Balancing organic agriculture expansion target and climate goals in Europe without outsourcing emissions is possible

Supplementary Material A : Supplementary figures, discussion and methods

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Content

1 Supplementary Figures

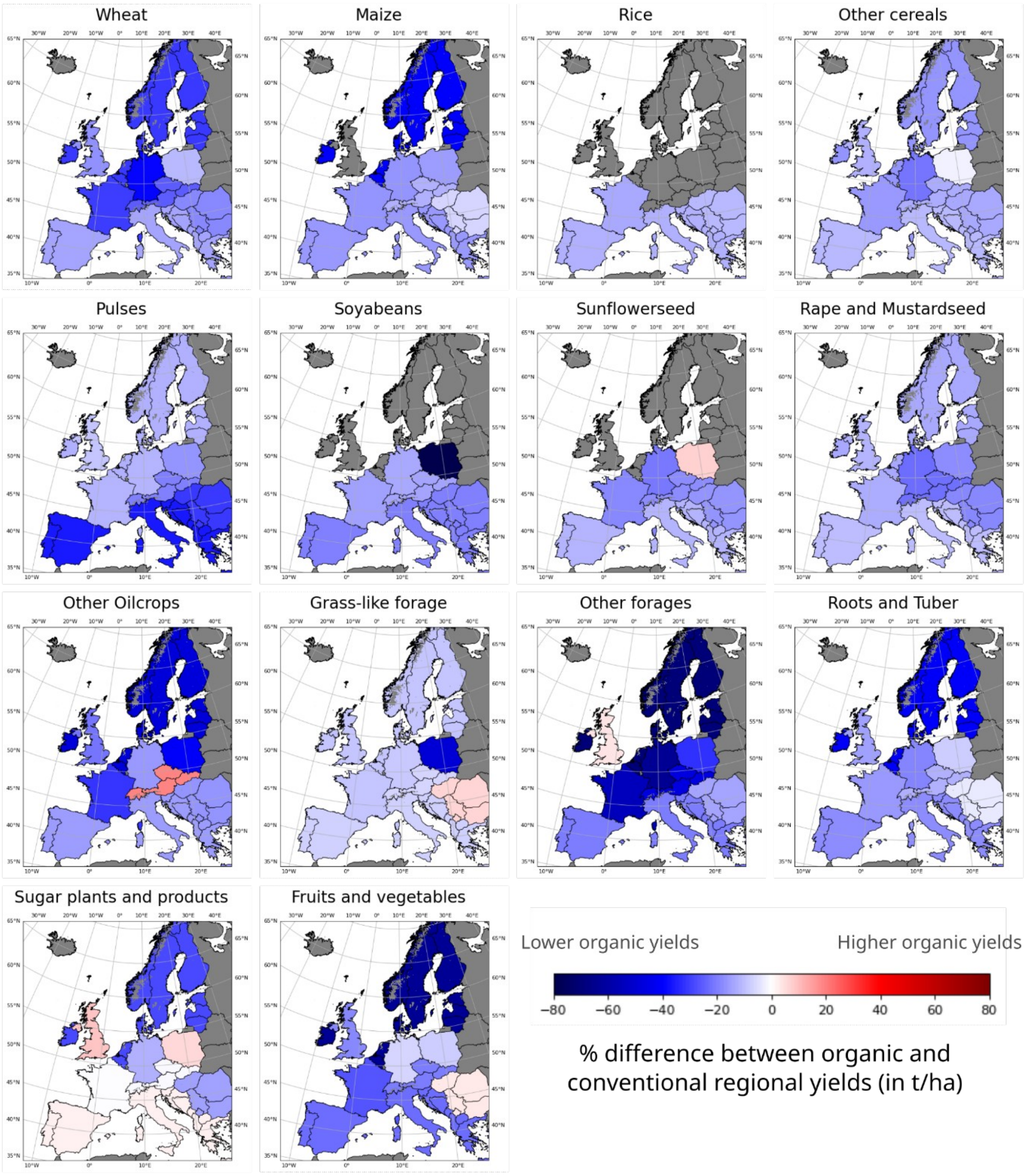

Figure S1 - Difference, in %, between organic and conventional average yields in 2050 in the OAU scenario for the variant with 25% organic croplands, expressed at the regional level (8 European sub-regions) and at the level of 14 GlobAgri crop groups. Organic crop yields were computed at the grid cell and specie level in GOANIM. Regional averages are area based weighted averages. The grey color indicates that a region does not produce the considered crop group.

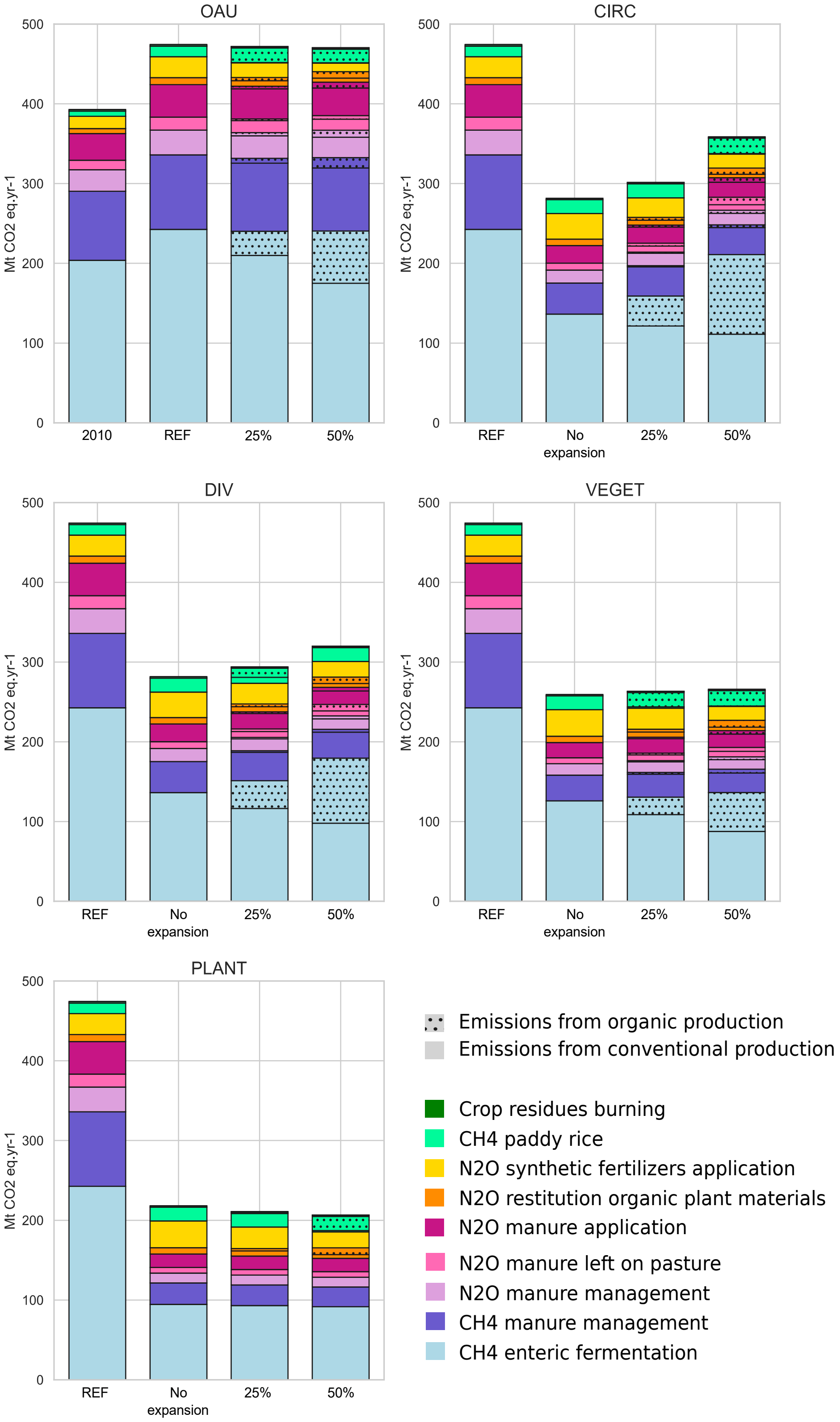

Figure S2 - Greenhouse gas emissions from agriculture in Europe, in milion tons CO$_2$ equivalent per year, in the different scenarios, distinguished per emissions source and type of farming systems. Emissions from agriculture refer to emissions from crop and livestock production. Those associated with livestock production are manure management and enteric fermentation, the other being associated with crop production. In the first panel, values for the OAU scenario are compared to 2010 and REF. In the other panels, values are compared to REF only. In the PLANT scenario, some emissions linked to livestock production remain because conventional livestock products are still produced for export to foreign market

