than cereals, in a land-use—rather than climatic—perspective (Van Zanten *et al.*, 2016).

The second hypothesis on reducing crops-based bioenergy production to zero[7] was based on our analysis of the scale effects linked to the development of industrial facilities for the agricultural bioeconomy.[8] Experience over the last 20 years in this field—concerning in particular biofuels in France (Schott *et al.*, 2010) or anaerobic digestion in Germany (Emmann *et al.*, 2013)[9]—has shown that the development of these installations has resulted in the simplification of cropping systems in their

7 It must also be noted that the development of agroecological infrastructures such as hedges and agroforestry can logically lead to increased woody biomass use. This potential has not been properly accounted for so far.

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

9 In Germany, the development of biogas production has led to a situation where nearly 7% of the national UAA is cropped with maize for biogas production.

supply area, whereas an agroecological 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 (Gerlach *et al.*, 2013 ; Couturier, 2014) has been suggested as a possible response to these questions, assuming their generalisation against the argument of economies of scale is, in our view, challenging. This assumption was comforted in the case of biofuel by the fact that first generation biofuels produced in Europe from rapeseed, wheat or sugarbeet perform poorly from a sustainability perspective (de Vries *et al.*, 2010), while second generation biofuels from agricultural feedstock are likely to impact upon carbon and nitrogen cycles (hence soil fertility) by removing large amount of biomass from fields (Schrama *et al.*, 2016)

The question of relying on anaerobic digestion was a bit more critical. This technology is indeed often presented as a key solution to simultaneously decrease greenhouse gases and enhance agroecological practices, as it is supposed to simultaneously contribute to:

— (i) Limiting emissions from in-house manure—providing that manure is regularly collected and properly stored before used by digesters;
— (ii) Valorizing cover crops that have beneficial effects on soils and water quality (Szerencsits *et al.*, 2015);
— (iii) Maintaining grasslands with fewer ruminants (by using grass from grassland as feedsock), thus decreasing the amount of greenhouse gases from enteric fermentation;
— (iv) Producing biogas, and possibly electricity and heat that can substitute fossil fuels.

However, controversies exist on the effects on soil organic matter as well on water quality of spreading digestate instead of composted manure. In particular, a review of the existing literature conducted by Möller (2015) shows that the remaining organic matter returned to soils after anaerobic digestion would be more stable, enabling a "similar reproduction of the soil organic matter as obtained by direct application of the feedstock or by composting of the feedstock"—albeit with potentially important direct and short-term effects on the soil microbial activity and community. Other research carried out in France are more cautious regarding the carbon return to soils. Comparing the effects of digestate and compost applications on soil carbon sequestration, Bodilis *et al.* (2015) indeed shows that: (i) the C content of composted manure is slightly above the one of digestate, as measured in terms of similar organic C/ha; (ii) at a territorial level, the methanisation chain as a whole reduces the proportion of carbon likely to return to the soil in favour of that mobilised in gaseous form (CH_4 and CO_2) when compared with a compost chain. The nitrogen contained in the digestate is under a mineral form, and therefore has (potentially) the same impacts as synthetic nitrogen on soil life and on water quality through greater nitrogen leaching (Reibel-Geres, 2018). The consequences of cutting grass from grassland for biogas production instead of having ruminants on them is also likely to negatively impact upon their biodiversity, as suggested by recent research focusing on the "rewilding" of temperate grasslands (Garrido *et al.*, 2019). Lastly, while the GHG balance of biogas is positive for well-managed facilities, the impact can turn to negative when the process is not fully controlled, with undesired emissions of NOx. Although such risks cannot easily be accounted for in a model, they potentially hamper the actual interest of biogas from the GHG perspective. A recent study has shown that the actual NOx emissions of the German chain is 22-75% above the current standards, affecting the overall balance of biogas (Paolini *et al.*, 2018).

The risks linked to biogas production in agronomic and biodiversity terms, associated with the socio-economic aspects—biogas development leading potentially to capital dependent facilities, based on economies of scale—led us to exclude this option in TYFA scenario at first instance. However, this radical vision prevents from considering and therefore measuring the benefits in terms of renewable energy associated with a controlled and limited development of the biogas sector. As an alternative, plausible and desirable assumption testing the possibility to transform biomass into gas was then considered possible, upon certain carefully considered conditions that would alleviate above-mentioned social and environmental trade-offs. This led to envisage a variant of the scenario that would rely on this option to further decrease greenhouse gas emissions. Such a variant of the scenario would enable to make different hypotheses regarding the size of the bovine herd, but with potential implications for two aspects that we are about to discuss in the following paragraphs: biodiversity and adaptation.

1.3. TYFA-GHG: a variant to better address climate issues

In essence, the TYFA-GHG variant to the TYFA scenario aims at decreasing the size of the bovine herd to reduce the amount of emissions coming from enteric fermentation—the first source of GHG emissions in the EU—without diminishing the area under natural grasslands—for biodiversity & natural resources conservation, and fertility management purposes (see below).[10] It relies on two main levers:

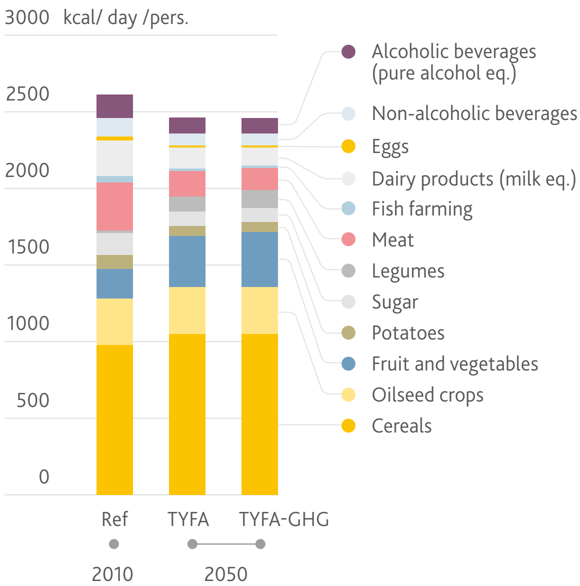
— A slight reduction in milk and bovine meat consumption/head compared to the initial scenario: -16% on dairy (from 300g/day/pers to 250g/day/pers) and -20% on bovine meat (from 30g/day/pers to 26g/day/pers). This enables to decrease the bovine herd by 21% compared to the original TYFA scenario, and by 34% compared to 2010;
— The development of anaerobic digestion using biomass from cut grasslands and animal manures. It is hypothesized that 18% of the dry matter produced by grassland would be used as feedstock along with 50% of all bovine manures.

10 This, in a context where the area under natural grassland has been continuously decreasing in Europe over the last 25 years (-11% since 1995)

In order to limit the impact of cutting grass—rather than grazing it—on grassland biodiversity, the assumption is that grassland will be used for biogas production only one year out of five. The use of cover crops as feedstock—generalized under TYFA—was not considered, while it would enable to produce a significant amount of biogas (Szerencsits *et al.*, 2015). Harvesting cover crops in view of their use as feedstock implies indeed important constraints with respect to the minimum yields to reach (see also for a more detailed discussion Solagro *et al.*, 2016, p. 57). There have also been a number of controversies recently on the economic realism of mobilising as much biomass from cover crops and pasture for biogas production (Baldino *et al.*, 2018). While we will not discuss these controversies in details here, let us just mention that the points raised in these debates are well aligned with the cautions expressed above, on the potential (and detrimental) environmental impacts associated with the high investment costs in biogas facilities.

The main characteristics of both scenarios—TYFA and TYFA-GHG—are quickly presented in the next paragraph, before turning to a detailed presentation of their potential for climate mitigation.

FIGURE 5. European diets in TYFA/TYFA-GHG compared to 2010 (in kcal/day/agricultural products)



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

1.4. Main characteristics of the two scenarios

Following the assumptions presented above, the European food system would be dramatically transformed by 2050. In the following pages, we briefly present its main characteristics under the two scenarios discussed here—TYFA and TYFA-GHG—and compare it to the 2010 situation. Three main aspects are discussed: diets; levels of production (and associated export capacity); the land use.

1.4.1. On diets

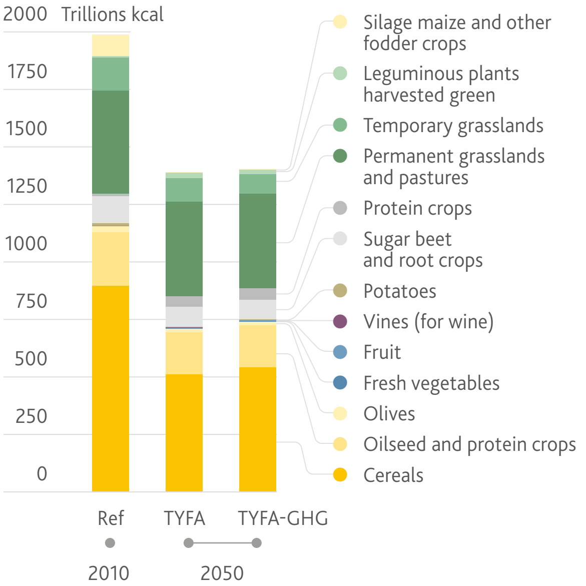
On diets, three criteria were combined to define the average European diet under TYFA: nutritional, environmental and cultural ones. On nutrition, recommendations from the European Food Safety Authority and of the World Health Organization on macronutrients & energy uptake were used (EFSA Panel on Dietetic Products & Allergies, 2010 ; EFSA, 2017), as well as upper safety limits for certain products or food groups (for example 100 g/day for sugar, 70 g/day for red meat), and minimum requirements for others (400 g/day for fruits and vegetables or above 30 g/day for fibres). From a cultural viewpoint, the proposed diet was constructed from the "average" food matrix rebuilt for 2010, with main changes concerning proteins (a reduction in animal proteins and an increase in plant proteins), sugar (a significant reduction), and fruit and vegetables (a much higher proportion). Finally, on the environmental level, three aspects were taken into account: land use; the need to introduce symbiotic nitrogen; and the need to maintain grasslands in order to conserve biodiversity. This led 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.

The main changes between TYFA and TYFA-GHG concern the daily consumption of dairy and beef meat, which is slightly reduced. To compensate for the loss of proteins and calories associated to these changes, the daily consumption of legumes and fruits and vegetables increases a little bit. The resulting diet is really close to that retained in TYFA, as illustrated in **Figure 5**.

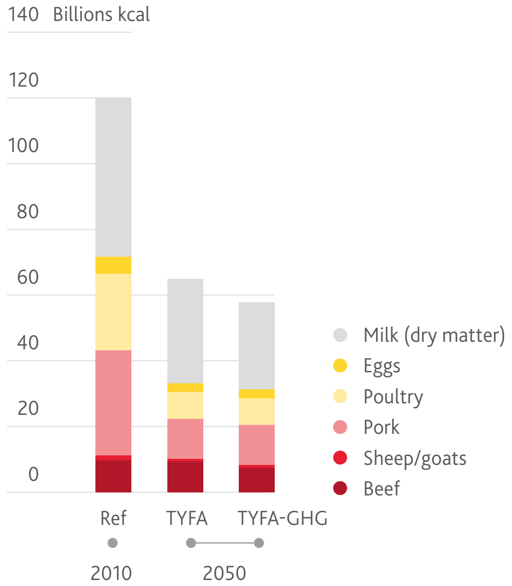
1.4.2. On the production side

On the production side, both TYFA and TYFA-GHG are characterised by a strong decline of the overall production: -35% on average for TYFA, -32% for TYFA-GHG. This stems from the strong hypothesis regarding the extensification of the production, for animal as well as vegetal production. Despite this decline, European needs would be covered by European production under both scenarios, leaving even a certain export capacity on two key productions: dairy and wheat. This is made possible by the associated changes in diets and most notably the decrease in animal proteins consumption. As livestock is today the main consumer of vegetal production, a decrease in animal production leads to "release" the pressure for vegetal production.

FIGURE 6. Evolution of animal and vegetal production under TYFA and TYFA-GHG, compared to 2010 (in kcal)

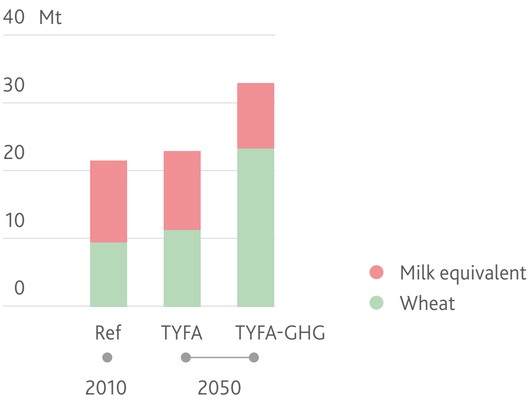


Source: TYFAm.



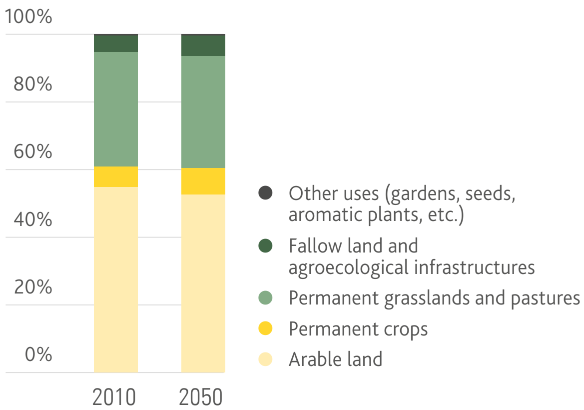
Source: TYFAm - Eurostat.

FIGURE 7. Evolution of cereal and milk surplus under TYFA and TYFA-GHG compared to 2010 (in Mt)



Source: TYFAm and FAOstat.

FIGURE 8. Evolution of agricultural land use by broad categories for both TYFA/TYFA-GHG



Source: TYFAm.

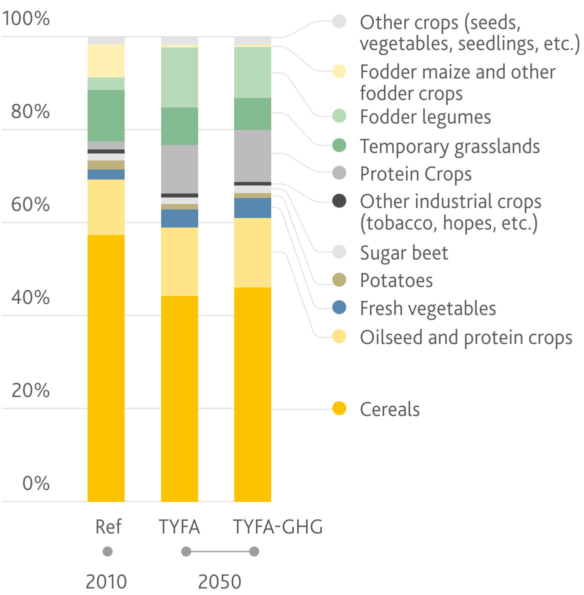
The differences of production between TYFA and TYFA-GHG well illustrate this point. The relative decrease of the bovine herd under TYFA-GHG reduces the demand for cereals used as feed; and the increase in vegetal production that follows, expressed in calories, is relatively higher than the decrease in animal production. **Figure 6** and **Figure 7** illustrate those points.

