Science of the Total Environment 908 (2024) 168160

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Beyond the Farm to Fork Strategy: Methodology for designing a European agro-ecological future

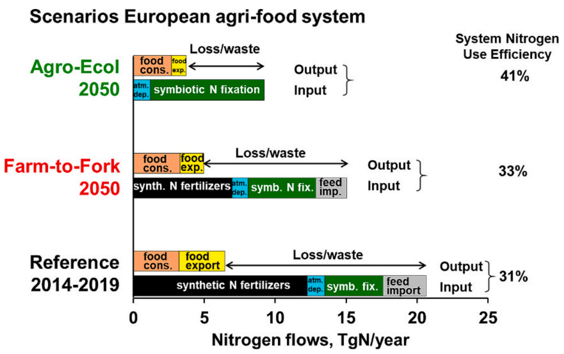
Gilles Billen[a,*], Eduardo Aguilera[b], Rasmus Einarsson[b,c], Josette Garnier[a], Simone Gingrich[d], Bruna Grizzetti[f], Luis Lassaletta[b], Julia Le Noë[e], Alberto Sanz-Cobena[b]

[a] *SU CNRS EPHE, Umr Metis 7619, Paris, France*
[b] *CEIGRAM, ETSI Agronomica, Alimentaria y de Biosistemas, Universidad Politécnica de Madrid, Spain*
[c] *Swedish University of Agricultural Sciences, Uppsala, Sweden*
[d] *Institute of Social Ecology (SEC), Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Vienna, Austria*
[e] *IRD, IEES, Paris, France*
[f] *European Commission Joint Research Centre (JRC), Ispra, Italy*

HIGHLIGHTS

- GRAFS is used as a prospective tool for scenarios design for Europe in 2050.
- Three scenarios were compared for food security and environmental N losses.
- The Farm to Fork scenario does not meet the objectives of halving N losses while feeding the population.
- An agro-ecological scenario with reduced livestock and no synthetic fertilizers meets these objectives.

GRAPHICAL ABSTRACT



ARTICLE INFO

Guest Editor: Estela Romero

Keywords:
European Agri-food system
Scenario design
Farm to Fork Strategy
Agro-ecological scenario
Crop rotations
Crop-livestock reconnection
Halving N waste

ABSTRACT

The publication of the European Commission's Farm to Fork Strategy has sparked a heated debate between those who advocate the intensification of agriculture in the name of food security and those who recommend its de-intensification for environmental reasons. The design of quantified scenarios is a key approach to objectively evaluate the arguments of the two sides. To this end, we used the accounting methodology GRAFS (Generalized Representation of Agri-Food Systems) to describe the agri-food system of Europe divided into 127 geographical units of similar agricultural area, in terms of nitrogen (N) fluxes across cropland, grassland, livestock, and human consumption. This analysis reveals, in current European agriculture, a high level of territorial specialization, a strong dependence on long distance trade, and environmental N losses amounting to about 14 TgN/yr, i.e. nearly 70 % of the annual N input (including N synthetic fertilizers, symbiotic N fixation, oxidized N deposition and import of food and feed). Based on the analysis of the yield-fertilization relationship of cropping systems at the scale of their full rotation cycle, and on a simplified model of livestock ingestion, excretion and production, we advanced the GRAFS methodology for prospective scenario design. Three scenarios for the European agri-food

---

* Corresponding author.
E-mail address: gilles.billen@upmc.fr (G. Billen).

https://doi.org/10.1016/j.scitotenv.2023.168160
Received 11 May 2023; Received in revised form 25 September 2023; Accepted 25 October 2023
Available online 2 November 2023
0048-9697/© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

system were explored for 2050: a business-as-usual (BAU) scenario, a scenario based on the measures considered by the EU Farm to Fork Strategy (F2F), and a fully agro-ecological scenario (AE). The results show that the F2F scenario reduces the dependence of Europe on imports of synthetic fertilizers and feed resources by 40 % as well as the environmental N losses by 30 %, but not to the level of its claimed ambitions as N lost to the environment still amounts to about 10 TgN/yr, i.e. 67 % of N inputs. Of the three scenarios studied, only in the AE scenario, involving the relocation of feed production, the generalization of organic crop rotations with N fixing legume crops, and a shift of agricultural production and food consumption toward less animal-based products, would Europe be able to dispense with N imports, still being able to export some cereals, meat, and milk products to the rest of the world, while halving today's reactive N emissions to the environment.

1. Introduction

Nitrogen (N) is at the heart of the debates on the socio-ecological transition of agri-food systems for several reasons, relating to human nutrition, agricultural productivity, ecosystem functioning and planetary boundaries. First, proteins, the main N-containing constituents of food, are primarily required for tissue build-up and renewal, contrary to carbohydrates and lipids (free of N) which are mainly used for metabolic energy. Therefore, a rather constant per-capita protein requirement of ca. 3.6 kgN/cap/yr can be defined, taking into account ca. 20 % unavoidable losses before final intake (WHO, 2007; Gustavsson et al., 2013), while requirements in terms of kilocalories is much more variable according to lifestyle and socio-professional activity (WHO, 1985, 2007). Supplying the required N protein ration to all inhabitants of the planet is the condition for global food security.

Second, N is a main limiting factor of terrestrial and aquatic primary production, and in particular N fertilization is the major factor, besides water availability, controlling agricultural yields (Vitousek and Howarth, 1991; Galloway, 1998; LeBauer and Treseder, 2008). However, synthetic fertilizers are not the only form of N fertilization, as animal or human manure, symbiotic fixation and atmospheric deposition also contribute substantially in many agricultural systems. For instance, organic farming is committed to not using synthetic fertilizers (and pesticides), thus developing less intensive cropping most often with an obvious environmental benefit in terms of biodiversity and environmental losses per unit area, while crop yields are generally lower when compared to high input systems (Seufert and Ramankutty, 2017).

Third, N is a very mobile element, existing in several gaseous forms and highly soluble in water, thus subject to important losses to the environment. These losses cause major ecosystem dysfunctions and are responsible for one of the major transgressions of planetary boundaries defining the safe operating space of the Earth system (Galloway et al., 2003; Rockström et al., 2009, 2023; Steffen et al., 2015; Schulte-Uebbing et al., 2022). The ambition of *halving nitrogen waste* by 2030 (Sutton et al., 2021), as agreed in 2019 by the UN Colombo declaration (https://www.inms.international/colombo-declaration/colombo-declaration), appears to be of the scale required to address the multiple issues of N pollution and Earth System Boundaries. Nitrogen wastes include all forms of reactive N pollution and anthropogenic losses, whether intentional and unintentional, and also anthropogenic denitrification to di-nitrogen (N_2), which is equally a waste of reactive N resources. In the EU, the Biodiversity Strategy, Farm to Fork Strategy, and the Zero Pollution Action Plan have set the target of reducing nutrient losses to the environment by 2030. Very recently (December 2022) also the United Nations Biodiversity Conference (COP15) with the Kunming-Montreal Global Biodiversity Framework has announced the ambition of reducing excess nutrients lost to the environment by at least half by 2030 (Target 7).

Many forecasting exercises (FAO, 2009; United Nations, 2009; Blum, 2013; van Dijk et al., 2021), considering the 2050 horizon, when the world population is expected to be close to its peak of 10.5 billion people (https://population.un.org/wpp/Graphs/Probabilistic/POP/TOT/900), conclude that global agricultural production needs to be increased by 70 to 100 % of its level in the 2000–2010. This is not only because of the expected population growth, but mostly because of the projected increase in total per capita consumption, and even more, the trend toward more animal products in diets. These trends in diets, in many countries far exceeding public health recommendations (Chatzimpiros and Harchaoui, 2023), are often not questioned, and the demand is considered as an external control factor of the agri-food system.

An approach often adopted to analyze the possibilities of increasing agricultural production is a crop-by-crop analysis of yield gaps of the main current staple crops. The yield gap is defined as the difference between optimum yield obtained in agronomical stations and the actual yield observed in real situations (Van Ittersum et al., 2013). Increasing food production means closing the yield gap (Licker et al., 2010; Suh et al., 2020). From this perspective, organic farming would be suboptimal, as for many cultivated crops taken one by one, the observed yield is ca. 20–30 % lower than in conventional agriculture (De Ponti et al., 2012; Ponisio et al., 2014). While lower organic yields are a reality in most staple crops, the picture is considerably more complex when considering the full crop-livestock system which includes large quantities of arable forage crops and temporary and permanent grasslands, and the role of livestock as net consumers and recyclers of nutrients (Lemaire et al., 2023; Morais et al., 2021; Einarsson et al., 2022). Not questioning the human diet and focusing narrowly on staple crop yield gaps might lead to the conclusion that land sparing (intensifying agricultural production on the smallest possible agricultural land area, in order to maintain space for wildlife and biodiversity) is better than land sharing (using more extensive farming practices in order to make room for biodiversity within agricultural space) (Fischer et al., 2008; Phalan et al., 2011; Green et al., 2005; Folberth et al., 2020). Recently, a growing scientific literature has explored alternative paradigms and come to more nuanced conclusions. Quite consistently, Billen et al. (2015) and Erb et al. (2016) explored the “option space” of global food supply under specific constraints and found a vast range of opportunities to meet food supply in 2050 without necessarily increasing agricultural production or agricultural surfaces. Muller et al. (2017) and Morais et al. (2021) further demonstrated that feeding the world with organic agriculture in 2050 is possible by implementing particular combinations of agro-ecological strategies. As highlighted by, e.g., Theurl et al. (2020) and Bodirsky et al. (2022), a shift toward less livestock-intensive production and consumption is the most important lever for reaching food security.

The case of Europe is paradigmatic, as this continent, although very fertile and productive with modern intensive agricultural practices, in fact imports more proteins from outside than it exports. In that sense, it is dependent on the rest of the world, in terms of protein supply, for feeding its population (Billen et al., 2021). Even so, nutrient emissions from European agriculture have deteriorated air, soil and water quality, and impacted human health, biodiversity and climate (Sutton et al., 2011; van Grinsven et al., 2013; Kanter et al., 2020; Musacchio et al., 2020). N inputs to cropping systems have to be consistently reduced to avoid the trespassing of territorial boundaries for protecting biodiversity and water quality (de Vries et al., 2021). To address these issues, the European Union (EU) has introduced agri-environmental measures in the Common Agricultural Policy since the 1990s and adopted several legislations to reduce nutrient pollution (i.e., the Nitrates Directive 91/

676/EEC, the Water Framework Directive 2000/60/EU and the National Emission Reduction Commitments Directive 2016/2284/EU). Recently, the European Commission has set an ambitious goal to halve nutrient losses to the environment (air, water, soil) by 2030 (Biodiversity Strategy (European Commission, 2020a), Farm to Fork Strategy (European Commission, 2020b), Zero Pollution Action Plan (COM, 2021)). In the Farm to Fork Strategy, the Commission announced several targets by 2030: to reduce both the use of pesticides and the nutrient losses to the environment by 50 %, and to increase organic farming to 25 % of the EU's agricultural land. Because these targets were estimated to lead to a 10–20 % decrease of crop production across the EU (Beckman et al., 2020; Bremmer et al., 2021), the strategy met the strong opposition of some European agricultural lobbies, who advocated on the contrary for an intensification of agricultural production, particularly in the context of the Ukraine crisis (Schebesta and Candel, 2020; Poiron, 2022; Hénin, 2023; Cerier, 2023).

In the context of these heated debates, there is a need to develop integrative approaches to the functioning of the agri-food system that enable both an objective diagnosis of the current situation and an assessment of the performance of alternative, less intensive systems. This paper explores several scenarios for the future of the European agri-food system at the 2050 horizon, using a quantitative methodology based on nitrogen (N) fluxes that sheds light on contrasting solutions to the interrelated issues of food supply, self-sufficiency, and environmental quality outlined above. Using scenario results, our aim is to comprehensively compare the functioning of systems differing in the degree of territorial specialization, autonomy and use of agricultural inputs. Methodologically, this paper makes two main contributions. First, we increase the resolution of our previous analysis of the European agri-food system using the GRAFS approach (Generalized Representation of Agri-food Systems) (Billen et al., 2021) by adopting subnational Geographical Units (GU), based on the EU NUTS classification (Nomenclature of Territorial Units for Statistics). This subnational approach is more demanding in terms of data supply but accounts much more accurately for the regional specialization of the agri-food system and the ensuing regional environmental pressures. Second, we also make explicit a number of methodological principles and assumptions regarding the yield/fertilization relationships of cropping systems, and the relation between production and feed resources for livestock systems. These relationships form the basis of the GRAFS approach when used as a tool for agri-food system scenario design.

The remainder of the paper is organized in three parts: In Section 2, the GRAFS approach is introduced as an accounting method for synthetizing available information about current N fluxes in the European agri-food systems at sub-national scale in order to quantify their structure and function. After stating the principles of the application of the GRAFS approach to the construction of hypothetical scenarios and testing the validity of this modelling approach (Section 3), we then apply these principles to calculate three such scenarios (and their variants) (Section 4) including a business-as-usual (BAU) scenario, a scenario based on the measures considered by the Farm to Fork (F2F) Strategy, and an agro-ecological (AE) scenario. In the final discussion (Section 5), the scenario results are used to put the F2F Strategy into perspective and advocate the need for even deeper transformations of the agri-food system for reducing N losses to the environment.

2. GRAFS description of the current European agri-food system

2.1. Choice of the relevant spatial resolution and data required

For the purpose of this study, similarly to what we did in a previous work at national level (Billen et al., 2021), we refer to "Europe" (or "European countries") as the ensemble of countries located inside the outermost borders of the current European Union thus including 540 million people from the current EU27 plus UK, Norway, Switzerland, Albania, Serbia, Montenegro, and North Macedonia.

The GRAFS approach (Billen et al., 2014; Le Noë et al., 2017, 2018) describes the food production and consumption of a region in terms of the N fluxes between cropland, grassland, livestock and human consumption (including food waste), without explicitly assessing agro-industrial transformation and retailing. As an accounting method, GRAFS consistently quantifies N fluxes between these compartments based on commonly available agricultural activity data including agricultural land areas and crop yields, fertilizer use, livestock populations and livestock production, and food consumption at an annual resolution. In principle, GRAFS can be applied at various spatial scales, e.g., farm or catchment (Benoit et al., 2016; Garnier et al., 2016), subnational and regional (Le Noë et al., 2017, 2018), national (Lassaletta et al., 2014; Billen et al., 2021; Garnier et al., 2023), or global (Billen et al., 2014; Lassaletta et al., 2015). If the purpose is to reveal the structure of regional agri-food systems, or to design sustainable configurations of producer-consumer interactions, the choice of spatial resolution of the GRAFS approach is critical. Working at country level, which is facilitated by the availability of national data in FAOSTAT (https://www.fao.org/faostat/en/#data), is insufficient in many countries because such a resolution inadvertently conceals regional specialization which is an important determinant of environmental issues. The ideal resolution would however not be too high, not only because of the increased difficulty of obtaining the required data, but also because some features sought in the scenario construction, such as regional agricultural autonomy or reconnection of crop and livestock farming, are only meaningful at a reasonable minimum size of the entities considered (Spiegal et al., 2020; Bai et al., 2022), well above the farm or village scale, but below the level where aggregation effects could mask opposing territorial specializations accompanied by long-distance transport of materials.

For the present application of the GRAFS approach to Europe we investigated regional specialization and ensuing environmental pressures. Therefore we decided to establish geographical units (GUs) across Europe representing a similar area of agricultural land, typically between 1 and 2.5 Mha, based on the European NUTS classification (https://ec.europa.eu/eurostat/web/nuts/background, a hierarchical system for dividing up the European economic territory for collection of regional statistics). The size of NUTS units is quite heterogeneous among countries. For a number of them (Albania, Bosnia and Herzegovina, Croatia, Estonia, Finland, Latvia, Luxemburg, the Netherlands, Montenegro, North Macedonia, Norway, Serbia, Slovakia, Slovenia, Switzerland) the country level (NUTS0) meets our agricultural area criterion. Czechia, Denmark, and Lithuania are also not far above the threshold of 2.5 Mha. NUTS1 level was considered a good resolution for Austria, Belgium, Bulgaria, Germany, Greece, Hungary, Italy, Poland, Sweden, and the UK. NUTS2 level was used for France, Ireland, Portugal, Romania, and Spain. This leads us to consider 127 GUs for "Europe" as defined above.

With this choice of resolution, most input data could be obtained from the Eurostat database (https://ec.europa.eu/eurostat/data/database), complemented, when required, by data from national or subnational statistics of some countries. Details about data sources and processing procedures are given in the following sections and in the supplementary material (SM1). The full description of the agri-food system according to the GRAFS accounting method for the period 2014–2019 involves: (i) crop production on arable land, permanent cropland, and permanent grassland, expressed in N content; (ii) N inputs to these three agricultural land categories as synthetic fertilizers, manure, atmospheric deposition, and symbiotic N fixation; (iii) the number of ruminant and monogastric livestock, its production of edible and non-edible products and its excretion; (iv) estimates of the main N losses to the atmosphere and the hydrosphere. A net balance of supply and demand for each considered crop or livestock product within each GU is established, from which net imports or exports are calculated. By adding the N fluxes of all GUs, we arrive at a schematic quantified representation of N fluxes linking cropland, grassland, livestock, and apparent human

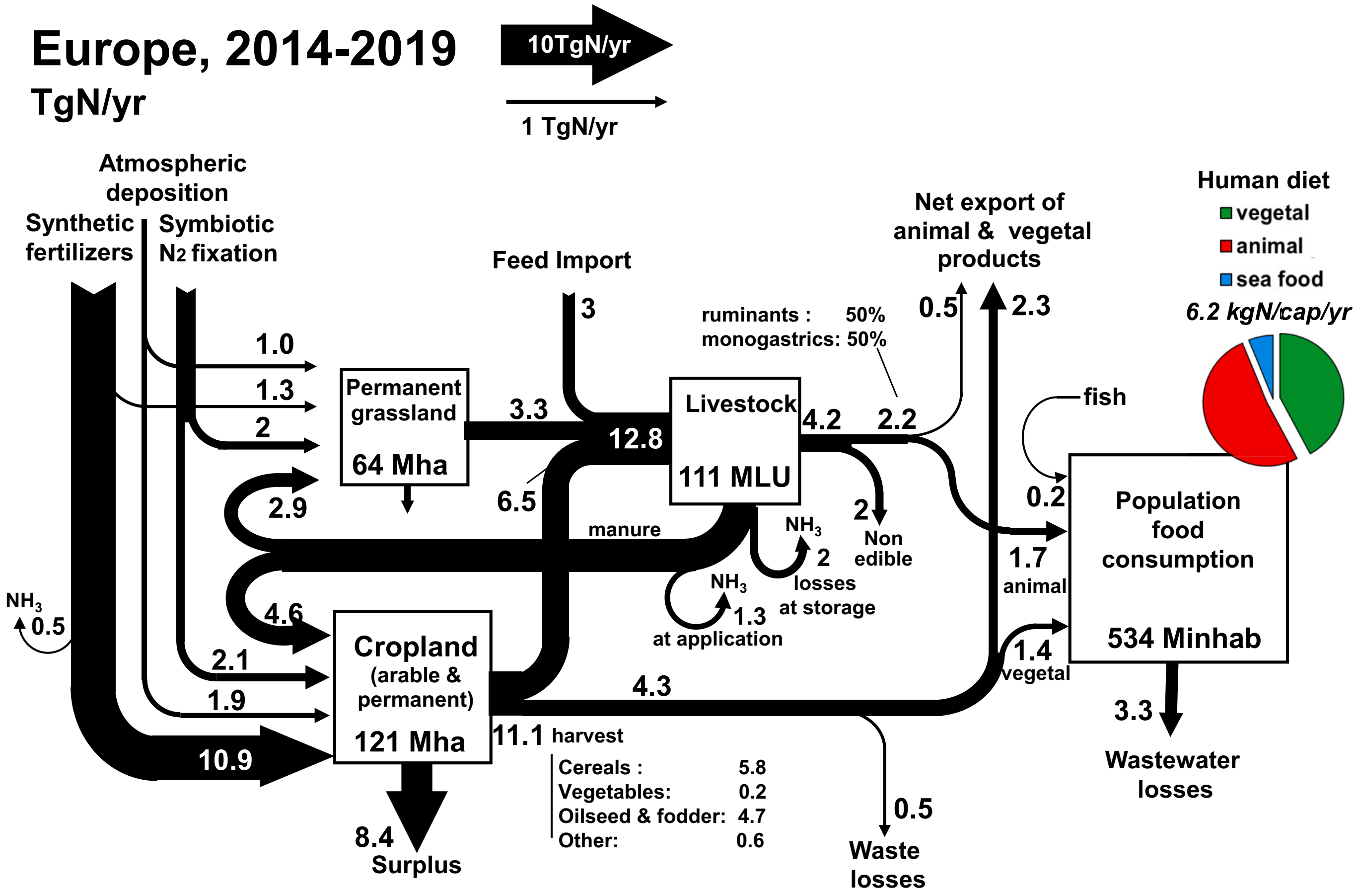


Fig. 1. Aggregated GRAFS representation of the current N fluxes through the European agri-food system in the period 2014–2019. This represents the sum of the fluxes for all 127 GUs considered across Europe. ("Surplus", calculated as the balance of soil N inputs (after NH_3 volatilization at fertilizer and manure application) and harvest export, refers to losses through leaching and denitrification as well as to possible net increase of soil N pool).

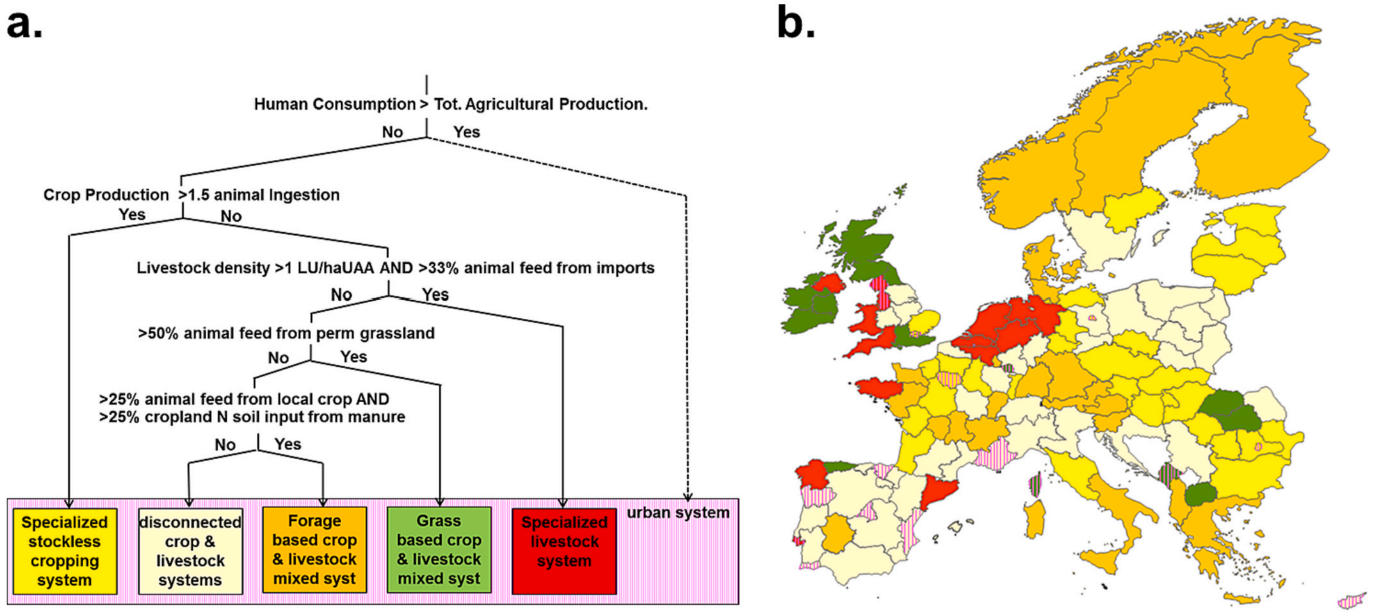


Fig. 2. (a) Decision tree for agri-food system typology and (b) application to the current (2014–2019) situation of European regional agri-food systems.

consumption, including food waste, for the whole of Europe (Fig. 1).

At this aggregated scale, several characteristics of the European agri-food system as a whole clearly appear. The first is a strong dependence of the agricultural system on synthetic N fertilizers, which represent more than 55 % of annual N input to agricultural land. Another dependence is the one on feed imports which provide 23 % of livestock N needs. Simultaneously, Europe exports substantial amounts of cereals and animal products, which in terms of contained proteins do not fully counterbalance the imports of feed. A further characteristic of the system is that a large amount of N is lost to the atmosphere and the hydrosphere through ammonia volatilization, denitrification and nitrate leaching (see below; see also Garnier et al., 2023).

2.2. *Production-consumption balance and agri-food system typology*

Regionalizing the GRAFS analysis of Europe at the GU level enables defining a typology of the regional agri-food systems based on the pattern of major N fluxes between cropland, grassland, livestock and population. This typology is intended to characterize the degree of coupling between crop and livestock systems as well as between local production and consumption. It allows to identify territories that are structurally incapable of closing their nutrient cycle, as shown by several previous studies (Le Noë et al., 2017, 2018; Rodríguez et al., 2023). The criteria used here are very similar to those proposed by Le Noë et al. (2018) for analyzing the trajectory of regional agri-food systems in France from 1850 to 2014, with a few modifications as reported in Garnier et al. (2023). The decision tree is shown in Fig. 2a and distinguishes the following systems.

Urban systems are those for which human food demand exceeds local food production (cropland production + livestock edible production), so that import of food is the major component of the regional agri-food system.

Specialized intensive livestock farming systems are characterized by a high livestock density combined with a large share of imported feed to meet livestock feeding; in these systems, livestock farming is weakly connected to crop farming.

Mixed crop and livestock systems have a high degree of coupling between crop and livestock farming activities because (i) manure provides a relatively high share of cropland N inputs, and (ii) local agricultural production provides a high share of livestock feed. In **Grass-based systems**, permanent grassland provides at least half the livestock feed, while in **Forage-based systems**, local cropland provides at least one third.

In **Disconnected crop and livestock systems**, crop and livestock farming both co-exist but without strong connections in terms of manure used by cropland and local feed products in livestock feeding.

Specialized stockless cropping systems refer to agri-food systems where crop production is much more important in terms of material flow than livestock farming.

The application of this typology to the different GUs of Europe (Fig. 2b) shows that the largest number of them are classified as either specialized (33 of 127 as specialized stockless cropping systems and 15 as specialized livestock systems) or disconnected systems (44 of 127), while mixed crop and livestock systems occupy only 35 regions; Among the 127 GUs, whatever their agricultural classification, 21 are characterized as Urban.

3. Principles for using the GRAFS approach as a modelling tool

While the GRAFS approach can be used to describe N fluxes empirically based on input data as outlined above, it can also be operationalized for modelling future scenarios involving deep structural changes in the agri-food system. This requires additional model assumptions on how land and livestock productivity depend on inputs and what controls environmental N losses. This enables modelling N fluxes from agricultural production, as well as outflows to the environment, based on a limited amount of input parameters. The GRAFS approach has been recently advanced for the improved representation of environmental N losses for France and the Iberian Peninsula (Garnier et al., 2023). Here we present a complete description of the advanced model applied in this study (see also SM1).

3.1. *Yield-fertilization relationship and the role of symbiotic N fixation*

An agricultural system consists of the entire crop rotation cycle in a given land area (equivalent to the full crop distribution of arable land at regional scale). Except for permanent cropping or permanent grassland systems, crops are typically in rotation. The function of agricultural systems is characterized by the extraction of nutrients through harvest, i.e., in our model the crop N yield (Y), and by the compensating soil nutrient inputs (F), here taken as the sum of applied synthetic fertilizers and manure (both adjusted by discounting NH_3 volatilization), symbiotic fixation, and atmospheric deposition. For a given agricultural system, a simple relationship of the form of a single-parameter hyperbolic relation, is observed between yield and fertilization integrated over the whole rotation cycle,

$$Y = Ymax^*F/(F + Ymax) \tag{1}$$

It has been shown empirically (Lassaletta et al., 2014; Anglade et al., 2015b; Billen et al., 2018) that the same relationship with the same Ymax parameter holds for a wide variety of cropping systems (e.g., either organic or conventional) in the same pedo-climatic and socio-technical context. As examples of the robustness of this relationship, Fig. 3 illustrates four cases chosen under different climatic contexts in Europe, including (a) several historical and current cropping systems in the Central Paris basin, and (b) on the Burgundy Plateau “*Petites Terres*” (NE France), (c) the performances of arable land of organic and conventional Swedish dairy farms, with alternating leys and cereal crops, (d) a Mediterranean example of cereal monoculture and cereal-legume rotation. In all cases, the data nicely fit a single Y-vs-F relationship.

The identity of the Ymax value for quite different agricultural practices, including either organic or conventional, under a given pedo-climatic context has considerable implications, because it suggests that the yield difference between organic and conventional cropping is mainly an effect of less intensive fertilization at the scale of the whole rotation cycle rather than of an intrinsically lower productivity of organic farming.

Where representative data for Y and F are available for current or past situations of cropping systems in a given region, the value of the parameter Ymax can be calculated. Based on the evidence above, we consider it an indicator of the intrinsic “fertility” of the region's agricultural land. The data gathered at the European regional level (described in SM1) allows describing the spatial distribution of Ymax across Europe for arable land, permanent crops, and permanent grassland separately (Fig. 4). Compared with arable cropland and permanent grassland systems, which have Ymax of the same order of magnitude, permanent cropland typically shows much lower values. This is related to their low harvested N yields: they produce harvestable products with high C/N ratio and accumulate a large fraction of their net primary production in wood structures. This calls for dealing separately with these agricultural systems in further analyses.

Once the Ymax value of the different regional cropping systems has been calibrated based on observed yield and fertilization rates, this calibrated parameter can be used for calculating the yield under different fertilization inputs. This is the basis for the calculation of agricultural production from fertilization resources in prospective scenarios.

In this process, legume crops play a particular role, as they are both involved in Y (as harvested products) and in F (through their symbiotic atmospheric N fixation), particularly in agro-ecological systems, where symbiotic fixation represents a major share of fertilization.

Symbiotic fixation (Nfix) by legume crops is calculated from their N

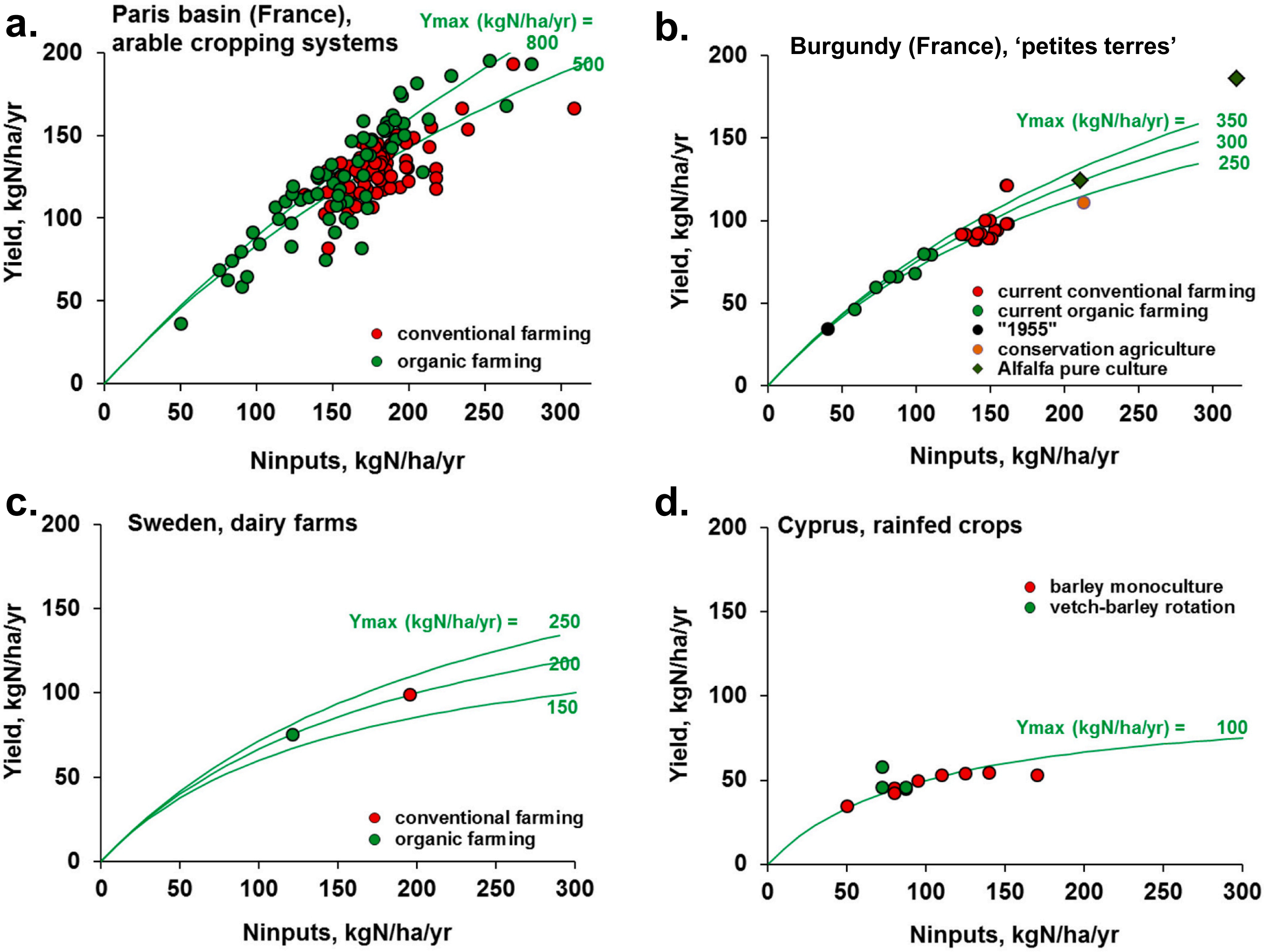


Fig. 3. Yield-Fertilization relationships for full rotations in different cropping systems under organic or conventional farming. a. Current organic and conventional cropping systems in Central Paris Basin (France); b. Historical and current cropping systems in "Petites Terres" of the Burgundy Plateau (North East of France), including short and long crop rotations in organic, conventional and conservation agriculture. c. Organic and conventional dairy farms in Sweden with leys and cereals in rotation; d. Rainfed barley in monoculture or in rotation with legume crops in Cyprus. Details and sources of data are provided in SM2.

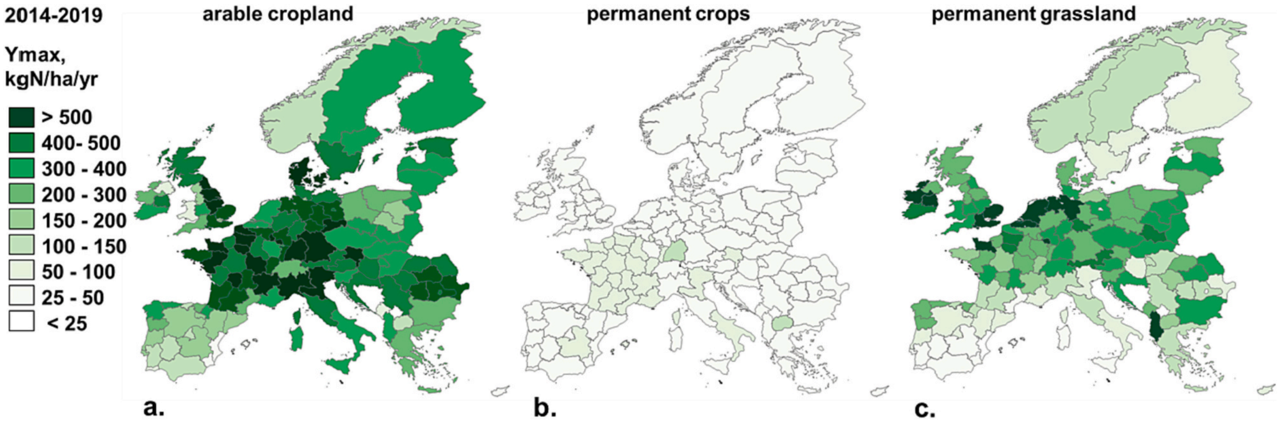


Fig. 4. Regional distribution of Ymax in arable cropland (a), permanent crops (b) and permanent grasslands (c) in Europe, as calibrated from the results of the GRAFS analysis at regional resolution over the period 2014–2019.

yield (Yleg), using the relationship established by Anglade et al. (2015a) and Lassaletta et al. (2014b),

$$\mathrm{Nfix} = 1/\mathrm{NHI}^{*}\mathrm{Ndfa}^{*}\mathrm{BGN}^{*}\mathrm{Yleg} = \alpha\ \mathrm{Yleg}, \tag{2}$$

where NHI is the N Harvest Index (i.e., the harvested fraction of the above-ground legume N production), for which values of 0.75 and 0.8 are assumed for grain legumes and forage legumes respectively; Ndfa is the fraction of total legume plant N derived from atmospheric symbiotic fixation, for which values of 0.71 and 0.82 are assumed for grain legumes and forage legumes, respectively; and BGN is a factor related to the belowground part of the crop N. BGN can be represented as (1 + R/S), where R/S is the ratio of root to shoot net N primary production. Based on the meta-analysis of Anglade et al. (2015a), we used values of R/S of 0.39 and 0.67 for grain and forage legumes respectively. It follows that the value of α, relating N fixation to N yield for grain and fodder legumes was assumed 1.4 and 1.7 for grain and forage legumes respectively.

The yield of legumes, whether grain or forage is considered independent of N fertilizer inputs to the rotation. It is documented in most regions from a literature review on organic cropping systems in Europe (Billen et al., 2021) as well as from Eurostat data at national level. The latter data are available for both general agriculture (apro files) and organic systems (org_croppro files, available until 2011): both data do not show a systematic difference, although the range of values is quite large. For consistency, we assume that legume yield in a given region is related to Ymax by a relationship such that the Y vs. F relationship holds in the hypothetical case of a legume monoculture in which symbiotic fixation would constitute the only source of fertilization, i.e.:

$$\mathrm{Yleg} = \mathrm{Ymax}^{*}\mathrm{Nfix}/(\mathrm{Nfix} + \mathrm{Ymax}) \tag{3}$$

Combining Eq. (3) with Eq. (2), it follows that.

$$\mathrm{Yleg} = (\alpha - 1)/\alpha^{*}\mathrm{Ymax} \tag{4}$$

The comparison of this theoretical relationship with the yield data available in the different European regions shows a good agreement (see SM 3). We used this relationship to fill some missing values of Yleg.

The case of permanent grassland deserves some specific comments. Establishing a yield-fertilization relationship for grassland as for cropping systems (see Fig. 4c) requires that total fertilizing inputs and total harvest (through mowing and grazing) are known. Assembling a comprehensive and coherent dataset of permanent grassland yield required a special effort, due to the lack of consistent data at NUTS2 level in European statistics. The estimation of symbiotic N fixation in grassland also required particular attention, as the application of the relationship (2) above is less tightly constrained than for arable crops, as many of the parameters involved vary with the rate of N inputs other than biological fixation (nBNFI). From an extensive literature survey, reported in detail in SM1, we derived the following empirical relationship to assess symbiotic fixation in permanent grassland:

$$\mathrm{Nfix}\ (\mathrm{kgN/ha/yr}) = \mathrm{Ygrassland}^{*}0.75^{*}exp(-3^{*}\mathrm{nBNF}/280) \tag{5}$$

3.2. The livestock system

Just as the GRAFS modelling of crop production considers the yield response to fertilization at the scale of the full crop rotation cycle rather than individual crops, so livestock production is estimated on the basis of feed resources ingested, without considering the detailed herd composition of each livestock species. Also, potential effects of efficiency gains in livestock production are not explicitly considered and their effects no explored in this paper. The GRAFS approach distinguishes two livestock classes, ruminants (cattle, sheep, and goats) and monogastrics (pigs and poultry). Livestock Units (LU) are defined as the number of animals excreting 85 kgN/yr (Le Noë et al., 2017, 2018). This arbitrary definition based on excretion differs from the LSU of Eurostat based on feed requirements (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Livestock_unit_(LSU)).

In the descriptive GRAFS approach, livestock populations and live weight per animal species were obtained from Eurostat and the total amount of N excreted was calculated from livestock populations by animal categories, using country-specific excretion coefficients (Velthof, 2014; https://ec.europa.eu/eurostat/web/agriculture/agri-environmental-indicators/projects). Production of meat (carcass weight) and milk was also obtained from Eurostat. Egg production figures were obtained at national level from FAOstat and regionalized according to poultry numbers. To estimate N flows in edible and non-edible carcass parts, coefficients for slaughter and cutting compiled by Le Noë et al. (2017) were used. Livestock ingestion was then calculated as the sum of excretion and production of edible and non-edible products. Details are provided in SM1.

In contrast, in the predictive GRAFS approach the calculations of livestock fluxes, carried out separately for ruminants and monogastrics, are based on the following mass-balance relationships:

$$\mathrm{Excretion} = 85\ \mathrm{kgN/LU/yr} \tag{6}$$

$$\mathrm{Ingestion} = \mathrm{Edible\ Prod} + \mathrm{Non\ \ edible\ Prod} + \mathrm{Excretion} \tag{7}$$

$$\mathrm{Edible\ Prod} = \mathrm{conveff}^{*}\mathrm{Ingestion} \tag{8}$$

$$\mathrm{Non\ \ edible\ Prod} = \mathrm{nedr}^{*}\mathrm{Edible\ Prod} \tag{9}$$

hence

$$\mathrm{Edible\ Prod} = \mathrm{conveff}^{*}(\mathrm{Edible\ Prod} + \mathrm{Non\ \ edible\ Prod} + \mathrm{Excretion}) \tag{10}$$

and

$$\mathrm{Edible\ Prod} = [\mathrm{conveff}/(1 - \mathrm{conveff} - \mathrm{conveff}^{*}\mathrm{nedr})]^{*}\mathrm{Excretion} \tag{11}$$

These relationships rely on two parameters: (i) the conversion efficiency (conveff), defined as the amount of N in edible products (Edible Prod, i.e. meat, milk, eggs) obtained from the ingestion of one unit of feed N; (ii) the non-edible to edible ratio (nedr) related to the whole animal (with skin, bones and blood).

Both parameters can be estimated for the current situation in each region from the descriptive data collected, separately for ruminants and monogastrics. They reflect the variability of regional livestock systems in terms of animal species, milk or meat orientation of the ruminant production, and intensity of animal husbandry practices.

For *ruminants*, the conversion efficiency, which is much higher for dairy than for suckler cows, shows an empirical relationship with time spent outdoors (frtout) (see SM1), so that the latter parameter can also be considered as an indicator of production intensity.

$$\mathrm{conveff}_{\mathrm{rum}} = 0.05 + 0.2\ exp(-\mathrm{frtout}/0.4) \tag{12}$$

The non-edible to edible ratio for ruminant production is strongly related to the share of milk in the production, hence also to the conversion efficiency. The following empirical relationship can be used:

$$\mathrm{nedr}_{\mathrm{rum}} = 0.1 + 1.5\ exp(-\mathrm{conveff}_{\mathrm{rum}}/0.05) \tag{13}$$

For *monogastrics*, the conversion efficiency of the entire herd varies from 0.15 to 0.31 with a median at 0.25. The nonedible to edible ratio is close to 0.8 everywhere.

For the sake of scenario design, the above relationships are used to calculate the sustainable livestock populations according to the feed resources available. The nature of feed resources by ruminants and monogastrics is first decided. Ruminants can be fed with grass (including forage legumes), fodder crops (including oilseed meal), grain legumes, cereals, and imported feed. The degree of production intensity is set as a lever in the scenario design. The same procedure is applied for monogastrics, except that they cannot be sustained on grass and green fodder. As the resources available depend to a certain extent on livestock density itself because of the effect of manure on crop and grassland yield, a calculation routine is used to adjust livestock populations in each region: starting from a negligible number, both ruminant and monogastric livestock populations are gradually increased up to the limit in terms of feed resources decided in the storylines of the scenario.

3.3. Environmental losses to the atmosphere and the hydrosphere

The GRAFS approach also makes it possible to assess the agricultural N emissions in multiple forms to the atmosphere and the hydrosphere, initiating the N cascade at the origin of several environmental concerns (Galloway et al., 2003). The methodology for assessing these reactive N losses to the atmosphere and the hydrosphere was discussed in detail by Garnier et al. (2023) for France and the Iberian Peninsula. A summary of these methods and their results for all regions of Europe is provided in SM1. Ammonia volatilization occurs during manure storage and management as well as manure and synthetic fertilizer application; its distribution mostly follows that of livestock density (See Fig SM1.18). Nitrous oxide emissions occur both from manure storage and as the result of fertilizer and manure inputs to crops and grasses; it also strongly depends on soil water content (Cayuela et al., 2017), thus showing a distinct South-North gradient (See Fig SM1.19). Nitrate leaching is the main fate of N surplus of arable land, i.e., the difference between soil N inputs and export through harvest (see Fig. SM1.24).

4. Scenario construction

Starting from the description of a reference state which is used to calibrate a number of region-specific parameters (see Section 3), we first validated the scenario calculation procedure (scenario S0) and then developed three major scenario storylines (some of which including variations) differing by the constraints related to land use, agricultural practices in the broadest sense, human population, and human diet. The GRAFS model calculates all N flows across the agri-food system resulting from these new constraints, using the relationships established in the preceding section and calibrated on the reference GRAFS description. Except for feed imports to each GU, which are set as exogenous model constraints, net commercial exchange of agricultural products between regions is determined endogenously by the model, calculated by the balance between production and consumption.

4.1. Validation of the procedure for scenario calculation: scenario S0

To validate the calculation procedure which is used below for the three scenarios and their variants, a control scenario (henceforth scenario S0) was constructed, which is almost identical to the 2014–2019 reference situation, except that some variables are calculated endogenously instead of being provided from statistical data, to ensure that all scenarios are consistent and directly comparable. The differences between scenario S0 and the reference data are that (i) crop production is calculated from total fertilization using the Y vs. F relationship, with calibrated Ymax parameters for each cropping system and GU; (ii) livestock populations are calculated using the routine described above which adjusts ruminant and monogastric populations to their respective available feed resources in each GU; and (iii) livestock production and excretion are calculated with the calibrated conversion efficiencies in each GU. The S0 scenario can then be compared with the original description. This comparison is a limited sort of model validation, testing how well the scenario prediction model is able to reproduce the reference (2014–2019) situation.

Fig. 5 thus compares the individual data obtained by the GRAFS accounting method and the GRAFS modelling method in each GU. At the aggregated European level, the agreement is within 10 % for the variables related to crop production, while permanent grassland production is 18 % higher in S0. Logically, livestock populations calculated from the available feed resources (including grass) also overestimate the officially reported values by about 23 %. It goes together with an overestimation of the same order of the calculated production of animal products, and their net exports. This indicates that grassland production remains the most uncertain issue in quantitative scenario design.

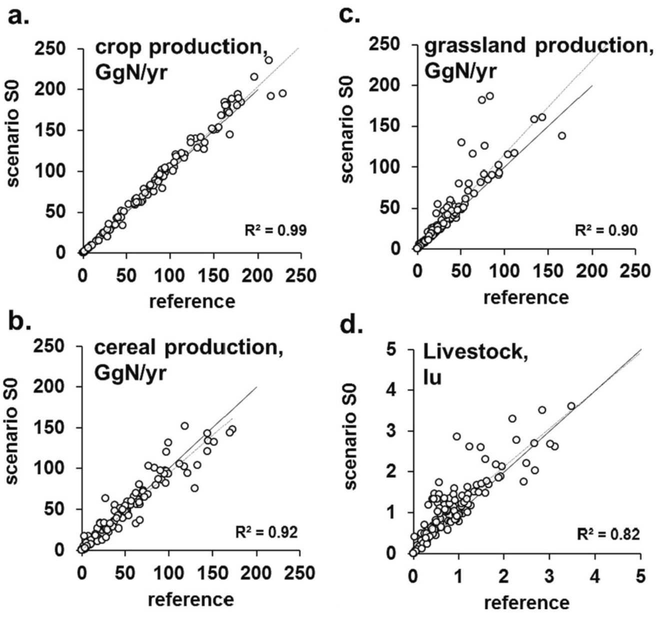


Fig. 5. Comparison of some major variables provided by the GRAFS accounting method for the Reference 2014–2019 situation of the European agri-food system at regional scale with the results of the scenario S0 established by the GRAFS Model for the same situation. (a.) Total cropland production; (b.) Cereal production; (c.) Permanent grassland production; (d.) Livestock units (1 LU = 85 kg N excretion/year). In the former approach, the variables in each region are directly derived from available statistical agricultural data, while in the latter approach they are calculated from total fertilization or available feed resources using the calibrated relationships discussed in Section 2.

In the following discussion, the calculated S0 scenario will serve, together with the reference description, as the basis for comparing the scenarios with the current situation.

4.2. Scenario storylines

Three major scenario storylines, plus their variants, were established as outlined below: Business as Usual (BAU), Agro-Ecological (AE) and Farm to Fork (F2F). The scenarios differ mainly by three aspects: (i) the diet of the population, specifically the fraction of animal-based proteins, (ii) the type of cropping systems, from conventional to agro-ecological, (iii) the type of livestock farming and its connection to cropping systems (Table 1).

For all scenarios, land use was unchanged, i.e., the surface area of arable land, permanent crops, and permanent grassland was kept constant in each region in all scenarios (except for a limited 10 % cropland set aside in the Farm to Fork scenario).

All scenarios also consider the same prospect of population in each region for 2050, as reported by Eurostat (https://ec.europa.eu/eurostat/databrowser/view/proj_23np/default/table?lang=en, central estimate) This corresponds to a total for Europe of 538 million inhabitants, very close to the current population (534 million), and 10 % lower than the FAO prospect for population in 2050 (medium hypothesis) used in our previous study (605 million) (Billen et al., 2021). The difference is not surprising because of uncertainties in estimating birth rate and net immigration. These official prospects only extrapolate current trends of population concentration and increase in large urban centers, particularly in the UK, western and southern France, Scandinavia, Austria, and southern Germany, contrasting with demographic decline in other regions. Although the spatial distribution of future population is definitely

Table 1
Summary of the storylines of the agri-food scenario storylines and their variants considered in this study.

Scenario storyline	Business as usual			Agroecology		Farm to fork
Scenario variant name	BAU	BAU −20%ferti	BAU low diet	AE	AE Current diet	F2F
Population	Projected 2050 population and spatial distribution					
Human diet	Current diet in each GU		Lower protein, lower animal share diet:		Current diet in each GU	
total apparent protein consumption (incl food waste)	mean 6.2 kgN/cap/yr		5 kgN/cap/yr		mean 6.2 kgN/cap/yr	
Animal share (incl fish), %	mean 58 % animal prot.		30 % animal proteins		mean 58 % animal proteins	
Agricultural areas	Current area of cropland, permanent crop and permanent grassland					−10 % for ecological infrastructures
Agricultural practices	Current	Current - 20 % synthetic fertilizers	Current	Agro-ecological		Combination of BAU-20%ferti and AE current diet up to 25 % organic farming
Livestock feed resources	Current local resources, plus current feed import			AE local resources, no feed import		

the result of political choices, we decided not to modify this aspect of the scenario construction at the moment, for the sake of comparability, and to consider the same population distribution in all the prospective scenarios. In further work, the sensitivity of alternative population distributions could be explored as well.

The **BAU scenario** is intended to provide a picture of the European agri-food system in 2050 in the absence of significant change in its structure and operating logic, however with the predicted changes in population and associated changes in food demand. Human diet is kept constant at the current per-capita values in each country. The rate of synthetic fertilizer application remains identical, and the import of feed from outside each GU is the same as in the current situation.

We quantified two variants of the BAU scenario to explicitly test the effect of isolated changes in production and consumption respectively: (i) In "BAU -20%ferti" we quantified the effect of a reduction by 20 % of synthetic fertilizer application to all cropland without any structural changes of the agricultural sector. (ii) In "BAU low diet" we assess the effect of a change in human diet, consisting of the generalization of a healthy diet based on WHO and EAT-Lancet (Willett et al., 2019) recommendations. Specifically, this entails a reduction of the current total apparent protein consumption including food waste (5 kgN/cap/y), of which 30 % derived from animal products.

The **AE scenario** (previously called ARD, for Autonomy, Reconnection, Demitarian diet in its application to France at a subnational scale, Billen et al., 2018, 2019) involves deeper structural modifications of the agri-food system. The scenario assumptions are:

(1) A human diet with less total apparent protein ingestion (5 kgN.cap/yr instead of the current average 6.2 kgN/cap/yr), and less animal-based products (30 % instead of the current average of 58 % animal in this total protein consumption) is universally adopted. This implies a 20 % reduction in avoidable food wastes.

(2) All agriculture adopts agro-ecological practices excluding the use of synthetic fertilizers, but using rotation schemes currently in use for organic agricultural systems in the different regions of Europe, with legumes providing most of the N input.

(3) Livestock are reconnected to cropping and grazing systems, with no import of feed, and efficient recycling of manure to cropping systems. Livestock density is adjusted to available local feed resources in each region. For ruminants, these consist of permanent grassland, and forage legumes and other forage crops on arable land. For monogastrics, feed resources consist of 25 % of the cereals produced in surplus of the requirements of the local human consumption, 80 % of the surplus of legume grains, 100 % of the surplus of starchy roots, cakes of oilseeds and residues of the oil and sugar industry (the N containing part of the production), as well as half the human food waste produced. No import of feed from outside the GU is allowed in the scenario, implying the necessity of reconnecting crop and livestock farming.

(4) The scenario also assumes that 25 % of the N content of human excreta in each GU is recycled locally to agriculture.

(5) Trade exchanges of food between regions can freely occur and help to compensate for inequalities in population distribution and regional productive potentials, but trade is not an objective of production, as this scenario follows a paradigm of food de-commodification (Jackson et al., 2021).

A more detailed quantitative description and justification of the constraints of the AE scenario are provided in SM3.

In order to explore the effect of the composition of human diets in shaping the performances of agri-food systems, we established a variant of the AE scenario with the population predicted for 2050 but without change in human diet, i.e., with the same per capita diet as in the current reference. We called this scenario "AE current diet".

The **F2F scenario** is intended to assess the effect of the several measures prescribed in the Farm to Fork and Biodiversity Strategies of the European Commission for future European agriculture. The measures considered here are the following:

(1) Although the importance of dietary choices is mentioned by the Farm to Fork Strategy, no change in human diet is prescribed. Our F2F scenario therefore assumes the same diet in each region as in the current situation and the BAU scenario.

(2) The Farm to Fork Strategy has the objective to halve nutrient losses to the environment and it is stated that this is expected to entail a reduction of the use of synthetic fertilizer by at least 20 %. Our F2F scenario assumes, in addition to an increased organic agriculture area, without any synthetic fertilizers, that the remaining conventional agriculture has a 20 % reduction of synthetic N input, as in the BAU -20% ferti scenario. The net result is that European agriculture uses ca. 43 % less synthetic N inputs compared to the reference situation.

(3) The share of agricultural area under organic farming management has to reach at least 25 %.

(4) At least 10 % of agricultural area has to be under high-diversity landscape features, e.g., hedgerows or set-aside areas.

The previous scenarios have been established in such a way that the F2F scenario can be constructed as a linear combination of the results of the AE current diet and BAU -20%ferti scenarios. In each GU, the current agricultural area is reallocated as follows: 10 % of all agricultural surfaces were removed from production and considered as forest. The remaining was allocated to either agro-ecological management (AE current diet) or to conventional management with 20 % reduction of fertilizer (BAU -20%ferti). Given that the 2014–2019 reference situation already involves a variable share of organically managed areas, and that the effect of this management is reflected in the current description of the reference and BAU -20%ferti agri-food systems, we considered that

F2F measures concerning organic farming imply to allocate to each GU a mix of AE current diet (100 % organic) and BAU -20%ferti (with the current share of organic farming in each GU) such that the mix has 25 % organic areas. We calculated this GU-dependent mix of AE current diet and BAU -20%ferti using subnational statistics on 2014–2019 agricultural area shares from Eurostat (SM3). In the few GUs where more than 25 % of the agricultural area is already under organic management (as in Sweden and Austria), all agricultural surfaces were allocated to the BAU -20%ferti scenario.

4.3. Scenario results

Because the projected 2050 population is not very different from the current one, and no change is assumed regarding crop and livestock farming in the **BAU scenario**, no substantial differences appear in any modelled variable compared to the current reference, or to the S0 scenario (Table 2).

Reducing synthetic fertilizer application by 20 % without structural change in the agriculture (**BAU -20%fert scenario**) results in a reduction of cropland production by 6 % and grassland production by 2 %. Without change in the domestic demand, this affects the capacity to export vegetal proteins (22 % reduction) and animal proteins (17 % reduction). In terms of pollution, the total soil N surplus (an indicator of environmental losses defined as the difference between total N soil input (after deducting NH_3 volatilization at manure and fertilizer application) and removal through harvest and grazing) is reduced by 20 %, and the median nitrate leaching concentration from arable land is reduced from 12–16 mgN/L in the BAU to 10–15 mgN/L in the BAU -20%ferti scenario (see SM3 for details).

Shifting the human diet to a lower total protein consumption with less animal-based products partly compensated by more plant-based food (**BAU low diet**) has very limited effect on domestic agricultural production, hence on environmental imprint, but decreases the capacity to export vegetal products by 10 % while increasing the exports of animal products substantially (by 114 %). In this scenario, more than 2/3 of the animal production (2.5 TgN/yr) would be for export. Note, however, that the feed resources used for livestock raised for export could well be used for other purposes, such as bioenergy or biomaterials.

Application of agro-ecological principles to the agri-food system (**AE scenario**) results in much more changes (Fig. 6a). The first one is a considerable extensification of crop production, marked for instance by a halving of European cereal production compared to the current reference (Table 2). It must be kept in mind however that the use of cereals for livestock feeding is much decreased as well, as cereals are by priority reserved for human consumption. Average livestock density is 0.40 LU/ha of agricultural land in the AE scenario, compared to 0.60 LU/ha in the reference situation, and is much more evenly distributed (see SM3 for details). In the agro-ecological scenario, Europe as a whole is not only self-sufficient in cereals (as well as in grain legumes), but can even sustain a small export of 0.61 TgN/yr (25 % of the BAU value). Although no import of feed is allowed in this scenario, Europe is self-sufficient in terms of animal products and can even export meat and milk at about half the current rate (0.45 TgN/yr compared to 0.56 and 0.74 TgN/yr in the 2014–2019 reference and S0 respectively). Indeed, in the hypothesis of a largely vegetal-based diet, the feed resources generated in the agro-ecological scenario allow to sustain a larger livestock than required for human nutrition. Substantial surpluses of animal products are therefore available for export. Here, again, other uses are possible for the corresponding feed resources.

Although agro-ecology in Europe as a whole would still export agricultural products outside its borders, not all regions would be self-sufficient. This is particularly the case for some regions around the Mediterranean Sea, Norway, and the highly populated urban regions. Nevertheless, more regions are self-sufficient in AE than in the current situation. Fig. 6b shows the distribution of agri-food system types among regions. As expected, all specialized livestock systems, and most of the

Table 2
Summary of the results of the scenarios for the main modelled variables, compared with the 2014–2019 reference situation established with the GRAFS accounting tool, and the control scenario S0. (BAU: business as usual, AE: agro-ecology, F2F: Farm to Fork). For the scenarios, items representing control variables imposed as assumption are written in italic; the rest are results from the calculation by the model. Full detailed data are available, for each of the 127 GUs, in the .xlsx file SM4.

Major indicators of the scenarios	Ref 2014–2019	S0 control	BAU	BAU −20%ferti	BAU low diet	AE	AE current diet	F2F
Population, M inhabitant	533	533	538	538	538	538	538	538
Human consumption, TgN/yr	3.2	3.2	3.3	3.3	2.7	2.7	3.3	3.3
Vegetal	1.4	1.450	1.4	1.4	1.9	1.9	1.4	1.4
Animal (excl. fish)	1.7	1.7	1.7	1.7	0.67	0.67	1.7	1.7
Livestock population, MLU	111	137	146	140	141	81	87	107
Farming practices and production								
Synthetic N fertilizers, TgN/yr	12.3	12.3	12.3	9.8	12.3	0	0	6.9
Symbiotic N fixation, TgN/yr	4.1	4.6	4.4	4.5	4.5	8.0	8.0	4.8
Crop production[a], TgN/yr	11.3	11.4	11.5	10.8	11.8	7.3	7.5	9.1
Grassland production, TgN/yr	4.7	5.6	5.6	5.5	5.6	5.1	5.1	4.7
Livestock edible production, TgN/y	2.2	2.4	2.5	2.4	2.5	1.1	1.2	1.9
Import (+)/Export(−), TgN/yr								
Vegetal food	−2.5	−2.2	−2.4	−1.9	−2.1	−0.61	−1.0	−1.4
Livestock feed	2.9	2.9	2.9	2.9	2.9	0	0	2.1
Animal products (food)	−0.56	−0.75	−0.84	−0.70	−1.8	−0.45	0.49	−0.23
Environmental losses								
Total N soil surplus, TgN/yr	10.7	11.8	12.4	10.4	11.7	4.8	5.0	8.5
kgN/ha/y	58	63	67	56	63	26	27	51
NH_3 volatilization, TgN/yr	3.1	4.0	3.5	2.5	2.8	1.6	1.7	2.3
N_2O emission, TgN/yr	0.35	0.39	0.38	0.36	0.39	0.17	0.17	0.28
Median NO_3^- conc[b], mgN/l	10–14	12–17	12–16	10–15	13–17	3–4.7	3.3–5.5	8.5–13
Total N losses, TgN/yr	14.1	14.9	14.4	12.8	14.3	5.5	5.5	10.1
System NUE, %	31	30	31	32	33	41	44	33

[a] Permanent grassland not included.

[b] From arable cropland.

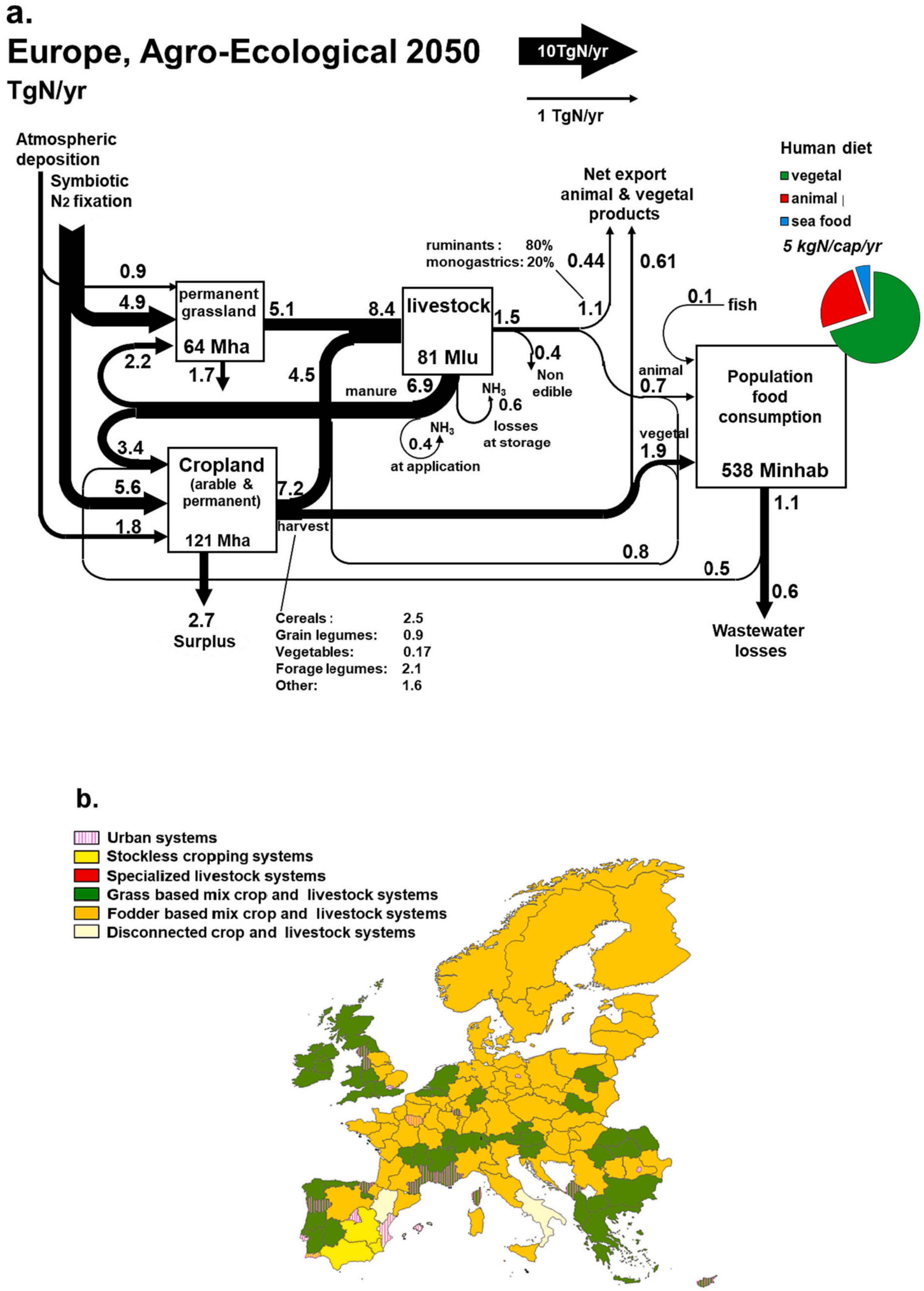


Fig. 6. a. GRAFS representation of N fluxes through the European agri-food system in 2050 in the Agro-Ecological scenario. b. corresponding distribution of the typological classes of regional agri-food systems.

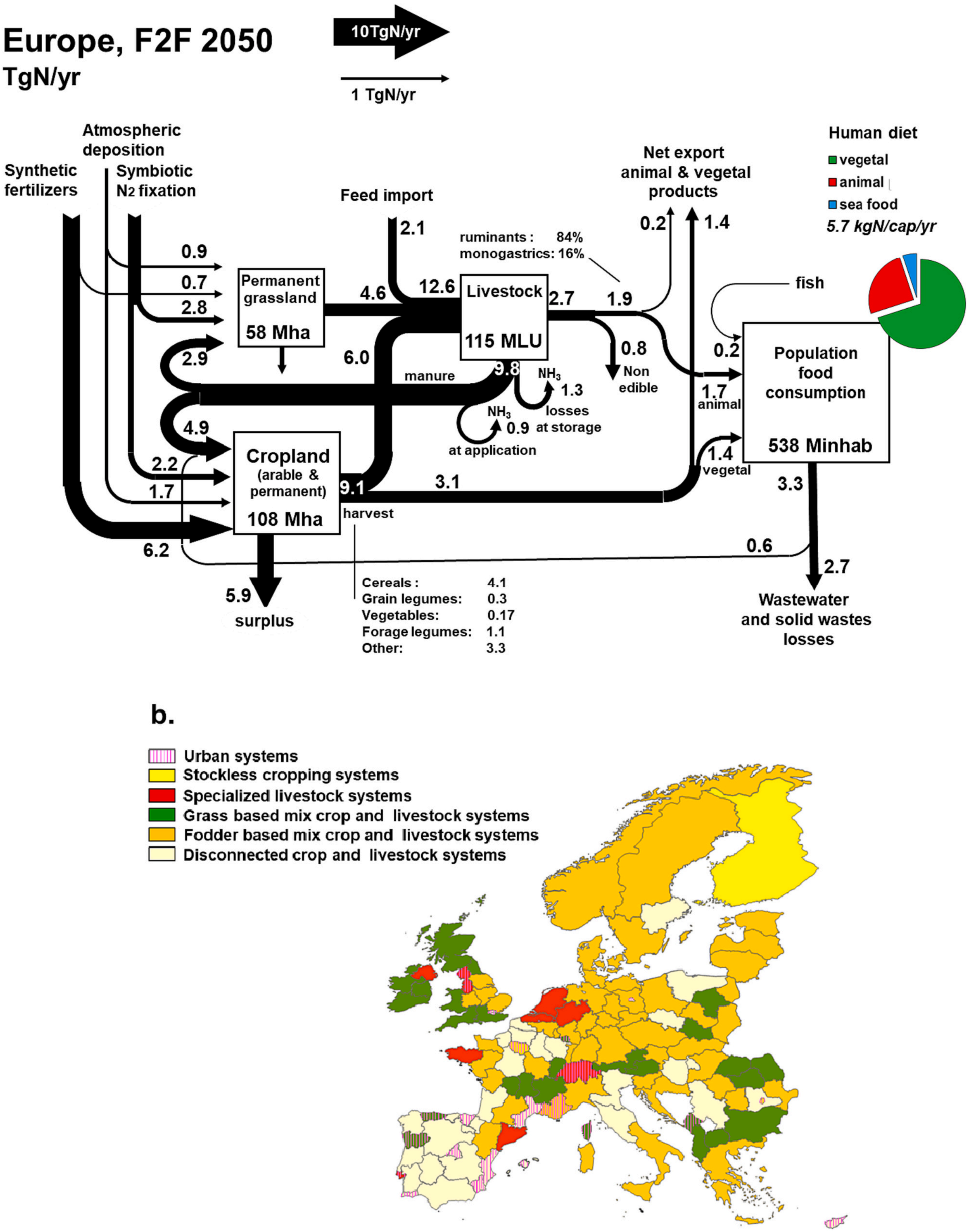


Fig. 7. a. GRAFS representation of N fluxes through the European agri-food system in 2050 in the F2F scenario. b. corresponding distribution of the typological classes of regional agri-food systems.

specialized stockless cropping systems in the current situation are replaced by mixed crop and livestock systems in the AE scenario.

Environmental pressure is much lower in the AE scenario than in the reference and BAU scenarios. For instance, the total surplus (total N inputs to soils minus total harvested and grazed production) amounts to 4.8 TgN/yr (60 % lower than in the BAU scenario). The median nitrate leaching concentration from arable land ranges between 3.0 and 4.7 mgN/L, much lower than the values in all variants of the BAU scenario (Table 2). NH_3 emissions are reduced to 1.6 TgN/yr compared to 3.5 TgN/yr in the BAU scenario. Although on average, both figures are much lower than the critical regional boundary of 5–20 kgN/ha/yr proposed by de Vries et al. (2022) and Schulte-Uebbing et al. (2022) for terrestrial NH_3 emissions, the threshold of 20 kgN/ha/yr is exceeded in only 5 regions in the AE scenario, vs. in 57 regions in the BAU scenario.

As a whole, much less N resources are used in the AE scenario: these “resources” consist of “new” (as opposed to “recycled”) forms of fertilization, i.e. including synthetic fertilizers, symbiotic fixation, oxidized N atmospheric deposition and imported food and feed, but excluding manure inputs and reduced N deposition. In the AE scenario the resources used amount to 9.2 TgN/yr, vs 21 TgN/yr in the BAU scenario. With these resources, 2.7 TgN vs 3.3 TgN/yr of food is supplied to the population in the AE vs. BAU scenario, while 1.1 TgN/yr vs 3.3 TgN/yr of food and feed are exported for the two scenarios respectively. The total system N use efficiency (systNUE) is therefore of 41 % in the AE vs. only 31 % in the BAU scenario, and the total environmental losses are respectively 5.5 and 14 TgN/yr.

The **current diet** variant of the **AE scenario** allows to disentangle the effect of diet in the changes observed in the AE scenario with respect to reference and BAU. In this scenario the local agro-ecological feed production is not sufficient to sustain the livestock required to meet the increased demand for meat and milk and Europe would thus become a net importer of 0.49 TgN/yr of animal protein (about 1/3 of the human consumption, Table 2). The capacity to export vegetal products on the other hand would be increased from 0.61 TgN/yr in the AE scenario to 1.0 TgN/yr in the AE variant (Table 2). Exploring in more detail the effect of varying the proportion of animal proteins in the diet, hence the human demand for animal products, while maintaining the ban on feed imports, shows that the sustainable livestock density in each region does only vary in a rather limited degree. The most important effect is on the balance between production and human consumption of cereals and animal products, so that the capacity to export (or the need to import) food is highly and linearly dependent on the diet. Beyond a value of 45 % animal protein (excluding fish) in the human diet, an agro-ecological Europe would become a net importer of animal products (see SM3).

The **F2F scenario** is a kind of hybrid between the AE and BAU scenarios, borrowing elements from both of them. The result is a considerably modified agri-food system compared to the current situation, although the transformation is less pronounced than in the agro-ecological scenario (Fig. 7a). The de-intensification of the F2F scenario results in 43 % lower inputs of synthetic N and a 20 % drop in crop yields compared to BAU. The total livestock density amounts to 0.69 LU/ha agricultural area in the F2F scenario, 13 % lower than in the BAU scenario. With these productive characteristics, the F2F scenario would still be able to meet the food demand of the European population as well as to export vegetal food at the rate of 1.4 TgN/yr, compared to 2.4 TgN/yr in the BAU and 0.6 TgN/yr in the AE scenario (Table 2). Its capacity to export animal products would remain substantial (0.231 TgN/yr) although much reduced compared to the BAU (0.84 TgN/yr) and AE (0.45 TgN/yr) scenarios.

The distribution of the types of agri-food systems at the regional scale in the F2F scenario (Fig. 7b) shows a certain degree of reconnection of cropping and livestock systems compared to the current situation (Fig. 2b), as many specialized stockless cropping regions would convert into mixed crop-livestock systems. However, most regions of specialized livestock farming would remain as such in the F2F scenario.

In terms of environmental pressure, the performances of the F2F scenario are intermediate between BAU and the AE, with a total N soil surplus of agricultural land of 8.5 TgN/yr, and a median nitrate leaching concentration from arable land between 8.5 and 13 mgN/L. NH_3 volatilization amounts 2.3 TgN/yr, and the threshold of 20 kgN/ha/yr is exceeded in 26 regions. The total N resources used (15 TgN/yr) are lower by 30 % than in BAU, but the system NUE (33 %) is hardly higher than in the BAU and the total N losses (10 TgN/yr) are only reduced by one third (Table 2).

5. Discussion

Using the GRAFS modelling approach, we established a range of scenarios for possible futures of the agri-food system of Europe in 2050. Some of them only involve adjustment of farming practices without structural change in the system (e.g., a 20 % reduction of fertilizer use, scenario BAU-20%ferti). Others consist of profound changes in cropping systems (e.g., agriculture with organic crop rotations, scenario AE and AE current diet), in livestock production (e.g., crop and livestock farming reconnection excluding feed import, scenario AE and AE current diet), and/or in human diets (scenarios AE and BAU low diet). Whereas the AE and BAU scenarios highlight the extremes of two different orientations for the future of agri-food systems, a last scenario combines elements of both directions to simulate the measures considered by the European Farm to Fork Strategy (F2F scenario). The common assumption to all these scenarios is that of a status quo in the yield-fertilization response currently observed in each region, thus overlooking both possible negative effects of climate change on Ymax and possible improvements owing to technological or agronomical innovations, such as precision agriculture, variety selection, etc. Until now, models that attempt to account for the effect of climate change on global or regional agricultural production are very uncertain because of the difficulty in evaluating the antagonistic effects of temperature rise, change in precipitation, increase in atmospheric CO_2 content, and climatic extremes (Ruane et al., 2018; Basso et al., 2018; Toreti et al., 2020, Cui et al., 2023. Indeed, climate change has already impacted N use during the last decades, however this impact has been diverse in intensity and direction (Ren et al., 2023; Lassaletta et al., 2023). A recent article analyzing yield chronicles from 1961 to 2019 (Helman and Bonfil, 2022) suggests that in the most important wheat producing countries (France, Germany, Russia, China) the effect of the increase in CO_2 in the atmosphere over the last 6 decades has been more than offset by the negative effects of increased periods of heat and drought. Note however that if we assume that climate change is marked by a reduction in Ymax (which would be consistent in our scenario calculation approach), the effect of this reduction on crop production would be more important at higher than at lower fertilization rates. In other words, scenarios characterized by a lower level of fertilization intensity (such as AE) would be less impacted by climate change than more intensive scenarios (such as BAU). Indeed, by simply testing the effect of a 30 % drop of Ymax in all GUs (as a sensitivity test for climate change), an 8 % reduction on cropland production is observed in AE vs 13 % in BAU.

In all studied scenarios the European dietary needs would be met, albeit with different dietary composition and different levels of international trade. Table 2 and Fig. 8 summarize the performances of these scenarios, from the point of view of the productive capacity of the European agri-food system to meet the domestic requirements of its population and to export to the international market, as well as from the angle of environmental N losses.

For a few decades, Europe has been able to meet the food requirements of its population with a positive net balance of cereals, meat and milk (Billen et al., 2021). This is in part due to large imports of feed (Fig. 8a). These feed imports however, mainly from South-America, depend on massive agricultural expansion at the cost of deforestation (Kehoe et al., 2019; Pendrill et al., 2022; Roux et al., 2022), thus bearing a very high environmental imprint. In the BAU and BAU-20%ferti scenarios, this trade balance remains broadly unchanged. In contrast, the

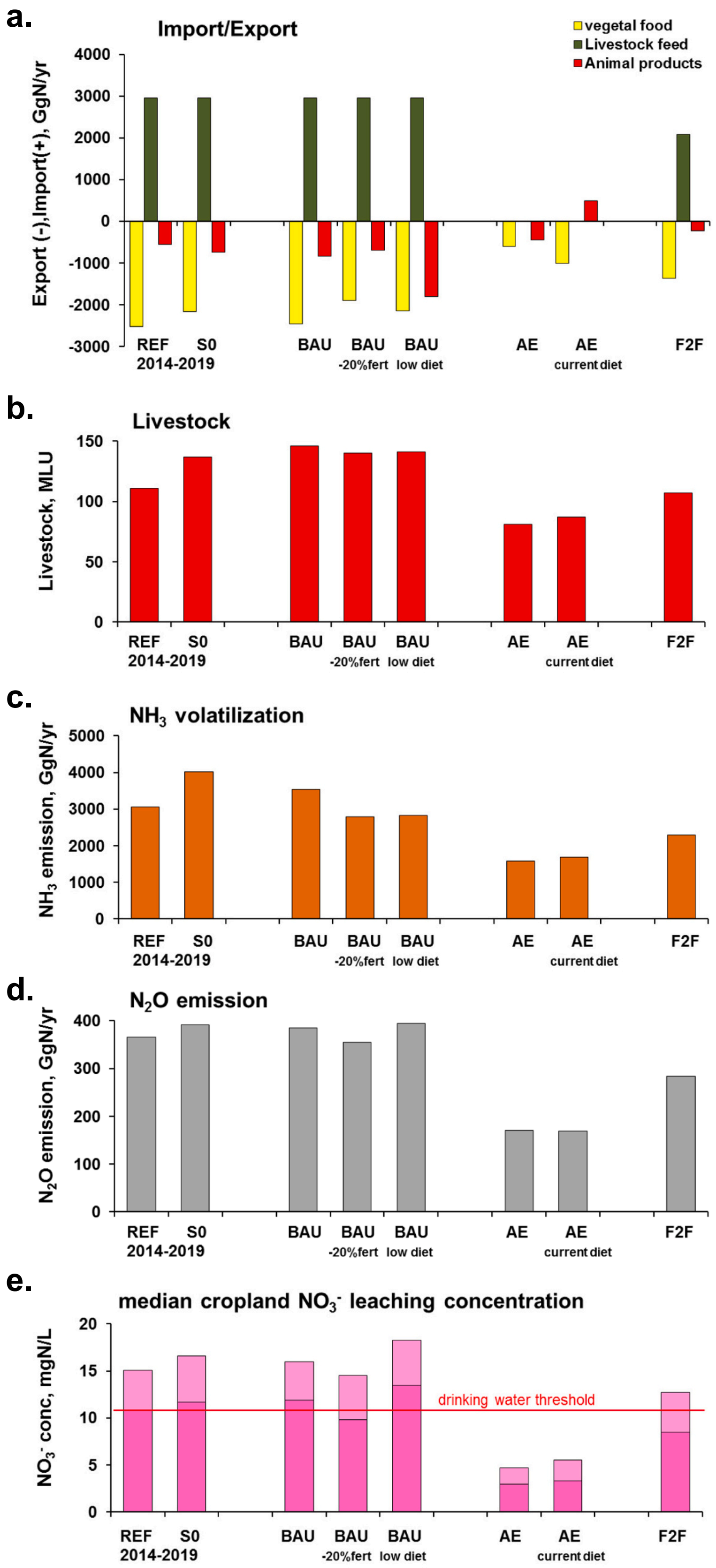


Fig. 8. Comparison of the performances of the different scenarios established for a. Import/Export balance of Europe for vegetal food, meat and milk and feed; b. Livestock populations; c. Agricultural ammonia volatilization rates; d. Nitrous oxide emission by agriculture; e. median nitrate leaching concentration below arable cropland.

generalization of agro-ecological practices (AE scenarios) would completely change the agri-food system since livestock feeding would be restricted to regional feed production and feed imports banished, resulting in a reduction of livestock populations by about 35–45 % compared to the current situation (Fig. 8b, Table 2). Europe would remain a net exporter of cereals (Fig. 8a), but would depend on imports of meat and milk in the absence of a major change in the human diet, i.e. without reducing animal proteins (AE current diet). With a change in diet (AE), otherwise recommended for public health and environmental reasons (Willett et al., 2019), Europe would become fully self-sufficient for food and feed, and would even be able to export non-negligible amounts of both vegetal and animal food. The F2F scenario does not operate the lever of human diet change while reducing synthetic N inputs by 43 %, only partially replaced by biological N fixation due to a limited increase of organic agriculture to 25 % of the agricultural area: as a result, Europe in the F2F scenario would halve its export of cereals and animal products and would have to continue to import feed in substantial amounts.

As shown by our scenarios, and supported by the theory (see SM1, § 2.2) decreasing the agricultural production intensity is by far the lever with the highest potential to reduce emissions of reactive N to the atmosphere and the hydrosphere. This message is aligned with alternative paradigms considering degrowth options not only based on technical efficiency improvements or also integrating the social cost of pollution in the account (van Grinsven et al., 2015; van Grinsven et al., 2022). The Agro-Ecological scenarios and its variant are the only ones among those considered here for which the median nitrate leaching concentration from arable cropland clearly drops below the drinking water standard of 11.3 mgN/L (Fig. 8e). These AE scenarios are also those in which nitrous oxide emissions would be reduced by more than a factor 2 with respect to the current rate (Fig. 8d). Regarding ammonia volatilization, an important effect is linked to lower livestock densities and to the assumed improvement in manure application practices, namely a shortening (to less than 12 h) of the delay between application and soil incorporation (see Fig. 8c.) This improvement has been considered in AE, AE current diet, BAU -20%ferti and BAU low diet, but not in BAU (nor in S0) (Fig. 8c). The critical NH_3 emission rate of 20 kgN/ha/yr assessed by Schulte-Uebbing et al. (2022) is only exceeded in 5 regions in the AE scenario, vs 57 and 26 in the BAU and F2F scenario respectively.

Our analysis confirms that the measures advocated by the EU Farm to Fork and Biodiversity Strategies might lead to a 20 % reduction of Europe crop production (Table 2). This would not endanger European food security, as exports of cereals and animal products would still be possible at levels 54 % and 41 % of current ones, while imports of feed could be reduced by 30 %. The reduction of cropping intensity in F2F would indeed enable reducing N losses to the atmosphere (25 % reduction of ammonia and nitrous oxide emissions) and the hydrosphere (23 % reduction of median nitrate leaching concentration). These reductions, although very substantial, however remain insufficient to achieve the Farm to Fork Strategy's objective of halving environmental N losses.

To reach the objective of halving N losses, more structural changes are necessary, combining more ambitious transitions both at the production level and at the consumption level. The agro-ecological scenario is one example of a possible transition combining these two levels. It involves generalization of crop rotation where legume crops are bringing most of the new N soil inputs and where livestock is fully reconnected with cropland, in combination with a transition in the current dietary patterns toward less animal products. This scenario would certainly lead to a strong reduction of European crop production (by 36 %), but would nevertheless be able to fulfill the dietary needs of the population, while still exporting some surplus. Overall the System Nitrogen Use Efficiency in this scenario would be much better (41 %) compared to that of the current system (31 %) or of the F2F scenario (33 %). Among the scenarios explored in this study, the agro-ecological ones are the only ones reaching the objective of *halving N waste,* and not regionally exceeding the just and safe Earth System Boundaries (de Vries et al., 2022; Schulte-Uebbing et al., 2022; Rockström et al., 2023).

Beyond their immediate relevance for the EU F2F strategy, our results inform scientific debates on regional-scale sustainability of agri-food systems. Moreover, the results can be used as a starting point for more detailed exploration of possible management policies at national and subnational scale, in line with the current EU Common Agricultural Policy (CAP) and EU F2F strategy, which are open to adaptation to territorial specificities and vulnerabilities.

Confirming that the fraction of livestock products in diets plays a major role in the overall environmental impact of agri-food systems (e.g., Theurl et al., 2020), our findings underscore the importance of the way in which livestock products are being produced (e.g., Kaufmann et al., 2022; Roux et al., 2022). In particular, the results of the AE and F2F scenarios highlight that livestock production based on regional biomass production generates a double (or triple) benefit of providing healthier diets while reducing local and remote environmental impacts. In addition, the fact that both the AE and F2F scenarios increase regional food self-sufficiency and decrease dependency on synthetic N inputs, compared to the current situation, also points to potential additional sustainability benefits of these scenarios in the sense of a higher human-environment connectedness at the regional scale (Dorninger et al., 2017) and potentially lower vulnerability to external shocks on global markets causing increased input costs or export restrictions (Pinsard et al., 2021), such as those derived from the Ukraine war (Alexander et al., 2023). The greater reliance on regionally-available land resources, and the appreciation of their limits, may contribute to leveraging deeper transformation, even beyond the material characteristics of the agri-food system (Ives et al., 2018).

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168160.

Credit authorship contribution statement

All authors contributed equally to the conception and realization of the study. GB wrote the first version of the ms and all other authors contributed by their comments, corrections and additions to the final version.

Declaration of competing interest

The authors declare no competing interest.

Data availability

The data and code are attached as a supplementary xls file.

Acknowledgements

This study was partly financed through two expert contracts between the authors and the Joint Research Center of the European Commission, under contract numbers CT-EX2020D401426-102 and CT-EX2020D401426-103 in the scope of the INMAP project. E. Aguilera is supported by a Juan de la Cierva research contract from the Spanish Ministry of Economy and Competitiveness (IJC2019-040699-I).

The opinions expressed are those of the authors and should not be considered as stating an official position of the European Commission.

References

Alexander, P., Arneth, A., Henry, R., Maire, J., Rabin, S., Rounsevell, M.D.A., 2023. High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment. Nat. Food 4, 84–95.

Anglade, J., Billen, G., Garnier, J., 2015a. Relationships for estimating N2 fixation in legumes: incidence for N balance of legume-based cropping systems in Europe. Ecosphere 6, 1–24. https://doi.org/10.1890/ES14-00353.1.

Anglade, J., Billen, G., Makridis, T., Garnier, J., Puech, T., Tittel, C., 2015b. Nitrogen soil surface balance of organic vs conventional cash crop farming in the Seine watershed. Agricult. Syst. 139, 82–92.

Bai, Z., Fan, X., Jin, X., Zhao, Z., Wu, Y., Oenema, O., Velthof, G., Hu, C., Ma, L., 2022. Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population. Nat. Food 3 (2), 152–160.

Basso, B., Dumont, B., Maestrin, L., Shcherbak, G.P., Robertson, J.P., Porter, P., Smith, E., Paustian, P.R., Grace, S., Asseng, S., Bassu, C., Biernath, K.J., Boote, D., Cammarano, G., De Sanctis, J.-L., Durand, F., Ewert, S., Gayler, D.W., Hyndman, J., Kent, P., Martre, C., Nendel, E., Priesack, D., Ripoche, A.C., Ruane, J., Sharp, P.J., Thorburn, J.L., Hatfield, J.W., Jones, J.W., Rosenzweig, C., 2018. Soil organic carbon and nitrogen feedbacks on crop yields under climate change. Agric. Environ. Lett. 3, 180026 https://doi.org/10.2134/ael2018.05.0026.

Beckman, J., Ivanic, M., Jelliffe, J.L., Baquedano, F.G., Scott, S.G., 2020. Economic and Food Security Impacts of Agricultural Input Reduction Under the European Union Green Deal's Farm to Fork and Biodiversity Strategies. USDA Economic Brief n°30. https://www.ers.usda.gov/amber-waves/2021/march/FarmtoFork-initiative-to-restrict-european-union-agricultural-inputs-may-increase-food-prices-further-global-food-insecurity/.

Benoit, M., Garnier, J., Beaudoin, N., Billen, G., 2016. A network of organic and conventional crop farms in the Seine Basin (France) for evaluating environmental performance: yield and nitrate leaching. Agric. Syst. 148, 105–113. https://doi.org/10.1016/j.agsy.2016.07.005.

Billen, G., Lasseletta, L., Garnier, J., 2014. A biogeochemical view of the global agro-food system: nitrogen flows associated with protein production, consumption and trade. Glob. Food Sec. 3, 209–219. https://doi.org/10.1016/j.gfs.2014.08.003i.

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

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

Billen, G., Lassaletta, L., Garnier, J., Le Noë, J., Aguilera, E., Sanz-Cobena, A., 2019. Opening to distant markets or local reconnection of agro-food systems? Environmental consequences at regional and global scales. Chapter 25. In: Lemaire, G., Carvalho, P., Kronberg, S., Recous, S. (Eds.), Agroecosystem Diversity. Reconciling Contemporary Agriculture and Environment Quality. Elsevier.

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

Blum, W.E.H., 2013. Soil and land resources for agricultural production: General trends and future scenarios. A worldwide perspective. Int. Soil Water Conserv. Res. 1, 1–14.

Bodirsky, B.L., Chen, D.M.-C., Weindl, I., Soergel, B., Beier, F., Molina Bacca, E.J., Gaupp, F., Popp, A., Lotze-Campen, H., 2022. Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. Nat. Food 3, 341–348. https://doi.org/10.1038/s43016-022-00500-3.

Bremmer, J., Gonzalez-Martinez, A., Jongeneel, R., Huiting, H., Stokkers, R., Ruijs, M., 2021. Impact assessment of EC 2030 Green Deal Targets for sustainable crop production. In: Report / Wageningen Economic Research; No. 2021-150. Wageningen Economic Research. https://doi.org/10.18174/558517.

Cayuela, M.L.M.L., Aguilera, E., Sanz-Cobena, A., Adams, D.C.D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L.W.L., Alfaro, M.A.M.A., Pappa, V.A.V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A., Lassaletta, L., 2017. Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data. Agric. Ecosyst. Environ. 238, 25–35.

Cerier, S.E., 2023. Farm to Fork : how the Ukraine war exposed Europe's Form to Fork green plan as unsustainable. https://www.europeanscientist.com/fr/opinion/lukraine-un-grain-de-ble-dans-la-machine-f2f/.

Chatzimpiros, P., Harchaoui, S., 2023. Sevenfold variation in global feeding capacity depends on diets, land use and nitrogen management. Nat. Food. https://doi.org/10.1038/s43016-023-00741-w.

Cui, J., Zhang, X., Reis, S., Wang, C., Wang, S., He, P., Chen, H., van Grinsven, H.J.M., Gu, B., 2023. Nitrogen cycles in global croplands altered by elevated CO2. Nat. Sustain. 1–11.

De Ponti, T., Rijk, B., van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. Agric. Syst. 108, 1–9. https://doi.org/10.1016/j.agsy.2011.12.004.

de Vries, W., Schulte-Uebbing, L., Kros, H., Voogd, J.C.H., Louwagie, G., 2021. Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. Sci. Total Environ. 786, 147283.

de Vries, W., Schulte-Uebbing, L., Kros, J., JCH, Voogd, 2022. Assessment of Spatially Explicit Actual, Required and Critical Nitrogen Inputs in EU-27 Agriculture. Wageningen Environmental Research, Wageningen. Report 3199. 132 pp. https://library.wur.nl/WebQuery/wurpubs/fulltext/578175.

Dorninger, C., Abson, D.J., Fischer, J., von Wehrden, H., 2017. Assessing sustainable biophysical human–nature connectedness at regional scales. Environ. Res. Lett. 12, 055001 https://doi.org/10.1088/1748-9326/aa68a5.

Einarsson, R., Billen, G., Aguilera, E., Garnier, J., Gingrich, S., Grizzetti, B., Lassaletta, L., Le Noë, J., Sanz-Cobena, A., 2022. The relative productivity of organic agriculture must be considered in the full food-system context. A comment on Connor (2022). Agric. Syst. 199, 103413. https://doi.org/10.1016/j.agsy.2022.103413.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat. Commun. 7, 11382.

European Commission, 2020a. COM (2020) 380 final. https://eur-lex.europa.eu/resource.html?uri=cellar:a3c806a6-9ab3-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF.

European Commission, 2020b. COM (2020) 381 final. https://eur-lex.europa.eu/resource.html?uri=cellar:ea0f9f73-9ab2-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF.

FAO, 2009. High level expert Forum. In: How to feed the world in 2050. Rome, Italy. https://www.fao.org/wsfs/docs/Issues_papers/.

Fischer, J., Brosi, B., Daily, G.C., Ehrlich, P.R., Goldman, R., Goldstein, J., Lindernmayer, D.B., Manning, A.D., Mooney, H.A., Pejchar, L., 2008. Should agricultural policies encourage land sparing or wildlifefriendly farming? Front. Ecol. Environ. 6, 382–387.

Folberth, C., Khabarov, N., Balkovic, J., Skalsky, R., Visconti, P., Ciais, P., Janssens, I.A., Penuelas, J., Obersteiner, M., 2020. The global cropland sparing potential of high-yield farming. Nat. Sustain. 3, 281–289.

Galloway, J.N., 1998. The global nitrogen cycle: changes and consequences. Environ. Poll. 102, 15–24.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J., 2003. The NITROGEN cascade. BioScience 53, 341–356.

Garnier, J., Anglade, J., Benoit, M., Billen, G., Puech, T., Ramarson, A., Passy, P., Silvestre, M., Lassaletta, L., Trommenschlager, J.-M., Schott, C., Tallec, G., 2016. Reconnecting crop and cattle farming to reduce nitrogen losses in river water of an intensive agricultural catchment (Seine basin, France). Environ. Sci. Policy 63, 76–90. https://doi.org/10.1016/j.envsci.2016.04.019.

Garnier, J., Billen, Aguilera E., Lassaletta, L., Einarsson, R., Serra, J., do Rosário Cameira, M., Marques-dos-Santos, C., Sanz-Cobena, A., 2023. How much can changes in the agro-food system reduce agricultural nitrogen losses to the environment? Example of a temperate-Mediterranean gradient. J. Environ. Manag. 337 https://doi.org/10.1016/j.jenvman.2023.117732.

Green, R.E., Cornell, S.J., Scharelmann, J.P.W., Balmford, A., 2005. Farming and the fate of wild nature. Science 307, 550–555.

Gustavsson, J., Cederberg, C., Sonesson, U., Manuelsson, A., 2013. The Methodology of the FAO Study "Global Food Losses and Food Waste: Extent, Causes and Prevention". In: SIK report N°857. Lund, Sweden, 70 pp.

Helman, D., Bonfil, D.J., 2022. Six decades of warming and drought in the world's top wheat-producing countries offset the benefits of rising CO2 to yield. Nat. Sci. Rep. 12, 7921. https://doi.org/10.1038/s41598-022-11423-1.

Hénin, F., 2023. Souveraineté alimentaire et guerre en Ukraine : l'Union européenne doit produire plus pour exporter plus selon l'APCA. Wikiagri. https://wikiagri.fr/articles/souverainete-alimentaire-et-guerre-en-ukraine–lunion-europeenne-doit-produire-plus-pour-exporter-plus-selon-lapca-/22790.

Ives, C.D., Abson, D.J., von Wehrden, H., Dorninger, C., Klaniecki, K., Fischer, J., 2018. Reconnecting with nature for sustainability. Sustain. Sci. 13, 1389–1397. https://doi.org/10.1007/s11625-018-0542-9.

Jackson, P., Rivera Ferre, M.G., Candel, J., et al., 2021. Food as a commodity, human right or common good. Nat. Food 2, 132–134. https://doi.org/10.1038/s43016-021-00245-5.

Kanter, D.R., Chodos, O., Nordland, O., Rutigliano, M., Winiwarter, W., 2020. Gaps and opportunities in nitrogen pollution policies around the world. Nat. Sustain. 3 (11), 956–963.

Kaufmann, L., Mayer, A., Matej, S., Kalt, G., Lauk, C., Theurl, M.C., Erb, K.-H., 2022. Regional self-sufficiency: a multi-dimensional analysis relating agricultural production and consumption in the European Union. Sustain. Prod. Consum. 34, 12–25. https://doi.org/10.1016/j.spc.2022.08.014.

Kehoe, L., Reis, T., Virah-Sawmy, M., Balmford, A., Kuemmerle, T., et al., 2019. Make EU trade with Brazil sustainable. Science 364, 341-+.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9 https://doi.org/10.1088/1748-9326/9/10/105011.

Lassaletta, L., Billen, G., Garnier, J., Bouwman, L., Velazquez, E., Mueller, N.D., Gerber, J.S., 2015. Nitrogen use in the global food system: Past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand. Environ. Res. Lett. 11 (2016), 095007 https://doi.org/10.1088/1748-9326/11/9/095007.

Lassaletta, L., Einarsson, R., Quemada, M., 2023. Nitrogen use efficiency of tomorrow. Nat. Food 4, 281–282.

Le Noë, J., Billen, G., Garnier, J., 2017. How the structure of agro-food systems shapes nitrogen, phosphorus, and carbon fluxes: the Generalized Representation of Agro-Food System applied at the regional scale in France. Sci. Total Environ. 586, 42–55. https://doi.org/10.1016/j.scitotenv.2017.02.040.

Le Noë, J., Billen, G., Esculier, F., Garnier, J., 2018. Long-term socioecological trajectories of agro-food systems revealed by N and P flows in French regions from 1852 to 2014. Agric Ecosyst. Environ. 265, 132–143. https://doi.org/10.1016/j.jenvman.2017.09.039.

LeBauer, D.S., Treseder, K.K., 2008. Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. Ecology 89, 371–379.

Lemaire, G., Garnier, J., da Silveira Pontes, L., de Faccio Carvalho, P.C., Billen, G., Assmann, T.S., 2023. Domestic herbivores, the crucial trophic level for sustainable agriculture: avenues for reconnecting livestock to cropping systems. Agronomy 13, 982.

Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., Ramankutty, N., 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? Glob. Ecol. Biogeogr. 19, 769–782. https://doi.org/10.1111/j.1466-8238.2010.00563.x.

Morais, T., Teixeira, R., Lauk, C., Theurl, M., Winiwarter, W., Mayer, A., Kaufmann, L., Haberl, H., Domingos, T., Erb, K.-H., 2021. Agroecological measures and circular economy strategies to ensure sufficient nitrogen for sustainable farming. Global Environ. Change 69, 102313. https://doi.org/10.1016/j.gloenvcha.2021.102313.

Muller, A., Schader, C., El-Hage Scialabba, N., Brüggemann, J., Isensee, A., Erb, K.-H., Smith, P., Klocke, P., Leiber, F., Stolze, M., Niggli, U., 2017. Strategies for feeding the world more sustainably with organic agriculture. Nat. Commun. 8, 1290.

Musacchio, A., Re, V., Mas-Pla, J., Sacchi, E., 2020. EU Nitrates Directive, from theory to practice: environmental effectiveness and influence of regional governance on its performance. Ambio 49, 504–516.

Pendrill, F., Gardner, T.A., Meyfroidt, P., Persson, U.M., Adams, J., Azevedo, T., Bastos Lima, M.G., Baumann, M., Curtis, P.G., De Sy, V., Garrett, R., Godar, J., Goldman, E. D., Hansen, M.C., Heilmayr, R., Herold, M., Kuemmerle, T., Lathuillière, M.J., Ribeiro, V., West, C., 2022. Disentangling the numbers behind agriculture-driven tropical deforestation. Science 377 (6611), eabm9267. https://doi.org/10.1126/science.abm9267.

Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333, 1289–1291.

Pinsard, C., Martin, S., Léger, F., Accatino, F., 2021. Robustness to import declines of three types of European farming systems assessed with a dynamic nitrogen flow model. Agric. Syst. 193, 103215.

Poiron, A., 2022. Why attacks against the EU farm to fork strategy completely miss the point. Slow Food. https://www.slowfood.com/why-attacks-against-the-eu-FarmtoFork-strategy-completely-miss-the-point/, 9 februari 2022.

Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C., 2014. Diversification practices reduce organic to conventional yield gap. Proc. R. Soc. B: Biol. Sci. 282 (1799) https://doi.org/10.1098/rspb.2014.1396.

Ren, C., Zhang, X., Reis, S., Wang, S., Jin, J., Xu, J., Gu, B., 2023. Inequality of nitrogen use and losses in global croplands under climate change. Nat. Food 1–11.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin 3rd, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.

Rockström, J., Gupta, J., Qin, D., et al., 2023. Safe and just Earth system boundaries. Nature 619, 102–111. https://doi.org/10.1038/s41586-023-06083-84.

Rodríguez, A., Sanz-Cobeña, A., Ruiz-Ramos, M., Aguilera, E., Quemada, M., Billen, G., Garnier, J., Lassaletta, L., 2023. Nesting nitrogen budgets through spatial and system scales in the Spanish agro-food system over 26 years. Sci. Total Environ. 892, 164467 https://doi.org/10.1016/j.scitotenv.2023.164467.

Roux, N., Kaufmann, L., Bhan, M., Le Noe, J., Matej, S., Laroche, P., Kastner, T., Bondeau, A., Haberl, H., Erb, K., 2022. Embodied HANPP of feed and animal products: Tracing pressure on ecosystems along trilateral livestock supply chains 1986–2013. Sci. Total Environ. 851, 158198 https://doi.org/10.1016/j.scitotenv.2022.158198.

Ruane, A.C., Antle, J., Elliott, J., Folberth, C., Hoogenboom, G., Mason-D'Croz, D., Müller, C., Porter, C.H., Phillips, M., Raymundo, R., Sands, R., Valdivia, R., White, J., Wiebe, K., Rosenzweig, C., 2018. Biophysical and economic implications for agriculture of +1.5° and +2.0°C global warming using AgMIP Coordinated Global and Regional Assessments. Clim. Res. 76, 17–39. https://doi.org/10.3354/cr01520.

Schebesta, H., Candel, J.J., 2020. Game-changing potential of the EU's Farm to Fork Strategy. Nautre Food 1, 586–588. https://doi.org/10.1038/s43016-020-00166-9.

Schulte-Uebbing, L.F., Beusen, A.H.W., Bouwman, A.F., de Vries, W., 2022. From planetary to regional boundaries for agricultural nitrogen pollution. Nature 610, 507–512.

Seufert, V., Ramankutty, N., 2017. Many shades of gray-The context-dependent performance of organic agriculture. Sci. Adv. 3, 14.

Spiegal, S., Kleinman, P.J.A., Endale, D.M., Bryant, R.B., Dell, C., Goslee, S., Meinen, R.J., Flynn, K.C., Baker, J.M., Browning, D.M., McCarty, G., Bittman, S., Carter, J., Cavigelli, M., Duncan, E., Gowda, P., Li, X., Ponce-Campos, G.E., Cibin, R., Silveira, M.L., Smith, D.R., Arthur, D.K., Yang, Q., 2020. Manuresheds: advancing nutrient recycling in US agriculture. Agric. Syst. 182, 102813.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223). https://doi.org/10.1126/science.1259855.

Suh, S., Johnson, J.A., Tambjerg, L., Sim, S., Broeck-Smith, S., Reyes, W., Chaplin-Kramer, R., 2020. Closing yield gap is crucial to avoid potential surge in global carbon emissions. Glob. Environ. Change 63, 192100. https://doi.org/10.1016/j.gloenvcha.2020.102100.

Sutton, M., Howard, C., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), 2011. The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge University Press, 601 pp.

Sutton, M.A., Howard, C.M., Kanter, D.R., Lassaletta, L., Móring, A., Raghuram, N., Read, N., 2021. The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond. One Earth 4, 10–14.

Theurl, M., Lauk, C., Kalt, G., Mayer, A., Kaltenegger, K., Morais, T.G., Teixira, R.F.M., Domingos, T., Winiwarter, W., Erb, K.H., Haberl, H., 2020. Food systems in a zero-deforestation world: dietary change is more important than intensification for climate targets in 2050. Sci. Total Environ. 735, 139353 https://doi.org/10.1016/j.scitotenv.2020.139353.

Toreti, A., Deryng, D., Tubiello, F.N., Müller, C., Kimball, B.A., Moser, G., Boote, K., Asseng, S., Pugh, T.A.M., Vanuytrecht, E., Pleijel, H., Webber, H., Durand, J.L., Dentener, F., Ceglar, A., Wang, X., Badeck, F., Lecerf, R., Wall, G.W., van den Berg, M., Hoegy, P., Lopez-Lozano, R., Zampieri, M., Galmarini, S., O'Leary, G.J., Manderscheid, R., Mencos Contreras, E., Rosenzweig, C., 2020. Narrowing uncertainties in the effects of elevated CO_2 on crops. Nat. Food 1, 775–782. https://doi.org/10.1038/s43016-020-00195-4.

United Nations, 2009. Food production must double by 2050 to meet demand from world's growing population. https://press.un.org/en/2009/gaef3242.doc.htm.

van Dijk, M., Morley, T., Rau, M.L., Saghai, Y., 2021. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010-2050. Nat. Food 2, 494–501. https://doi.org/10.1038/s43016-021-00322-9.

van Grinsven, H.J., Holland, M., Jacobsen, B.H., Klimont, Z., Sutton, M.A., Jaap Willems, W., 2013. Costs and benefits of nitrogen for Europe and implications for mitigation. Environ. Sci. Technol. 47 (8), 3571–3579.

van Grinsven, H.J.M., Erisman, J.W., Westhoek, H., 2015. Potential of extensification of European agriculture for a more sustainable food system, focusing on nitrogen. Environ. Res. Lett. 10, 25002.

van Grinsven, H.J.M., Ebanyat, P., Glendining, M., Gu, B., Hijbeek, R., Lam, S.K., Lassaletta, L., Mueller, N.D., Pacheco, F.S., Quemada, M., Bruulsema, T.W., Jacobsen, B.H., ten Berge, H.F.M., 2022. Establishing long-term nitrogen response of global cereals to assess sustainable fertilizer rates. Nat. Food 3, 122–132.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance. A review. Field Crop Res 143, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009.

Velthof, G.L., 2014. Task 1 of Methodological studies in the field of Agro-Environmental Indicators. Lot 1 excretion factors. Final draft. Alterra, Wageningen. http://ec.europa.eu/eurostat/documents/2393397/8259002/LiveDate_2014_Task1.pdf/e1ac8f30-3c76-4a61-b607-de99f98fc7cd.

Vitousek, P.M., Howarth, R.W., 1991. Nitrogen limitation on land and in the sea: how can it occur? Biogeochemistry 13, 87–115.

WHO, 1985. Energy and protein requirements : Report of a joint FAO/WHO/UNU expert consultation WHO Technical Report Series n°724. Switzerland, Geneva.

WHO, 2007. Protein and amino acid requirements in human nutrition Joint WHO/FAO/UNU. In: WHO Technical Report Series. 935:1-265. Switzerland, Geneva. https://apps.who.int/iris/bitstream/handle/10665/39527/WHO_TRS_724_(chp7-chp13).pdf?sequence=2.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al., 2019. Food in the Anthropocene: the EAT–*Lancet* Commission on healthy diets from sustainable food systems. Lancet Commissions 393 (10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.