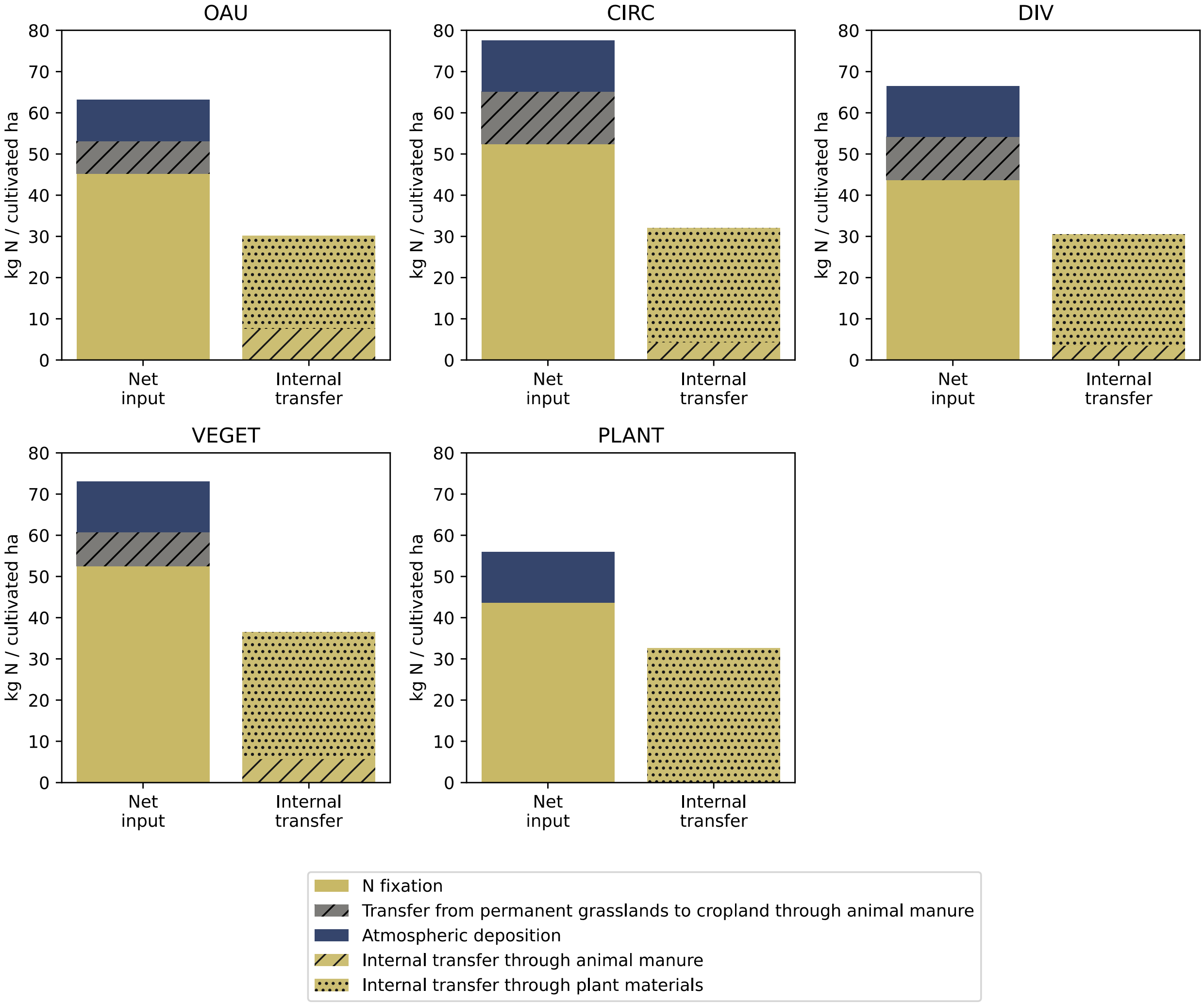

Figure S3 - Nitrogen (N) inputs to organic croplands simulated in GOANIM, in kg N per ha cropland, in the different scenarios for the variant with 25% organic croplands. These figures represent the share of N inputs effectively available for crop uptake (after deducing direct and indirect losses following application of organic fertilizers). N inputs were computed at the grid cell level in GOANIM. Here, the values are summed-up at the level of Europe. For each animal species, we assumed that the proportion of N in manure originating from permanent grasslands (which represents a net input to croplands, conversely to N in manure originating from temporary grasslands) is represented by the share of protein intake from permanent grasslands consumption relative to the total intake of proteins, retrieved from GOANIM output

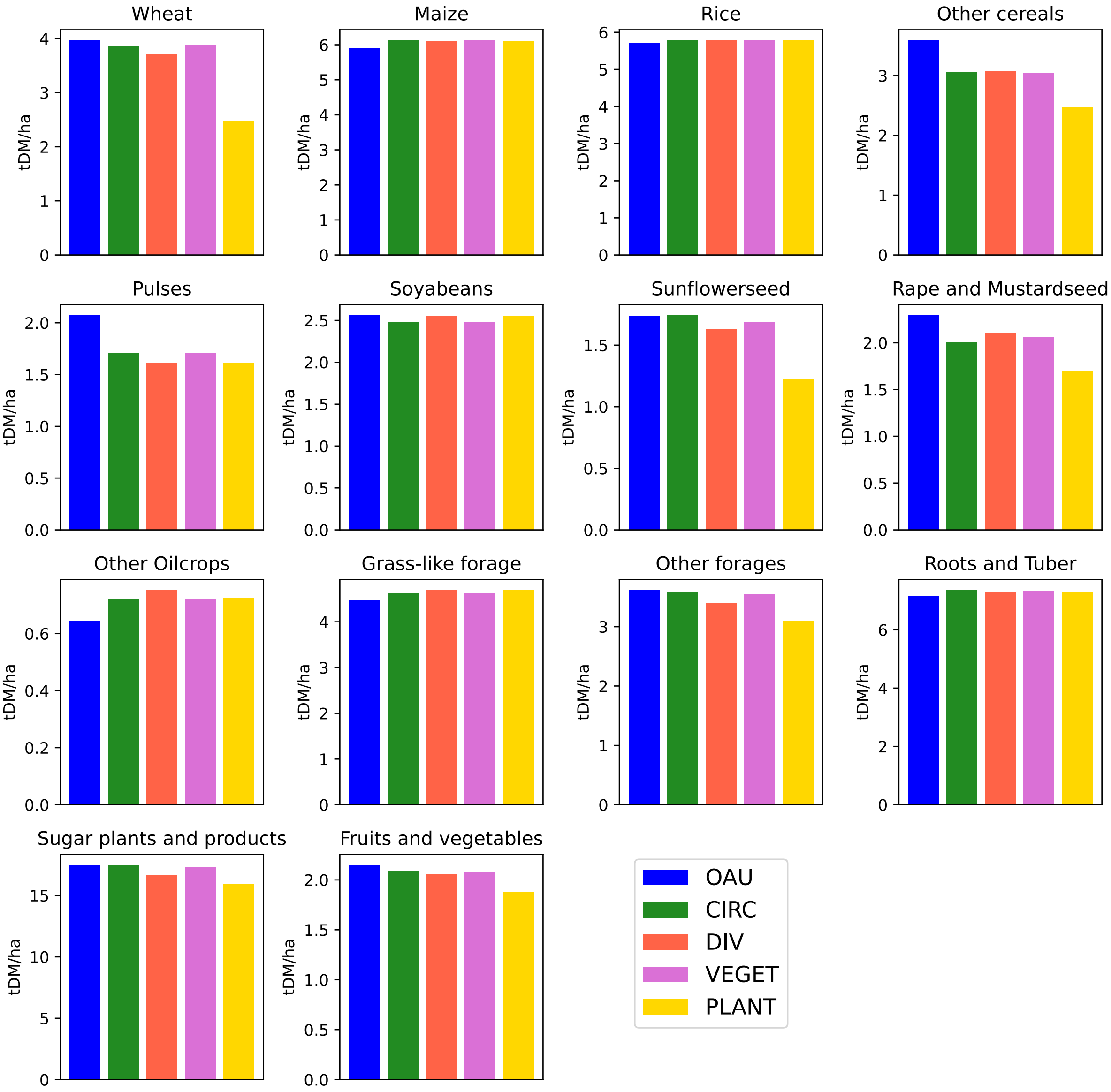

Figure S4 - Average organic crop yields per crop group, in tons of dry matter (DM) per ha, in Europe in the different scenarios for the variant with 25% organic croplands. In the GOANIM model, crop yields are computed at the species level in each grid cell. In the figure, the yields are aggregated at the European scale and grouped into 14 crop groups according to GlobAgri's terminology (Table S11). Note that the average yields of other cereals and pulses include those of crops cultivated in mixed cropping, which is why yields are on average higher in the OAU scenario for these two groups, as mixed cropping is not practiced in this scenario (see the computation of mixed cropping, section S3.1.1.2)

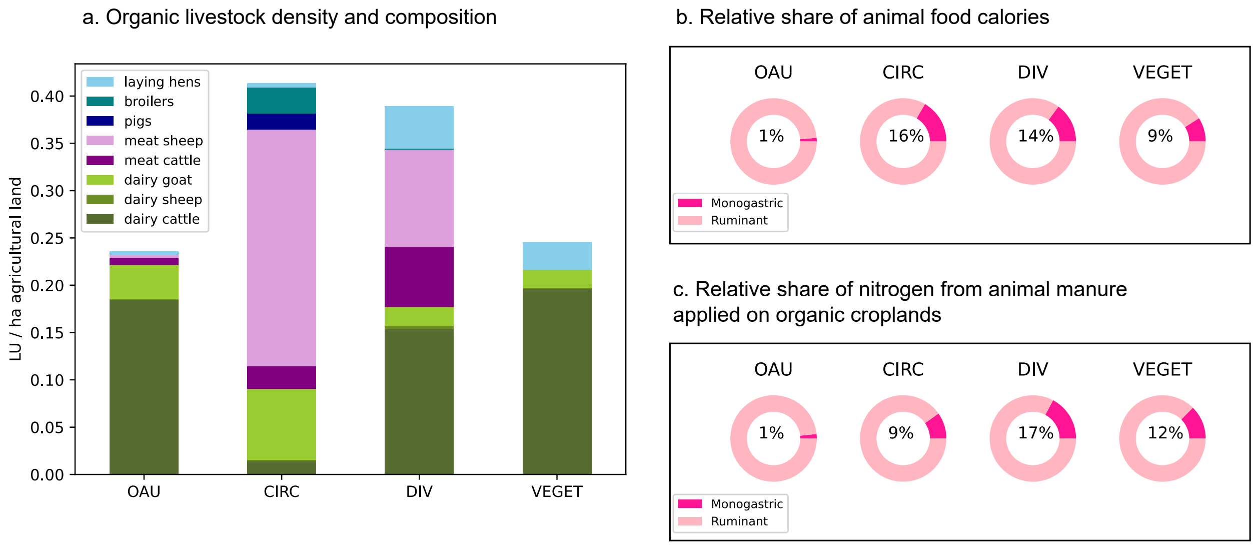

Figure S5 - Panel a). Organic livestock density, in livestock units[1] (LU) per ha of agricultural land, and composition of livestock production, as simulated in GOANIM in the different scenarios for the 25% organic variant. Panels b) and c) illustrate the relative contributions of ruminant and monogastric to organic animal calorie production (b) and nitrogen from animal manure applied to organic croplands (c). In the GOANIM model, livestock numbers were calculated for each grid cell. Here, the figures represent the European average. The PLANT scenario assumes no organic livestock production and is not represented in these figures.

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[1] Reference unit used to aggregate livestock from various species and age as per convention, through coefficients established on the basis of feed requirement of each type of animal. https://ec.europa.eu/

2 Supplementary results and discussion for the 75% and 100% organic variants

We simulated all scenarios with 75% and 100% organic farming variants. Our results show an acceleration in the demand for croplands in Europe when organic farming share exceeded 50% of croplands (Figure S6).

This acceleration can be explained by some main features of our approach:

(i) The initial trade structure (product specific import ratios and export shares) is based on the 2010 observed situation, with conventional farming being predominant in Europe.

(ii) Export market shares can only decrease if a region reaches its maximum available cropland area. This assumption was retain to explore how to expand organic farming in Europe without driving a shift in emissions to other regions.

(iii) Since organic crop rotations constrain the relative share of each crop group in the total organic cropland area, increasing the organic area of a particular crop group means increasing the total organic cropland area

(iv) The proportion of organic area within the total agricultural area (i.e. the organic share) is exogenous. This means that conventional production has less freedom to adjust when the share of organic farming is high.

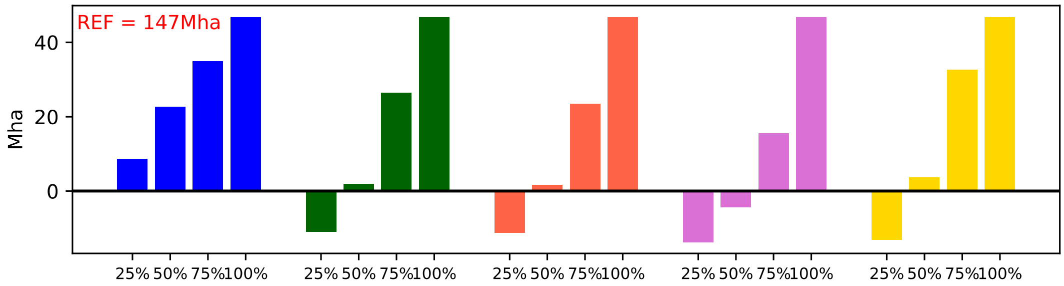
In 2010, Europe was a net exporter of wheat (51 Terra kcal net exports) and secondary cereals (17.7 Tkcal). Some sub-regions, such as South Europe, were also significant exporters of fruits and vegetables, while others, such as France, Eastern Europe, and Central Europe, were net exporters of oil crops.

When the simulated share of organic farming exceeds 50%, the limited proportion of these crops in organic crop rotations, combined with comparatively lower yields in organic farming, would lead Europeans regions to significantly increase their total cropland requirements in order to be able to produce enough quantities to supply both domestic and export markets. However, at a certain point, the maximum cultivable land constraint would become binding in Europe and export market shares would be reduced regardless. In the OAU, CIRC, and VEGET scenarios, this is primarily illustrated by oil crops (Figure S7). In the DIV and PLANT scenarios, it would mostly be the low share of primary cereals in organic rotations that would lead to the additional cropland requirements. Furthermore, at 100% organic farming, the proportion of land allocated to fruits and vegetables would be insufficient to maintain export shares, regardless of the scenario.

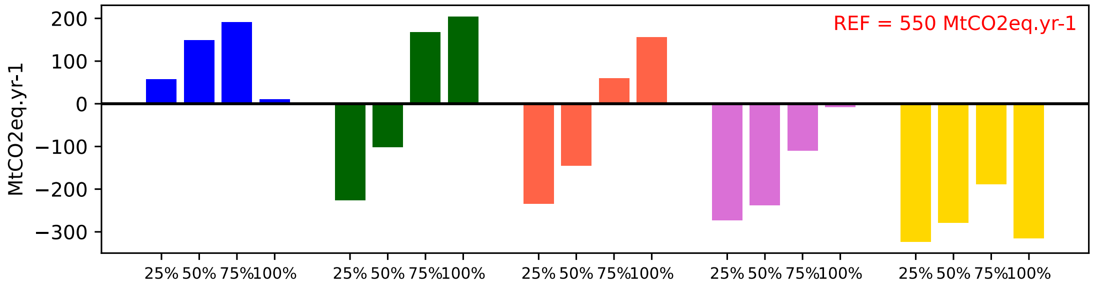
It is important to note that the decrease in export market shares would not always result in a deterioration of the European net export balance. For instance, in CIRC and DIV, even though exports volumes of oil crops would not be maintained in the 100% organic variants, the net balances would improve following a decreased demand for oilseed cakes for animal feed (Figure S8). Moreover, in all scenarios, Europe's contribution to global exports of pulses, soybeans, secondary cereals, and roots and industrial crops would improve significantly (with the exception of OAU for roots).

Therefore, the results of the 75% and 100% organic farming scenarios lead us to conclude that the trade structure of Europe in 2010 is incompatible with organic farming rotations as presented in this study. The demand for croplands in these scenarios could be significantly reduced by simulating human diets and trade structure better suited to organic production.

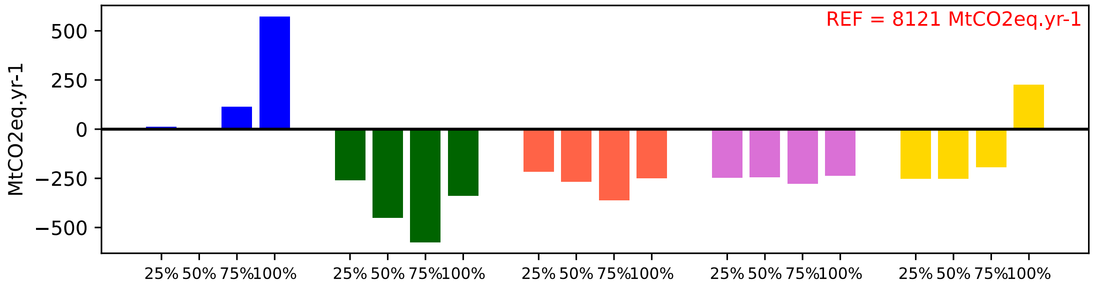
a). Changes in cropland requirements in Europe compared to the REF scenario.



b). Changes in GHG emissions (Agriculture + LUC) in Europe compared to the REF scenario.



c). Changes in GHG emissions (Agriculture + LUC) outside Europe compared to the REF scenario.



d). Changes in global GHG emissions (Agriculture + LUC) compared to the REF scenario.

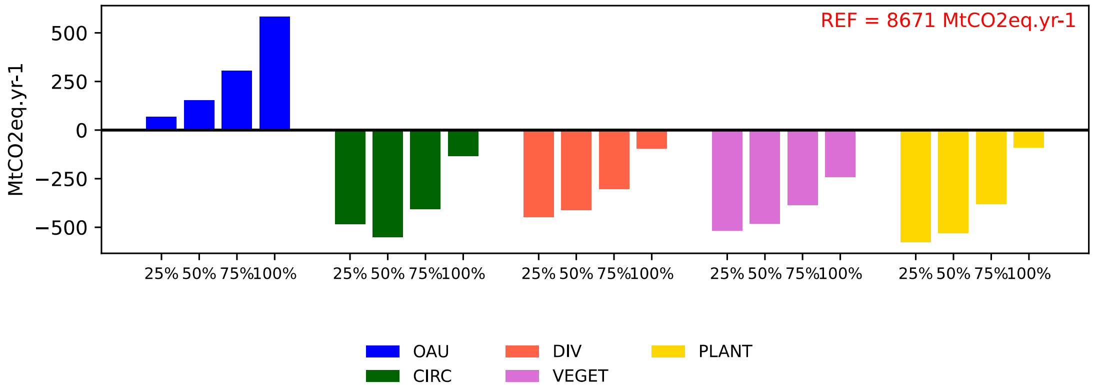


Figure S6 - Changes in cropland requirements in Europe (a), GHG emissions from agriculture + LUC in Europe (b), outside Europe (c), and globally (d) in each scenario compared to REF under the 25, 50, 75 and 100 % organic variants. The difference is expressed in milion ha (a) or milion tons CO_2 equivalent per year (b,c,d). In each panel, the absolute value for the REF scenario is indicated in red.

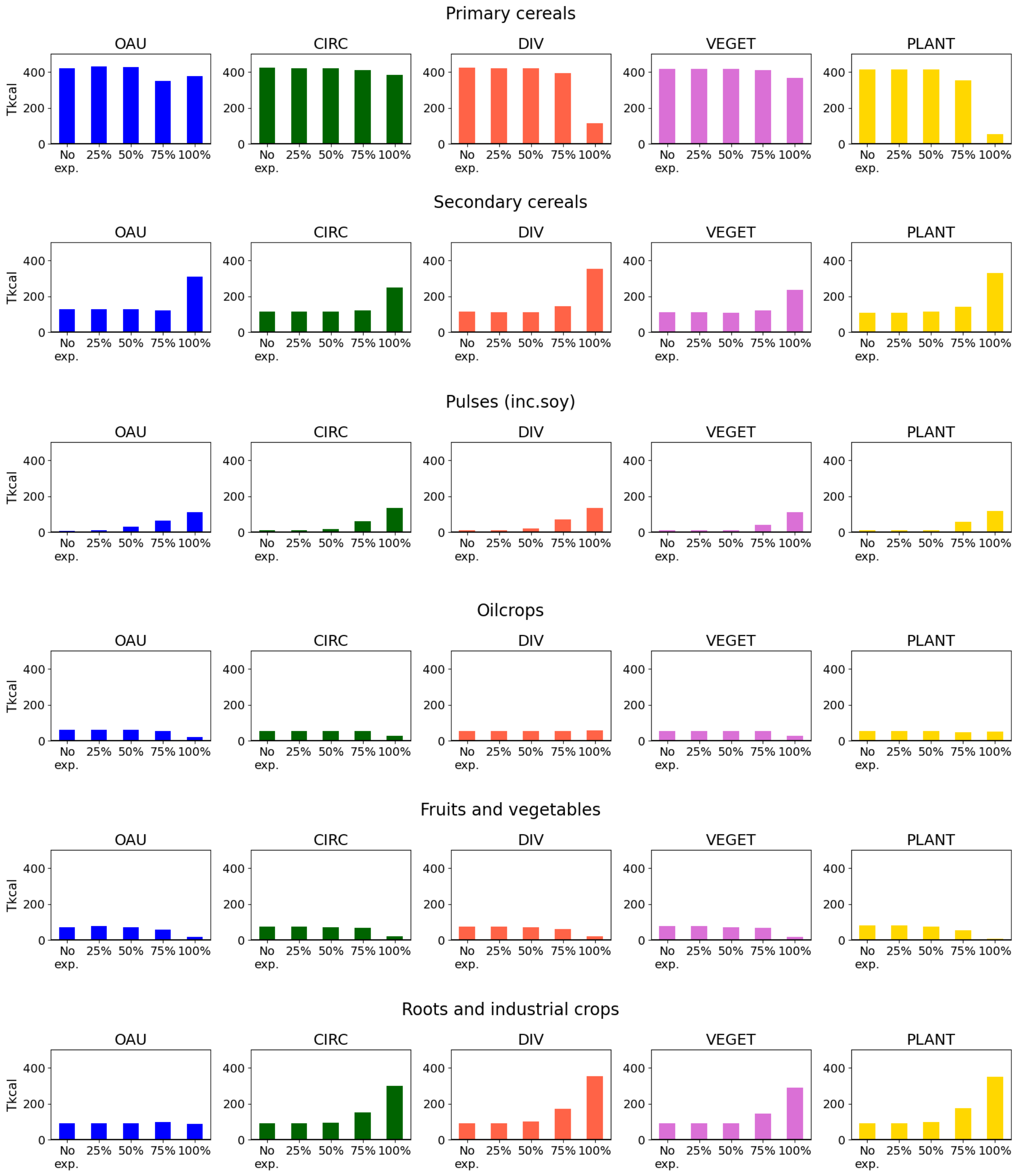


Figure S7 - European exports of crops, in Terra kilocalories, in the five scenarios for organic farming under organic cropland shares varying from no expansion (no exp.) to 100%

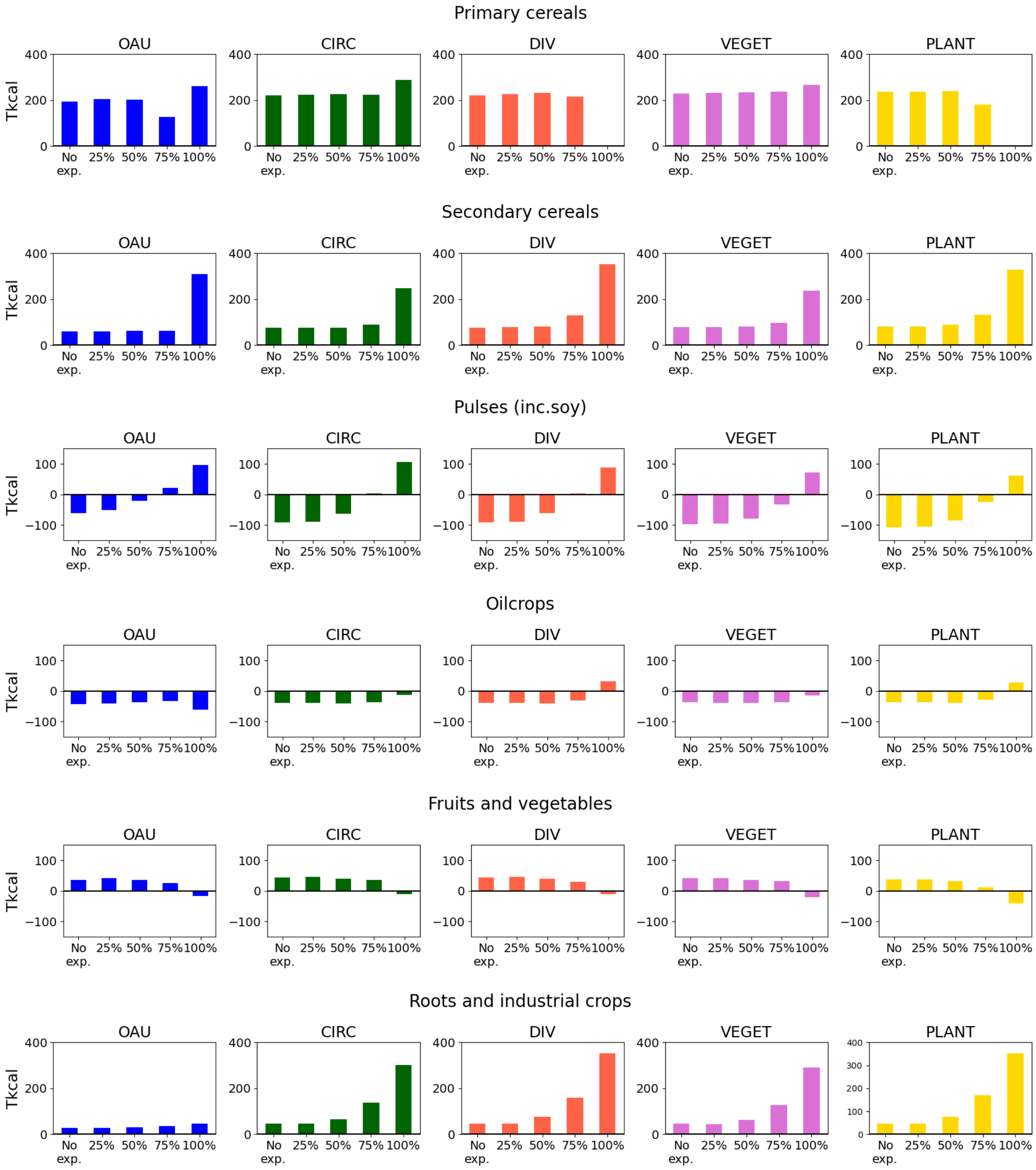
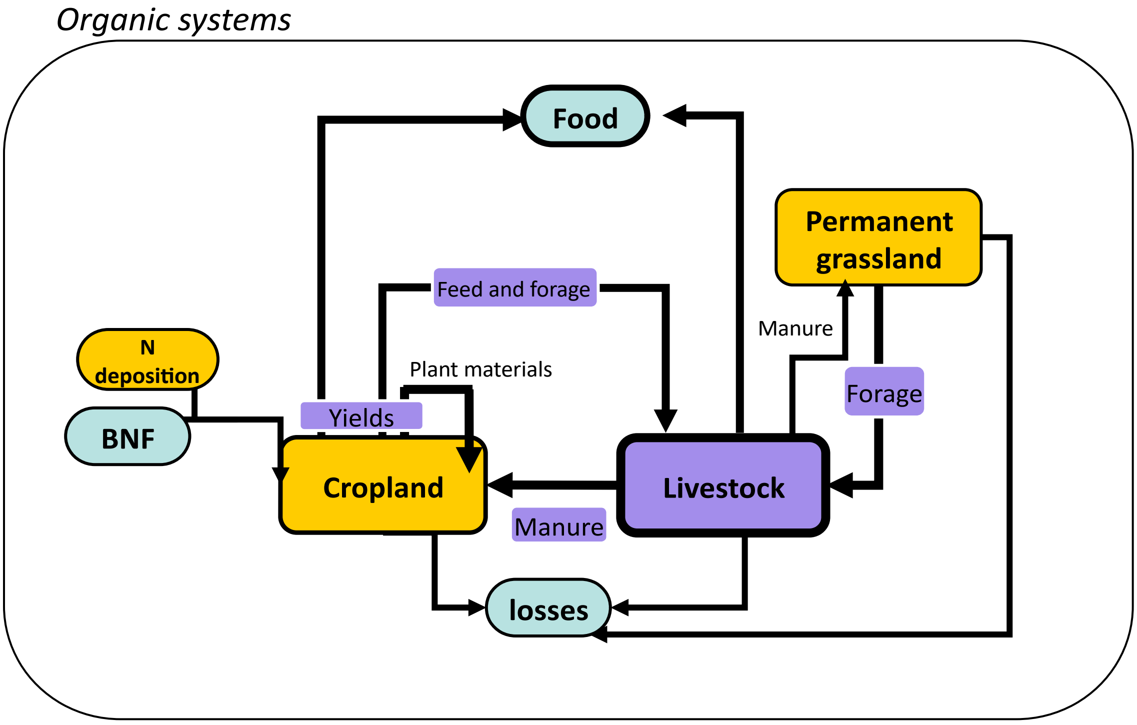


Figure S8 - European net exports of crops, in Terra kilocalories, in the five scenarios for organic farming under organic cropland shares varying from no expansion (no exp.) to 100%. Net exports correspond to the sum of export minus the sum of imports.

3 Supplementary Methods

3.1 Parameterization of quantitative input data in the GOANIM Model



Legend :
Input variables (yellow) , Output variables (blue),
Output variables used in GlobAgri-CLINORG (purple)

Figure S9 - Structure of the GOANIM model, represented by the boundaries, biomass and nitrogen flows considered in this work. Flows and variables were computed in each grid cell independently. Purple color is used to highlight output variables that are exchanged with GlobAgri. Adapted from Barbieri et al., (2021). BNF : Biological Nitrogen Fixation

3.1.1 Organic crop production

3.1.1.1 Crop areas

GOANIM runs on fixed areas of cropland and permanent grassland. However, the composition of croplands varied depending on scenarios' assumptions for organic crop production.

For the OAU scenario, we used gridded maps developed by Barbieri et al. (2019) to set the organic harvested area of each crop specie in GOANIM. These maps were based on conventional harvested area data for 61 crop species in the year 2000 from Monfreda et al., (2008), with modifications to account for observed differences between conventional and organic crop rotations (Barbieri et al., 2017). We adapted the methodology of Barbieri et al., (2019) to generate harvested areas maps for the other scenarios. Our approach first involved defining crop rotations tailored to the options for organic crop production at the crop group level, based on a dataset gathering currently observed organic crop rotations. Subsequently, we allocated crop areas assuming that the spatial allocation would be representative of the temporal sequence. The methodology is summarized in Figure S10. Two crop rotations were defined for each option in order to be able to approximate the average frequencies observed in the dataset (Figure S11). We assumed that these rotations would be applied evenly across Europe.

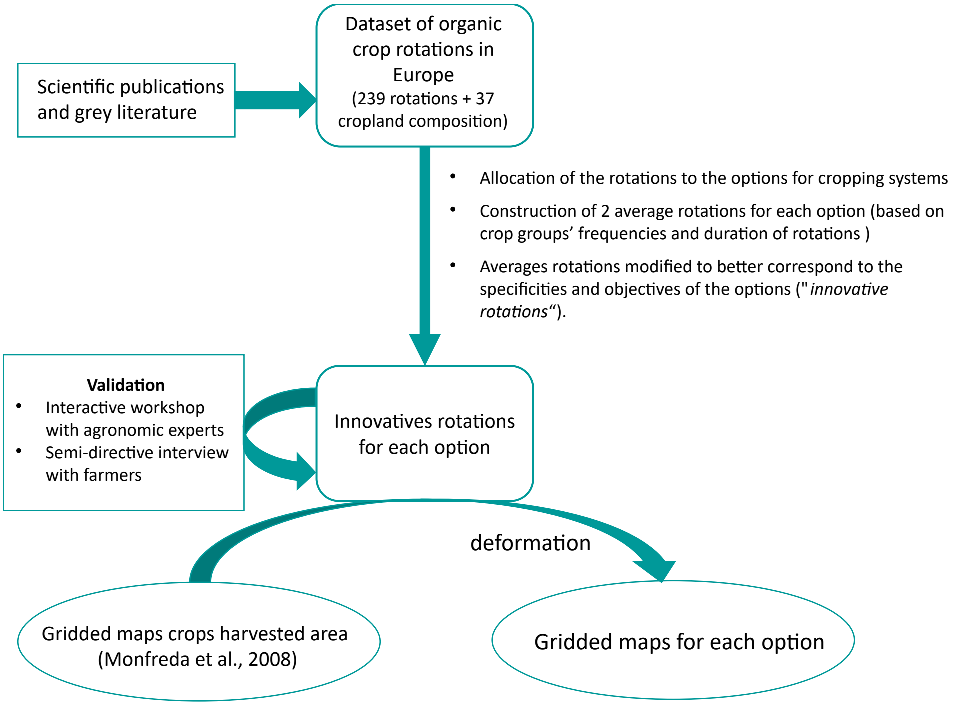


Figure S10 - Methodological framework for generating crop rotations and gridded maps of crop areas for each option

The first step for generating maps involved adjusting the area data from Monfreda et al. (2008) at the crop group level. This was done by (i) reducing the area occupied by crop groups whose initial frequency (i.e., the fraction of area occupied by the group in conventional data), was higher than the target frequency for organic in the scenario; (ii) allocating the resulting freed-up area to crop groups whose target frequencies were higher than initial frequencies. The share of freed-up area allocated to each group was calculated based on their occurrences in the crop rotations. Fruits and vegetables and other crops areas were kept to their initial levels.

Example:

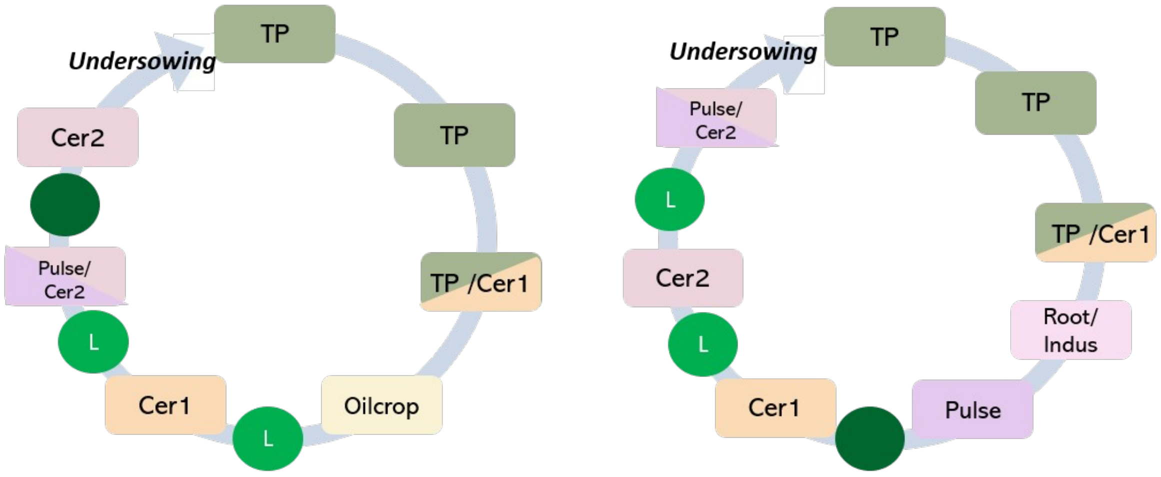
Suppose a grid cell, which contains 200ha of primary cereals and 100ha of temporary grasslands in the initial situation. Now suppose that the organic crop rotation consists of 2/5 primary cereals, 2/5 temporary grasslands and 1/5 pulses.

Primary cereals area is fixed to 2/5 *300 = 120ha, which means that 80ha become available.

Temporary grasslands' coefficient for allocation of the available area is $\left(1-\frac{0.33}{0.4}\right)=0.175$.

Pulses coefficient is 1 because they are not initially present in the grid cell. Therefore, the fraction of available area allocated to temporary grasslands is $\left(\frac{0.175}{1+0.175}\right)=0.15$(12 ha) and the one allocated to pulses is $\left(\frac{1}{1+0.175}\right)=0.85$ (68 ha). After calculations, the grid cell contains 120 ha of primary cereals, 112 ha of temporary grasslands and 68 ha of pulses.

Option maximizing protein and N autonomy (CIRC and VEGET)



Option priority to food crops on arable land (DIV and PLANT)

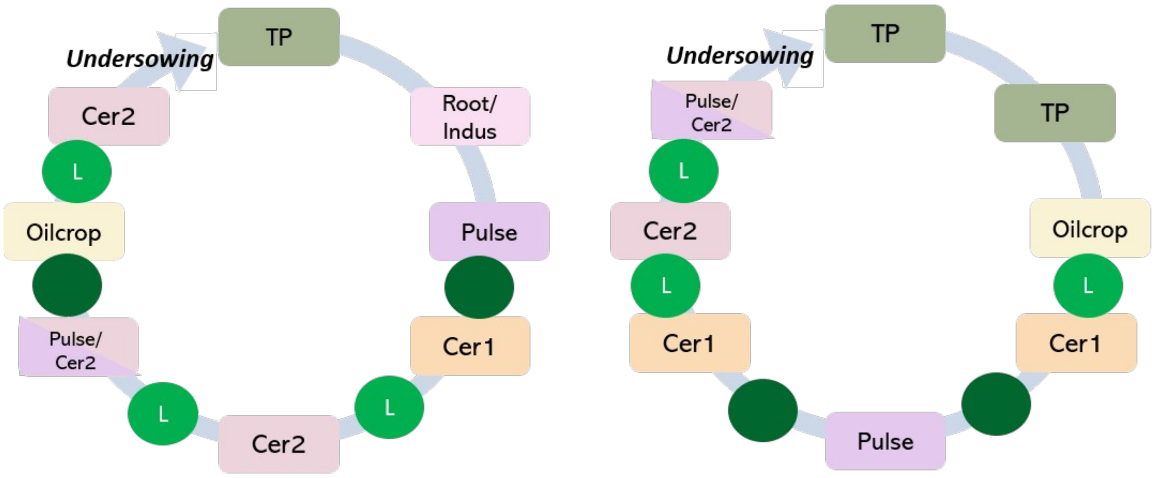


Figure S11 - Organic crop rotations according to the cropping systems options in our scenarios. We supposed that the two rotations defined for each option were equally represented across Europe. Main crops are represented with squares, at the crop group level (Cer1: primary cereals, Cer2: secondary cereals, Oilcrop: oilcrops , Root/Indus: root and industrial crops, TP: temporary fodder crops, Pulse: pulses (inc. soy)). Cover crops are represented with circles (L: leguminous cover crops, otherwise non-leguminous).

To account for the mixed cropping of secondary cereals and pulses, we defined two distinct crop groups: "cer2 mix" and "pulses mix." The area occupied by each of these crop group was calculated based on the frequency with which the group appeared in mixed cropping compared to its total occurrences in the entire crop rotation (whether as part of mixed cropping or as a sole crop). This method implies that, in some cases, the area of cer2 mix and pulses mix could be unequal, yet they are allegedly cultivated on the same plot. Therefore, we subsequently fixed the area of both groups to the lowest area of the two. Here note that mixed cropping leads to higher cropping intensity, which translates into greater harvested area in GOANIM (while the cultivated area remains the same). Similarly, when we assumed that temporary grasslands were sown under the preceding crop cover, or that a primary cereal was sown during the third year of temporary grassland (Figure S11), it increased cropping intensity. As a result, cropping intensity was +3% and +13% higher in the option ‘Priority to food crops’ and ‘Maximizing N autonomy’, respectively, compared to OAU.

Table S1 - Share of organic harvested area at the crop group level in each option for organic crop production. In OAU, the temporal sequence is unknown. The share of harvested areas at the crop group level have been calculated from gridded maps developed by Barbieri et al., (2019). In the other scenarios, the share of harvested areas is defined on the basis of specific crop rotations developed for each option for organic crop production.

	Primary cereals	Secondary cereals	Pulses (inc.soy)	temporary fodders	Oilcrops	Roots and industrial crops	Fruits and vegetables	Other
OAU	0.23	0.17	0.10	0.34	0.06	0.03	0.06	0.01
Option Maximizing N autonomy (CIRC, VEGET)	0.21	0.16	0.16	0.26	0.09	0.06	0.05	0.01
Option Priority to food crops (DIV, PLANT)	0.13	0.22	0.17	0.18	0.15	0.08	0.06	0.01

To allocate harvested area at the species level, we took a conservative approach and kept the species distribution within each crop group similar to the distribution observed for year 2000 in Monfreda et al. (2008). Some crop groups could be missing in some grid cells. To address this, we defined 14 zones in Europe (with a horizontal zoning of 5°C latitude and a vertical zoning of Eastern and Western Europe) and assumed that the species distribution was the average distribution of the corresponding zone. Regarding mixed cropping of cereals and pulses, we did not assume a specific specie composition. Instead, we defined an “average mix cereal” and an “average mix pulse” species based on the species mix already present in the grid cell.

3.1.1.2 Maximum attainable organic crop yields

In GOANIM, organic crop yields are computed based on crop specific linear response curves to soil available N. However, a maximum attainable yield (that is, yield under no N limitation) is set for each specie. We retrieved the maximum organic yields for the year 2000 from Barbieri et al. (2021).

These yields correspond to observed conventional yield, corrected to account for yield losses due to biotic stresses, but not for N limitation. Subsequently, we projected these attainable yields to the year 2050 (Table S2). To do so, we calculated the variation between conventional yields at year 2000 retrieved from FAOStat (1999-2001 average) and projected yields for 2050 from Tibi et al. (2020) at the crop group level, and multiplied the attainable organic yields at year 2000 with these coefficients. We accounted for the effects of mixed cropping on grain yields, by correcting maximum yields for ”cer mix” and ”pulses mix” on the basis of the relationship between the total yield of the intercrop and the mean yield of the corresponding sole crops described in Bedoussac et al. (2015), as :

$$Y_{IC} = 0.95 * Y_{SC} + 0.08$$

With Y_{IC}, the total grain yield of cereal/grain legume intercrops and Y_{SC} the mean sole crop grain yield, in $kg.m^{-2}$.

Table S2 - Average maximum attainable organic yields in GOANIM in the OAU scenario (in tDM per ha, average of European grid cells), with variability illustrated with the standard deviation (no unit), and % changes between 2000 and 2050.

	Mean maximum organic yield 2050 (tDM.ha-1)	sdt	Changes 2000-2050 (%)
Cereals	3.93	1.94	*+25*
Oilseeds	1.53	0.92	*+39*
Fruits and vegetables	4.35	6.94	*+34*
Grass-like forage	4.68	2.46	*+25*
Other forages	5.85	4.07	*+10*
Pulses	1.69	0.96	*+8*
Roots and Tuber	7.25	2.93	*+35*
Sugar plants and products	17.84	7.20	*+52*
Other plant products	0.49	0.85	*+1*

3.1.1.3 Cover crops

The scenarios CIRC, DIV, VEGET and PLANT assume that cover cropping is maximized in organic cropping systems. We supposed that cover crops would be implemented between every main crop, except following fodders, roots or industrial crops. Cover crops consisted in mix of leguminous species, except when grown before or after a pulse or a mix of pulses and cereals (mix of non-leguminous species). In GOANIM, leguminous cover crops are entirely left on field to maximize N input, whereas non-leguminous cover crops are treated as any fodder crop (more details in Supplementary Material C: *Description of the models' variables and equations*). In the OAU scenario, we assumed no cover cropping for simplicity, as the temporal sequence of the crops is unknown. This is an evident simplification considering the current frequency of cover cropping in Europe, especially in the winter period (Fendrich et al., 2023).

Area occupied by cover crops was calculated based on the area occupied by the preceding and following crop groups in each grid cell. In accordance with the method used for mixed cropping, we chose to use the smallest area of the two crop groups. The time available for implementing cover crops was computed by estimating the annual bare soil period. We used gridded data of planting and harvesting months of main crops from the MIRCA 2000 dataset (Portmann et al., 2010) and supposed that the average of the bare soil months over a year for the preceding and following crops (that is, 12 minus the cropping period) represented the available time frame for implementing a cover crop. If the average bare soil period was less than one month, cover crops were not implemented in the grid cell.

We set the yields of the cover crops on the basis of yields of leguminous and non-leguminous cover crops mixtures from three experimental sites in France retrieved from Tribouillois et al. (2016) in kg per ha per degree day. To account for the variability in cover crops productivity across countries, we adopted the approach outlined by Gaudaré et al. (2023). We calculated the ratio of the country specific mean yield to the French mean yield for the most productive crop species between wheat and maize. We then applied this ratio to the French estimate of cover crops yields to obtain an estimate of cover crops yields in the respective country. DM content and N content of cover crops were estimated as the average values of each specie in the cover crop mixture, obtained from Feedipedia website[1]. N fixation of leguminous cover crops was calculated using the equation of Høgh-Jensen et al. (2004) (more details in Supplementary Material C: *Description of the models' variables and equations*).

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[1] https://feedipedia.org/

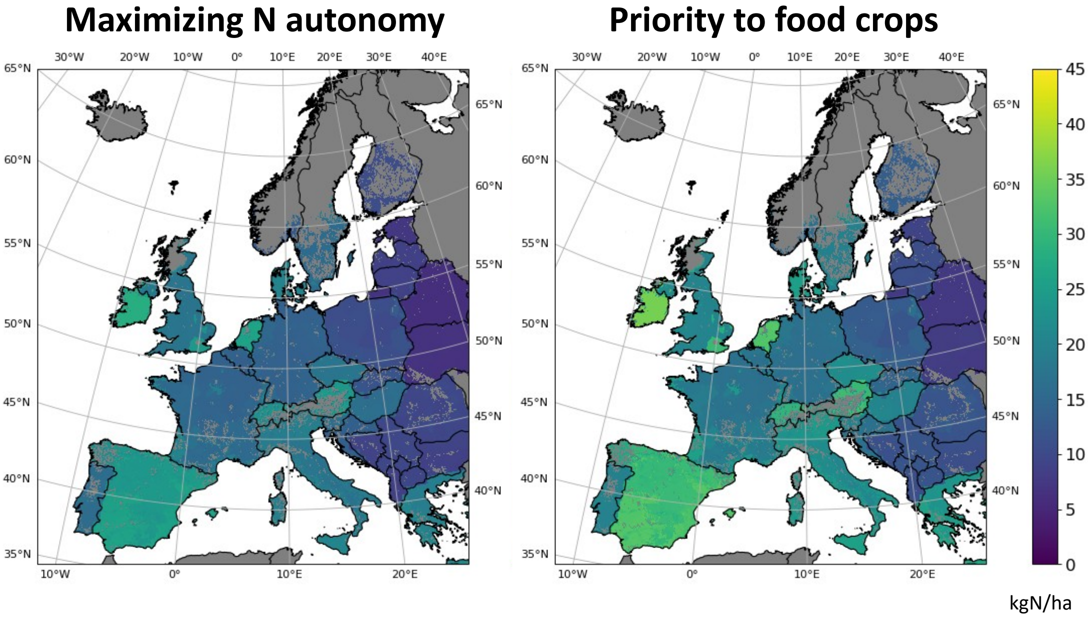


Figure S12 - Biological N Fixation (BNF) of leguminous cover crops, in kg N /ha, in two options for organic crop production : maximizing N autonomy (scenarios CIRC, VEGET) and priority to food crops (scenario DIV, PLANT). In the OAU scenario, we suppose that cover crops are not implemented.

Lastly, non-leguminous cover crops have been reported to reduce nitrate leaching (Thapa et al., 2018; Abdalla et al., 2019; Nouri et al., 2022). We considered this effect by correcting the fraction of N lost via leaching in GOANIM (in grid cells where leaching occurs) with the following calculation:

$$L_{corr} = (Frac_{cc} * 0.44 * 0.24) + ((1 - Frac_{cc}) * 0.24)$$

Where L_{corr} is the fraction of N lost via leaching (where leaching happens). $Frac_{cc}$ is the fraction of the grid cell area occupied by non-leguminous cover crops. 0.24 is the coefficient of N fraction lost through leaching from the Intergovernmental Panel on Climate Change (IPCC) (2019b). 0.44 is the fraction of N leaching that still occurs when cover crops are implemented (from Thapa et al. (2018) who found that non-leguminous cover crops reduce leaching by 56% compared with bare soils). We chose to use the values from Thapa et al. (2018) because they were the only ones providing generic values for non-leguminous cover crops.

While there is a general agreement that non-leguminous cover crops reduce nitrate leaching, there is no consensus on a significant effect of leguminous cover crops (Thapa et al., 2018; Abdalla et al., 2019; Nouri et al., 2022). For this reason, we assumed that only non-leguminous cover crops had an effect on leaching.

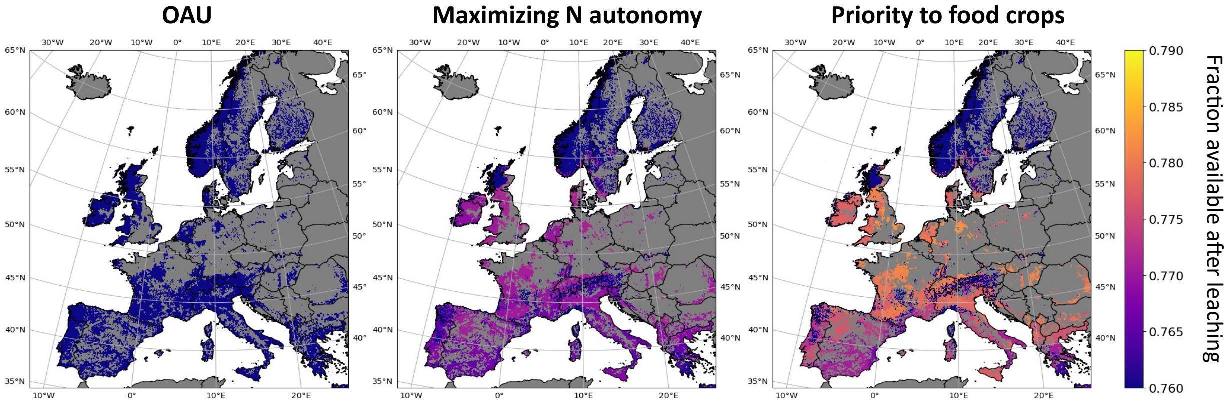


Figure S13 - Fraction of nitrogen (N) available after leaching (No unit) in the three options for organic crop production : Organic-as-usual (OAU), maximizing N autonomy (scenarios CIRC, VEGET) and priority to food crops (scenario DIV, PLANT) . Only grid cells where leaching occurs are represented. 0.76 is the average fraction after leaching losses according to the IPCC (2019b). (0.24 is the default fraction leached). More N is available after leaching in some grid cells because a correction of leaching losses by -44% was applied on the share of cropland areas covered by non-leguminous cover crops in these grid cells

3.1.2 Organic livestock production

GOANIM considers three monogastric production types (broilers, laying hens, pigs) and five ruminant production types (dairy cattle, beef cattle, dairy sheep, meat-producing sheep and dairy goats). In this work, we considered different options for organic animal production systems for each scenario.

In GOANIM, the data were expressed at the level of one Standing Livestock Head (SLH). This unit is used to characterize livestock at the scale of the livestock system rather than at the individual level. Doing so, we accounted for feed consumption and N excretion on an annual time step, while considering producing and non-producing animals (e.g., young animals kept for renewal). For poultry meat systems, the values for one SLH consist in individual broilers values multiplied by the number of batches per year. For laying hens, individual performances were reported to one year by dividing 365 with the lifetime. For pig production, one SLH refers to one sow and her offspring over one year. Lastly, for ruminant systems, one SHL refers to the breeding female and her offspring in the CIRC, DIV and VEGET scenarios. In the OAU scenario, because data were derived from FAOStat, which do not distinguish livestock numbers per age class, one ruminant SLH refers to an average producing animal (Producing heads in the FAOStat database) accompanied by non-producing animals (Stocks in the database).

3.1.2.1 Performances and diets

We defined the performances of poultry (broilers and laying hens) and pig production systems on the basis of breeds or genetic types selected considered as adapted to each option's rationale (Tables S3 and S4), according to technical references and expert’s knowledge (Table S5)..

For pig production, performances of growing-finishing pigs (feed conversion ratios and slaughter weights) were calculated using INRAPorc software (Dourmad et al., 2008; van Milgen et al., 2008), which is sensitive to feed composition. Animal diets were formulated using a linear optimization procedure that incorporated nutritional constraints, and specific objective functions tailored to each option (Denoual, 2022; Méda et al., 2023). One diet was formulated for each physiological stage. Synthetic amino acids were not used, as they are not authorised in organic agriculture. Except in OAU, the use of insects and food catering waste was considered feasible in 2050. Animal diets were defined by feed type, but the data were subsequently aggregated. The final input used in GOANIM consisted of the total energy and protein intake, along with the proportions derived from grains and grain co-products, forages, and crop residues.

Table S3 - Quantitative data for parameterization of organic pig production in GOANIM. Production and feed requirements are indicated per one Standing Livestock Head (SLH), which is the reference unit for livestock production in GOANIM. One SLH refers to the reproductive sow and her offspring. The category 'other' in animal diets refers to other feed sources not computed in GOANIM (additives, household food wastes, insects, and lactoserum). LFS : livestock farming systems. ME: metabolisable energy. CP : Crude protein.

	OAU	**CIRC**	**DIV**
LFS option	**Unchanged**	**LFS minimize feed-food competition**	**LFS provide services to crops**
Objective diet formulation	Minimize feed cost	Minimize feed-food competition	Maximize the non-digestible protein fraction in feed
Genetic type	cross-bred pigs of (Large White x Landrace) x Pietrain	Krškopolje pigs	Krškopolje pigs
Productivity (kg carcass/SLH/year)	1987	1496	1497
Slaughter weight pigs (kg live weight)	121.5	160.7	160.8
Slaughter weight sow (kg live weight)	240	240	240
Renewal rate (%)	47	23	23
time spent on range (sows only) (%)	38	73	73
Animal diet grain-coproducts - fodder – crop residues - other (%)	66-29-1-0-4	32-13-24-0-31	27-18-22-0-33
Energy requirements(ME MJ/ SLH / year)	106 781	99 856	103 869
Protein requirements (kg CP / SLH /year)	1350	1603	1593

Table S4 - Quantitative data for parameterization of organic poultry production in GOANIM. For egg production, production and diet are indicated per one SLH (Standing Livestock Head), which is the reference unit for livestock production in GOANIM. One SLH refers to the laying hen. For meat production, one SLH refer to one broiler multiplied by the number of batches per year. Here, for clarity, the data are given for one broiler. The category 'other' in animal diets refers to other feed sources not computed in GOANIM (additives, household food wastes, insects, and lactoserum). LFS : livestock farming systems. ME : metabolisable energy. CP : Crude protein.

	OAU	**CIRC**	**DIV & VEGET**
LFS option	**Unchanged**	**LFS minimize feed-food competition**	**LFS provide services to crops**
Objective of diet formulation	Minimize feed cost	Minimize feed-food competition	Maximize the non-digestible protein fraction in feed
Eggs production systems	**OAU**	**CIRC**	**DIV & VEGET**
Genetic type	Lohman tradition	Lohman tradition	Lohman dual
Productivity (kg eggs/SLH/year)	13.6	13.6	10.9
Live weight (kg)	1.89	1.89	1.89
% time on range	25	25	25
Animal diet grain-coproducts - fodder – crop residues - other (%)	42-48-0-0-11	22-58-0-0-20	44-27-0-0-29
Energy requirements (ME MJ/SLH/year)	435	506	410
Protein requirements (kg CP/SLH/year)	9	9	9
Meat production systems	**OAU**	**CIRC**	**DIV**
Genetic type	genetic strain "JA757N"	genetic strain "JA757N"	Lohman dual
Productivity (kg carcass/head)	1.564	1.564	1.625
Live weight (kg)	2.3	2.3	2.5
Batches / year	3.4	3.4	2.6
% time on range	25	25	25
Animal diet grain-coproducts - fodder – crop residues - other (%)	55-42-0-0-3	30-48-0-0-22	15-54-9-0-22
Energy requirements (ME MJ/head)	83.6	92.1	117.3
Protein requirements (kg CP/head)	1.4	1.9	2.5

Table S5 - Technical references used to characterize animal performances, careers and diets

	Technical references
Pig production systems	IFIP, 2013; Brossard et al., 2019; Candek-Potokar et al., 2019; Monteiro et al., 2019; García-Gudiño et al., 2020
Poultry production systems	Guerder et al., 2009; I.D.M. Gangnat et al., 2020; Guyot et al., 2022; ITAVI, 2022a, 2022b; Bonnefous et al., 2024; Ravon et al., 2024
Ruminant production systems	Iger-Centres-de-Gestion, 1989; INRA, 2007; Idele, 2012; Jousseins et al., 2014; Benoit & Veysset, 2021

To assess animal performances and diets in ruminant production systems, we first selected the breeds that are the best adapted to production goals in the three alternative scenarios for organic farming development CIRC, DIV and VEGET (Tables S6 and S7). Different breeds were also selected for lowland areas and upland areas (the boundary being set at 500 m altitude in GOANIM). In VEGET, there were no beef cattle and no meat-producing sheep. Animal live weight, energy and protein requirements, annual milk and meat productivity, and herd renewal rate were characterized according to technical references (Iger Centres de Gestion, 1989; Idele, 2012; Jousseins et al., 2014; Table S5) and expert's knowledge. In accordance with the renewal rate of each ruminant type in each scenario, we calculated the productive lifespan of the animals and the proportion of adult animals in the herd. In the OAU scenario, we rather used country specific data developed for previous modelling exercises using GOANIM (Gaudaré et al., 2023), aggregated at the European scale using gridded maps of livestock densities from Robinson et al., (2014). The approach involved characterizing the performances and diets composition of conventional systems based on FAOStat national data and Herrero et al, (2013), respectively, and then correct them to account for differences in organic systems described in the meta-analysis of Gaudaré et al., (2021).

For CIRC, DIV and VEGET, diets composition and the types of feed resources were selected according to the rationale of each scenarios. For each ruminant type in each scenario, we therefore distinguished (in % of dry matter (DM)) the proportion of fodder, grain, crop residues and co-products. Co-products were soya cake (which provides nitrogen) and beet pulp (which provides energy) for dairy animals, or wheat bran for suckler animals. For fodder, we distinguished between grazed grass vs. hay and silage that constitute the core of animal diet during the grazing season vs. the winter feeding-period indoor. DM intakes were calculated for one livestock unit (LU) from technical references (Idele 2012 for cattle; Jousseins et al., 2014 for small ruminants), and subsequently multiplied by breed LU values. The LU values for each breed were calculated according to the methodology developed by Benoit & Veysset (2021). Lastly, the energy and protein content of the diets were calculated using energy and protein content of the feed resources selected for each scenario (INRA, 2007), taking into account that the nutritive values of fodder resources vary throughout the year. For the OAU scenario, the estimates of energy and protein requirement per day and kg live weight were retrieved from Barbieri et al. (2021).

Lastly, meat production from culling animals in dairy and eggs systems was considered in GOANIM. The production of meat was estimated on the basis of animals live weights and renewal rates (Tables S4 and S6)

Table S6 - Quantitative data for parameterization of organic dairy systems in GOANIM. Productivity and diets are expressed at the level of one Standing Livestock Head (SLH), which is the reference unit for livestock systems in GOANIM. One SLH refers to the dairy female and her offspring, except in the OAU scenario in which data are derived from FAOStat which do not distinguish age classes. Therefore, one SLH refers to one dairy female and the non-producing animals accompanying it. (L) refers to data specific to lowland areas. (U) refers to data specific to upland areas. LFS: livestock farming systems. ME : metabolisable energy. CP : Crude protein.

	OAU	**CIRC**	**DIV & VEGET**
LFS option	**Unchanged**	**LFS minimize feed-food competition**	**LFS provide services to crops**
Dairy cattle	**OAU**	**CIRC**	**DIV & VEGET**
Breed	NA	Simmental (U)	Brune des Alpes (U) Jersey (L)
Annual productivity (kg milk/SLH/yr)	5817	4642	4126 (U) 4642 (L)
Liveweight (kg)	471	750	650 (U) 430 (L)
Ratio total LU / producing LU	1.5	1.5	1.5
Renewal rate (%)	30	25	25
% time on pasture	25	62	60 (U) 70 (L)
Animal diet: grain-coproducts-fodder-crop residues (%)	14-0-80-6	0-10-85-5	5-5-90-0
Energy requirement (MJ ME / SLH /year)	76 599	102 200	91 126 (U) 81 809 (L)
Protein requirement (kg CP / SLH / year)	1216	1364	1173 (U) 1068 (L)
Dairy sheep	**OAU**	**CIRC**	**DIV & VEGET**
Breed	NA	Thones & Marthod (U)	Thones & Marthod (U)

Annual productivity (kg milk/SLH/yr)	209	156	156
Live weight (kg)	34	60	60
Ratio total LU / producing LU	1.15	1.15	1.15
Renewal rate (%)	30	25	25
% time on pasture	74	62	62
Animal diet: grain-coproducts-fodder-crop residues (%)	11-0-89-0	0-10-85-5	5-5-85-5
Energy requirement (MJ ME / SLH /year)	6975	9 733	10 172
Protein requirement (kg CP / SLH / year)	142	132	133
Dairy goats	**OAU**	**CIRC**	**DIV & VEGET**
Breed	NA	Chèvre des Fossés (L)	Chèvre des Fossés (L)
Annual productivity (kg milk/SLH/yr)	266	218	218
Live weight (kg)	19	35	35
Ratio total LU / producing LU	1.15	1.15	1.15
Renewal rate (%)	30	25	25
% time on pasture	74	50	50
Animal diet: grain-coproducts-fodder-crop residues (%)	11-0-89-0	0-10-90-0	5-5-90-0
Energy requirement (MJ ME / SLH /year)	4 193	6673	6684
Protein requirement (kg CP / SLH / year)	86	90	86

Table S7 - Quantitative data for parameterization of organic ruminant meat systems in GOANIM. Productivity and diets are expressed at the level of one Standing Livestock Head (SLH), which is the reference unit for livestock systems in GOANIM. One SLH refers to the breeding female and her offspring, except in the OAU scenario in which data are derived from FAOStat which do not distinguish age classes. Therefore, one SLH refers to one producing (slaughtered) animal and the non-producing animals accompanying it. (L) refers to data specific to lowland areas. LFS : livestock farming systems. (U) refers to data specific to upland areas. ME : metabolisable energy. CP : Crude protein.

	OAU	**CIRC**	**DIV**
LFS option	**Unchanged**	**LFS minimize feed-food**	**LFS provide**

		competition	**services to crops**
Beef cattle	**OAU**	**CIRC**	**DIV**
Breed	NA	Aubrac (U) Angus (L)	Aubrac (U)
Annual productivity (kg carcass/SLH/yr)	272	165 (U) 178 (L)	126.5
Live weight (kg)	490	650 (U and L)	650
Ratio total LU / producing LU	1.3	1.8	1.8
Renewal rate (%)	25	18	25
% time on pasture	46	65 (U) 78 (L)	80
Animal diet: grain-coproducts-fodder-crop residues (%)	7-0-93-0	0-10-90-0 (U) 0-0-90-10 (L)	0-0-100-0
Energy requirement (MJ ME / SLH /year)	47 981	88 456 (U) 81 044 (L)	79 508
Protein requirement (kg CP / SLH / year)	755	1194 (U) 1091 (L)	1018
Meat-producing sheep	**OAU**	**CIRC**	**DIV**
Breed		Arles Merino (U) Charmoise (L)	Charmoise (L)
Annual productivity (kg carcass/SLH)	15	15.5 (U) 17 (L)	17
Live weight (kg)	30	55 (U) 60 (L)	60
Ratio total LU / producing LU	1.3	1.4	1.4
Renewal rate (%)	25	18 (U) 25 (L)	25
% time on pasture	84	90 (U) 87 (L)	87
Animal diet: grain-coproducts-fodder-crop residues (%)	12-0-88-0	0-0-100-0 (U) 0-0-85-15 (L)	0-0-85-15
Energy requirement (MJ ME / SLH /year)	8 059	6 175 (U) 7 184 (L)	7 184
Protein requirement (kg CP / SLH / year)	143	79 (U) 97 (L)	97

3.1.2.2 Nitrogen excretion rates

We calculated the annual N excretion rates with a mass-balance approach, as the difference between the total feed N intake and the N retained in animal products (milk, eggs) and body weight, at the level of one SLH to include N intake and N excretion of non-producing animals. Table S8 shows the N content data used to calculate N in body weight and animal products. Considering that GOANIM may allocate excess protein to meet the energy requirements of livestock, N intakes and excretion rates were corrected after one run in GOANIM to account for the surplus of protein consumed (Figure S14). GOANIM was run a second time with the corrected excretion rates to obtain the final results.

To estimate the share of N available for application on cropland soils, we assumed that the proportion of animal manure excreted outside buildings was proportional to the time spent on pasture (defined on the basis of the length of the grazing season) or free-range. The remaining fraction (i.e. excreted indoor) was supposed to be available for application on croplands after deducing N_2O and N_2 losses from manure management, calculated following the IPCC Tier 1 guidelines (IPCC, 2019a). For ruminants, we split the manure excreted during grazing periods between permanent grasslands and temporary pastures (included in croplands). In the first run, performed to calibrate surplus protein intake and correct N excretion rates, the allocation between temporary and permanent pastures was based on their respective areas at the grid cell level. In the second run, the allocation was based on the relative share of DM intake from permanent and temporary fodders, as simulated in GOANIM for each specie in the first run.

Table S8 - Nitrogen content of the livestock products and body weight used to calculate excretion rates. For pig production, the reported value was used for sows and piglets. N content of growing-finishing pigs was computed on the INRAporc software (Dourmad et al., 2008; van Milgen et al., 2008)

	[N] in body weight (kgN.kg-1)	[N] in milk or eggs (kgN.kg-1)	Source
Broilers	0.0293		ITAVI, 2013
Laying hens	0.0184		
Pigs	0.0256		Experts communication
Dairy cattle	0.024	0.00528	Public Health England, 2002; Arvalis, 2020
Dairy sheep	0.024	0.00864	
Dairy goats	0.024	0.00496	
Beef cattle	0.029		Arvalis 2020
Meat-producing sheep	0.029		

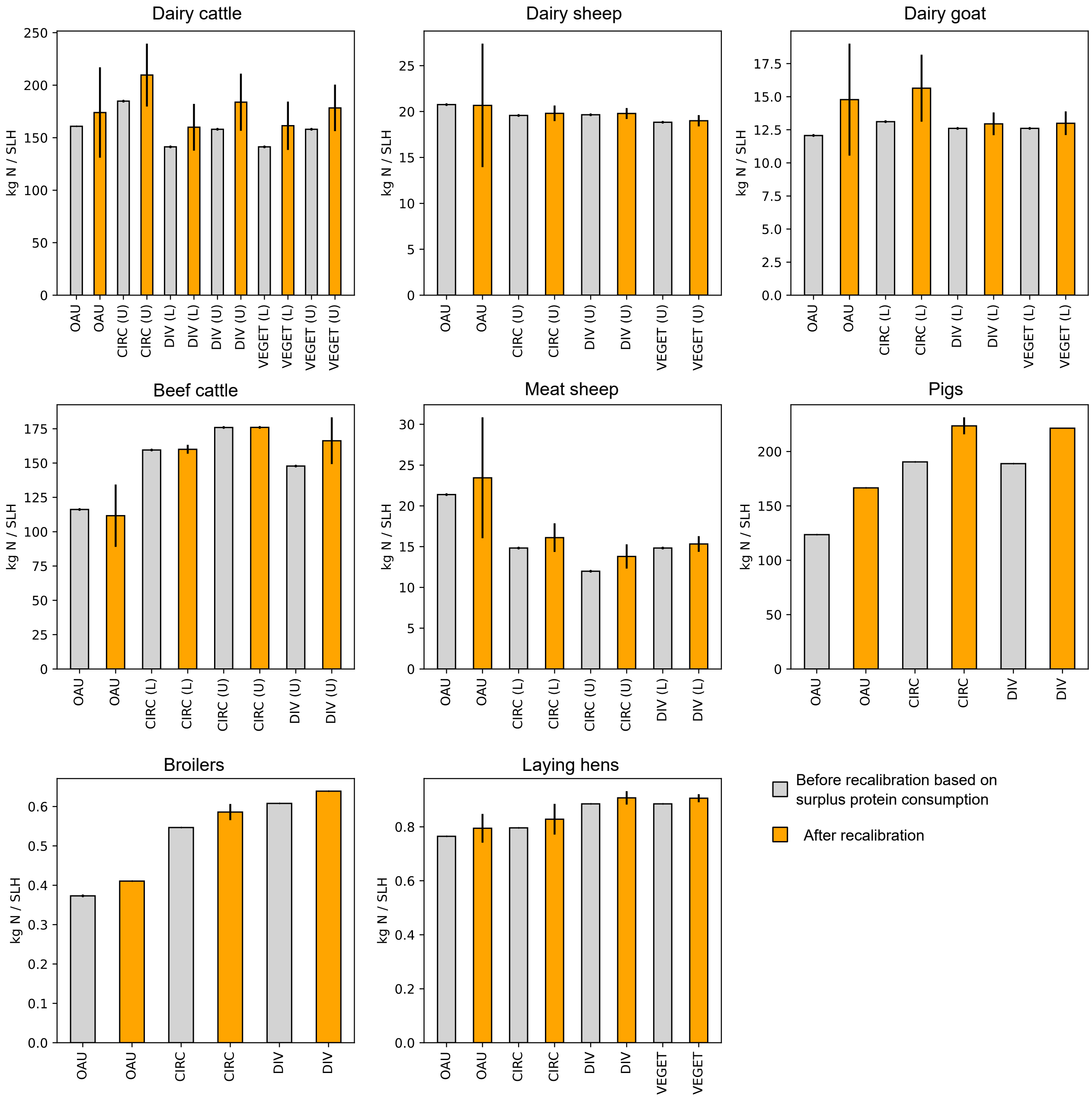


Figure S14 - Nitrogen (N) excretion rate per Standing Livestock Head (SLH) / year. The grey bars represent the values before recalibration of N intake based on surplus protein consumed (same value for all grid cells). The orange bars represent the average values of European grid cells and standard deviations after recalibration. (U): upland values, (L): lowland values.

3.2 Parameterization of quantitative input data for permanent grasslands in the GOANIM and GlobAgri-CLINOrg models

In this work, we define permanent grasslands using the definition from Global Land Cover-SHARE (GLC-SHARE) database (Latham et al., 2014), as:

> *"… any geographic area dominated by natural herbaceous plants (grasslands, prairies, steppes and savannahs) with a cover of 10% or more, irrespective of different human and/or animal activities, such as: grazing, selective fire management etc. Woody plants (trees and/or shrubs) can be present assuming their cover is less than 10%"*

This choice was motivated by the need to distinguish grasslands from other land types (e.g., shrub covered areas) in order to calculate changes in soil and vegetation carbon stocks induced by land-use changes.

Grasslands areas in 2010 were retrieved from GAEZ-4 (Fischer, 2021), based on the GLC-Share database (Latham et al., 2014). For consistency between GOANIM and GlobAgri, we calculated permanent grasslands yields at the grid cell level (for GOANIM) and then aggregated the results at the level of GlobAgri regions (weighted average based on grid cell areas). Biomass production was estimated by combining remote sensing estimates of Net Primary Production (NPP) (Zhao et al., 2011) with the fraction of each grid cell occupied by the land use 'Grassland' in GAEZ-4. To derive biomass production in tDM we considered an above ground fraction of 60% (Fetzel et al., 2017) and a 50% carbon content (Haberl et al., 2007). To project the yields to 2050, we used regional coefficients of grass yield variation between 2010 and 2050 from Tibi et al. (2020) (Concentration pathway RCP 6.0, no CO_2 fertilization effect).

Lastly, we ensured that permanent grasslands exploitation by livestock remained within sustainable limits by setting a maximum grazing intensity threshold retrieved from Erb et al. (2016). This threshold was set to 70% in area where NPP was above $200gC.m^{-2}.yr^{-2}$ and 40% otherwise (Table S9).

Table S9 - Regional yields of permanent grasslands , in tons dry matter per ha, in 2010 and 2050 under assumption of maximum sustainable grazing threshold

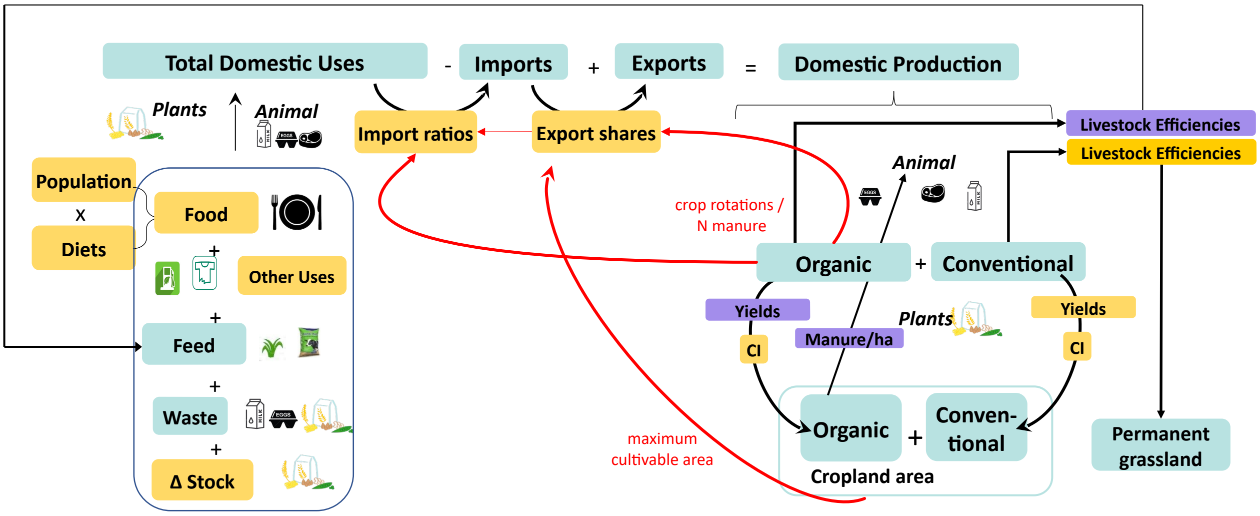
	2010 tDM/ha sustainable grazing	2050 tDM/ha sustainable grazing
France	6.52	6.31
Germany	4.23	4.15
United Kingdom	5.19	5.09
Poland	3.10	2.99
South Europe	3.79	3.62
East Europe	3.07	2.92
Central Europe	3.76	3.63
Rest of Europe	5.02	4.94
Canada, USA	2.22	2.16
Brazil, Argentina	3.35	3.27
Rest of America	4.76	4.60
Former Soviet Union	1.60	1.57
China	1.92	1.89
India	1.54	1.50
Rest of Asia	2.50	2.45
Near and Middle East	1.51	1.51
North Africa	1.51	1.48
West Africa	0.85	0.82
ECS Africa	2.44	2.35
Oceania	2.10	2.01
Rest of the World	1.40	1.37

3.3 Breakdown of regions in the GlobAgri-CLINOrg model

Table S10 - Region breakdown

GlobAgri regions	Composition
European regions	
France	France
Germany	Germany
United Kingdom	United Kingdom
Poland	Poland
South Europe	Croatia, Spain, Greece, Italy, Portugal, