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Perspective

Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity

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SUMMARY

After World War II, the evolution of Europe's agro-food system has been marked by intensified use of synthetic fertilizers, territorial specialization, and integration in global food and feed markets. This evolution led to increased nitrogen (N) losses to aquatic environments and the atmosphere, which, despite increasing environmental regulations, continues to harm ecosystems and human well-being. Here, we explore how these N losses can be drastically reduced in a scenario synergistically operating three levers: (1) a dietary change toward less animal products and an efficient recycling of human excreta; (2) the generalization of region-specific organic crop rotation systems involving N_2-fixing legumes, making it possible to do without synthetic N fertilizers; and (3) the reconnection of livestock with cropping systems allowing optimal use of manure. This scenario demonstrates the possibility to feed the projected European population in 2050 without imports of feed and with half the current level of environmental N losses.

INTRODUCTION

The European agro-food system, tightly integrated into international food and feed trade networks, is a paradigmatic example of industrial agriculture shaped by the post-World War II Green Revolution.[1,2] Here, 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. From the end of World War II to the collapse of the USSR, voluntarist state policies across Europe—despite the quite opposed conceptions of economy in communist and capitalist countries—encouraged the transformation of the structure of agricultural systems with the shared aim of increasing production in the name of social progress, the explicit objective of providing universal access to affordable food.[3–5]

Synthetic nitrogen (N) fertilizer, produced using the Haber-Bosch process, has played a major role in the intensification of European agriculture by boosting crop productivity. However, the increased N supply in agriculture also led to increased N losses to the environment, causing multiple severe impacts on ecosystems and human health through tropospheric air pollution, stratospheric ozone depletion, greenhouse gas emission, groundwater pollution, freshwater and coastal marine eutrophication, and loss of aquatic and terrestrial biodiversity. The European Nitrogen Assessment[6] provides a comprehensive analysis of nitrogen challenges in the European context.

The dominant agricultural policies in European countries have greatly evolved over the last three decades. From the 1990s on, after the collapse of the USSR, the focus has gradually shifted from agricultural productivity toward more consideration for environmental issues through regulations and economic incentives. Meanwhile, the pursuit of territorial specialization has been accelerated by market forces, fostered by increasing integration of agricultural products in international trade following the progressive abandonment of protectionist policies.[7] One aspect of this specialization trend is the abandonment of agriculture on less suitable lands,[8,9] resulting in forest expansion in regions less favorable for agricultural production,[10] and contraction of intensive agriculture on more favorable land.[11,12]

This trend of simultaneous intensification and land abandonment, although mostly resulting from a purely economic logic, has recently been justified from an environmental perspective by opposing the land-sparing versus land-sharing alternatives.[13–16] The main argument put forward in favor of land sparing—intensification on the best soils to leave more land for natural areas—is that increasing the production per unit area would allow providing food for a growing population while

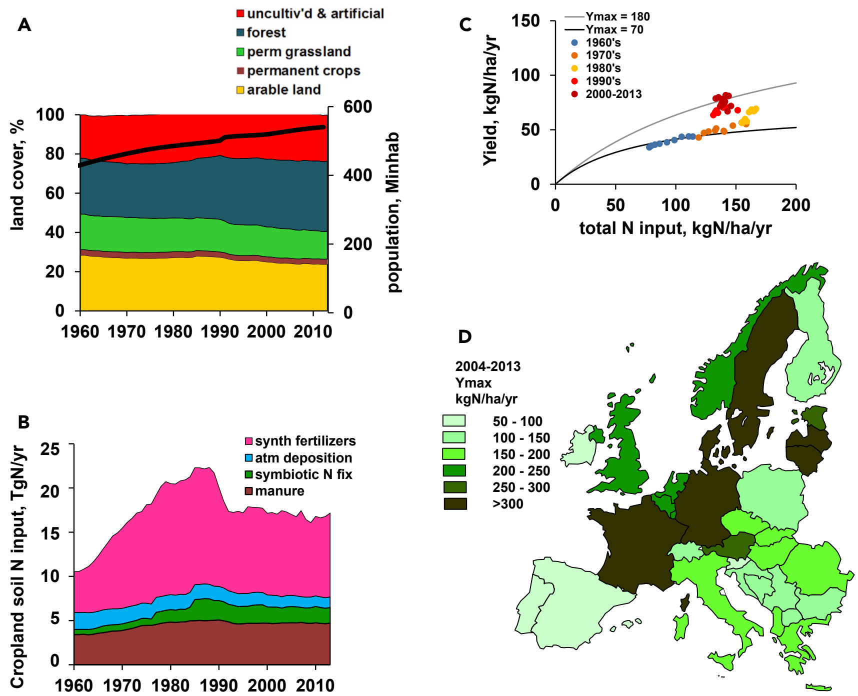

Figure 1. The agro-food system of Europe and its trajectory from 1960 to 2013

(A) Changes in the population (black line) and land cover.

(B) Changes in total nitrogen inputs to cropland soils.

(C) The apparent yield-fertilization relationships for cropland: each point represents the average European yield (Y) versus the total N inputs to cropland soil (F) for each year since 1961, with its color representing the decade. The data are fitted with the relationship $Y = Y_{max}. F/(F + Y_{max})$.

(D) Geographical distribution of Y_{max}, the theoretical maximum yield at saturating N input for each country.

limiting the spatial footprint of agricultural activities, hence devoting more space to nature and biodiversity.

In this context it is increasingly recognized that European land use patterns have global ramifications through international trade. For example, as the new European Farm to Fork strategy[17,18] addresses the ambitions of the EU Green Deal of drastically reducing N pollution, concerns have been raised that action to protect the environment in Europe could result in increased pollution on other continents, causing inequality across countries,[19] e.g., in terms of natural resource inputs, food/nutrient outputs, and nutrition/health outcomes. Furthermore, food systems have been shown to be responsible for one-third of greenhouse gas emissions.[20] To avoid this, Fuchs et al.[21] advocate a reinforcement of the land-sparing scheme through “sustainable intensification” approaches to simultaneously increase productivity and reduce impacts inside as well as outside Europe. Here, we explore a different approach, based on agro-ecological land sharing, de-intensification, and search for autonomy, within a systemic approach.

This paper proceeds in two steps. We first examine the past 50-year trajectory of the European agro-food system from the point of view of the involved N fluxes. Starting from the analysis of the current situation, we then explore a paradigm shift, inspired by the land-sharing concept, and describe what an agro-ecological future for Europe could look like in 2050, based on a set of transparent and biophysically feasible assumptions. We present a scenario implying a deep reshaping of the agro-food system as a whole, quantifying the combined potential of dietary change (toward a more healthy and frugal diet), generalization of agro-ecological farming practices[22,23] (low nutrient input agriculture), and increased circularity[24] (crops and livestock reconnection). This scenario is an extension of previous work developed for the cases of France and Spain,[24,25] and for the whole of Europe.[26] In the present analysis, we demonstrate that such a scenario would substantially reduce agricultural N pollution while providing healthy food to the predicted population of Europe in 2050, with minimal recourse to imports.

The past trends of Europe’s agro-food system

Our analysis is mainly based on country-level data from FAOstat (http://www.fao.org/statistics), processed following the GRAFS (Generalized Representation of Agro-Food Systems) approach as described by Lassaletta et al.[27] The full dataset and code generated during this study are available as an Excel file (hereafter named XLSfile) at https://doi.org/10.6084/m9.figshare.14610105.

From 1961 to 2013, Europe’s population increased from 428 to 540 million inhabitants. During the same period, the apparent per capita protein consumption increased from 4.9 to 5.7 kgN/cap/year. More importantly, the share of animal proteins (excluding fish) in the consumption grew from 35% to 55%, which means that per capita animal protein consumption increased by about 80%; however, with significant disparities between the different countries (see section S2). While these trends imply an increased demand for agricultural production, the area of agricultural land gradually decreased (from 238 to 206 Mha), mostly in favor of forested land (which increased from 484 to 501 Mha) (Figure 1A).

Cropland N inputs increased across Europe from 1960 to a peak in the 1980s and have since fallen on average (Figure 1B), albeit with national differences. These changes mainly lie in the application of synthetic N fertilizers. A rapid drop in synthetic N fertilizer use occurred in the early 1990s, reflecting both the economic collapse of communist countries and the emergence of environmental regulations in western countries, particularly focused on water pollution. These changes occurred together with a shift in the relationship between N yield and N fertilization of croplands.[28,29] Between 1961 and 1985, cropland yields generally followed a simple hyperbolic relationship (Figure 1C), but as N inputs decreased from the 1990s, yields did not decrease, and often increased, revealing another relationship between yield and N fertilization. This shift suggests a higher theoretical maximum yield at saturating N inputs (Y_{max}), a trend already shown at the global scale.[27] The value of Y_{max}

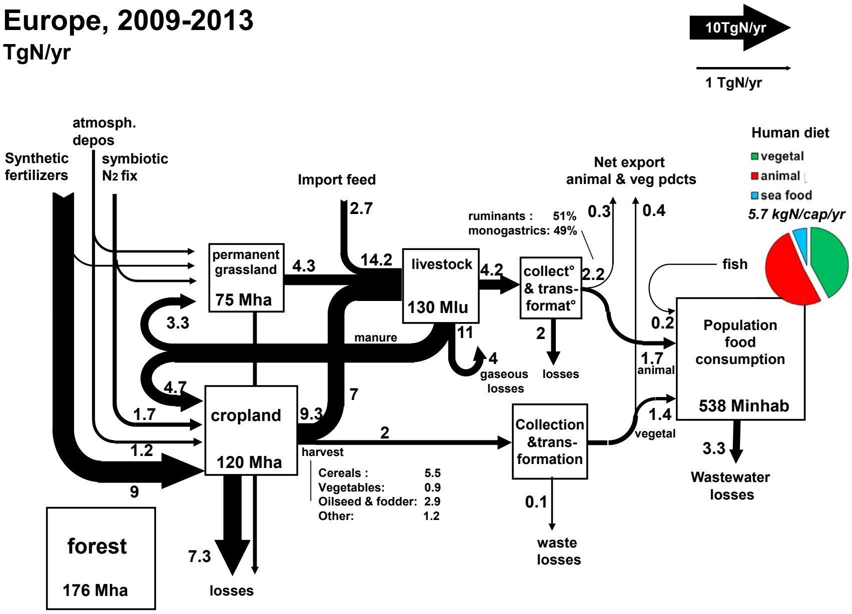

Figure 2. GRAFS representation of the N fluxes involved in the agro-food system of Europe

The data shown were calculated for the 2009–2013 period as the sum of all country data. Data for each individual country are available at https://doi.org/10.6084/m9.figshare.14610105.

characterizes the potential productivity of cropland as the result of pedoclimatic conditions, agricultural management, and crop mix. In this paper, we use it as an overall indicator of the geographical variation in potential cropland productivity across Europe (Figure 1D).

The major N fluxes involved in the agro-food system of Europe in the recent period are represented according to the GRAFS approach[30–33] in Figure 2. This representation highlights several essential characteristics of the European agro-food system. The first one is that the system is heavily dependent on synthetic N fertilizer inputs ultimately resulting in N losses to the environment from various compartments of the agro-food system. The second feature is the large burden of livestock metabolism in the overall agricultural N cycle. Livestock consume 75% of Europe's crop protein production in addition to 2.7 million metric tons of N (TgN) per year in imported feed (19% of total livestock ration), mainly maize from the USA, and soybean from South America, contributing to deforestation.[34] The size of this N import greatly exceeds Europe's N exports in cereals (0.398 TgN/year) and animal products (0.030 TgN/year) to the rest of the world. Indeed, while Europe has become self-sufficient in cereals, and even a net exporter since the late 1990s, these exports are more than outweighed by increasing imports of protein crops (Figure 3A).

A major driver for this increased dependency is the specialization of European countries (or of regions within these countries) into either stockless cropping systems (i.e., specialized cropping system with no or very limited livestock breeding, thus entirely dependent on N synthetic fertilizers) or specialized intensive livestock farming systems. This is most clearly shown by an analysis at sub-national territories,[24,32,33,35–38] rather than at country level. In specialized intensive livestock farming, local grass and crop production is in most cases not sufficient for feeding the animals, which makes the system dependent on long-distance feed trade. The contribution of extra-national import of feed in total European livestock nutrition increased from 12% to 20% between 1960 and 2015, while the share of permanent grassland grazing dropped from 54% to 30% (Figure 3B; XLSfile). The resulting decoupling of crops and livestock[39] is also responsible for a suboptimal use of animal excreta causing over-fertilization of crops.

Agricultural N losses to the environment occur mainly from cropland (both to aquatic environments and the atmosphere) and from manure management and storage (mainly to the atmosphere). For cropland soils, a good proxy for N losses to the environment is the N surplus, defined as the difference between total N inputs (manure, N synthetic fertilizers, symbiotic fixation, atmospheric deposition, and urban sludges) and N export (harvested products). The average cropland surplus increased from 6.4 TgN/year (47 kgN/ha/year) in the early 1960s to 7.3 TgN/year (63 kgN/ha/year) in the mid-2010s. Apart from a fraction of the N surplus which can be stored within the soil organic matter pool, most of the cropland N surplus is either leached to ground and surface waters in the form of nitrate (NO_3^-), volatilized as ammonia (NH_3) or denitrified, with a significant share emitted as nitrous oxide (N_2O), a potent greenhouse gas. For manure management, N losses to the atmosphere have been estimated to 2.5–3.5 and 3.5–4.5 Tg N/year in 1961 and 2013, respectively (see details in Note S1). Roughly, the N losses associated with agriculture have thus increased from 9.5 to 11.3 TgN/year during the period 1961–2015.

Summing up, the development of European agriculture since the 1960s, despite a clear inflection following successive reforms of the EU Common Agricultural Policy (e.g., 1984, reduction of surpluses, implementation of production quotas; 1991, land set-aside) together with more environmental regulations around 1980–2000, is still characterized by a logic of intensification on reduced cropland areas and specialization of activities in the most suitable territories, denying the advantages of their possible complementarity and resulting in huge environmental losses of reactive N. These now amount to 77% of the total new N imported to the system (as N fertilizers, symbiotic fixation, atmospheric deposition, and import of feed). Therefore, the observed trajectory of Europe's agro-food system is characterized by a low overall nutrient use efficiency (NUE) and damaging N losses to the environment, threatening water, air, and soil quality as well as contributing to climate change (see the European Nitrogen Assessment[5] for a comprehensive assessment).

An agro-ecological scenario for Europe in 2050

Faced with this increasing openness of the N cycle associated with the European agro-food system, the need for a profound structural change is imperative. Previous studies[25,40,41] showed

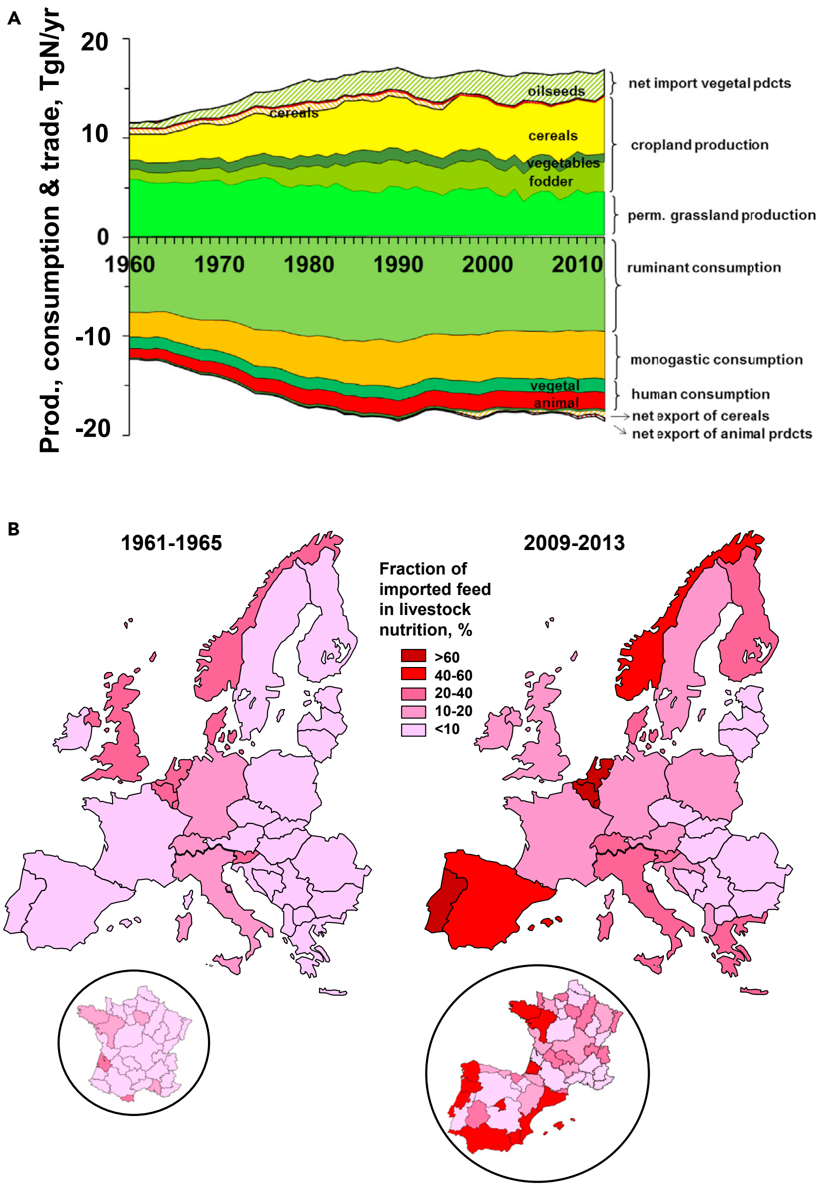

Figure 3. Production, consumption, and trade of agricultural commodities

(A) Availabilities (positive values) and consumption/exports (negative values) of crop production in Europe since 1960. Note that this diagram is not a real balance sheet, as N embedded in animal products export and consumption by human is counted twice, as it is already included in livestock ingestion.

(B) Fraction of imported feed in livestock nutrition in the different European countries in the early 1960s and in the recent period. Data at sub-national scale are also shown for France,[33] Spain, and Portugal[24] to illustrate regional specialization.

that a strong reduction of N environmental losses can be achieved by operating three main levers: (1) changing the composition of human diets and an efficient recycling of human excreta; (2) using agro-ecological practices to avoid the use of synthetic N fertilizers; and (3) reconnecting livestock farming to cropping systems (with livestock feeding only relying on local production of grass and fodder resources), thus ensuring the availability of N from manures as fertilizers for crops. For each of these levers, we adopt transparent assumptions relying either on already observed strategies (e.g., organic farming practices) or on realistic proposals from the literature (e.g., diets). Operated synergistically, these levers unlock a fundamental agro-ecological transformation for Europe.

Toward more frugal and healthy diets

FAO[42] predicts an increase of the European population by 12% at the horizon 2050 (medium scenario). More important for predicting human food requirements is the hypothesis made regarding dietary choices. Numerous studies have proposed "desirable" diets in future scenarios of the agro-food system at different scales. A few of them are summarized in Table 1. More interesting than the numbers themselves is the approach taken to get to define these diets.

The starting point of the scenarios proposed by the EAT-*Lancet* report[45] is the prescription of a "reference healthy diet" based primarily on health considerations. Compared with the current European diet, it implies a strong reduction of total protein intake and of the share of animal products, particularly that of dairy products and beef meat, leaving poultry and pork as the main suppliers of animal products. The Afterres 2050[46] scenario for France similarly defines an *a priori* desirable human diet, but with much higher contribution of dairy products. The Ten Years For Agroecology scenario for Europe[26] is on the same line, as its main objective is to maintain and develop grassland areas and extensive ruminant livestock farming.

The "Nitrogen on the Table" ENA report[47] does not prescribe a particular diet, but tests scenarios of 50% reduction in the consumption of (1) beef and dairy products, or (2) pork, poultry, and eggs, or (3) all types of animal products excluding fish. The corresponding caloric intake is replaced by increased cereal consumption. Billen et al.[43] tested a large number of combinations of per capita total protein intake and share of animal protein at the global scale to define the "equitable diet," i.e., a diet that can be shared by the global human population in 2050 at the current agricultural production capacity. A different approach is offered by the "ECOLEFT" method[48,49] based on the concept of ecological leftovers for livestock production: arable land should be used primarily to produce plant-based food for humans, and livestock should be fed on biomass not suitable for humans, such as grass from semi-natural grassland and by-products from crop production and food processing. The productive potentials of each territory then define the suitable human diets. This approach was applied to Sweden[49] with three variants: (1) intensive milk production, (2)

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Table 1. Comparison of several human diets (in terms of apparent consumption) currently observed or prescribed in prospective scenarios

	Apparent N consumption	Cereals	Legumes	Fruits and vegetables	Animal[a] *(fraction of ruminants)*	Seafood
	kgN/cap/year	% of total	% of total	% of total	% of total	% of total
European diet (this work)						
1961–1965	5.2				45	5
2009–2013	6.1	29	0.8		55 *(0.51)*	6
EAT-Lancet, World[b] (Willett et al.[45])						
reference healthy diet	5.7	35	21	4	33 *(0.16)*	7
Afterres 2050 (Couturier et al.[46])						
France	4.9	51	4.6	11.7	31	1.7
TYFA (Poux and Aubert[26])						
France	5.1	43	3	13	38 *(0.62)*	3
Nitrogen on the Table (Westhoek et al.[48])						
EU27 reference	6.0	31	0.4	9.6	51 *(0.57)*	8
50% milk and red meat	5.7	42	0.4	10.6	39 *(0.40)*	8
50% eggs and white meat	5.8	40	0.4	10.6	41 *(0.72)*	8
50% all animal products	5.4	52	0.4	11.6	28 *(0.57)*	8
World equitable diet (Billen et al.[43])						
High animal diet	4				40	
Low animal diet	5				25	
ECOLEFT, Sweden (Garnett et al.,[48] RÖÖs et al.[49])						
Reference Sweden	5.0	25	0.5		47	12
Intensive milk diet	4.1	48	1.7		14	15
Extensive milk diet	4.2	52	2.8		22	14
Suckler diet	3.9	59	4.2		22	15
2050 European healthy diet (this work)						
agro-ecological scenario	5	45	10	15	25 *(0.67)*	5

[a]Excluding fish and seafood. The share of ruminants (meat + milk) is shown *(italics),* expressed as a fraction of total animal (non-fish) proteins.
[b]Converted into apparent consumption (supply) values using the coefficient derived from Esculier et al.[44]

extensive milk production, or (3) extensive beef meat production with eggs and pig meat production.

In this paper's scenario, we assume fixed common per capita apparent protein consumption for all European countries, namely 5 kgN/cap/year, of which 45% cereal products, 15% fresh fruits and vegetables, 10% grain legumes, and 30% animal products (meat, milk, eggs, and fish), close to the equitable diet defined above, consistent with FAO-WHO[50] recommendations and roughly in the middle of the various recommendations presented in Table 1. The rationale for assuming the same diet for all Europe is the convergence in the diets of the different countries since 1960 (see Note S2). What varies regionally, according to specific geographical and cultural features, is the proportion of fish and seafood, as well as the share of livestock products from ruminants (beef, mutton meat, and milk) versus monogastrics (pork, poultry meat, and eggs) in each country. These specificities are kept at their relative value in the 1960s, considered as still representative of the geographic and cultural differences between countries.

Agro-ecological practices and crop rotations

Agro-ecological practices, including organic farming, have been developed as an alternative to "industrial agriculture,"[51] strictly banning the use of synthetic inputs (fertilizers and pesticides). There is quite a large diversity of agro-ecological systems worldwide, as these are based on subtle mix and exchanges of farmer and scientific knowledge strongly linked to territorial peculiarities.[23,52] Moreover, the innovation capacity of farmers is an important aspect for the adaptability and performances of these systems in a changing world.[53,54] However, establishing a hypothetical agro-ecological scenario at the 2050 horizon has to rely on systems that have already been tested and have proved their worth in the various regions of Europe. Our scenario is therefore based on a typology of existing organic systems, which currently cover about 8% of the total agricultural area of EU27.[55]

Here, we mostly deal with cropping systems on arable land, leaving apart permanent crops as well as market gardening systems, which function according to a rather different logic. In the scenario, for each country, the area of permanent grassland and permanent crops has been kept constant, and a small fraction of arable area has been devoted to market gardening to meet the domestic needs for vegetables defined according to the prescribed diet and the organic gardening productivity figures published by Anglade et al.[56] What follows concerns the remaining part of cropland area, which is by far the largest part (60%) of the agricultural land.

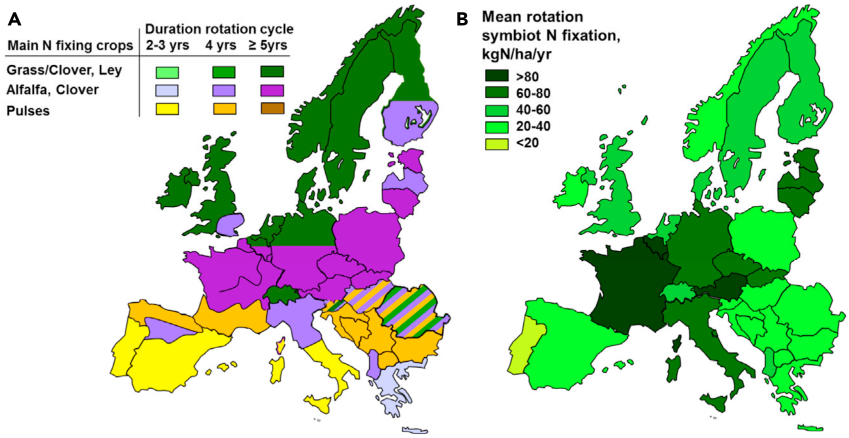

Figure 4. Organic farming systems in Europe

(A) Typology of dominant crop rotations in organic cropping systems in Europe, based on the duration of the rotation cycle and the nature of the main N-fixing crop.

(B) Mean of soil N input through symbiotic N fixation integrated over the whole rotation cycle of arable cropping systems described in (A) (see Note S3 for details and references).

Based on an extensive literature compilation of crop rotations in organic farming systems in European countries (Note S3), a map of the major organic crop rotations currently in use in Europe has been established (Figure 4A). It relies on two criteria: (1) the length of the rotation and (2) the nature of the main N-fixing crop. In temperate western and central regions of Europe, long crop rotations (over 5 years), with 2 or 3 years of temporary sown grassland, such as clover, alfalfa, or mix grass and legumes, preceding cereal crops are the prevalent systems. They may or may not include grain legumes in the rotation, but these latter are not the dominant N-fixing crop. In the Netherlands, however, long crop rotations alternating vegetables, cereals, and grain legumes are widespread. In Nordic countries, Great Britain and Ireland, leys, i.e., sown grasslands, made of grass and clover mix (with typically 20%–35% clover), provide the main N supply of long and diversified rotations. Leys are harvested for silage as well as grazed by livestock and plowed after 2–4 years, for sowing annual crops, commonly cereals. In Southern European countries, where water scarcity prevents the development of abundant grass and forage legume crops, pulses (such as peas, chickpeas, lentils, vetches, and fava beans)—most often harvested for grains or sometimes used for hay or green manure and undersown with cereals—are the basis for N supply to the rotation, generally limited to 2- to 4-year cycles. Soybeans, although less adapted to arid conditions, are commonly used in crop rotations in Italy. Simple fallow, with ample spontaneous development of weeds are often grazed and can be considered as sort of leys under semi-arid conditions. Of course, under irrigation, other crop rotations are possible, including alfalfa or grass/clover cover crops.

Anglade et al.[57] and Billen et al.[25] have shown that organic and conventional cropping systems under the same pedoclimatic conditions follow the same yield-soil N input relationship. The Y_{max} values characterizing current conventional systems (Figure 1D) therefore also apply to organic crop rotations. The overall yield of these crop rotations thus depends on their average N supply. In organic farming, besides N inputs from animal manure and atmospheric N deposition (see below), N is introduced mainly through symbiotic fixation by the legume crops inserted in the rotation, which gives farmer autonomy in terms of fertilizers. Symbiotic N fixation for each of the crop rotations described in Figure 4A has been calculated from the N content of legume crop yields according to the simplified method of Anglade et al.,[58] as proposed by Lassaletta et al.[28] (Note S3; Tables S4 and S5). It ranges from 20 to 100 kgN/ha/year across the different European countries considered here (Figure 4B). By applying current Y_{max} values for 2050, we choose a conservative approach for our scenario, considering that likely future technological improvements shall first aim at offsetting the negative impacts of future climate change, particularly in Mediterranean climate areas of the South of Europe.[59] In other parts of Europe, the overall effect of climate change might be positive.[60]

In addition, we assume N input from the recycling of a substantial fraction (70%) of human N excretion. Patel et al.[61] and Martin et al.[62] have recently reviewed the available technologies for recovering nutrients from source-separated human urine, which contains 80% of N excretion,[44] and have advocated for reusing them as fertilizers. Note that this reuse would imply that the current prohibition of human excreta in the European organic farming regulation would be lifted.

Crop-livestock reconnection for circularity

In agro-ecological systems, livestock is not only needed for providing meat and milk; it is also the agent able to convey nutrients from grassland to arable land and from N-fixing crops to other crops.[63] In this way, as no synthetic N fertilizer inputs are considered and as symbiotic fixation is fixed *a priori* by the choice of a crop rotation scheme (see above), livestock density remains the only lever of intensification of organic cropping systems, through the application of manure. To ensure full connection with cropping systems, livestock must be fed locally, without import of feed from distant origin, and its excreta returned to cropland and grassland. In the present scenario, the N inputs to cropland as manure have been established considering the losses during management and application (see Note S3).

Atmospheric total N deposition (as both wet and dry deposition) also contributes to cropland N inputs. Although most of the deposition comes from car traffic and electrical power generation from fossil fuels, a part also comes from livestock systems (up to 20% in livestock-dense regions), as demonstrated for French regions[33] (see Note S3; Figure S7).

In summary, in addition to symbiotic N_2 fixation, which is the only major net source of N in organic agriculture, livestock density influences cropland productivity by enabling a strategic recirculation of manure N, and thereby the capacity to locally provide food and feed. Livestock is also a key determinant of environmental N losses, through the resulting surplus and the direct atmospheric N losses linked to manure management

Table 2. Systemic hypotheses and constraints of the agro-ecological scenario for Europe in 2050

Human nutrition and excretion	Population: 601 million inhabitants Diet: 5 kgN/cap/year with 45% cereals, 10% grain legumes, 15% fruits and vegetables 25% animal excluding fish, 5% fish and sea food Recycling 70% of human excreta
Cropping systems	No changes in land cover Generalization of currently used organic crop rotations in the different climatic zones of Europe (Figure 4) No synthetic N fertilizers Production calculated from total N input, using current Y_{max} for each country
Livestock	Fed with local production of grass and fodder (no import of feed) Manure recycled to grassland and cropland, with a maximum cropland N soil surplus of 35 kgN/ha/year for "good" water quality

and application.[64] Given a limit on environmental N losses, the maximum allowable livestock density can be calculated. Here, we used arable cropland soil N surplus as a simple proxy for environmental N losses, and set its maximum admissible value at 35 kgN/ha/year. This upper limit guarantees a groundwater recharge concentration below 50 $mgNO_3$/L (~11.3 mgN/L) under temperate climate conditions—the threshold established by the EU nitrate directive—with 200 mm/year subsurface runoff, considering leaching of about 70% of the surplus.[30]

Scenario construction and assessment

The main systemic hypotheses and constraints defined above for the establishment of the agro-ecological scenario are summarized for the three major levers (Table 2).

To define the N fluxes characterizing the agro-food system in the scenario, the following procedure is applied. The livestock density in each country is assumed as the maximum that can be fed domestically within the stated environmental targets related to N losses. Livestock composition in terms of proportion of ruminants and monogastrics is taken for each country as it was in the 1960s, a period considered here, by lack of other data, as a reference for the traditional state of the agriculture. Grasslands and forage legumes (in pure stands or mixed with temporary grassland) are the only sources of feed for ruminants and also supplies 25% of monogastric ingestion, as shown possible by many recent studies.[65–70] These assumptions result in strongly reducing the livestock density compared with the current situation and a more even distribution across European countries (Figure 5A). Cropland production is calculated for each country from the total soil N input, based on the currently observed yield-fertilization relationship and its Y_{max} parameter (Figures 1C and 1D).

The XLSfile provides the details of the calculations and the results for each country. Figure 5 shows the resulting distribution of livestock density (Figure 5B), and atmospheric N losses linked to the management of livestock excreta are reduced by 53%. N surplus is reduced by 57% of its 2013 value.

In the scenario, the total production of the crop rotation, calculated for each country as indicated above, is allocated to either legume crops or cereals (and other non-legume crops) according to the stated yield of legumes (independent on N inputs) and the frequency of the different crops in the rotation. As underlined by Barbieri et al.,[71] this leads to a much lower cereals production than the current conventional agriculture. This reduced availability, however, is compensated by much lower animal consumption of cereals and a lower share of animal products in the diet.

Surpluses or deficits of vegetal and animal products are calculated in each country from the balance between production and requirements of humans and livestock. With the constraints imposed, some densely populated countries cannot meet their own needs in animal or vegetal proteins, despite the frugal diet assumption and the reduction in livestock. In that case, the supply is complemented by imports from neighboring European countries or, if needed, from outside Europe. In the opposite case, exports are assumed. Overall, in the scenario described here, trade between countries (Table 2) is roughly halved compared with today, owing to the scenario constraints aiming as far as possible at self-sufficiency (Table 3). Net exports of cereals and animal products outside of Europe continue at a level of around, respectively, 7% and 36% of the current ones.

The budget and the full representation of N fluxes through the agro-food system for the whole of Europe in the 2050 scenario are shown in Figure 6. These results can be compared with the present situation illustrated in Figures 2 and 3A. The most striking differences lie in (1) the absence of synthetic N fertilizers, (2) the lower environmental N losses, and (3) the absence of feed import, while a small export of cereals and animal products outside Europe is still possible. This scenario thus demonstrates the possibility to feed Europe in 2050 with a healthy diet, using agro-ecological farming practices without dependency on synthetic N fertilizers (and pesticides) and imported protein feed, and with considerably reduced threats to water resources and air quality. Note that this scenario also strongly differs from the agro-food system in the 1960s by a higher NUE, less dependency upon food, and feed imports (Figure 5B), and even lower N leakage to the environment (Figure 6B).

This scenario does not pursue the objective of maximizing productivity. Rather than *sparing land*, it aims to locally close N cycles and could hence be termed *nitrogen sparing*. To be truly biophysically consistent, this paradigm should be extended to *nutrient sparing*, thus including other nutrients, such as phosphorus (P) and potassium (K). The specificity of the biogeochemical cycle of P and K, namely the facts that they do not have gaseous forms and are quite immobile in the soils, would require to account for the soil reserves and past legacy.[72,73] Although such a multi-nutrient approach was not developed in the present paper, it has been shown[74] that moving toward an agro-ecological scenario would be feasible in the next three decades without phosphorus shortage for such an intensive agricultural country as France.

While not excluding food trade when required, the scenario privileges local food supply. This implies giving up land specialization in favor of a multifunctional conception of land planning. In this sense, the scenario described here falls within the *land sharing* paradigm, in which each country or territory aims at

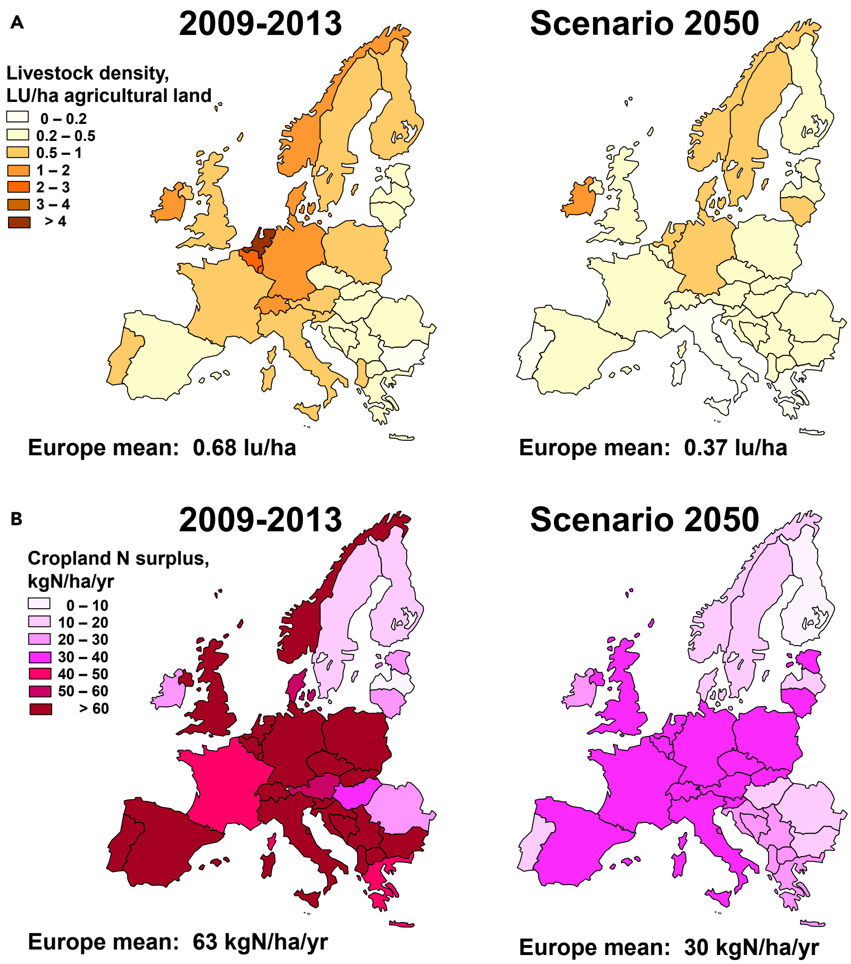

Figure 5. Comparing the agro-ecological scenario with the current situation

Livestock density and cropland surplus Livestock density (in LU per ha total agricultural area) (A) and cropland N soil surplus (B) in the current situation (average 2009–2013) and in the agro-ecological scenario.

delivering the largest possible basket of the required food products, while preserving water resources and air quality; this commitment to the territorial de-specialization of agricultural activities leads to more landscape biodiversity, thereby offering more habitats for non-cultivated species than a specialized agricultural territory.

Table 3. Total European gross traded volume (i.e., sum of imports and exports) between European countries and with other countries, and net import for cereals, oilseeds, fruits/vegetables, and animal products in the periods 1961–1965, 2009–2014 and in the agro-ecological scenario

	Total traded volume, GgN/year			EU net import, GgN/year		
	1961–1965	2009–2014	Scenario 2050	1961–1965	2009–2014	Scenario 2050
Cereals	682	1,228	608	585	−398	−27
Oilseeds and forage	625	2,745	0	624	2,678	0
Fruits and vegetables	77	113	0	61	74	0
Animal products	88	410	248	30	−267	−97

CONCLUSION

We show in this perspective paper, that a fundamental agro-ecological transformation of European agro-food systems is biophysically possible. While not providing directly actionable information for current policy negotiations, our analysis informs about the biophysical option space of sustainable food production and consumption in Europe. A legitimate question about the scenario explored here is whether it has the potential of being generalized globally, from a purely biophysical point of view, given the rapidly growing world population. If not, the search for European self-sufficiency could be seen as a selfish position, denying Europe's role in addressing the global environmental challenge.

However, Europe today is a net importer of proteins from other continents (Figures 2 and 3). Its large imports of protein crops for feeding livestock are far from balanced by the small amounts of proteins exported in cereals and animal products, even accounting for the vegetal to animal conversion efficiency. Therefore, shrinking Europe's integration in world markets would actually relieve some pressure from agriculture outside of Europe.

Based on similar hypotheses as the ones made in the present work, Lassaletta et al.[27] developed a scenario for the global agro-food system at the scale of 12 macroregions in the world at the 2050 horizon. They assumed an equitable diet of 4 kgN/cap/year with 40% animal proteins, preference for animal feeding on the currently available grass and fodder production without feed import, symbiotic N fixation adjusted to the local agronomical possibilities, and recycling of human excreta. International trade was considered to only fill the uncovered needs of some macroregions. With these hypotheses, the world population could be fed in 2050 with much less international trade and much less N pollution than predicted by "classical" prospective scenarios linking diet to GDP in each country, considering agricultural specialization according to competitive advantages of each country, and adjusting synthetic N fertilizer use to the national needs and economic possibilities.[75–80] Several authors[43,81–83] have explored the "option space" of the world agro-food system for diverse human diet and cropping systems intensity while feeding the world population and maintaining unchanged the current total agricultural land, thus avoiding any deforestation. These analyses show that there is a vast range of options for feeding the future world

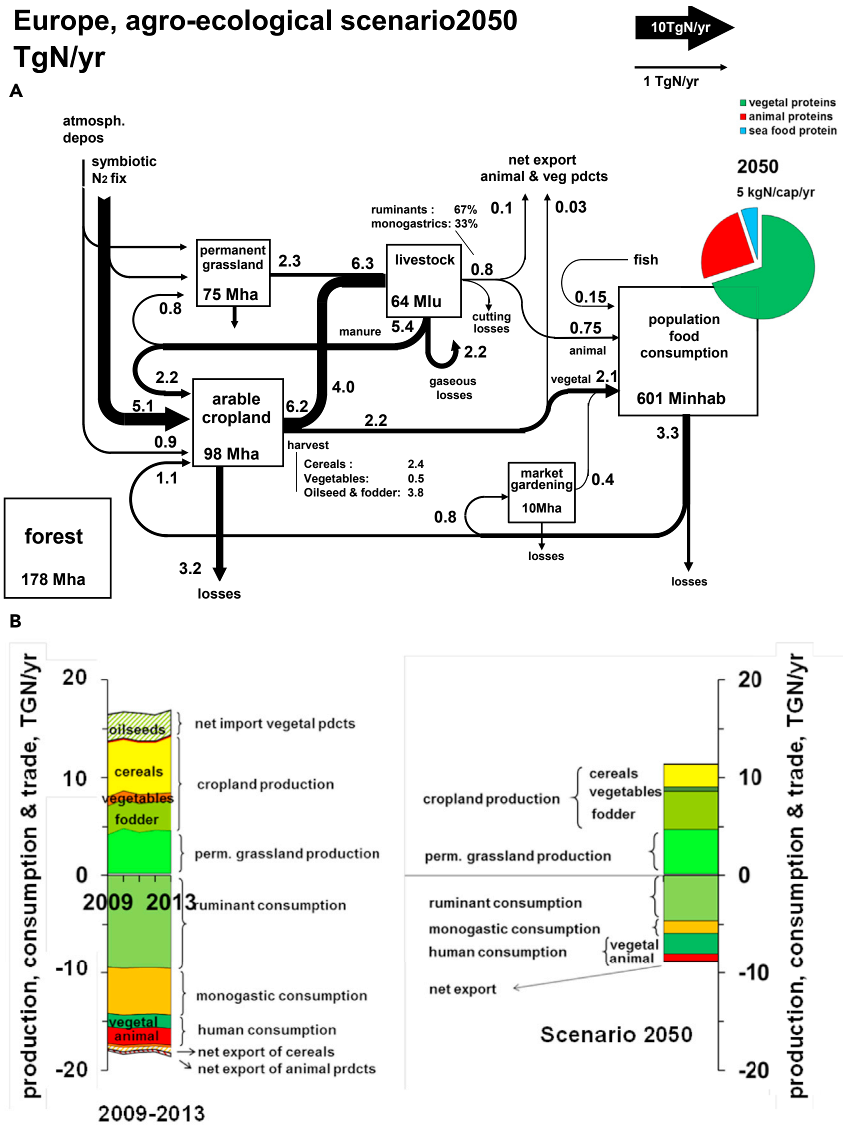

Figure 6. The agro-food system in the agro-ecological scenario for 2050

(A) GRAFS representation of the N fluxes involved. To be compared with the current situation shown in Figure 2.

(B) Availabilities (positive values) and consumption/exports (negative values) of crop production in Europe in 2009–2013 and in the 2050 agro-ecological scenario. (The data shown are calculated as the sum of all country data.) Data for each individual country are available in the XLSfile at https://doi.org/10.6084/m9.figshare.14610105.

population, and that human diet (in particular, the level of animal protein consumption) rather than crop yield is the strongest determinant for that possibility.

The invention, one century ago, of the Haber-Bosch process, and the generalization of industrially synthesized N fertilizer as the basis of the "Green Revolution," in the second half of the 20th century, have often been hailed as major breakthroughs for humanity. As early as 1924, Lotka[84] wrote: "This extraordinary development [of the nitrogen fixation industry] represents nothing less than the ushering in a new ethnological era in the history of the human race, a new cosmic epoch." Several authors[85,86] have estimated that half of humanity's food supply depends on Haber-Bosch N fixation. As a matter of fact, this process has put the global agro-food system on an industrial socio-ecological trajectory from which we now have great difficulty to escape. The success of the Haber-Bosch process and the Green Revolution was such that, for a long time, very little resources were invested in the development of more sustainable agro-ecological options, such as those exposed in this paper.

EXPERIMENTAL PROCEDURES

Resource availability

Further information and requests for resources related to this paper should be directed to the lead contact, Gilles Billen (gilles.billen@upmc.fr).

Materials availability

This research did not produce any new material.

Data and code availability

All the datasets, codes, and algorithms generated during this study are available as a single .xlsm file in the FAIR-aligned Figshare repository at address: https://doi.org/10.6084/m9.figshare.14610105.

Methods and hypothesis for assessing N fluxes

N fluxes through the agro-food system of European countries are calculated from FAOstat data from 1961 to 2013 according to the GRAFS approach.[27] A summary of the main methods and assumptions is presented in Note S1, together with some specific calculations related to the case of Nordic countries for which inconsistencies exist in the FAO data regarding arable fodder crops.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.05.008.

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AUTHOR CONTRIBUTIONS

All authors conceived, discussed, shared the data and calculations, and contributed equally to the study.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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One Earth, Volume *4*

Supplemental information

Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity

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Supplemental Notes

Note S1. Methods and hypothesis for assessing N fluxes

Crop production calculation includes all annual and perennial food and feed crops (grouped as cereals, fodder, fruits and vegetales and others). Detailed N contents used to calculate N harvest are from Lassaletta et al[1].

Total N inputs to arable land include synthetic fertilizer application (corrected for estimation of fertilizer application to grassland [2]), symbiotic N fixation (estimated according to the approach developed by Anglade et al [2,3]), manure application (calculated from animal excretion according to Lassaletta et al[2]) and atmospheric deposition obtained from Dentener et al[4].

Grass production is defined as grass consumed by ruminants (in terms of N), calculated from the food and feed balance of each country:

Grassland production (including scavenging and swill uses) = human needs of vegetal proteins + animal ingestion - local crop production – net import of crop products (equ 1)

This approach was developped by Lassaletta et al [5]. Uncertainties, limitations and comparisons with other models are provided in the supplements of that paper. Our estimates of grass production (except for Nordic countries, see below) are generally in good agreement with estimates from other approaches.

Animal excretion is calculated from the number of animal headsof ruminants (cattle, sheep, goats and other ruminants) and monogastrics (pigs, poultry and other domesticated birds) using time- and region-specific excretion coefficients. A fraction of the excreted N is applied to crops as estimated by Lassaletta et al [2] with some correction for The Netherlands, Ireland and United Kingdom.

Total livestock production is the N content of produced carcasses, milk and eggs, skins, offals and fats. Edible fraction of each products is taken into account for calculating edible production.
Livestock ingestion is calculated as the sum of excretion plus production.

Ammonia volatilization is calculated as 30% of the excreted N that is stored and managed before spreading of manure[6,7]. The calculations were made separately for ruminants and monogastrics.

Cereal consumption by livestock is estimated from the food and feed balance of each country:

Livestock cereal consumption = total cereal production + net import - human consumption (equ 2)

The N fluxes in trade are estimated from the N content (protein-N) of traded agricultural products.

In **Norway, Sweden, and Finland**, about 30-50% of the cropland is used for cultivation of roughage fodder. This area is dominated by temporary grassland, more specifically perennial grass-clover mixtures, in rotation with other crops. This temporary grassland, and other fodder crops, are incompletely covered by the FAOSTAT fodder crop dataset used for most countries in this paper. Therefore we have used various other data sources to assemble a dataset on arable fodder crop production in these three countries.

Specifically, we have estimated the cultivated area, N harvest, and symbiotic N fixation of the main arable fodder crops in these three countries 1961–2013.
The analysis covers, to the extent possible, the crops included in the Eurostat crop category G0000 “Crops harvested green from arable land”, which is subdivided as follows:

- G0000 Plants harvested green from arable land
  - G1000 Temporary grasses and grazings
  - G2000 Leguminous plants harvested green
    - G2100 Lucerne
    - G2900 Other leguminous plants harvested green n.e.c.

G3000 Green maize
G9000 Other plants harvested green from arable land
G9100 Other cereals harvested green (excluding green maize)
G9900 Other plants harvested green from arable land n.e.c.

Where possible, we used **area data** from Eurostat's Annual Crop Statistics[8] to cover the crop codes G1000, G2100, G2900, G3000, and G9000. Data gaps were filled using data from national statistical databases[9,10,11]. Minor remaining data gaps were filled by extrapolation backwards from the earliest available value. The data collection includes the following crops: in Norway, G1000; in Sweden, G1000, G3000, G9000; in Finland G1000, G2900, G9000.

The **N harvest** (including grazing) of each crop was estimated as
harvest (GgN) = area (Mha) · yield (Ggdrymatter/Mha) · N content (GgN / Ggdrymatter).(equ 3)

Yields were based on Eurostat's annual crop statistics[8]. Eurostat and national databases report time series of production, but these time series are incomplete and furthermore not fully comparable over time. However, based on the available data[9,10]. it appears that yields in temporary grassland, the absolutely most important fodder crop in all three countries, have been roughly constant over the last 50 years. We therefore used the average of available yields from the Eurostat annual crop statistics 2000-2017. In Norway, the dry matter content of crop code G1000 was not reported but assumed to be 85% since national yield data are normalized to hay units[9].

A complication with the yield levels of temporary grassland (G1000) is that these grasslands are both mechanically harvested and grazed. Some areas are only mown, others are only grazed, and some are mown one or more times and then grazed in the late season. The available harvest statistics for G1000 appear to account only for mowing which means that they underestimate the total crop production. Relevant data to accurately estimate the grazing component are very scarce, but a recent investigation of Swedish data suggest that the grazing contributes about 20% in addition to the mechanical harvest[11]. At least in Finland and Sweden, similar proportions of temporary grassland are used exclusively for grazing[10,12]. Based on this, we inflated the Eurostat based G1000 harvest data by 20% across all three countries.

N contents of the fodder crops were assumed according to Table S1.

Table S1: ***Assumed composition of fodder crops***.

Eurostat crop code	N content (% of DM)	Comment	References
G1000	2.3	80% grass (2.0% N), 20% clover (3.3% N)	13, 14, 15, 16
G2100	3.0		16
G2900	3.2	90% clover (3.3% N), 10% grass (2.0% N)	16,17, 18, 19
G3000	1.2		20, 21
G9000	2.0	75% cereal forage (1.6% N), 25% legumes (3.0% N)	22, 23, 24

Symbiotic N fixation was calculated assuming the legume shares given in Table 1, and using the same model for symbiotic N fixation as elsewhere in this paper[2,3] .

Note S2. Past trajectory of human diet

Human diet can be estimated as the amount of food actually ingested (actual consumption, i.e., the plate content) or as the amount economically consumed (the supply, i.e., the basket content). FAO data, as well as most national data from economic studies, are issued from availability calculations and refer to the latter, thus including food wastes at the final consumption level (basket content). Dietetic recommendations issued from Public Health organisms, or data issued from individual inquiries, refer to the former (plate content).

The distinction between **supply and effective consumption** has been looked at for the case of France[25], allowing to estimate losses at the final consumption stage, differing between animal and vegetal products (Table S2.1). In the current work, final consumption is defined as supply, thus including losses at the consumption stage.

Table S2. ***N composition of per capita food supply, actual consumption and losses*** *in France in 2001-2009* [25]

	Supply kgN/cap/yr (% total supply)	**Effective consumption** kgN/cap/yr (% total consumpt)	**Losses** kgN/cap/yr (% total losses)
Seafood	0.7	0.3	0.4
Dairy and eggs	1.7	1.0	0.7
Meat	2.8	2.1	0.7
Fruits and vegetables	0.7	0.4	0.3
Cereals	1.3	1.1	0.2
Total animal	5.3 (72%)	3.5 (71%)	1.8 (75%)
Total vegetal	2.0 (28%)	1.4 (29%)	0.6 (25%)
Total	7.3 (100%)	4.9 (100%)	2.4 (100%)

The analysis of the FAO data reveals a rapid increase of **per capita supply of total protein apparent consumption** in most countries of Europe, from a mean of 5.2 kgN/cap/yr in the early 1960s to 6.1 kgN/cap/yr in 2013. Czechoslovakia and Bulgaria are the only countries having experienced a slight decrease in total protein diet during the period (Figure S1)

The **share of animal products** (excluding fish and seafood) in this diet has also increased in all countries, except in UK and Ireland. The average value increased from 44% to 52% during the period from 1961 to 2013; Mediterranean countries (Italy, Greece, Spain, Portugal, Cyprus) but also Romania and Bulgaria, are those where the increase in animal products in the diet was the most significant, reflecting the abandonment of a traditional Mediterranean diet (with 25-30% animal products excluding fish) in favor of a standard modern western diet[26] (Figure S2)

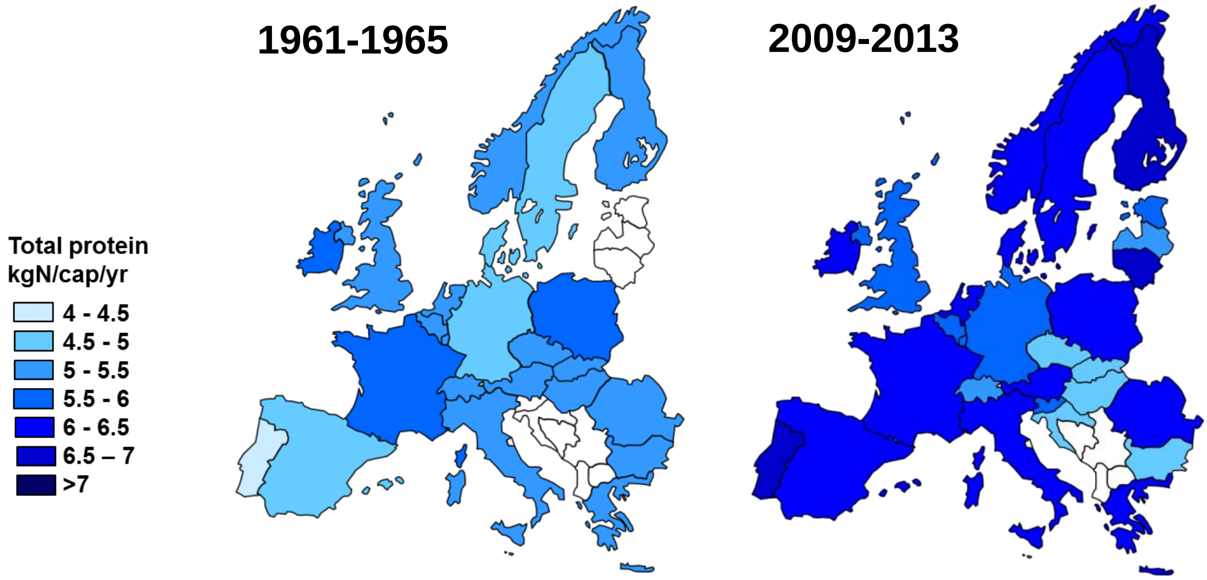

Figure S1. ***Total per capita intake in European countries*** *in the early 1960s and in 2009-2013 (FAO data)*

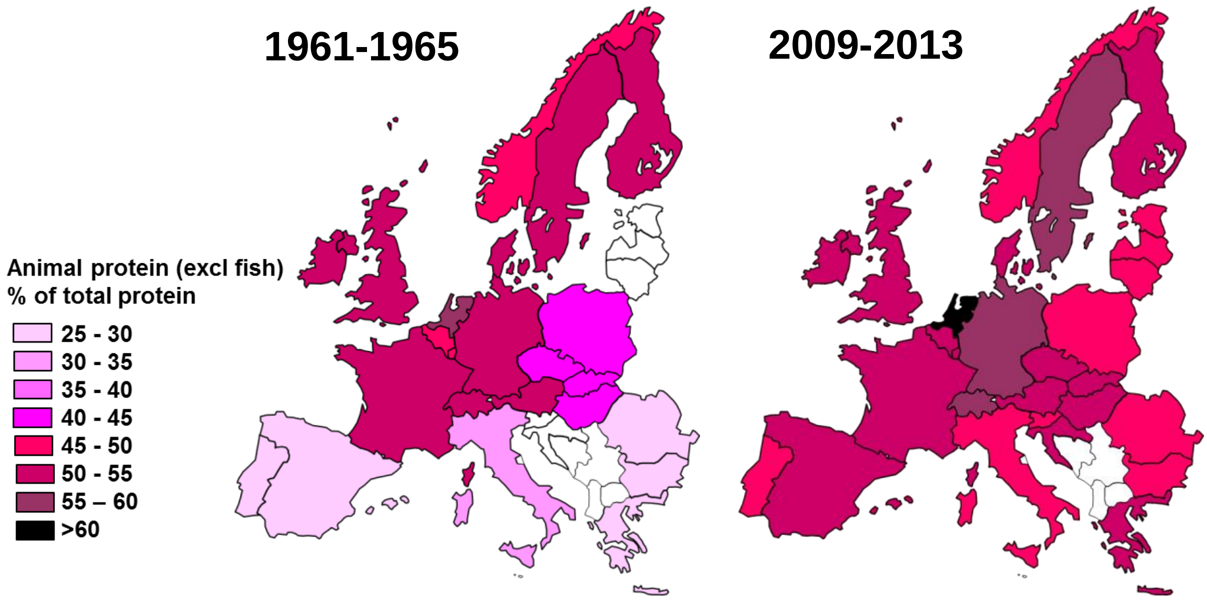

Figure S2. ***Fraction of animal products*** *(excluding fish and seafood) in total per capita intake in European countries in the early 1960s and in 2009-2013 (FAO data)*

Within animal products (excluding fish) currently consumed in Europe, the **share of ruminant products** (milk, cheese, beef and mutton and goat meat) dominates over that of monogastric products (eggs, poultry and pig meat), representing about 56%, with strong contrasts between countries (Figure S3).

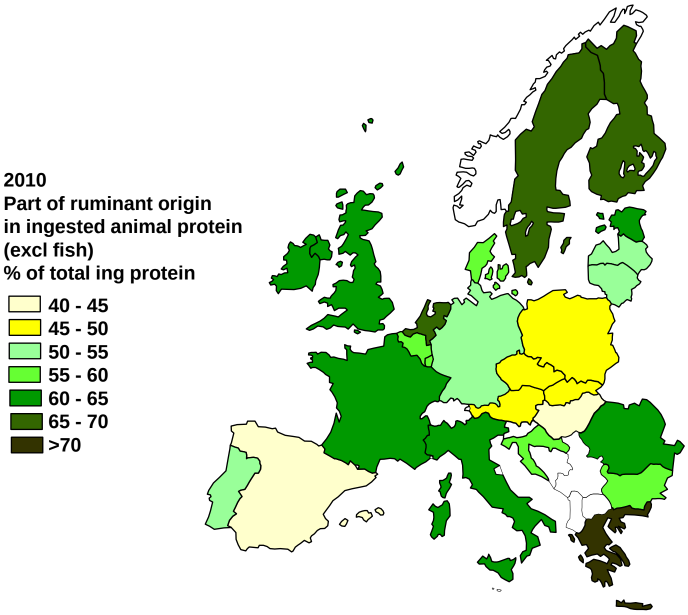

Figure S3. ***Share of ruminant products*** *(milk, cheese, beef, mutton and goat meat) in total animal protein consumption (excluding fish and sea food) in 2010* [2.].

The share of **fish and seafood** in total protein diet did not change a lot since the 1960s. As a mean, it currently represents 6% of total protein diet in Europe. Large disparities between countries reflect strong cultural differences (Figure S4).

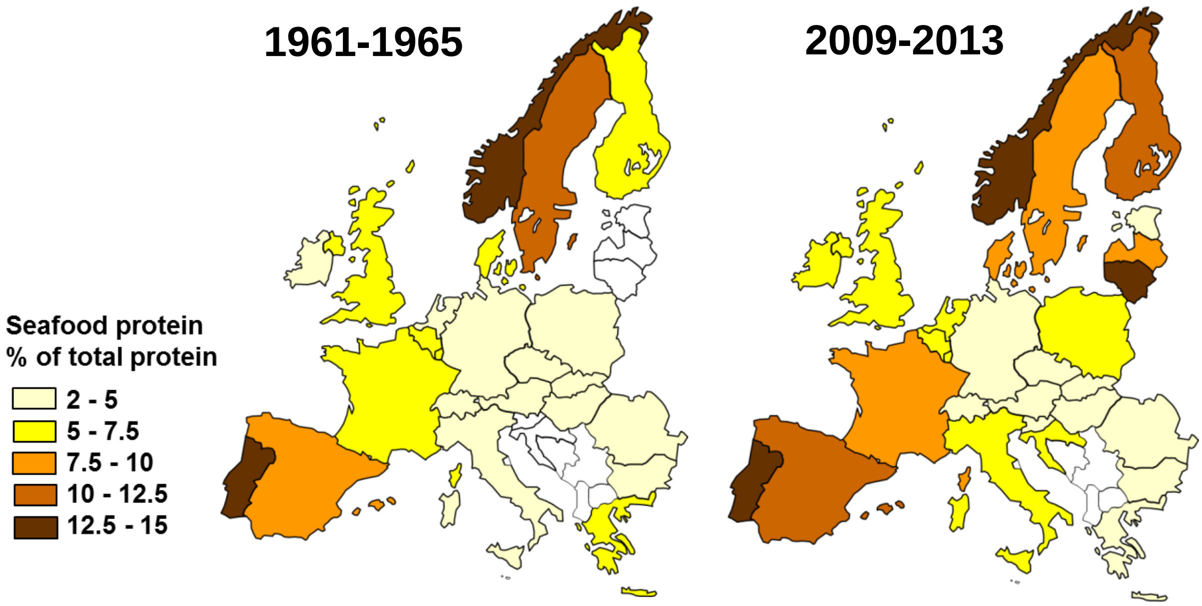

Figure S4. ***Share of fish and seafood products*** *in total protein consumption (FAO data).*

Note S3. An analysis of current agro-ecological cropping systems in Europe and their N supply

The agro-ecological scenario established in this work was based on the analysis of currently used organic farming practices in Europe, which have proved their worth and sustainability despite a reduced production in cereals, but much less exogenous fertilizer inputs. This note presents the data available to establish a **typology of organic crop rotations** in the different European countries, as well as to quantify their level of nitrogen supply.

Eurostat[8] provides data on the **arable area under organic farming**, distinguishing between cereals, dry pulses, root crops, industrial crops and plants harvested green from arable land. Pulses and fodder legumes harvested green represents the N fixing components of the rotation. Pulses and plants harvested green most often account for more than 60% of the total arable area under organic farming in Nordic countries, UK, Slovakia and Portugal. Pulses cover less than 20% of total N fixing areas, except in Romania, Bulgaria and Mediterranean regions of Greece and Spain. In the latter country they reach more than 50% of the total N fixing area.

Unfortunately, the Eurostat data do not provide a comprehensive picture of the main organic rotations in European cropping systems.

An extensive literature compilation of **crop rotations in organic farming** systems in European countries was therefore undertaken (Table S3). It complements the data already gathered for France and Spain[28], as well as for the whole of Europe[29,30].

Based on this information, a tentative map of the major organic crop rotations in current use in Europe has been established (Figure S5), relying on two criteria: the length of the rotation and the nature of the main N fixing crop.

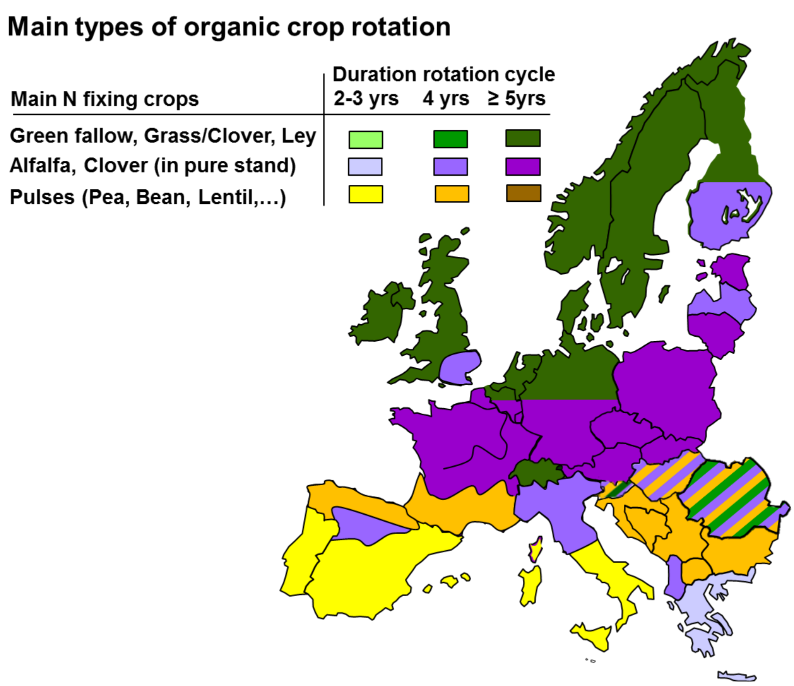

Figure S5. *Tentative map of **dominant crop rotations in organic cropping systems** in Europe.*

Table S3. ***Crop rotations in arable organic cropping systems*** *in different regions of Europe, described in the literature. The rotations effectively used in commercial organic farms are given priority. Those in agronomic assays are only included if it was stated that they are representative of commercial farms.*

Country /Region	Rotation	nb years	refs
France			
(Paris basin)	Alf(x2) - wWh - Cer2 - other - GrL – wWh - Cer2	8	31,32,33
(Normandy)	Clo(x2) - Maize -wWh - GrL - wWh - Cer2	7	34
(N-Pas-de-Calais)	Alf-Potato - wWh - GrL - wWh - Cer2	6	34
(Grand Est)	Ley(x2) - wWh - Cer/GrL - wWh - Cer2	6	34
(Alsace)	Alf(x2)-wWh - Cer2 - Cer3 - Soy(x2) - Maize - Cer2	9	34
(Britanny)	Clo(x2) - Maize - wWh - Cer2 - GrL - wWh - Cer2	8	34
(Vendée, Charente)	Soy - wWh - Maize - GrL - wWh - Maize	6	34
(Loire Aval)	Clo(x2) - Maize - GrL - wWh - other	6	34
(Loire Centrale)	Alf(x2) - wWh - Cer2 - GrL - wWh - other	7	34
(Loire Amont)	Alf(x3) - wWh - Cer2 - Sunflower - GrL - Maize Sunflower - Cer2	10	34
(Jura)	Alf(x2) - GrL - wWh - Cer2 - Maize	7	34
(Savoie)	Alf(x3) - wWh - Cer2 - Sunflower - GrL - wWh - Cer2	9	34
(Ain-Rhone)	Alf(x2) - Maize - GrL - wWh - Cer2 - Maize	7	34
(Alpes)	Alf(x3) - wWh - Cer2 - Sunflower - wWh - Cer2	8	34
(Isère-Drome-Ardeche)	Alf(x2) - wWh - Cer2 - Sunflower	5	34
(Aveyron-Lozère)	wWh - Sunflower - GrL	3	34
(Garonne, W Pyrénées)	Soy - Sunflower - Cer2	3	34
(Gironde, Landes, Dord)	Soy - Maize - Cer2 - GrL	4	34
(Cantal, Corrèze)	Alf(x3) - wWh - Cer2 - Sunflower - GrL - Maize -Sunflower - Cer2	10	34
(Cd'Azur, Gard, Héraut)	wWh - Sunflower - GrL	3	34
Spain			
(Galicia, Asturias, Cantabria, Basque C.)	sBarl - Fababean - Potato - wWh	4	35
(N Castilla Leon)	Alf – Root crop – Potato – Maize (irrigated)	4	30
(Mediterranean Spain)	green fallow - Cereal	2	36
	Vetch (hay or green manure) – Cereal		
	Chickpea - Cereal		
Italy (Northern Italy)	Grass - wWh – Alfalfa (x2) - Maize	5	37
(Central & North)	Soy - Maize - Wheat	3	38
	wWh - Alf(x3)	5	39
	GC/Maize - sBarl - Clover - DWh	4	39
Austria (Central)	sBarl - wWh - GC(x2) -sWh – Potato	6	37
(Foothills Alps)	Alf(x3) – wWh – Sunflower – Barl – FabaBean -wWh(x2)	9	30
Denmark (Western)	GC(x2) - Barl/Gras - Beet - Oat/Grass-Barl/Peas - Pea/Grass	6	37
	GC – Cabbage - Barl/Grass – Carrots - Peas/Radish-Barl	6	
	Sbarl/GC - GC(x3) - wWh	5	40
	Sbarl/GC(x2) - WWh - sOats - sBarl/Pea	5	40
	Sbarl/Pea - GC(x2) – sOats – wWh - SugarBeet	5	40
	Ley(x2) – sBarl – wWh – Maize - wBarl	6	30
Finland (Southern)	Rye - Peas/Oat - Barl - Grass	4	37
	Rye - Clover Ley(x2) - Potato	4	38
Germany (NE)	Oat - WRye - Peas - WRye - Fallow	5	41
	WWh - wRye - Peas - Triticale- Fallow	5	42
	Green fallow – wWh - Peas - Rye - sBarl	5	43
(Southern)	GCA - Potato - wWh - Sunflower - GCA - wWh – wRye	7	44
Netherlands (Central)	GreenPea - sWh - Potato - KidneyBean - Onion –Carrot	6	45
	Potato - GC - Cereal - Cabbage - Cereal - Carrot – Peas	7	46
	GC(x3) - sBarl - wWh - Potato - SugarBeet	7	47
Sweden (South)	Broadbean/Oats - Ley(x2) - SugarBeet - Lupine/oats - wWh	6	48
	SBarley – Ley (x2) - SugarBeet - Oats/Peas - Potato	6	48
	Oats/Pea - Ley (x3) - sBarl - Potato	6	48
(all country)	Barl - Ley(x2) - wWh - wWh - Beans	6	49
	Barl/Pea - Ley(x3) - wWh	5	49
	Oats - Ley(x3) - Oats/Peas	5	49
	Oats - Ley(x2) - wWh - Oats - Peas	6	49
Poland	Potato - Wh - Oat/Peas - Cereal/Legume - Rye	5	50
	Potato - wWh - sBarl - CG	4	50
	Alf (x2) - WWh(x2) - SugarBeet - Barl	6	30

UK	Red Clover - Potato - wWh - Oats	4	51
	Red Clover - wWh - FabaBeans - wWh	4	51
(East England)	RedClover(x2) - Potato - wWh - sBean - sWh/Clover	6	51
	CG(x2) - wWh - Potato - Beans - Potato - sBarl	7	52
	Ley(x3) - Cer(x2)	5	53
Latvia	Barl - Red Clover - Rye - Potato	4	54
Norway	Barl-Ley (x3) - Fodder Beet - GC - sWh - Oat/Pea	8	55
	Sbarl-CloverLey(x3) - Swede - Oats	6	56
	Barl - GC - SWh - Oats - Peas	5	57
Switzerland	Potato - wWh/vetch - Cabbage - wWh - wBarl – GC	6	58
	Barl - GC(x2) - Cabbage - wWh	5	59
Slovakia	Bean/Alf - Alf - wWh - Maize - wRape - Peas - Maize - wWh	8	60
Greece	Clover - Maize	2	61
	Cereal - Green manure - Cotton	3	62
Romania	Oats/Clover - Clover - Wh - Maize	4	63
	sWh/Fodder Turnip - Fodder Maize - Potato – GC	4	64
	Peas – wWh – Rapeseed - wWh	4	65
	wWh – Maize – Sunflower - Soy	4	66
Portugal (Alentejo)	DurumWheat – Sunflower - Pea	3	67
Slovenia	Maize – sBarl – RedClover - wWh	4	68
	Maize - Oats/Grass - Maize - wWh/Fodder Rape	4	68
	Oats - GC - Pumpkin - WWh - Maize	5	68
	Peas - wWh - wBarl - Maize - Oats	5	68
Albania	Maize-wWh - Clover/Bean - wWh	4	69
Bulgaria	Soy – sOats - Pea/Vetch - Maize	4	70
	Peas - wWh - Maize - Fallow	4	71
Croatia	Soy - wWh - Oilseed - Maize	4	72
Estonia	Barl - Red Clover - wWh - Peas - Potato	5	73
Lithuania	Ley(Alf40%,Clov40%)(x2) - wWh - Potato - sBarl	5	74
Hungary	Lupine (x2) - Rye - Potato	4	75
	Alf - wWh - Oats - Sunflower	4	76

w (prefix) = winter cultivation
s (prefix) = spring cultivation
Alf = Alfalfa
Wh = Wheat
sBarl = Barley
Cer2,3 = secondary cereal
GrL = grain legume
GC = Grass/Clover
GCA = Grass/Clover/Alfalfa

The **overall yield of a crop rotation** depends on its average N supply. In organic farming, besides inputs of animal manure and atmospheric deposition (see below), N is brought mainly through symbiotic fixation by the legume crops inserted in the rotation which introduces new N into the system. Symbiotic N fixation can be calculated from the N content of legume crops yield according to the simplified method of Anglade et al.[2,3].

For grain legumes: N fix = 1.23 * Nyield

For fodder legumes: N fix = 1.47 * Nyield

N content in the most common N fixing crops were taken as shown in Table S4

Table S4: ***Nitrogen (N) content in legume crops** (*[1, 77]*)*

crop	%N in harvested products
Pulses in green manure	3.5
Dry vegetables (lentils, chick peas, etc)	3.6
Faba bean, horse bean	3.5
Alfalfa and clover	2.8
Non legume grass	1.25
Natural meadow	2.05

The **yield of the main N fixing crops** involved in the organic crop rotation listed in Table S3 is provided by Eurostat[8]. We used the data for pulses. For fodder legume, the data provided by the sources listed in Table S3 were used. Table S5 gathers the result of these calculations.

Table S5: *Symbiotic nitrogen fixation rate of the main fixing crops* *involved in organic crop rotations in Europe*

Country	crop	Frequency in the rotation*	Yield (tonDM/ha/yr)	N Yield (kgN/ha/yr)	N fixation (kgN/ha/yr)	refs
Albania	Clover	1/4	3	84	123	59
	Bean	1/4	1.3	46	56	78
Austria	Alfalfa	3/9	5.5	154	225	37
	Pulses	1/9	3.9	137	168	8
Belgium	Pulses	1/6	5	175	216	8
	Alfalfa	1/6		200	295	34
Bulgaria	Pulses	1/4	2.7	94	115	8
Croatia	Pulses	1/4	2.9	103	126	8
Czechoslovakia	Pulses	1/6	3.9	137	168	8
	Clover/Alfalfa	1/6	11.4	200	295	78
Denmark	Peas	0.5/5	5.3	116	143	37
	Grass/Clover	2/5	7.8	160	71	40
Estonia	Grain legume	1/5	1.4	49	60	8
	Clover	1/5	10	200	294	8
Finland	Grain legume	1/5 [40%	1.4	49	60	8
	Clover	1/5 [40%]	9.3	260	383	8
	Grass/Clover	2/6 [60%]	9.3		78	8
France	Alfalfa	2/8 [70%]		275	400	34
	Pulses	1/8 [70%]		60	74	34
	Pulses	1/3 [30%]		40	50	34
Germany	Peas	1/5 [15%]			66	42
	Grass/Clover	2/7 [75%]			260	82
Greece	Red Clover	1/3	4.1	122	179	8
Hungary	Pulses	1/4 [50%]	1.4	51	62	8
	Alfalfa	1/4 [50%]	3	84	123	8
Ireland	Grass/Clover	3/6	4.9	100	61	8
Italy	Pulses	1/3 [40%]	3.3	115	141	8
	Alfalfa	2.5/5 [45%]			175	37
	Clover	1/4 [15%]	3.9	109	134	39
Latvia	Clover		10	200	295	8
Lithuania	Clover	2/5	10	200	295	8
Netherlands	Pulses	1/6	4.1	142	175	8
	Grass/Clover	1/6	30	300	132	8
Norway	Ley		7.5	154	93	55
Poland	Pulses	1/6	1.2	42	52	8
	Alfalfa	1/6	4.4	123	181	8
Portugal	Pulses	1/3	0.7	25	30	8
Romania	Pulses	1/4 [33%]	1.7	60	73	8
	Clover	1/4 [33%]	4.9	137	202	8
	Grass/Clover	1/4 [33%]	4.9	100	61	8
Slovenia	Pulses	1/4 [33%]	1.7	61	75	8
	Clover	1/4 [33%]	5.8	162	239	8
	Grass/Clover	1/4 [33%]	5.8	119	72	8
Spain	Chick Pea	1/2 [30%]		40	50	80
	Vetch(green manure)	1/2 [20%]		70	103	80
	Alfalfa	1/4 [20%]		70	103	80
Sweden	Ley	3/6	6.6	120	81	48
	Pulses	0.5/6	2.2	75	94	8
Switzerland	Ley	2/5	4	107	64	8
	Pulses	1/5	3.9	137	168	8
UK	Ley	3/5 [70%]	4.9	100	61	8
	Pulses	1/4 [30%]	3.1	109	133	51
	Red Clover	1/4 [30%]	10	200	295	51

*The fraction indicates the number of occurrence in the total number of years in the rotation, from the data in Table 1; [%] indicates the fraction of total cropland area occupied by the corresponding rotation, when several rotations are considered in the same country.

Using the dominant crop rotations described in Table S3 and the figures of Table S4, the mean soil N input through symbiotic N fixation over the complete crop rotation cycle can be estimated for each country (Figure S6). It ranges from 20 to 100 kgN/ha/yr. To this should be added the N fixation by legume intercrops possibly inserted in the rotation before spring crops, or undersown with cereals.

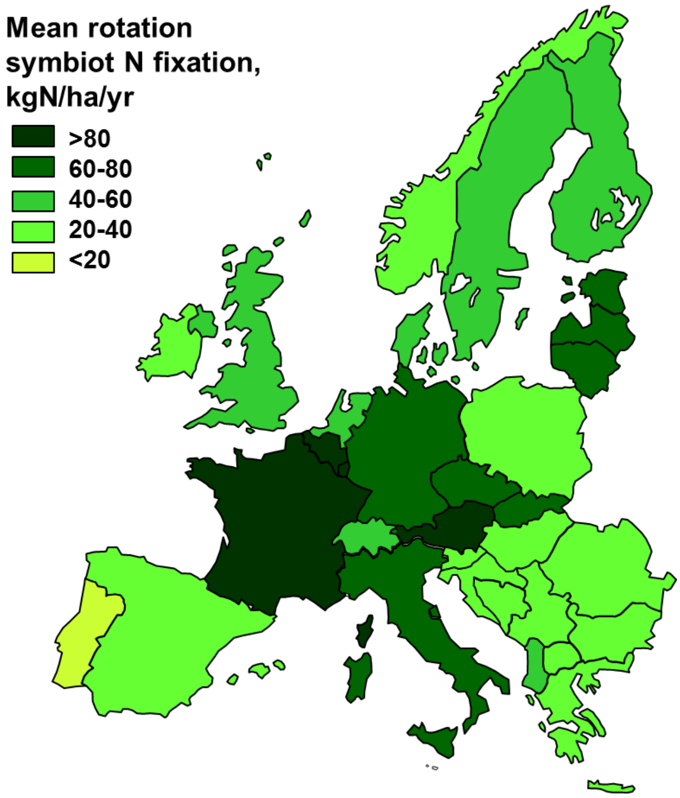

Figure S6. ***Mean of N soil input through symbiotic N fixation*** *integrated over the whole crop rotation cycle of arable cropping systems described in Tables 1 and 3.*

In the elaboration of the agro-ecological scenario, because no synthetic N fertilizer input is considered and because symbiotic fixation is fixed a priori by the choice of a crop rotation scheme (see above), livestock density remains the only lever of intensification of cropping systems, through the **application of manure**. Moreover, livestock density also determines the level of atmospheric deposition of reduced N compounds such as ammonia (see below).

As a simplified way of calculating N inputs to cropland as manure, the following calculation rules are applied:

(i) 30% of total N excreted indoors by livestock of all kinds is considered lost to the atmosphere during the processes of manure management and storage [81,82]
Ruminants are considered to spend 0, 3 or 6 months/yr indoors in Southern, temperate or Nordic countries respectively. Monogastric animals are considered spending most of their time indoors or on non-productive land.

(ii) An additional 20% loss occurs during application of manure, which will be assumed concentrated on arable land, including temporary grassland, but excluding permanent grassland[81,82].

(iii). Direct ruminant excretion outdoors concerns temporary grassland (leys and alfalfa or clover meadows) as well as permanent grassland, pro rata their respective areas. During excretion outdoors, 20% loss of ammonia occurs, but this part of the excretion is not subject to management loss.

Atmospheric total N deposition (as oxidized and reduced species, under wet and dry forms) is provided by the results of the EMEP model[83] at the resolution of a 50×50-km grid over the whole of Europe since 1980.These data are the result of a transport and deposition model fed by national inventories of the sources of atmospheric pollution and validated with measurements of deposition.

These data generally show a gradual decrease since 1980 in most regions, except in those with high livestock densities. For French regions, Le Noë et al[84] showed that Inter-regional variability is largely explained by differences in livestock density (expressed in LU per km² territory), as shown in Fig. S7. The extrapolation to zero livestock provides a background value of 10 kgN/ha/yr, which accounts for about 60% of the maximum deposition rate observed in France. This background value reflects atmospheric deposition related to other sources than local livestock, probably mainly traffic and industry, including in remote regions.

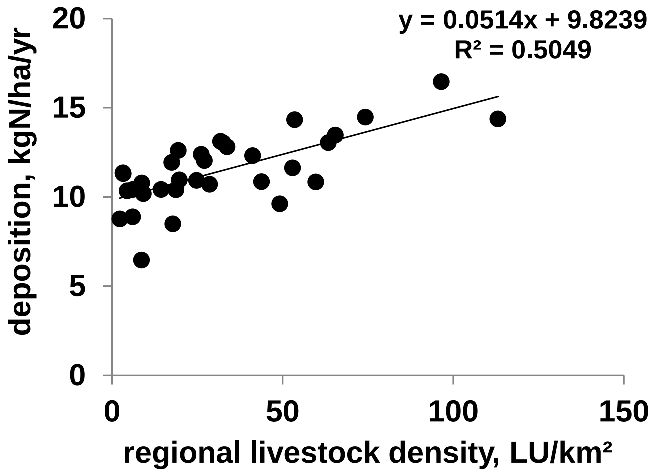

Figure S7. ***Relationship between atmospheric nitrogen deposition and livestock density*** *for agricultural regions in France in 2006* [84].

Based on the results of Figure S7, a livestock-related N deposition value can be determined:
livestock-related deposition = 0.05 kgN/ha/yr x livestock density (in LU (LU/km². (equ 4)

In the scenario, this value is used to calculate atmospheric N deposition for each country in Europe (see the manuscript), as a function of livestock density (LD), assuming no change in the background deposition of each country:

$$\text{deposit}_{(scen)} = \text{deposit}_{(current)} - 0.05 \times [\text{LD}_{(current)} - \text{LD}_{(scen)}] \quad \text{(equ 5)}$$

In coherence with the options of reconnection and circularity in the agro-ecological scenario, the **re-use of human wastes** as fertilizer has been considered in the scenario. This would imply a paradigmatic change in the management of urban wastes, as deep as the change in the logic of agricultural systems we propose here for agricultural practices themselves. Simple technologies for source collection of human urine (which contains 80% of the excreted nitrogen[25]), recovery or concentration of N from urine as well as field application as fertilizer are already available[85,86]

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