1.4.3. On the land use

Changes in the land use associated to TYFA and TYFA-GHG are comparable, and follow logically from the hypotheses made on cropping and livestock systems. Compared to 2010, and considering broad categories of land-use (arable land, permanent crops, permanent grasslands, other agricultural land), they remain limited, as shown in **Figure 8**. The fraction of permanent grasslands remains unchanged, as a key hypothesis of the scenario. 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.

But 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

FIGURE 9. Evolution of overall crop rotation within arable land



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

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. The main changes of land use are thus within the arable land category, with slight differences between TYFA and TYFA-GHG (**Figure 9**).

The share of the UAA occupied by cereals decreases significantly (a bit less under TYFA than under TYFA-GHG) and is compensated by an increase 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 (and almost disappear under TYFA-GHG due to the relatively higher decrease in 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.

2. THE CLIMATE IMPLICATIONS OF TYFA

As discussed in the introduction, there are actually three main ways by which the agricultural sector can contribute to the decarbonisation of the economy: by reducing its emissions as much as possible, by sequestering carbon in agricultural soils (or in forests if cropland or grassland are converted to forestland), and by producing biomass that can be used as a substitute for fossil carbon (bioenergy, biomaterial). Each of those three options are discussed below for the TYFA and TYFA-GHG scenarios.

2.1. Emissions reduction: -36 to -47% compared to 2010

As a methodological preamble, let us mention that the impact of both scenarios in terms of GHG emissions (and thus their potential of emissions reductions) has been assessed using the ClimAgri® calculator (see for a presentation Eglin *et al.*, 2016). The detailed structure of the calculator, and how it has been used in this report is detailed in the annex, section 7.1. In a nutshell, ClimAgri® assesses GHG emissions from the agricultural sector in a sectoral and comprehensive way, rather than restricting itself to the UNFCCC categories. As such, all emissions pertaining to the functioning of the sector are assessed, from upstream to downstream. Direct emissions include "classical" non-CO_2 emissions (CH_4, N_2O) coming from soil management, manure management and enteric fermentation, as reported to the UNFCCC; and CO_2 emissions associated with energy consumption at the farm level. Indirect emissions include CO_2 and non-CO_2 emissions originating from inputs fabrication as well as energy provision to upstream activities

2.1.1. The TYFA scenario: -36 to -40% of emissions reduction

Under the hypotheses mentioned above, direct and indirect GHG emissions originating from the agricultural sector could decrease by 36%. In addition, taking into account the fact that under the TYFA scenarios, protein imports are brought down to zero in a context where a significant share of those proteins comes from deforested areas in Latin America (Cuypers *et al.*, 2013), it was estimated that the total emissions reduction could be up to 40%.

The most important contribution of an agroecological system such as the one modelled in TYFA to the reduction of GHG emissions is through the decrease in N_2O and CO_2 emissions resulting from the use and fabrication of chemical fertilizer in general, and nitrogen in particular. In Europe, in 2016, emissions from agricultural soils accounted for almost 37% of direct agricultural emissions. By bringing the imports of synthetic nitrogen to the system down to zero, and by significantly improving the level of nitrogen use efficiency, N_2O emissions linked to the application of nitrogen to soils could significantly decrease (-48% according to ClimAgri® calculations), while CO_2 emissions linked to the making of nitrogen (55 Mt CO_2e according to ClimAgri® calculations) would be brought down to zero.

Emissions from manure management also significantly decrease under our hypotheses (-56%). Emissions reduction mostly come from the evolution of manure management practices of the bovine herd—the disappearance of liquid forms of manure following increases in the use of straw. Emissions reduction are less important in absolute terms for pork and chicken systems, but significant in relative terms (cut by more than half for pork, by almost 40% for chicken).

Direct emissions linked to the consumption of energy decrease by 16% partly by a decrease in the area of heated greenhouses (-20%), and indirect emissions by 43%, resulting from our hypothesis on the partial decarbonisation of the European electricity system (370 g CO_2/kWh to 120 g CO_2/kWh—see in annex, section 7.2.2, for more details on this hypothesis). Concerning the area under heated greenhouses, the TYFA scenario envisions a doubling of the area devoted to fresh vegetables production. As of today, it is estimated that around 72 500 ha of cultivated land is under heated greenhouses, or nearly 30% of the 200 000 ha covered by greenhouses. In a "business as usual scenario", a doubling of the area for fresh vegetables production would correspond to—at least—a doubling of the area of heated greenhouses. On the contrary, the idea defended in TYFA is that vegetables production should be seasonal as much as possible. Following this, the assumption was made that the area of heated greenhouses would not increase, and could even slightly decrease by 20% by 2050. No further hypotheses were made to increase the energy use efficiency for the heating of these greenhouses, nor for that of livestock buildings or agricultural machinery. It should also be noted that no specific hypothesis was made to reduce emissions from energy consumption in the agricultural sector through substitution of biofuels with biomass.

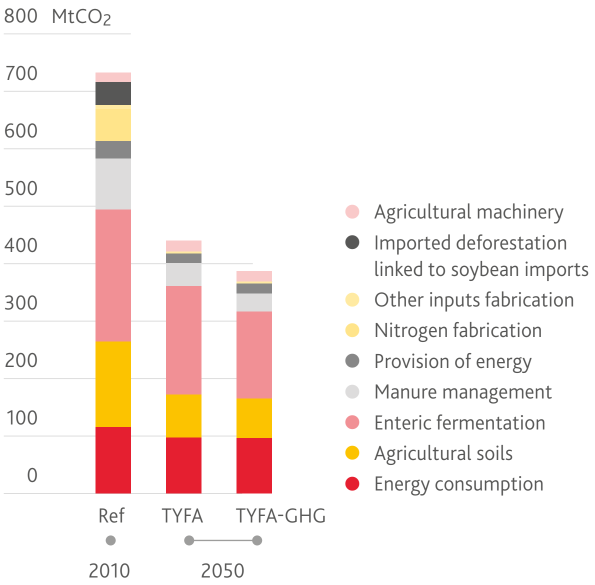
Emissions reduction linked to enteric fermentation is less significant (-18%), as the cattle population has been maintained important. As explained above, this results from the core hypothesis of TYFA regarding the key role of natural grassland in biodiversity conservation, and the need to have a sufficient number of animals to graze these grasslands. In order to reduce the amount of enteric emissions, we however made the hypothesis that half of the dairy and suckler cows would be given feed additive. Such additive are already available and can bring down the level of enteric emissions by 14%/cow—according to the existing literature (Pellerin *et al.*, 2013 ; Knapp *et al.*, 2014 ; Caro *et al.*, 2016). However, they can only be used in semi-intensified bovine herds, *i.e.*, given to animals which spend enough time within stables to allow for their feed to be managed. In the TYFA model, the share of cattle under a mixed system that could allow such feed management practices is 80%; we however made the hypothesis that only 60% of them would be concerned by this change.

The emissions reduction associated with the suspension of soybean imports from Latin America was calculated as follows: in 2010, the EU imported the equivalent of 30 million tonnes of soybean cakes from Brazil and Argentina, for which, following the "average" scenario of Weiss & Leip (2012), it can be estimated that 30% come from deforestation or the conversion of savannas. The level of GHG emissions from this soybean production can be estimated based on recent research on the topic (Castanheira & Freire, 2013 ; Raucci *et al.*, 2015 ; 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 CO_2/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 CO_2/kg of soybean). The resulting emissions reduction potential of the TYFA scenario is given in **Figure 10** together with that of TYFA-GHG.

2.1.2. TYFA-GHG: up to -47% of emissions compared to 2010

The potential of the TYFA-GHG scenario is slightly higher than that of the original TYFA scenario in that it enables for greater emissions reduction on all sources dependent upon the size of the bovine herd: enteric fermentation, manure management and, indirectly, agricultural soils—as the amount of manure used as fertilizer decreases. The emissions structure of the scenario is presented and compared to both 2010 and the original TYFA scenario in **Figure 10**.

FIGURE 10. Emissions reduction of TYFA / TYFA-GHG compared to 2010



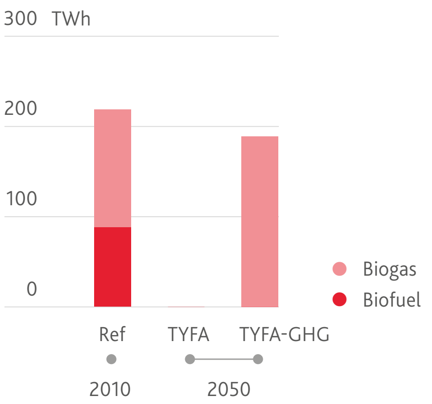
Source: ClimAgri®

All in all, the emissions reduction potential of TYFA-GHG is 7 points higher than that of the original scenario when considering all emissions (direct and indirect, CO_2 and non-CO_2). It is 12 points higher when considering only non-CO_2 direct emissions, following the IPCC reporting guidelines (35% for TYFA, 47* for TYFA-GHG). It also comes together with a potential of bioenergy production, which is presented in more details in the following section.

2.2. Fossil carbon substitution

Fossil carbon (hereafter "fossil C") substitution is a major aspect of all discussions pertaining to climate change. Decarbonising economies towards a "carbon neutral" world implies indeed, in most scenarios, that a large share of the remaining fossil C (under the form of a variety of fossil fuels) stay in the ground (Masson-Delmotte *et al.*, 2018). Given the determining role fossil fuels play in our life as both a source of energy and a source of material, keeping it in the ground implies in turn that alternatives be found. Renewable carbon under the form of biomass produced by farmers (or foresters) is such an alternative. The agricultural sector is thus asked to play a key role in supporting the transition towards a climate neutral world. Under both TYFA and TYFA-GHG scenarios, the contribution of the agricultural sector to such an objective is however limited. At a very aggregate level, and for both scenarios, the reduction of areas dedicated to industrial use is drastic: -91%. This reduction results from the abandonment of biofuels, which in 2010 occupied a significant share of the Utilized Agricultural Area (UAA) cropped with cereals and oilseeds (respectively 15 and 18%). Areas cropped with other industrial crops, as linen or hemp, were however kept constant at their 2010 level. However, possibilities to use a share of the area devoted to

FIGURE 11. Contribution of the TYFA and TYFA-GHG scenarios to European crop-based bioenergy production



Source: ClimAgri® & Bioenergy Europe.

grow wheat for export purposes (amounting to, respectively, 11 Mt and 27 Mt under TYFA and TYFA-GHG scenarios) for developing other bio-industrial crops do exist, but were not explored in details in TYFA. It would be a significant area of investigation, as the demand for bioplastic and other biopolymer is expected to grow significantly (Dammer *et al.*, 2013).

On the bioenergy side, as already mentioned, the contribution of TYFA is brought down to zero. Under the TYFA-GHG scenario, the use of natural grassland and animal manures as feedstock for the development of methanisation units enable for the production of approximately 189 TWh, or 16,25 Mtoe. This potential has been calculated as follows:

- Potential from natural grasslands: we assumed an average productivity of natural grassland of 4,5 tMS/ha (equivalent to 13,2 tMB/ha) and a methane yield potential of 98 m³ CH_4/tMB. Considering that 18% of the total production of grass is used each year as feedstock, it gives a potential production of 10 billion m³ of CH_4.
- Potential from animal manure: we assumed that 50% of the manure produced by dairy and suckler cows, as well as pork, would be used as feedstock, with a methane yield potential of 25% for bovine manure and 19% for pork manure. This results in a potential production of 9 billion m³ of CH_4.

These 19 billion of CH_4 represents 189 TWh, that is approximately 1% of the final energy consumption of the EU-28 in 2015 (Eurostat, 2018). It also represents an increase in biogas production from agricultural feedstock of 45% by 2050 compared to 2015 (Eurostat, 2018). Considering the drop of biofuel production to zero and this 45% increase in biogas production, the overall contribution of the agricultural sector to the production of renewable energy would decrease by 14% by 2050, as illustrated in **Figure 11**.

2.3. A potential for carbon removal by building soil organic carbon stocks

The generalisation of an agroecology based on the principles of organic agriculture would eventually offer important potential for soil carbon sequestration. Based on the existing literature, we estimate this potential to be around 159 $MtCO_{2eql}$/year, using cautious assumptions. These assumptions along with their justification are presented below. While this potential could seem important at first sight—it would allow the sector to offset a large share of its residual emissions—three key points should however not be neglected (see also for a complete discussion of the main limits to soil C sequestration with respect to the sole objective of climate mitigation Rumpel *et al.*, 2019)2019:

- (i) The potential for soil organic carbon (SOC) sequestration is limited over time, and also decreases over time: storage reaches an equilibrium value (that depend on the initial property of each and every soil and on the local agroecological conditions) and the rate of storage also starts to decrease once storage is initiated. As such, and as pointed out by Smith (2004), soil carbon sequestration can only play a temporary role in a medium-term strategy for climate mitigation, and has to be part of a broader sustainability policy.
- (ii) SOC sequestration is also *reversible*. In other words, the carbon sequestered in soils is non-permanent and a change in practices or land use at the plot level (e.g. converting a grassland to a cropland and vice-versa, or applying mineral fertilizers on an organically managed soil) can release part or the totality of the organic carbon that has been sequestered. Moreover, the rate of C gain is usually lower than the rate of C loss, emphasizing the fact that the perpetuation of practices compatible with C sequestration is essential to contribute to (temporarily) mitigating climate change (Smith, 2012).
- (iii) SOC sequestration can finally be partly offset by the rise in N_2O emissions associated with the changes in soil C turnover, as discussed recently by Lugato & colleagues (2018), although the complex interaction between SOC sequestration and non-CO_2 emissions are yet to be fully understood.

That said, it has also to be noted that soil carbon sequestration is not primarily an issue of climate mitigation—although it is reported here under this headings—but rather of fertility management, soil life and biodiversity, and climate adaptation (on this later point, see section 3.2).

To estimate the potential of SOC sequestration of the TYFA scenario (we considered that both TYFA and TYFA-GHG had overall the same potential), we distinguished between three main types of land uses: croplands, grasslands and agroecological infrastructures.

2.3.1. Croplands

For croplands, existing data/studies show that most practices at the core of the TYFA scenario are associated to important potential for SOC sequestration, such as high organic matter inputs under a composted form, crop rotation involving legumes, use of cover crops, extensification, and conversion to organic (Freibauer *et al.*, 2004 ; Smith, 2004 ; Lugato *et al.*, 2014). The first benefit of a generalisation of those practices—as hypothesized in TYFA—will be to halt the current decline in soil C content of most croplands across Europe (Lugato *et al.*, 2014, p. 3557)2014, p. 3557. The calculation of how much it could contribute to sequester is however complex due to many factors. First, most existing studies or modelling work tend to analyse the effect of different measures taking them one by one, while TYFA considers however a more systemic change in agricultural practices. Second, the potential annual rate of carbon sequestration resulting from changes in practices also greatly depends on initial conditions and the agroecological context, that both vary across European landscapes. In the absence of a dedicated, spatially explicit model, we took as a reference point the meta-anaysis published by Gattinger *et al.* (2012) discussing the effect of the conversion to organic farming on SOC concentrations, stocks and sequestration rates. Using data coming from temperate areas and net-zero input systems only,[11] they come to an average potential sequestration rate of 1 Mt $C0_{2eql}$/ha/y.[12] We retained this value and applied it to the whole area under annual and permanent crops, which is considered as constant under the TYFA scenario. This represents a maximum technical potential of 104.8 $MtCO_{2eql}$ /year. How this potential could translate into real carbon sequestration will most notably depend on the rate of adoption of the practices hypothesized in TYFA—which cannot be modelled nor projected at this stage.

2.3.2. Grasslands and agroecological infrastructures

The potential of soil C sequestration in grasslands has been the matter of intense and vivid debates over the last couple of years. In essence, some authors tend to argue that the potential is so high that it could offset all the emissions coming from ruminant livestock (including enteric ones)—and that, consequently, no further reduction in grass-fed livestock would be needed from a climate mitigation point of view. While these claims are supported by few robust researches in different sites in Europe (e.g. Soussana *et al.*, 2010)2010, recent meta-analysis leads to be much more nuanced on the question (Conant *et al.*, 2017 ; Garnett *et al.*, 2017)2017 ; Garnett<style face=»italic»> et al.</style>, 2017. Without re-opening this long-lasting debate, the calculation of the soil carbon sequestration potential under the TYFA scenario relies on the following set of hypothesis.

First, the respective shares of marginal land (20%), productive grasslands over 30 years (20%) and productive grasslands under 30 years (60%) among European grasslands was estimated based on expert consultation and on Huyghe *et al.* (2014). These hypotheses are crucial, as the SOC sequestration potential of grasslands heavily depends (as for croplands) on their ages and their agroecological conditions.

Second, we considered the potential for SOC sequestration in grasslands based on the meta-analysis proposed by Conant *et al.* (2017). In this meta-analysis, a broad range of treatments enhancing SOC stocks of grassland are considered: fertilisation, sowing legumes, sowing grasses, irrigation, introduction of earthworm or improved grazing management. Under the TYFA scenario, the average grazing intensity decreases to below 1 LU/ha[13]. Other management options such as sowing legumes or fertilizing grasslands are, however, not considered. As such, the average value retained for carbon sequestration rate in young productive grassland is 1.02 tCO_{2eql}/ha/y (+/- 0.48). This value is below the average one retained by Garnett *et al.* (2017) of 1.80 tCO_{2eql}/ha/y, which does not however distinguishes between management practices. For marginal land and grasslands over 30 years, the lower bound proposed by Conant *et al.* was retained, that is 0.54 tCO_{2eql}/ha/y. This value was also retained as an average value of C sequestration potential for areas under agroecological infrastructures.

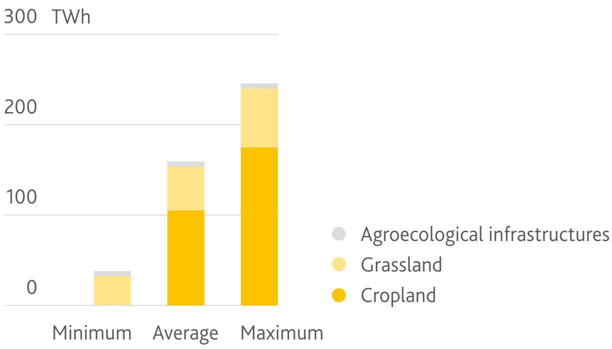
With those hypothesis in mind, a technical potential of C sequestration of 48.6 $MtCO_{2eql}$/y for all areas under grassland was estimated, to which another 5.9 $MtCO_{2eql}$/y can be added for agroecological infrastructures. As for croplands, this is only a technical potential. How much carbon will be actually stored in grasslands under TYFA will depend upon numerous factors. One of them is the fact that in the scenario, the total area of grassland will be kept constant but their geographies is expected to change through a selective redeployment of grasslands. In other words, while some grasslands will be converted to croplands in grass-dominated landscapes, some croplands will conversely return to grassland in arable land dominated landscapes (see for more details Poux & Aubert, 2018, p. 55-56). As such, and viewed in a dynamic/temporal perspective, a certain amount of carbon will first be released from the grasslands which will be converted, as the rate of C sequestration in croplands converted to grassland will be slower than that of emissions from converted grasslands. As the initial TYFA scenario has not yet been regionalized at a sufficient spatial resolution, it remains difficult to assess with more precision the impact of these processes on the overall C balance of grasslands. But it is obvious that the choices of which grassland will be converted back to cropland, and of which cropland will be converted to grassland will be a key parameter in this regard.

11 By net zero input system, they mean systems in which the amount of organic fertilizer applied on fields does not exceed that produced by 1 Livestock Unit (LU). This threshold allows to avoid considering too high SOC sequestration rate that would result in massive import of organic matter from elsewhere, thus simultaneously leading to important SOC decline in other parts of the world.

12 Based on the data discussed by Gattinger *et al.*, we considered a lower bound to be 0, and an upper bound to be 45 $MtCO_{2eql}$/ha/y. These data will be used in the last sub-section to estimate a minimum, average and maximum value to the technical potential for C sequestration (see section 2.3.3).

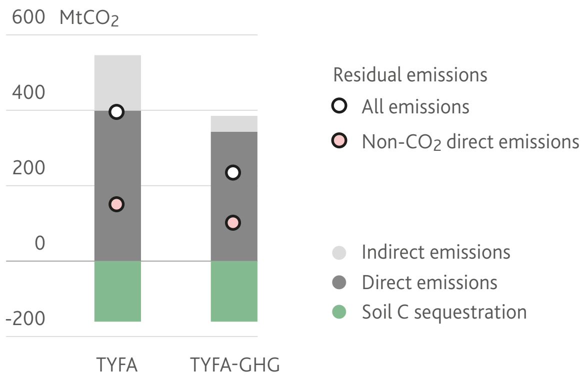
13 The grazing density as expressed here only considers the number of LU per the number of ha of natural grasslands, not of all fodder areas (as in Eurostat).

FIGURE 12. Technical potential for soil C sequestration under different land uses in TYFA



Source: authors, based on Conant *et al.*, 2017; Lugato et al., 2014; Gattinger *et al.*, 2012.

FIGURE 13. Residual emissions of TYFA and TYFA-GHG



Source: authors, based on ClimAgri®.

2.3.3. Technical potential for soil C sequestration under the TYFA scenario

Compiling the figures presented above, the total technical potential for soil C sequestration under TYFA appears to be around 156 $MtCO_{2eql}$/y. As explained above, this is only a technical potential which, if ever attained, would reduce year after year due to the progressive saturation of the soil sink. The respective role of the different land use compartments is given in **Figure 12**. Based on the 95% confidence interval given by each meta-analysis this estimate relies on, a minimum, average and maximum technical potentials are given.

Considering this technical potential of soil carbon sequestration, it is possible to estimate the amount of residual emissions of the agricultural sector under both TYFA and TFYA-GHG emissions (**Figure 13**). If only non-CO_2 direct emissions are considered (as in the UNFCCC framework), the residual emissions of TYFA could be of 144 $MtCO_{2eql}$/y, while that of TYFA-GHG of 92 $MtCO_{2eql}$/y.

The numerous uncertainties/controversies surrounding the estimation of the C sequestration potential in croplands should not conduce to overlook the numerous benefits that can be expected from increasing soil organic matter stocks in terms of adaptation, soil biodiversity and fertility conservation (Rumpel *et al.*, 2019). In the same perspective, the fact that the potential C sequestration of grassland is highly unlikely to offset the total emissions of grazing livestock (Garnett *et al.*, 2017)should be considered with respect to the numerous co-benefits grasslands offer in terms of biodiversity and natural resources conservation, adaptation and pest management, and landscapes. We now turn to a more precise discussion of the various co-benefits associated to the TYFA scenario.

3. A SCENARIO WITH MULTIPLE CO-BENEFITS

As outlined at the outset of this document, the original aim of the TYFA scenario was to take into account with the same level of importance several key issues associated to the food, agricultural and land sector, going beyond the sole question of climate mitigation: biodiversity and natural resources conservation; adaptation capacity at the farm and landscape levels; and human health issues, associated to both diets and exposure to agricultural chemicals. After having described in due details how the scenario deals with climate mitigation objectives in the previous section, the present section analyses how TYFA/TYFA-GHG could deliver on the other objectives. On this basis, section 4 will propose a structured comparison between TYFA/TYFA-GHG and other scenarios for the agricultural sector that have been recently published in view of (mainly) reducing its climate impact.

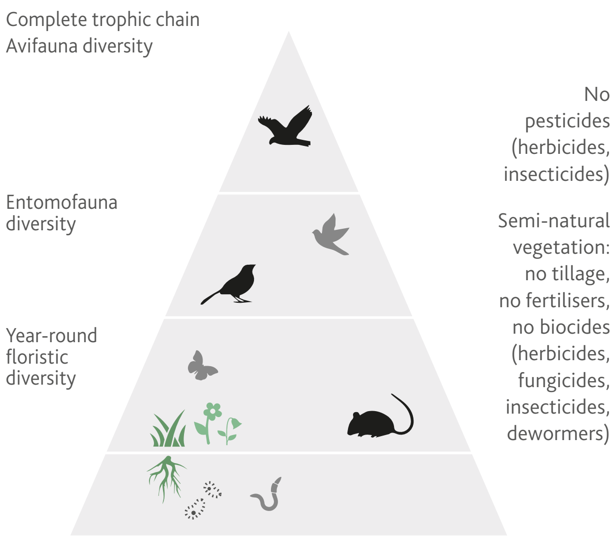
3.1. Biodiversity and natural resources conservation

The issue of biodiversity conservation needs to be considered at two interdependent levels: within Europe, at the farm and agricultural landscape level; and outside Europe, considering the indirect effect of the European food system functioning on other regions of the world. In this respect, it is often considered that while lower yields in Europe could potentially increase the level of biodiversity in European agricultural landscape, it is also most likely to increase the dependency of Europe to agricultural imports, and as such to increase its impacts on the rest of the world—most particularly tropical forests, whose value in terms of biodiversity conservation is utmost. This reasoning holds while considering no or only minor changes in diets. Yet, under the assumptions made in the TYFA scenario regarding diets, the overall dependency of Europe vis-à-vis the rest of the world would, on the contrary, *decreases*—and with it its pressure on biodiversity outside Europe. The way in which European diets can indeed change towards those hypothesized in TYFA remains of course to be explored in more details.

Regarding biodiversity and natural resources *within* Europe, and more precisely within agricultural landscapes, several research have underlined the importance of a multi-scale approach—from the soil to the landscape. Different groups of organisms occupy indeed different strata of the ecosystem and will respond differently to management changes at different scales (Gabriel *et al.*, 2010 ; Gonthier *et al.*, 2014). According to the literature, the changes in management practices hypothesized in the TYFA scenarios would have mostly beneficial impacts whatever the scale considered.

Regarding soils, numerous studies exist showing adverse effects of chemicals (both pesticide and synthetic fertilizers) on soil biodiversity and functioning (see for a review Thiele-Bruhn *et al.*, 2012). Conversely, other studies have demonstrated the positive impact of organic agriculture on soil fertility through the increased abundance and diversity of soil micro and macro organisms (Maeder *et al.*, 2002 ; Birkhofer *et al.*, 2008). This is also true for grasslands, in which the application of animal

FIGURE 14. Agroecological infrastructures and trophic chains



Source: authors.

antibiotics and mineral fertilizers tend to decrease the potential for soil carbon sequestration (Thiele-Bruhn *et al.*, 2012).

At the field level, a broad set of studies have looked at the impact of organic farming on a wide variety of taxa. While results do vary depending on which one is considered, the overall effect is undoubtedly positive, as stated in different reviews led by e.g. Tuck (2014) and Bengtsson (2005).

Finally, at the landscape level, it is now widely acknowledged that all forms of agroecological infrastructures (AEI)—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). In TYFA, the importance of AEI, which represent 10% of the cropped utilised agricultural area (considering only permanent and arable crops), will thus simultaneously increase the number of taxa and the complexity of trophic chains, as illustrated by the very simplified chain presented in **Figure 14**.

Amongst the different agroecological infrastructures, natural grasslands play a specific role in that they first contain a remarkable species diversity (79 species of vascular plants have been recorded in just 1 m^2 in some parts of central Europe, for example); and that 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).

At an even more aggregated level—that of the *pressure*—the IRENA indicators (Indicator Reporting on the Integration of Environmental Concerns into Agriculture Policy) developed by the European Environment Agency (2005) also give a sense of the positive impacts of TYFA. Of the 42 indicators developed by the EEA, six were used, as they more specifically identify pressure on biodiversity. To these indicators (the first six in **Table 1**) were added those concerning the proportion of agroecological infrastructures and of extensive livestock production.

TABLE 1. Indicators of determinants of biodiversity in TYFA 2050 *vs.* 2010 situation

Indicator	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 pesticides	380 kt of active substances, of which 40% fungicides (including copper sulphate)	0 ? for copper sulphate
Overall nitrogen balance (expressed in terms of coverage of requirements in cropland)	150 to 180% (according to different calculation methods – see Poux & Aubert, 2018, p. 53)	109 to 128%
Level of diversification (our calculation): proportion of the main crop in arable land proportion of the 4 main crops in arable land	20% (wheat) 50%	11% (leg. harvested green) 40%
Proportion of AEIs 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)

Following this quick literature review, **Table 2** proposes an evaluative summary.

TABLE 2. Summary of impacts on biodiversity in TYFA 2050 vs. 2010 situation

			2010		2050
Soil life	Nitrogen	-	Alteration of soil microbiota and macrofauna	+	Recovery of microbiota
	Biocides	--		+	
Cultivated crops	Crop diversification	±	Loss of plant diversity (harvest plants) and insects. Pollinators in decline	++	Recovery of plant diversity and microfauna Legumes encourage pollinators
	Nitrogen	-		++	
	Biocides	--		++	
Grasslands and rangelands	Nitrogen	-		++	
	Density	±		+	
Landscapes	Plot size	±	Loss of emerging biodiversity Decline in microfauna and mesofauna (birds, mammals, amphibians, etc.)	+	Recreation of trophic chains and varied habitats suitable for fauna
	AEI	±		++	
	Landscape diversity	-		++	
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

3.2. Adaptation capacity

A major issue for agricultural systems by 2050 will be to cope with highly different conditions. Both temperature and precipitation patterns will change significantly in most regions of Europe; and those changes will most probably be accompanied by pest outbreaks. According to the IPCC, increasing the adaptation capacity of agricultural systems includes "[reducing their] vulnerability through the actions of adjusting practices, processes, and capital in response to the actuality or threat of climate change" (IPCC, 2013, p. 513). Agricultural practices often mentioned in the literature as solutions for adaptation to climate change include adjustments in cultivars and sowing dates, technological options such as more efficient irrigation or fertilisation methods or new crops varieties for greater drought tolerance, and finally, ecosystem-based options (IPCC, 2013). Among these latest, a low-tech scenario such as TYFA could increase adaptation capacity by: (i) increasing the level of diversity in agricultural landscapes (from genes to species and ecosystems, at both spatial and temporal scales); (ii) improving soil organic matter, two solutions that are acknowledge as beneficial for adaptation (FAO, 2007; Scialabba and Müller-Lindenlau, 2010).

A greater diversity in agricultural landscape could contribute to adaptation in three different ways. In the face of pest/diseases outbreaks, a greater diversity increases natural control and regulation functions that can help manage pests and diseases, for example through the promotion of natural enemy abundance (Lin, 2011, p. 184-186). Adaptation options considered by the IPCC to tackle this issue read as follows: (i) biotechnology and genetically modified crops, with perceived risk to public health and safety and ecological risks associated with introduction of new genetic variants to natural environments; and (ii) increased use of chemical fertilizer and pesticides, with important trade-offs as well, including an increased discharge of nutrients and chemical pollution to the environment, adverse impacts of pesticide use on non-target species, increased emissions of greenhouse gases and increased human exposure to pollutants (IPCC, 2013, p. 98). The optimisation of biological pest control under an agroecological agricultural system could thus represent a third alternative option, without the above-mentioned trade-offs. This is well illustrated by the recent meta-analysis showing the greater capacity of organic system to promote pest control (Muneret *et al.*, 2018).

Diversified farming systems are also said to be more resilient to unpredictable weather patterns, as they offer buffering crop production (Pretty, 2008). Finally, agroecological infrastructures such as hedges and agroforestry systems can offer physical barriers in the case of extreme events that are deemed to become more and more frequent (Lin, 2011, p. 187).

Improved soil organic matter leads to more stable soil structure, that can make soils absorb higher amounts of water without causing surface run-off during flooding periods and improve water absorption capacity during extended drought periods (FAO 2007). Mäder *et al.* (2002), for instance, finds that in Switzerland, soil structure stability was 20 to 40% higher in soils under organic farming practiced than in conventional soils. The positive effects on adaptation to more frequent flooding and drought episodes caused by climate change would therefore be non negligible.

3.3. Human health issues

The impacts of a given agricultural and food system on human health has to be understood at least at two different, yet intertwined, levels: that of farmers/farm workers; and that of consumer. The health of farm workers and consumers are both affected by the intensity of use, and the relative toxicity of the products used.

Existing meta-analysis leave almost no uncertainties regarding the adverse health effects of pesticides on agricultural workers 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); important suspicion remain for at least four others (Inserm, 2013). In this context, a shift towards a pesticide-free agriculture as the one envisioned in TYFA would by no doubt improve the working conditions of agricultural workers, making them safer and healthier.

As far as consumers are concerned, no direct causal relationships demonstrating the effects of pesticides on health through food has been identified so far. It is nevertheless worth noting that in its latest collective appraisal, the French Institute of Health and Medical Research (INSERM) insists on the difficulty of detecting such effects using the assessment methods currently available. It highlights in particular three important limitations (Inserm, 2013, p. 117):

- Only active ingredients are tested, whereas adjuvants can change the degree of hazardousness 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.

Conversely, potential positive effects of organic food on human health are only hypothesized and have not been formally demonstrated, most notably because of the methodological difficulties associated with such a demonstration. While the higher quality of organic product with respect to chemical residues and heavy metals is most often related, too many parameters interact to isolate the sole effect of the origin of food (organic *vs* conventional) on consumer health. Most notably, high organic food exhibit better diet quality, richer in fruits and vegetabls and fibres, and poorer in cookies, dairy products and soda (Baudry *et al.*, 2017). Recent data from the same French cohort have shown that high organic consumption tends to be inversely associated with the overall risk of cancer (Baudry *et al.*, 2018).

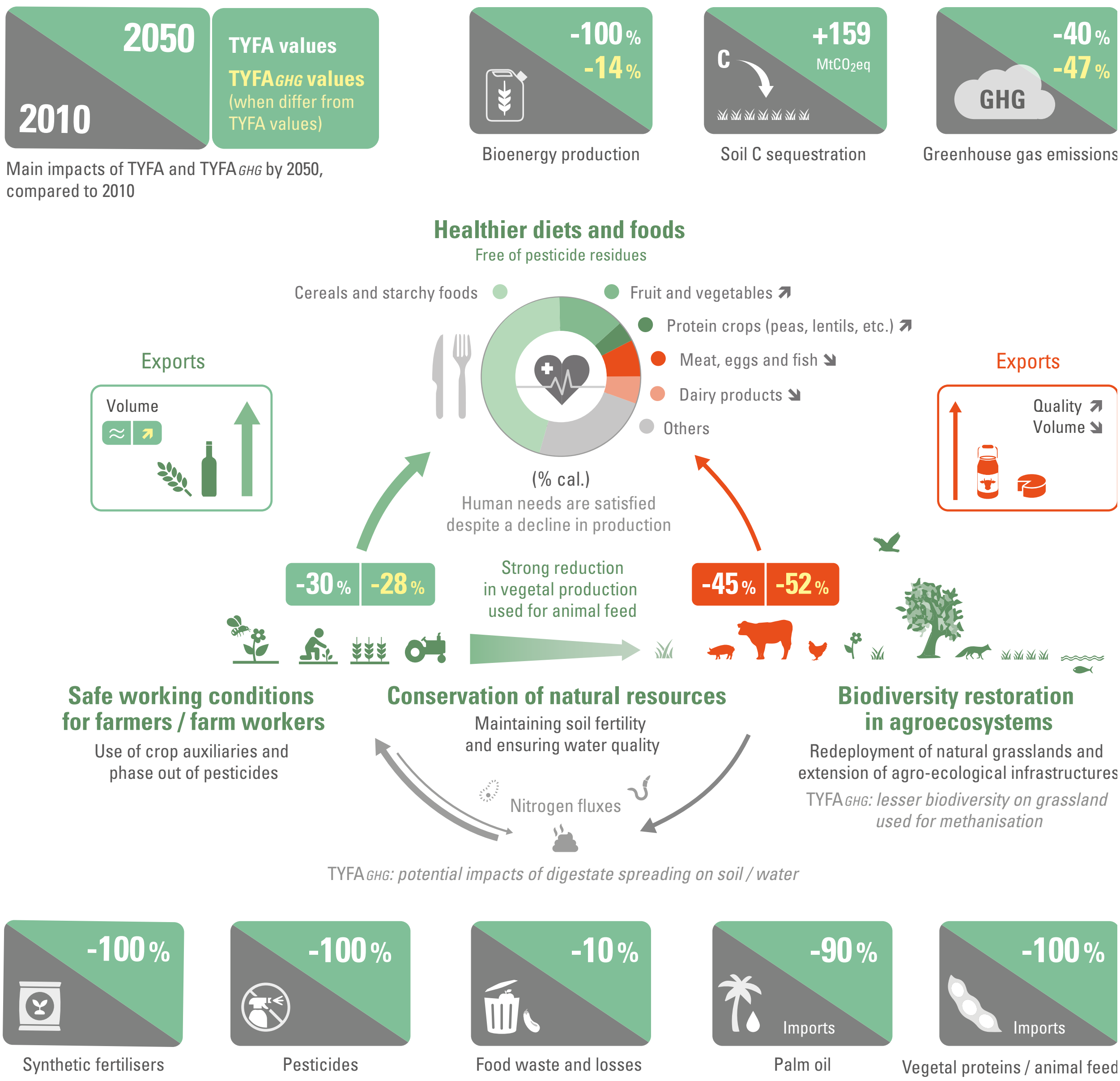
These data are indirectly comforted by recent meta-analysis published on this topic (Johansson *et al.*, 2014 ; Brantsæter *et al.*, 2017). While they confirm that few studies manage to identify direct causal links, several "feed experiments" are cited involving rabbits, rats, mouse or drosophila. These feed experiments show that (i) animals fed with organic and conventional food are rapidly able to recognize—and to give preference to—organic aliments; (ii) those animals fed with organic food exhibit (depending on the species) a better vitality, either through stronger immunity or higher fertility rate.

Last but not least, TYFA relies on important assumptions regarding diets, that take stock of the current situation—whereby a growing number of diseases (cardio-vascular diseases, diabetes type II, colorectal cancer, etc.) and death can be attributable to unbalanced diets , overall too rich in calories and proteins, and deficient in fresh fruits and vegetables (Mozaffarian, 2016 ; Blundell *et al.*, 2017). Under the TYFA scenario, the consumption of animal proteins would decrease down to 29 g/day (27 g for TYFA-GHG) and that of fresh fruits and vegetables would roughly double (for more details on the assumptions used under TYFA, see Poux & Aubert, 2018, p. 41-43).

3.4. Summary

Figure 15 below summarizes the climate implications of TYFA and TYFA-GHG and highlights the different co-benefits each scenario could exhibit. This analysis of the full range of benefits and trade-offs offered by both TYFA and TYFA-GHG lay the ground for a broader discussion comparing both scenarios to those that are currently discussed at the EU level.

FIGURE 15. Climate implications and main co-benefits of TYFA and TYFA*GHG* compared to 2010



Source: authors.

4. TYFA/TYFA-GHG IN THE LIGHT OF RECENT NET-ZERO SCENARIOS

4.1. A dashboard approach

Over the last few years, and most notably since the publication of the last IPCC 1.5 report (Masson-Delmotte *et al.*, 2018), several scenarios or studies have been published to showcase what a low-carbon/carbon neutral Europe could look like, and within it what would be the role of the agricultural sector. Among these studies, two were selected for extensive discussion with TYFA and TYFA-GHG:

— The scenarios produced as part of the proposal for a 2050 long-term strategy for the EU, published on November 28, 2018, by the European Commission (EC, 2018). Out of the 8 scenarios proposed in the document, the two reaching carbon neutrality by 2050 (1.5 TECH and 1.5 LIFE) were retained for the following discussion/comparison;

— The three net zero scenarios produced as per the "Net Zero Emission" study, published by the European Climate Foundation in September 2018 (ECF, 2018), which has been more recently completed by a specific analysis of the agricultural sector (Lóránt & Allen, 2019).

All these scenarios rest on specific, and sometimes divergent, assumptions to mitigate climate change while considering other issues (economic, environmental, social), which are described in more details in section 4.2. As such, while the potential of GHG reduction is of the same order of magnitude in all scenarios, the potentials for carbon sequestration on the one hand, and for bioenergy/biomaterial production on the other, are also quite different (section 4.3). The trade-offs and co-benefits associated to each scenario in terms of biodiversity/natural resources preservation, adaptation potential of farming systems, human health (for both producers and consumers) and food security, are also different (section 4.4). This led in the last section (4.5) to put the question of carbon neutrality in a broader perspective: while TYFA and TYFA-GHG might not be the best placed agricultural scenarios to attain carbon neutrality, the comprehensive comparison offered here enables to question the realism and the potential trade-offs associated to the other reviewed scenarios.

A more specific analysis is thus needed to uncover the specificity of TYFA and TYFA-GHG compared to the other scenarios vis-à-vis the objective of attaining carbon neutrality while taking into account trade-offs and co-benefits. In order to ensure a greater comparability between those scenarios, and following Waisman *et al*. (2019), we propose a *dashboard* for analysing and comparing various decarbonisation pathways for the European agricultural sector. This dashboard is made up of a handful of key indicators on three main themes, serving three purposes: (i) to compare the potential of climate mitigation of each scenarios; (ii) to provide a "driver dictionary", characterising the main transformations undergone by the sector under a given scenario and the associated determinants; (iii) to identify the most important associated trade-offs and co-benefits, under a quantitative or qualitative form. The full dashboard is given under the form of a table in annex 7.1 (**Table 6**). Each key dimension is discussed in subsequent sections. It is important to note that given the way in which each scenarios is presented, it has not been possible to inform all cells of the resulting table.

Scenarios / Dimension	EU LTS		ECF Net Zero from whether to how			TYFA	
	1.5 TECH	1.5 LIFE	Demand focus	Shared efforts	Technology	TYFA	TYFA-GHG
Main drivers of the sector's transformations							
Mitigation potential							
Co-benefits and trade-offs							

4.2. Different drivers embedded in two contrasted strategies

Three main categories of drivers are considered and combined differently in all scenarios: yields and climate efficiency of production; land use structure; and diets. A fourth and a fifth ones concern (i) the overall level of food waste and losses—which is not discussed with the same level of details in all scenarios—and

(ii) the level of production surplus that is expected/aimed at. The hypotheses made on each of those drivers for each scenario are presented in **Table 3**.

Broadly speaking, the five climate-focused scenarios all tend to adopt a strategy that can be labelled as a "land sparing" one:[14] they rely primarily on a (deemed) sustainable intensification of food production in a climate efficient way (for both animal and vegetal production) in order to spare land that can is used either for afforestation (ECF scenarios) or bioenergy production—eventually under the form of BECCS (LTS scenarios). In such a perspective, (i) emissions reduction per kg of food produced comes together with (ii) greater sequestration potential (through afforestation) and/or (iii) biomass production for energy (through the development of bioenergy crops).

Changes in diets are also considered but play contrasted roles in the five reviewed scenarios. The more the scenario relies on technological uptakes, the less changes in diets are considered—as illustrated in **Table 3**. In all cases, however, the envisioned changes are driven by the objective of reducing the consumption of the most carbon-emitting products, coming most notably from ruminants (dairy and meat) and are aligned with health recommandations. Other aspects related to diets or food quality are not considered, at least not explicitly discussed (e.g. fruits and vegetables intake).

Intensification takes different form in all scenarios but play in each case a central role, associated with an increase in the overall resource efficiency of the production: carbon efficiency, nitrogen efficiency, etc. While the ECF study is not explicit about which practices and technologies should be adopted for such changes to happen, the EU LTS relies on a cost-benefit approach to technology adoption. For each scenario, the level of efficiency and the yields attained are hence calculated based on the estimated cost of each technology relatively to the carbon cost (EC, 2018, p. 163). Without relying on such a reasoning, the ECF study assumes that yields can increase up to 40% (in the technology-driven scenario) and that a significant share of ruminants could be reared in feedlots (up to 50% of all cows in that same scenario). Detailed assumptions on yields are not made explicit in the EU LTS scenarios, but are also central in all of them. The total area under productive agricultural land indeed significantly reduces in all scenarios while the total production is assumed to increase with no significant substitution from imports (EC, 2018, p. 184 & 167). Such increases in

14 Although the land sparing/land sharing debate originated in a questioning on the impacts of different food production strategies on biodiversity conservation, we believe it has also influenced the way in which climate mitigation is considered. As such, the model on which it rests can be usefully mobilised here. In a nutshell, land sparing strategies ("LSP") rely on increases in yields to lower the amount of land needed to feed humans and thus to free up some land for restoring/conserving native habitats. On the contrary, land sharing strategies (LSH) seek to co-produce food and biodiversity within agricultural landscapes. The relative "performances" of both strategies have been widely debated over the last 15 years (Loconto *et al.*, 2019).

Table 3. Detailed hypotheses on the four main categories of drivers

	Main drivers	2010	EU LTS		ECF Net Zero			TYFA	
			1.5 TECH	1.5 LIFE	Demand focus	Shared efforts	Techno	TYFA	TYFA-GHG
1	Diets								
1.a	Caloric intake (kcal/day)	2,600	=	=	-10%	-8%	-6%	-6%	-6%
1.b	Decrease in meat consumption (g/day)	180	+4%	-13%	-75%	-60%	-50%	-49%	-53%
1.c	Share of ruminant meat	20%	17%	15%	10%	10%	13%	35%	32%
2	Intensity of production								
2.a	Crop yields		increase	increase	+28%	+32%	+40%	-25%	-25%
2.b	Livestock density 1: grazed intensity		increase	increase	+10%	+10%	+50%	stable	stable
2.c	Livestock density 2: share of cows in feedlots	30%	increase	increase	stable	stable	50% of all cows	0	0
3	Land use dynamics								
3.a	area of cropland for food (including temporary grasslands)	108	-6%	-18%	-45%	-35%	-30%	=	=
3.b	area under permanent grassland*	60			-27%	-27%	-27%	=	=
3.c	area of bioenergy crops	8	+263%	+175%	-100%	-100%	-63%	-100%	-100%
3.d	area of forests	176	+2%	+10%	+58%	+48%	+59%	=	=
3.e	area of unproductive grasslands/ shrubs	60	-53%	-27%	=	=	=	=	=
4	Food waste and losses		-50%	-50%	waste collection increases	waste collection increases	waste collection increases	-10%	-10%
5	Production surplus (in volume)		Import/ export kept ~ constant	Import/ export kept ~ constant	Import/ export kept ~ constant	Import/ export kept ~ constant	Import/ export kept ~ constant	Import/ export decrease	Import decrease; export ~ stable

*For ECF scenarios, no distinction is made between permanent and temporary grasslands – although having one or the other has quite different impacts on soil carbon sequestration and biodiversity conservation.

yields are expected to happen based on technological innovations. However, at least two parameters lead to question these optimistic hypotheses on yields. On the one hand, long-term analyses show that cereal yields in Europe have come to a plateau (Brisson *et al.*, 2010) that might be difficult to surpass in the future—although it is of course a matter of vivid controversies. Various environmental changes—including soil fertility degradation, soil life depletion, increases in pest/diseases outbreaks, climate instability—are widely cited as potential causes of this plateau effect. On the other hand, climate change will also impact upon yields and making too optimistic assumptions in a context of large uncertainties might be discussable (Wilcox & Makowski, 2014). We will come back on this crucial point in the section 4.5

Against this backdrop, and as it has been presented in previous sections, the TYFA/TYFA-GHG scenarios adopt what can be labelled as a land sharing approach. In this perspective, both climate mitigation and biodiversity conservation are achieved through important and systemic changes within agricultural landscape, and are dependent upon significant changes in diets, aligned with nutritional and health requirements. At this very general and strategic level, no significant difference appears between TYFA and TYFA-GHG apart from the hypotheses on diets (a slightly stronger reduction in meat consumption and a lower share of ruminant meat in the diet).

The two strategies (land sparing *vs* land sharing) result in a very different agricultural, food and land sector by 2050, first in terms of potential of climate mitigation, then in terms of other key co-benefits. These differences are reviewed below.

4.3. An overall lower mitigation potential: implication for carbon neutrality

In this section, we analyse all three "pillars" of climate mitigation in the agricultural sector, namely reduction of GHG emissions, carbon sequestration, and fossil carbon (C) substitution through bioenergy and biomaterial production. **Table 4** compares TYFA and TYFA-GHG ambition levels on these three dimensions.

Regarding emissions reduction, the reviewed scenarios tend to limit themselves to GHG emissions falling under "agricultural sector" categories reported to the UNFCCC. We believe, on the opposite, that it is crucial to take into account direct and indirect emissions from the consumption of energy (20% of total emissions), as well as emissions linked to the making of fertilisers (8%), and the imports of feed (more than 5%)—both being brought down to zero in the case of TYFA.

Despite this difference, **Table 4** shows that both TYFA and TYFA-GHG are well in line with the ambition levels of scenarios produced and discussed at the European level. Only two of the reviewed scenarios show a higher level of ambition than TYFA-GHG (the "shared effort" one being almost equal when considering the levels of uncertainty), while all but one (the 1.5 TECH scenario of the EU LTS) have a greater potential than the initial TYFA scenario. However, due to the broader strategy through which this potential is obtained, it comes along with a lower potential for carbon sequestration and for fossil C substitution.

In terms of carbon sequestration, TYFA and TYFA-GHG offer important potential for soil-C sequestration that appears much higher than the other scenarios reviewed. This results from the kind of agricultural practices promoted under TYFA which can be grouped under the general heading of "regenerative agriculture": -149 $MtCO_{2eql}$/y *vs* at best -137 $MtCO_{2eql}$ for the reviewed scenarios. However, TYFA and TYFA-GHG do not offer any sequestration potential through afforestation, as no land is freed up for other purposes than food production. On the contrary, the ability of the reviewed scenarios to reach carbon neutrality rests to a large extent on the expansion of the forest carbon sink, either through afforestation or through improved management. It is indeed expected that between 339 and 659 $MtCO_2$ could be annually stored in the European carbon sink, which more than compensate the residual emissions of the agricultural sector. It is however to be noted that no specific hypotheses were made on forest management improvement in TYFA, and that it could also contribute to greater C sequestration.

Finally, the potential for fossil C substitution of both TYFA and TYFA-GHG appears much lower than the reviewed scenarios. As outlined above (see section 2.2), the potential for bioenergy production from agricultural feedstock (residues, manure or dedicated energy crops) is of 189 TWh for TYFA-GHG, and null for TYFA. As for carbon sequestration, the production of bioenergy in general, and from agricultural feedstock in particular, is an important component of the reviewed scenarios in view of reaching carbon neutrality by 2050. The available energy production ranges from 322 TWh (demand focus scenario, ECF) to more than 1,673 TWh (1.5 TECH, EU LTS). This latter figure includes the energy produced from lignocellulosic grasses on the EU LTS scenarios, but not that from short rotation coppices. Indeed, no hypotheses were made in TYFA regarding the potential of bioenergy production from woody feedstock, neither coming from agroecosystems (hedges, agroforestery, permanent cultures), nor from forest areas. The total energy production from biomass in all scenarios represent a limited share of the total final energy consumption—between 5 and 9 % in all reviewed scenarios.

This more limited mitigation potential—relatively to other scenarios—comes along with co-benefits on other dimensions that need to be made explicit.

4.4. A broad range of co-benefits, more uncertain in other scenarios

As discussed throughout this report, the TYFA/TYFA-GHG scenarios were built considering a wide array of issues, beyond the sole question of climate mitigation: human health, natural resources and biodiversity conservation, adaptation capacity. Key indicators have been identified to assess the respective impacts of all reviewed scenarios on those different themes. These indicators are sometimes quantitative, sometimes more qualitative; some have been quite simple to estimate, others

Table 4: Comparison of the mitigation potential of the different scenarios

	Mitigation potential	2010	EU LTS		ECF Net Zero			TYFA	
			1.5 TECH	1.5 LIFE	Demand focus	Shared efforts	Techno	TYFA	TYFA-GHG
1	Emissions reduction (non-CO_2 direct emissions only)	412	-33%	-42%	-56%	-47%	-41%	-35%	-46%
1.a	Agricultural soils	156			-44%	-32%	-26%	-50%	-54%
1.b	Enteric fermentation + manure management	256			-63%	-56%	-50%	-27%	-41%
2	Bioenergy production/fossil C substitution	184	1,406	1,210	322	407	492	0	189
2.a	From agricultural residues (manure, straw, grass)	74	380	400	322	407	405	0	189
2.b	From bioenergy crops	110	1025	810	0	0	87	0	0
3	Sequestration potential	-368	-359	-458	-765	-645	-689	> -149	> -149
3.a	In agricultural soils (cropland + grassland)	66	-20	-6	-106	-87	-137	-149	-149
3.b	Through forest management and afforestation	-434	-339	-452	-659	-558	-552	n.a.	n.a.

were simply not at all discussed in many scenarios. Overall, very little attention is given to the above-mentioned issues in carbon-focused scenarios/discussions, beyond mentioning them as "important" but without any further investigations.

The full list of indicators and their tentative assessment for each scenario is presented in **Table 5** and discussed in more details below. Some indicators could not be filled-in for all scenarios, as they are not all fully explicit on their impacts on all the dimensions considered in this study. In this case, a question mark has been added.

In terms of human health, on the one hand, the phase-out of pesticides in TYFA/TYFA-GHG simultaneously provides safer working conditions for farmers, who are the first to be affected by pesticides use, and healthier food. The adoption of healthier diets, going beyond the mere reduction of total and animal calories in order to reduce emissions, but also considering the necessary increase in fruit and vegetables, animal products richer in omega 3, would also promote an improvement in the health status of consumers.

In terms of biodiversity, the extension of agroecological infrastructures—which by 2050 would represent 10% of arable land—combined with the redeployment of natural grasslands and the abandonment of pesticides and synthetic fertilizers ensure, under TYFA/TYFA-GHG, a real recovery of biodiversity through the redeployment of food webs at all scales, from soil to landscape. Other scenarios envisage a drastic reduction in the share of agroecological infrastructure considered «non-productive» in the territories, as well as of natural grasslands (up to -53% of non-productive areas in the LTS, and -91% of grasslands in the ECF «Technology» scenario), and make no explicit hypothesis regarding the use of pesticides. Taking into account the assumptions of yield increases, it can be assumed that their use will at best be slightly reduced in view of technological progress, at worst increased, to maintain yields in the face of new resistance and pathogens. The consequences in terms of biodiversity will remain potentially important in both cases.

Similarly, the impacts on water resources and soil health appear potentially very different. Where the abandonment of synthetic inputs and mineral nitrogen associated to the generalisation of cover crops and the importance of organic matter inputs to soils should make it possible to recover simultaneously good soil health and good water body status, the non-questioning of the high levels of territorial specialisation and the resulting imbalances in nutrient cycles as well as the use of synthetic inputs in the other scenarios leave doubts on their ability to effectively address these central issues, including for agricultural production itself.

Finally, the significant rediversification of plant systems, the reconnection of crop and livestock systems and the improvement of soil health appear in TYFA as fundamental assets to adapt to the already present impacts of climate change: increased water stress, risk of emergence of new pests/diseases, irregular rainfall. Nothing is said on this side in the other scenarios analysed, but here again, the non-questioning of the high levels of specialisation and the focus on increasing yields appear to be incompatible with an increase in the adaptive capacities of agroecosystems and production systems.

4.5. Carbon neutrality, yield increases and the agroecological transition

Given what precedes, it could seem difficult for the original TYFA scenario to be compatible with carbon neutrality, as the residual emissions of the agricultural sector could probably not be compensated by an increase in the land carbon sink, and as the potential for fossil C substitution would be extremely low. TYFA-GHG is better equipped and could probably fits into an economy-wide carbon neutral scenario, providing that radical changes are implemented in other sectors at a sufficient path (this however is true for any carbon neutral scenario!).

Table 5. Trade-offs and co-benefits associated to each scenario

	Mitigation potential	2010	EU LTS		ECF Net Zero			TYFA	
			1.5 TECH	1.5 LIFE	Demand focus	Shared efforts	Techno	TYFA	TYFA-GHG
	Co-benefits and trade offs								
1	Pesticide use (human health, biodiversity)	380 kt of active substance	stable?	stable?	stable?	stable?	stable?	0	0
2	Consumption of mineral fertilizer (soil health, water quality, emission)	11 Mt N	Δ+	Δ+	Δ+	Δ+	Δ+	0	~ 1 Mt from anaerobic digestate
3	Area of extensive permanent grasslands (biodiversity, natural resources, adaptation)	60 Mha	Δ-	Δ-	-59%	-57%	-91%	stable	stable – but 18% not continually grazed => potential impacts on biodiversity
4	Proportion of grasslands under extensive grazing (density < 1 LU/ha)	23%	?	?	Δ-	Δ-	Δ-	> 75%	> 60%
5	Area under agroecological infrastructures*	8%	Δ-	Δ-	Δ-	Δ-	Δ-	10%	10%
6	Agrobiodiversity								
6.a	proportion of the main crop in arable land	20% (wheat)	increase?	increase?	increase?	increase?	increase?	11% (leg. fodder)	15% (wheat)
6.b	proportion of the 4 main crops in arable land	50%	increase?	increase?	increase?	increase?	increase?	40%	45%

* Note: In all ECF scenarios, 30% of the agriculture land is considered to be managed under "land multi-use", defined as follows: muliple crops over a year or simultaneous combination of crops on the same land". Concrete practices incurred by such a definition are not clear and do not easily fall in the category of agroecological infrastructures.

But the systematic comparison made possible by our dashboard also enables us to question the realism and desirability of the agricultural components of the other reviewed scenarios, for at least two reasons. On the one hand, their (high) potential for decarbonation, sequestration and bioenergy production is mainly based on strong assumptions about increased yields from both animal and plant systems. However, recent trends regarding the plateauing of cereal yields in Europe, show that this assumption is not self-evident. If we add to this the potential impacts of the scenarios considered on soil life and biodiversity in the broad sense, as well as the low capacity of agricultural systems to adapt to climate change resulting from these hypotheses, it is the very productive potential of these systems that, in the medium or long term, could be called into question, leading in return not to an increase in yields but to their decline.

On the other hand, the likely—albeit poorly informed/discussed—consequences of these scenarios on biodiversity, human health (both for farmers and consumers) and landscapes mean that, even if the yield assumptions could be achieved, it is society and ecosystems as a whole that would be affected in the medium/long run. In view of this, climate change should probably not be considered as intrinsically more problematic and therefore more of a priority than biodiversity loss, the spread of pesticides and antibiotics in the environment or water eutrophication due to excess nitrogen. We come back to this in the conclusion.

5. CONCLUSION

This study eventually demonstrates that a scenario based on agroecology and a land sharing approach is compatible with a significant potential for climate mitigation, including GHG emissions reduction, carbon sequestration and, for the TYFA-GHG variant, fossil C substitution through bioenergy production. This potential would also come along strong co-benefits, including biodiversity and natural resources conservation, human health and (potentially) greater adaptation capacity. From a biodiversity point of view, this has a particular resonance in the European context, where an important share of biodiversity is associated with the maintenance of extensive agriculture—as recognized by tenants of the land sparing approach themselves (Garnett & Godfray, 2011, p. 30).[15] From a climate point of view, it shows that climate neutrality could be attained relying on a land sharing approach, and not only on a land sparing strategy, as could be inferred from the reading of most scenarios currently under discussion at the EU level and in most Member States.

TYFA/TYFA-GHG therefore illustrate the interest of a multifunctional agriculture, where climate and biodiversity are not opposed but dealt with simultaneously by changing practices within the agricultural landscape. It should be noted that in the European context, once again, past trends are similar to those advocated by land sparing: productive lands have been strongly intensified, while the overall area cropped has declined (through land take and abandonment); however, this has not led to any improvement in the state of biodiversity or even GHG emissions. The large-scale experimentation of a land sparing approach over 60 years tends to invalidate the very premises of the land sparing approach.

The corollary of such a result is that it is urgent to identify methodological approaches that would allow to better integrate, in the scenario development process, the other issues discussed here—biodiversity, natural resources, human health and adaptation, at least—beyond the sole focus on climate mitigation. This raises the question of the *metrics* associated to the scenario development process, and of the implicit *hierarchy* between issues that climate mitigation scenarios tend to endorse.

- On the metrics, discussions on climate mitigation rest on an unique indicator considered as "simple" and integrative—GHG balance expressed in CO_{2eql}. The apprehension of potential impacts of a scenario on biodiversity, natural resources, adaptation capacity or even human health, is more difficult to equip with simple indicators. Yet, this integrative indicator is based on data and parameterisations involving a lot of uncertainty and variability. Conversely, the reasoning on biodiversity loss for example, is not easy to model, but is based on premises relatively robust at the scale at which we work (on the impact of pesticides, on the importance of natural grasslands and ecological surfaces, etc.). In other words, the quantitative assessment on climate mitigation is not immediately more robust (or less) than assessment conducted more qualitatively but describing well-established causal relationships.
- On the way in which multiple environmental/social issues are considered in developing scenarios, the mere focus on GHG emissions refers to two possible visions on environmental issues from the part of scenario developers: (i) either the reduction of GHG emissions and carbon storage in a neutral perspective must be imposed on all other environmental issues, which would be secondary; (ii) or this metric integrates the other issues. While (ii) is invalidated by what precedes, (i) is also questionable. For example, considering adaptation challenges and their relationships to agroecosystem functioning, we noted above that the stagnation of wheat yields and the increase in their variability over the last 15 years suggest dysfunctions that may call into question the assumptions of carbon strategies based on productivity growth. As such, adaptation of agroecosystems to climate change is not a theme in addition to reducing emissions: it is a prerequisite for the targeted reduction. Similarly, if we

15 "The study only looked at one type of habitat (tropical forests); studies in other areas might have drawn different conclusions. For example, in regions such as the Mediterranean, the present mix of plant and animal species has been shaped by millennia of human agricultural activity and flourishes in areas of low-intensive food production. Exactly what pure 'land sparing' would be in this context is not clear and past land sharing has essentially sustained the biodiversity we now value".

consider all the planetary boundaries, there is no reason to believe that climate change is more problematic and therefore more of a priority than biodiversity loss, the spread of pesticides and antibiotics in the environment or eutrophication due to excess nitrogen. Emissions and GHG emissions are an important issue, but neglecting other themes is not more sustainable. From this point of view, TYFA proposes an effective approach to a plurality of environmental themes, more explicit than climate-centered approaches that tend to simply cite the existence of these themes without really addressing them.

A last point of this conclusion is the comparison of TYFA and TYFA-GHG. This variant was built to increase TYFA's climate performance, without altering its overall philosophy. In this perspective, the limited/controlled development of anaerobic digestion is on purpose. A rapid comparison of TYFA and TYFA-GHG could indeed suggests that the superiority of the latter is self-evident, if it were necessary to choose between the two: we gain a lot in terms of mitigation and production and we lose very little (but we cannot quantify it well—see the metric above) in biodiversity and soil life. As a result, one could question: why not to allocate a much higher fraction of grasslands (up to 30, 40, 50 or even 100 %) to anaerobic digestion to simultaneously reduce the size of ruminant herds and produce bioenergy of herbivores? Without being able to set at this stage a precise limit at which a TYFA-GHG+ variant would switch to a bioenergetic logic that would change the very nature of the agroecology envisaged in TYFA, we recall here the fact that anaerobic digestion is justified, in a multifunctional approach, only on a small scale. On the strict biotechnical level, its development raise questions regarding its impact on soil life—due in part to the mineral form of nitrogen from the sector—in addition to the question of the risks of NOx emissions associated with poor technical control of the sector.

On a more socio-economic level, we recall the risk of «drift» of methanisation towards units that mobilise dedicated resources, simplifications of agroecosystems, towards a supply of mineral nitrogen that carries the same environmental risks as synthetic nitrogen and logically calls for the same use of plant protection products. As such, scale changes the very nature of the supply chain. All in all, TYFA GHG is not a justification in principle for methanisation, it is the exploration of a variant that has its own interest only at the scale it is considered.

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7. ANNEXES

7.1. A detailed dashboard to compare TYFA and TYFA-GHG to agricultural scenarios compatible with carbon neutrality

TABLE 6. Detailed dashboard comparing TYFA/TYFA-GHG to carbon neutral scenarios

	Scenarios / Themes	2010	EU LTS		ECF Net Zero			TYFA	
			1.5 TECH	1.5 LIFE	Demand focus	Shared efforts	Techno	TYFA	TYFA-GHG
	Mitigation potential								
1	Emission reduction	412	-33%	-42%	-56%	-47%	-41%	-35%	-46%
1.a	Agricultural soils	156			-44%	-32%	-26%	-50%	-54%
1.b	Enteric fermentation + manure management	256			-63%	-56%	-50%	-27%	-41%
2	Bioenergy production / fossil C substitution	184	664%	558%	75%	121%	167%	0	3%
2.a	Agricultural residues (manure, straw)	74	414%	440%	335%	450%	447%	0	155%
2.b	Bioenergy crops	110	1285%	995%	-100%	-100%	-21%	0	0
3	Sequestration potential	-368	-359	-458	-765	-645	-689	> -149	> -149
3.a	Agricultural soils (cropland + grassland)	66	-20	-6	-106	-87	-137	-149	-149
3.b	Forest management and afforestation	-434	-339	-452	-659	-558	-552	?	?
	Sector transformation and main drivers								
1	Diets								
1.a	Caloric intake (kcal / day)	2600	=	=	-10%	-8%	-6%	-6%	-6%
1.b	Decrease in meat consumption (g/day)	180	++4%	-13%	-75%	-60%	-50%	-49%	-53%
1.c	Share of ruminant meat	20%	17%	15%	10%	10%	13%	35%	32%
2	Intensity of production								
2.a	Crop yields		increase	increase	++28%	++32%	++40%	-25%	-25%
2.b	Livestock density 1: grazed intensity		increase	increase	++10%	++10%	++50%	stable	stable
2.c	Livestock density 2: share of cows in feedlots		increase	increase	++30%	++30%	50% of all cows	0	0
3	Land use dynamics								
3.a	area of cropland for food (including temporary grasslands)	108	-6%	-18%	-45%	-35%	-30%	stable	stable
3.b	area under productive grassland	60			-59%	-57%	-91%	stable	stable
3.c	area of bioenergy crops	8	263%	175%	-100%	-100%	-63%	-100%	-100%
3.d	area of forests	176	2%	10%	58%	48%	59%	stable	stable
3.e	area of unproductive grasslands / shrubs	60	-53%	-27%	stable	stable	stable	stable	stable
4	Food waste and losses		-50%	-50%	waste collection increases	waste collection increases	waste collection increases	-10%	-10%
	Co-benefits and trade offs								
1	Pesticide use (human health, biodiversity)	380kt of active substance	stable?	stable?	stable?	stable?	stable?	0	0
2	Consumption of mineral fertilizer (soil health, water quality, emission)	11 Mt N	Δ+	Δ+	Δ+	Δ+	Δ+	0	~ 1 Mt from anaerobic digestate
3	Area of extensive permanent grasslands (biodiversity, natural resources, adaptation)	60 Mha	Δ-	Δ-	-59%	-57%	-91%	stable	stable – 18% not continually grazed => impacts on biodiversity?
4	Proportion of grasslands under extensive grazing (density < 1 LU/ha)	23%	?	?	Δ-	Δ-	Δ-	> 75%	> 60%
5	Area under agroecological infrastructures	8%	Δ-	Δ-	Δ-	Δ-	Δ-	10%	10%
6	Agrobiodiversity								
6.a	proportion of the main crop in arable land	20% (wheat)	increase?	increase?	increase?	increase?	increase?	11% (leg. fodder)	15% (wheat)
6.b	proportion of the 4 main crops in arable land	50%	increase?	increase?	increase?	increase?	increase?	40%	45%

7.2. ClimAgri®: a tool to evaluate emissions

7.2.1. The The ClimAgri® calculator

The ClimAgri® calculator was initially developed in 2009 by Solagro and Bio Intelligence Service for the French Environment and Energy Management Agency (Agence de l'Environnement et de la Maîtrise de l'Energie, or ADEME). The calculator aims at estimating direct and indirect greenhouse gases from agriculture and forestry at the national or departmental level in France. The calculator, which is based on Riedacker and Migliore's work on integrated environmental assessments (2006, 2008), also estimates emissions of atmospheric pollutants, amounts of carbon stored in agricultural and forest soils, as well as forest biomass, renewable energy production and agricultural and forestry production. For the purpose of this exercise, the calculator was used solely for estimating *direct* and *indirect GHG emissions* from the *agricultural sector*.

The categories of direct greenhouse gas emissions calculated by ClimAgri® are close to the ones reported to the UNFCCC. They include:

— Emissions linked to the consumption of energy: namely, CO_2 emissions linked to the combustion of fuel, gas, wood and coal for the purpose of running agricultural equipment, which include off-road vehicles and other agricultural machinery (UNFCCC 1.A.4.c.ii category) as well as stationary equipment (irrigation pumps, greenhouses, drying equipment and livestock buildings) (UNFCCC 1.A.4.c.i category);
— Emissions linked to the management of agricultural soils: namely, direct and indirect (linked to leaching and runoff) N_2O emissions linked to organic and inorganic fertilisers spread to crops, urine and dung deposited by grazing animals and crop residues (UNFCCC 3.D category); it also includes CO_2 emissions linked to liming (UNFCCC 3.G category);
— Emissions linked to enteric fermentation: namely, CH_4 emissions linked to enteric fermentation (UNFCCC 3.A category);
— Emissions linked to manure management (UNFCCC 3.B category): namely, CH_4 emissions linked to manure deposited within livestock buildings and pastures; and N_2O emissions linked to the storage of liquid and solid manure.

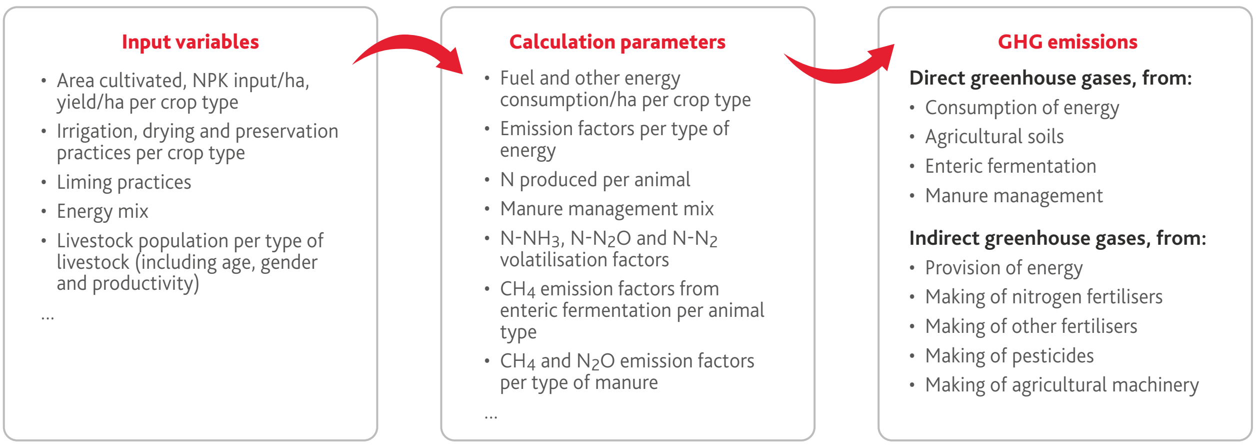
In addition, ClimAgri® also evaluates indirect greenhouse gas emissions, which include:

— Emissions linked to the provision of energy;
— Emissions linked to the making of nitrogen fertilisers;
— Emissions linked to the making of other fertilisers;
— Emissions linked to the making of pesticides;
— Emissions linked to the making of agricultural machinery.

In order to evaluate GHG emissions, the calculator takes into account a certain number of input variables linked to land use, livestock population and crop and livestock practices as well as parameters enabling to calculate GHG from crop and livestock (**Figure 16**).

Although ClimAgri® is mostly based on calculation methods similar to the ones used by countries when reporting agricultural emissions to the UNFCCC, differences remain, that are linked to the complexity of calculation, to the number of parameters used and to hypotheses that are made to tackle uncertainties when they exist. Coming up with a *reduction* potential by using ClimAgri® therefore implies not only to run the calculator for 2050, but also to run a first calculation to evaluate GHG emissions for a baseline—hereby set at 2010, in order to facilitate data collection. Running a first calculation to evaluate GHG emissions in 2010 also enabled to check the coherence of a certain number of hypotheses that were made to calibrate the calculator, which was originally designed to evaluate emissions from the agricultural sector in France, to the purpose of evaluating GHG emissions from the agricultural sector at the European level.

FIGURE 16. Simplified operational scheme of the ClimAgri® calculator



Source: authors.

7.2.2. Setting calculation parameters

In order to calibrate the calculator to the purpose of evaluating GHG emissions from the agricultural sector at the European level, a few adjustments were made, that are listed below.

First, as the calculator lists predefined types of crops that do not completely match the ones defined by Eurostat or by TYFAm, hypotheses had to be made for translating crop and animal categories from Eurostat and TYFAm to ClimAgri®. For categories aggregating several ClimAgri® crop types, different methods were used to select the appropriate corresponding crops, listed in **Table 7**.

Some crop types, for which data was difficult to find or non-existent in the ClimAgri® calculator (and for which no comparable crop type could be selected), were neglected, accounting for a total neglected area of 2.3% of the 2010 Utilized Agricultural Area (UAA) and 1.5% of the 2050 UAA. They are listed in **Table 8**.

For simplification purposes and to enable a sound comparison between Eurostat 2010 figures processed by ClimAgri® and results for TYFA 2050, livestock figures were entered solely for cattle, sheep, pig and chicken populations.

Once hypotheses had been made for translating crop and animal categories from Eurostat and TYFAm to ClimAgri®, further hypotheses had to be explored to adjust calculation parameters, in order to better represent the reality of the situation in Europe. The following tables summarize required information (input variables), calculation parameters, as well as the adjustments that were made for these latest, for each GHG emission category.

TABLE 7. Crop and pasture categories selected in the ClimAgri® calculator

TYFAm Crop Type	ClimAgri® Crop Type (French)	ClimAgri® Crop Type (English translation)	Selection method
Fruits	Pomme	Apple	Selection of the most representative crop type among the ones belonging to the aggregated category
Nuts fruits	Noix	Walnut	
Protein Crops	Pois (hiver, printemps) ou féverole	Peas (winter, spring) or faba beans	
Grapes (for wine)	Vin (mixte)	Wine (Mixed)	
Fresh vegetables	Tomates	Tomatoes	
Leguminous harvested green	PT Luzerne	Alfalfa	
Citrus fruits	Abricot	Apricot	Selection of the closest crop type (no citrus fruit category in ClimAgri® crop types)
Permanent grasseland and rangeland – 20%	Prairies peu productives	Marginal grasslands	Experts were consulted to assess the respective shares of marginal land, productive grasslands over 30 years and productive grasslands under 30 years among European grasslands. Estimates were completed with a review of the literature (Huyghe et al. 2014)
Permanent grasseland and rangeland – 60%	Prairie naturelle productives <30 ans	Productive natural grasslands <30 years	
Permanent grasseland and rangeland – 20%	Prairie naturelle productives >30 ans	Productive natural grasslands >30 years	
Temporary grassland 2010	PT mélangées	Mixed grassland	
Temporary grasseland 2050 – 70%	PT Autres Gram seule	Temporary pastures – Other grasses alone	The TYFA scenario sets a ratio of 70/30 for the proportion of grasses/leguminous in temporary grasslands in 2050
Temporary grasseland 2050 – 30%	PT autres Lég. seule	Temporary pastures – Leguminous plants alone	
Cover crops	CIPAN-Couvert-Légumineuse seule	Catch crop – Leguminous plants alone	Only catch crops are available among cover crop types in the ClimAgri® calculator. The TYFA scenario establishes that cover crops in 2050 are made of leguminous plants, for N balance purposes.
Cover crops – 50%	CIPAN-Couvert-sans légumineuse	Catch crop – Without leguminous plants	

TABLE 8. Crop categories neglected in the simulation

TYFAm Crop Type	Area 2010 (ha)	Area 2050 (ha)
Cultivated mushrooms	22,870	50,591
Other root crops	139,100	139,100
Tobacco	115,680	115,680
Hops	29,060	29,060
Flax and hemp	79,750	79,750
Other industrial crops	61,320	61,320
Cotton fibre	338,770	338,770
Other cereals harvested green	895,250	
Other plants harvested green	653,230	
Seeds and seedlings	271,460	271,460
Other arable crops	641,600	641,600
Other permanent crops	68,110	68,110
Kitchen gardens	340,710	340,710
Flowers and ornamental plants	71,500	71,500
Aromatic, medicinal and culinary	196,660	196,660
Nurseries	129,620	129,620
Total area neglected	4,054,690	2,533,931
% of neglected area among total UAA	2.30%	1.49%

TABLE 9. Direct emissions linked to the consumption of energy - Requested information and calculation parameters

Direct emissions linked to the consumption of energy			
Category	Information needed for calculation	Calculation parameters	Adjustments
Combustion of fuel linked to off-road vehicles and machinery for crops and pastures	Area per crop type (Eurostat 2010)	Liters/ha of fuel: Crop: 99.62 Arboriculture: 190 Productive pasture: 65 Emission factor for fuel (0.0029 t CO_2/liter)	None
Combustion of fuel linked to irrigation pumps	Volume of irrigation water used** Energy mix: 15% fuel, 75% electricity*	Emission factor for fuel (0.0029 t CO_2/liter)	None
Combustion of fuel, gas, wood and coal linked to the heating of greenhouses	Area of heated greenhouses** Energy mix: 15% fuel, 78% natural gas, 2% propane, 2.5% wood, 2.5% coal*	kWh per heated m²: 400	Raised, following experts' consultation and Campiotti *et al.* (2012)
		Emission factors: Fuel: 0.0029 t CO_2/liter Natural gas: 0.0023/m³ Propane: 0.0031/m³ Coal: 0.0029/kg	None
Combustion of fuel for livestock buildings	Structure of bovine herds (number, age, gender and productivity of animals) (Eurostat 2010)	Liter of fuel/dairy cow: 0.12 Liter of fuel/suckling cow: 0.08	None
Combustion of gas linked to drying practices	% of crops dried** Energy mix: 100% natural gas*	kWh/kg of crop dried, per crop type Emission factor for natural gas (0.0023/m³)	None

"*" indicates information that was left unchanged compared to what was originally proposed by the calculator (= based on an evaluation made for France), due to lack of data for Europe
"**" indicates information for which explanation can be found in section 7.2.3.

TABLE 10. **Indirect emissions linked to the consumption of energy - Requested information and calculation parameter**

Indirect emissions linked to the consumption of energy			
Category	Information needed for calculation	Calculation parameters	Adjustments
Provision of electricity for preservation practices	Volumes of crops preserved** Energy mix: 100% electricity*	kWh/kg of crop preserved, per crop type	None
		CO_2 emissions: 0.00037 tCO_2/kWh	Raised, following experts' consultations and ENTSO-E (2018)
Provision of electricity for irrigation	Volume of irrigation water used** Energy mix for irrigation: 15% fuel, 75% electricity*	kWh/m^3: 0.5	None
		CO_2 emissions: 0.00037 tCO_2/kWh	Raised, following experts' consultations and ENTSO-E (2018)
Provision of electricity for the heating of livestock buildings	Structure of herds (number, age, gender and productivity of animals) (Eurostat 2010) Energy mix: 100% electricity**	403 kWh/sow 3.15 kWh/laying hen 0.52 kWh/kg body weight for broilers; 0.46 kg body weight/broiler (place) for conventional broiler; 0.50 kg body weight/ broiler (place) for label broiler 440 kWh/dairy cow 93 kWh/suckling cow	None
		CO_2 emissions: 0.00037 tCO_2/kWh	Raised, following experts' consultations and ENTSO-E (2018)
Emissions linked to the making of nitrogen fertilizer	Area per crop type (Eurostat 2010) Use of N fertilizer (kg/ha) per crop type* Type of inorganic N: solution (12%), urea (21%), ammonium nitrate (55%), other (12%)**	tCO_2 per ton of inorganic N produced: Solution: 3.201 Urea: 3.454 Ammonium nitrate: 2.569 Other: 2.995	None
Emissions linked to the making of other fertilizer	Area per crop type (Eurostat 2010) Use of other P and K fertilizer per crop type (kg/ha)* Total area limed (100% field crop area) and use of lime per ha (70 kg)**	tCO_2 per ton of inorganic P produced: 0.548 tCO_2 per ton of inorganic K produced: 0.421 tCO_2 per ton of lime produced: 0.1519	None
Emissions linked to the making of pesticides	Area per crop type (Eurostat 2010) Energy consumption linked to the application of pesticides, per crop type*	tCO_2 per GJ of pesticides used: 0.03	None
Emissions linked to the making of agricultural machinery	Area per crop type (Eurostat 2010) Energy consumption linked to the use of agricultural machinery, per crop type*	tCO_2 per GJ of agricultural machinery used: 0.079	None

"*" indicates information that was left unchanged compared to what was originally proposed by the calculator (= based on an evaluation made for France), due to lack of data for Europe
"**" indicates information for which explanation can be found in section 7.2.3

TABLE 11. Direct emissions linked to soil management practices - Requested information and calculation parameter

Direct emissions linked to soil management practices			
Category	Information needed for calculation	Calculation parameters	Adjustments
Inorganic fertilizers spread to crops	Area per crop type (Eurostat 2010) Use of N fertilizer (kg/ha) per crop type* Type of inorganic N: solution (12%), urea (21%), ammonium nitrate (55%), other (12%)**	N-NH_3 volatilisation factors: solution (0.125), urea (0.243), ammonium nitrate (0.037), other (0.08) N-N_2O volatilisation factor: 0.01	None
Liming	Total area limed (100% field crop area) and use of lime per ha (70 kg)**	CO_2 in lime applied: 44%	None
Organic fertilizers spread to crops	Structure of herds (number, age, gender and productivity of animals) (Eurostat 2010) % of urine and dung deposited during paddock periods**	Kg N/animal: - dairy cow: 113; heifer <1 year: 20; heifer >1year: 66.91; male <1 year: 35.71; male >1 year: 71.31 - suckling cow: 101; heifer <1 year: 20; heifer >1 year: 66.91; male <1 year: 12; male >1 year: 71.31 - ewe: 14.28; lamb: 2.15 - sow (conventional): 24.6; sow (label): 30.75; piglet (conventional): 4.03; piglet (label): 5.04 - laying hen: 0.71 - broiler (conventional): 0.46; broiler (label): 0.5 N-NH_3 volatilisation rate: 0.1 for dairy cows and chickens, 0.06 for suckling cows, 0.09 for ewe, 0.25 for pigs N-N_2O volatilisation rate: 0.02 for dairy and suckling cows, 0.01 for ewe, 0.02 for chickens and pigs	None
Urine and dung deposited by grazing animals	Structure of herds (number, age, gender and productivity of animals) (Eurostat 2010) % of urine and dung deposited during grazing periods**		
Crop residues left on soils	Area per crop type for straw cereals (Eurostat 2010) Yield per crop type (Eurostat 2010)	Parameters to calculate t of residue/ha, per crop type (straw cereals) N content of crop residues left on soils, per crop type % of residues of straw cereals left on soils: 88.75	None
Crop residues within soils	Area per crop type (Eurostat 2010) Yield per crop type (Eurostat 2010)	Parameters to calculate t of residue/ha, per crop type N content of crops residues left on soils, per crop type	None
Crop residues in litter	Area per crop type for straw cereals (Eurostat 2010) Yield per crop type (Eurostat 2010)	Parameters to calculate t of residue/ha, per crop type (straw cereals) N content of crops residues left on soils % of residues of straw cereals collected: 11.25 Use of residues of straw cereals for litter: 50%	None

* indicates information that was left unchanged compared to what was originally proposed by the calculator (= based on an evaluation made for France), due to lack of data for Europe
** indicates information for which explanation can be found in 7.2.3

TABLE 12. Direct emissions linked to enteric fermentation - Requested information and calculation parameter

Direct emissions linked to enteric fermentation		
Information needed for calculation	Calculation parameters	Adjustments
Structure of herds (number, age, gender and productivity of animals) (Eurostat 2010)	CH_4 emission factors per type of animal, calculated according to tons of concentrate and fodder effectively eaten CH_4-CO_2e conversion factor: 28	None

* indicates information that was left unchanged compared to what was originally proposed by the calculator (= based on an evaluation made for France), due to lack of data for Europe
** indicates information for which explanation can be found in 7.2.3.

TABLE 13. Direct emissions linked to manure management practices - Requested information and calculation parameter

Direct emissions linked to manure management practices			
Category	Information needed for calculation	Calculation parameters	Adjustments
CH_4 emissions linked to manure deposited within livestock buildings	Structure of herds (number, age, gender and productivity of animals) (Eurostat 2010) % of urine and dung deposited during paddock periods** % of manure management type**	Tons of manure produced per type of animal, calculated according to feed effectively eaten CH_4 emission factors per manure management type CH_4-CO_2e conversion factor: 28	None
CH_4 emissions linked to manure deposited on pastures	Structure of herds (number, age, gender and productivity of animals) (Eurostat 2010) % of urine and dung deposited during grazing periods**	Tons of manure produced per type of animal, calculated according to feed effectively eaten CH_4 emission factor on pastures: 0.01 CH_4-CO_2e conversion factor: 28	None
N_2O emissions linked to the storage of liquid and solid manure	Structure of herds (number, age, gender and productivity of animals) (Eurostat 2010) % of manure management type**	Kg N/animal, per animal type (see **Table 5**) N_2O emission factors per manure management type N_2O-CO_2e conversion factor: 265	None

* indicates information that was left unchanged compared to what was originally proposed by the calculator (= based on an evaluation made for France), due to lack of data for Europe
** indicates information for which explanation can be found in 7.2.3.

7.2.3. Comparing emissions calculated by ClimAgri® with emissions reported to the UNFCCC for 2010

Comparing direct emissions calculated by ClimAgri® for 2010 with direct emissions reported by the European Union to the UNFCCC enabled both to check the relevance of hypotheses made for calculation parameters and to adjust hypotheses made for input variables.

For crop and pasture areas, yield, the structure of herds and the volume of water used for agricultural irrigation, information was retrieved from Eurostat (2010).

Liming application was set at 70 kg per hectare on 100% of the field crop area, following experts' consultations and in order to be the closest possible to the figures for emissions from liming reported to the UNFCCC. For inorganic fertilizer application, a coefficient was applied to the volumes entered for France per crop type, considering that the average volume applied in Europe was lowest than the one applied in France. The coefficient were set at 75% for N, and at 55% for P and K, in order to be the closest possible to the total volumes used for agriculture reported to the FAO (**Table 14**).

TABLE 14. Comparison of N, P and K uses calculated by ClimAgri® and reported to the FAO

	N	P	K
ClimAgri® 2010	10,658,296	2,479,168	3,084,511
FAO – European Union 2010	10,562,310	2,504,078	2,895,180

For the type of inorganic N applied, which includes solution, urea, ammonium nitrate and other inorganic N, figures for Europe were retrieved from Yara (2015): solution (12%), urea (21%), ammonium nitrate (55%), other (12%).

The area of heated greenhouses is a particularly sensitive input variable, but for which data is difficult to find. The area was estimated at 72,482 ha, or 3.5% of the total 2010 area of fresh vegetables. This calculation was made using data from Eurostat (2016), which estimates that 7.2 % of all European fresh vegetables are grown on land given over to cultivation under glass or other high accessible cover. We made the hypothesis that half of this area—that can be heated, as under glass or high accessible cover—needed heating, following experts' advice considering the repartition of greenhouses in northern and southern parts of Europe. This estimation of the area of heated greenhouses in 2010 is consistent with Campiotti *et al.* (2012): "as general figure, in Europe are operating about 200,000 hectares of greenhouses, of which about 30% with permanent [heated] structures".

The energy mix for the heating of livestock buildings is also an input variable for which figures were difficult to find out for Europe. As a first estimate, and in order to simplify the exercise, the energy mix was set at 100% of electricity, for the following energy needs[16]:

— 403 kWh/sow
— 3.15 kWh/laying hen
— 0.52 kWh/kg body weight for broilers; 0.46 kg body weight/broiler (place) for conventional broiler; 0.50 kg body weight/broiler (place) for label broiler
— 440 kWh/dairy cow
— 93 kWh/suckling cow

To these energy needs were also added additional fuel energy needs for the cattle (0.12 liter of fuel/dairy cow and 0.08 liter of fuel/suckling cow), based on estimated uses from French farms.

For preservation, the hypothesis was made that 100% of all cereals were preserved. For drying, the following hypotheses were made, following experts' recommendations:

— Straw cereals such as wheat, barley, oats…: 10%
— Protein crops: 20%
— Grain maize, rice, rape, soybean, sunflower, other oleaginous crops: 100%

16 Based on ClimAgri©'s parameters, calculated according to Guivarch *et al.* (2007).

Finally, manure management practices heavily influence the emission of greenhouse gases. ClimAgri® requires hypotheses on the share of manure excreted on pastures and the share of manure excreted in-door, but also divides this latest category into three categories for cattle (two solid manure systems: "solid storage" (manure mixed with litter, regularly collected) and "deep litter" systems, with higher emission factors; and one slurry/liquid manure system) and two categories for pigs and chickens (manure mixed with litter, regularly collected; slurry/liquid manure). Hypotheses for the percentages of manure deposited during grazing and paddock periods for cattle were retrieved from the European Union greenhouse gas inventory report (2012: 478).[17] Hypotheses to disaggregate manure management into liquid and solid systems were also retrieved from the same report. However, in the EU GHG inventory report, there is only one category for non-liquid manure management systems for the cattle, which combines "solid storage" and "dry lot". We decided to take into account only the "solid storage" category for the bovine herd, which has the lowest emission factors, in order to be the closest possible to the emissions reported to the UNFCCC. Figures linked to sheep, pigs and chickens were left unchanged compared to the situation in France (see below), but impact less greenhouse gas emissions.

Ruminant category	Pasture	Litter + manure		Slurry/liquid manure
		Solid storage	Deep litter	
Dairy cows	26%	13%	14%	47%
Suckling cattle	43%	6%	25%	26%
Sheep	70%	0%	30%	0%

Monogastric animal category	Pasture	Litter + manure	Slurry/liquid manure
Pigs	0%	17%	83%
Broilers and hens	2%	75%	23%

Although the orders of magnitude of calculated and reported emissions are comparable, several non-negligible gaps can be noted.

Half of the absolute gap between direct GHG emissions calculated by ClimAgri® and direct emissions reported to the UNFCCC are due to differences between reported figures for energy consumption. These latest, in this case, can easily be explained:

— The energy combustion figures for off-road vehicles and other agricultural machinery, as reported to the UNFCCC, are higher than the ones calculated by ClimAgri®. This is due to the fact that the figures reported to the UNFCCC also include energy combustion for forest machinery;

— The gap between energy combustion figures for stationary equipment, on its side, is positive, and quite large. This is due to the fact that an important part of energy combustion for stationary equipment reported under "energy industry" (ex.: energy for heating greenhouses obtained by co-generation linked to converting gas into electricity).

Figures for enteric fermentation differ as well, mostly because of gaps existing for cattle. Differences are mostly linked to calculation methods. Calculation methods used by ClimAgri® take into account CH_4 emission factors per type of animal, calculated according to the tons of concentrate and fodder effectively eaten by each animal. The variability of methods to detail herd structures as well as to evaluate emission factors explain the gap that exists between the results given by the calculator and the figures reported to the UNFCCC (**Table 15**).

TABLE 15. Calculation methods for cattle population and emission factors for countries representing two thirds of the cattle population in Europe (2010) – Source: European Union 2012

Member State's background information for CH_4 emissions from enteric fermentation – Activity, Emission Factor and other parameters
France Activity data is a one year average. Heifers are included in Other Cattle, but heifers more than 2 years old (40% of the total heifer livestock) are considered as Dairy cattle. The Emission Factor for Dairy Cattle is depending on milk production. Emissions factors are used for enteric fermentation from a study published in 2008 by the French National Institute of Agronomy. These emission factors are based on parameters equivalent to Ym and GE, but these parameters are not directly available in the study.
Germany Animal types are disaggregated, if significant differences exist between emission factors. For example, dairy cattle are grouped into sub-categories in each district on the basis of animal performance and feeding indicators. Other cattle include calves, heifers, bulls (beef), suckler cows and mature males. The calculation of the Emission Factor for Dairy Cattle is based on milk production, animal weight (derived from nation data on milk production and milk quality), and animal feed. Feeding composition (mixed grass/maize/feed concentrates and grass/concentrates) and their characterisation is available for each district. Feed digestibility is estimated as function of feed composition and productivity. For milk-feed calves it has been considered that they do not belong to the ruminant animals.
United Kingdom In the inventory the dairy cows weights are slaughter weight data provided by Sarah Thompson, Defra. The digestibility value (74%) was derived from calculations (Bruce Cottrill, pers. comm.) based on typical diets for cows over a dry and lactating period, combining forage and concentrates with the digestibilities of the gross energy for various feeds according to MAFF (1990).
Ireland The Irish cattle herd is now characterised by 11 principal animal categories for which annual census data are published by CSO. The number of Cows in each category given by CSO statistics was allocated to the regions using CMMS reports published by the Department of Agriculture and Food (DAF, 2007). The most important parameter is liveweight gain as it directly affects the energy requirement and thus feed intake. Emission factors for the Beef cattle categories were determined by calculating lifetime emissions for the animal and by partitioning between the first, second and third years of the animal's life.
Italy Data to calculate the emission factor from dairy and non-dairy cattle are national (ISTAT, Centro Ricerche Produzioni Animali, Reggio Emilia - CRPA). This information has been discussed in a specific working group in the framework of the MidetAIRaneo project (CRPA, 2006; CRPA, 2005).
Netherlands For cattle three categories are distinguished: Dairy cattle: adult female cows (for milk production); Non-dairy cattle: adult cows (for meat production); Young cattle showing a mix of different age categories (for breeding and meat production). The emission factors for three cattle types are calculated annually (e.g. adult dairy, adult non-dairy and young cattle, respectively

17 Although average figures exist only for the EU15, the EU15 represented in 2010 66% of the EU28 bovine herd.

TABLE 16. Calculated and reported 2010 GHG emissions for the European Union (28)

	ClimAgri® 2010	UNFCCC 2010
Fuel combustion in agriculture	115.22	79.39
among which energy combustion for off-road vehicles and other agricultural machinery	40.45	51.30
among which energy combustion for stationary equipment	74.78	28.09
Agricultural soils	149.55	157.50
among which direct N_2O emissions	109.75	124.36
among which indirect N_2O emissions	34.81	27.74
among which CO_2 emissions from liming	4.99	5.40
Enteric fermentation	229.69	188.22
from cattle	198.27	156.89*
from sheep	28.76	20.32*
from pig	2.66	4.47*
Manure management	89,17	57.12
from cattle	61.5	29.98*
from sheep	6.2	1.26*
from pig	7.42	21.46*
from other animals	14.07	4.4*
indirect N_2O from manure storage	n/a	8.28*
Total direct GHG emissions	583.46	490.51

* data retrieved from Eurostat

In addition, even though the EU National Inventory Report (European Union 2012) estimates that CH_4 emissions from enteric fermentation belong to the source categories in agriculture, which are less uncertain, with emission factors known with a precision better than 20% for most countries, uncertainties can go as high as 40% (for France, or for dairy cattle in Germany).

Both enteric fermentation and manure management emissions for the cattle are overestimated by the calculator. However, the purpose of using ClimAgri® is to compare 2010 and 2050 emissions according to the same calculation modes. Hence, emissions which are overestimated in 2010 will be overestimated for 2050, not putting back into question the interest of the comparative exercise or the tool used to perform it.

7.2.3 Setting parameters and calculation information for evaluating the GHG impact of the TYFA scenario

Only one parameter was modified between the calculator used for estimating 2010 GHG emissions and the calculator used for estimating GHG emissions in 2050. The amount of CO_2 emissions resulting from the provision of electricity decreases, to take into account a certain level of decarbonation of the European electricity sector. The hypothesis is not too ambitious, following experts' advice and figures given by "Ten Years Network Development Plans" from the ENTSO-E (ENTSO-E, 2018). It was estimated that emissions would drop down to 0.00012 tons of CO_2 per kWh produced.

Crop and pasture areas, yield, the structure of herds and inorganic fertilizer (brought down to zero) were directly retrieved from the TYFA scenario.

Although irrigation does not have the same impact on GHG emissions, it was an important aspect on which hypotheses had to be made to run the calculator. In order to estimate the total amount of water needed for irrigation, the area irrigated in Europe in 2008-2010 was first calculated using Aquastat data, per crop type. The area irrigated in Europe in 2050 under the TYFA scenario per crop type was calculated by multiplying the above-mentioned areas per crop type by the area increase rate calculated in the TYFA calculator.

The total area irrigated in 2050 was then obtained by summing up the area irrigated per crop. Finally, the ratio was applied to the amount of water used for agricultural irrigation in 2010. In order to calculate the amount of energy needed for irrigation, the same intermediate factor than the one chosen to evaluate 2010 emissions was selected (0.5 kWh/m^3).

Liming application was kept at 70 kg per hectare on 100% of the crop area, as in 2010. Percentages of crops dried and preserved were kept alike as well.

Specific attention was dedicated to hypotheses regarding greenhouses, as practices linked to greenhouses proved to have a high impact on resulting emissions, especially since the TYFA scenario almost doubles the area where fresh vegetables are grown. The hypothesis was made that all additional vegetables would only be open-grown, and that the area of heated greenhouses in 2010 would drop by 15% by 2050—i.e., greenhouses would be relocated to areas with more suitable climatic conditions, as maximizing the use of local ecosystems is one of the core principles of agroecology.

Finally, hypotheses were also made for manure management practices, with the elimination of liquid forms of manure.

Farming systems engaged in this type of manure management would emit less methane in livestock buildings and during storage and application, as solid forms of manure are less volatile. However, this would imply a rediversification of agricultural activities at the local level, both for straw from cereal farms to feed the manure management systems of livestock farms (especially since solid manure requires at least 3 kg of straw per livestock unit (Idele, 2005), and to shorten the transportation distance of heavy manure that would need to be spread to crops.

Ruminant category	Pasture	Litter + manure		Slurry/ liquid manure
		Solid manure	Deep litter	
Dairy cows	25%	75%	0%	0%
Dairy calves	50%	50%	0%	0%
Suckling cattle	62%	38%	0%	0%
Sheep and goats	70%	30%	0%	0%

Monogastric animal category	Pasture	Litter + manure	Slurry/ liquid manure
Pigs	10%	90%	0%
Broilers and hens	2%	98%	0%

7.3. Structure of herds, as retrieved from Eurostat (2010)

<table>
<tr><th>Animal category</th><th>Number</th><th>Number of days present</th></tr>
<tr><td colspan="3">Dairy cattle</td></tr>
<tr><td>Dairy cows (6,000 kg/year)</td><td>23,313,920</td><td rowspan="7">365</td></tr>
<tr><td>Heifers 0-1 year</td><td>8,030,052</td></tr>
<tr><td>Heifers 1-2 years</td><td>7,608,497</td></tr>
<tr><td>Males 0-1 year</td><td>4,262,722</td></tr>
<tr><td>Males 1-2 years</td><td>5,503,754</td></tr>
<tr><td>Heifers >2 years</td><td>3,983,608</td></tr>
<tr><td>Males >2 years</td><td>1,161,088</td></tr>
<tr><td colspan="3">Suckling cows</td></tr>
<tr><td>Suckling cows</td><td>12,379,560</td><td rowspan="7">365</td></tr>
<tr><td>Heifers 0-1 years</td><td>4,263,568</td></tr>
<tr><td>Heifers 1-2 years</td><td>4,039,743</td></tr>
<tr><td>Males 0-1 year</td><td>2,922,226</td></tr>
<tr><td>Males 1-2 years</td><td>2,115,102</td></tr>
<tr><td>Heifers >2 years</td><td>2,263,298</td></tr>
<tr><td>Males >2 years</td><td>616,482</td></tr>
<tr><td colspan="3">Sheep and goats</td></tr>
<tr><td>Ewes</td><td>44,519,111</td><td>365</td></tr>
<tr><td>Lambs</td><td>55,648,889</td><td>100</td></tr>
<tr><td colspan="3">Pigs</td></tr>
<tr><td>Sows</td><td>8,019,000</td><td>365</td></tr>
<tr><td>Piglets</td><td>144,342,000</td><td>180</td></tr>
<tr><td colspan="3">Broilers and chickens</td></tr>
<tr><td>Broilers</td><td>6,147,528,000</td><td>249</td></tr>
<tr><td>Laying hens</td><td>363,564,000</td><td>355</td></tr>
</table>

7.4. Structure of herds, as modelled by TYFA (2050)

Animal category	Number	Calculation method	Number of days present
Dairy cattle			
Dairy cows – Mixed (= 5,700 kg/year)	13,617,772	80% of the total number of dairy cows	365
Dairy cows – Grass-based (=5000 kg/year)	3,404,443	20% of the total number of dairy cows	
Heifers 0-1 year	7,659,997	Total number of dairy cows * (0.9 being the number of calves per dairy cow per year)	
Heifers 1-2 years	7,659,997		
Males 0-1 year	7,659,997		
Males 1-2 years	7,659,997		
Heifers >2 years	7,659,997		365 * 10/12 (only stays 10 months on fields before being slaughtered or before replacing cull cows)
Males >2 years	7,659,997		
Suckling cows			
Suckling cows	5,000,877		365
Heifers 0-1 years	2,250,395		
Heifers 1-2 years	2,250,395		
Males 0-1 year	2,250,395		
Males 1-2 years	2,250,395	Total number of suckling cows * (0.9 being the number of calves per dairy cow per year)	
Heifers >2 years	2,250,395		365 * 10/12 (only stays 10 months on fields before being slaughtered or before replacing cull cows)
Males >2 years	2,250,395		
Sheep and goats			
Ewes	30,917,829		365
Lambs	38,647,286	1.25 lamb per ewe	100
Pigs			
Sows (outdoor category selected, raising the N excreted)	4,178,628		365
Piglets (outdoor)	75,215,304	18 piglets per sow	335
Broilers and chickens			
Broilers (label category selected, raising the N excreted; also influences the body weight, hence the energy consumption of buildings)	2,250,534,125		140
Laying hens (label category selected, raising the N excreted)	179,957,273		355

Agroecology and carbon neutrality in europe by 2050: what are the issues?

Findings from the TYFA modelling exercise

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Citation: Aubert, P.M., Schwoob, M.H., Poux, X. (2019). Agroecology and carbon neutrality in Europe by 2050: what are the issues? Findings from the TYFA modelling exercise. IDDRI, *Study* N°02/19.

ISSN: 2258-7535

This article has received financial support from: The French government in the framework of the programme "Investissements d'avenir", managed by ANR (the French National Research Agency) under the reference ANR-10-LABX-01; The European Union, under the Executive Agency for Small and Medium-sized Enterprises (EASME); The foundation Charles Léopold Mayer pour le Progrès de l'Homme; The Fondation Didier et Martine Primat; and the Office français de la biodiversité (OFB).

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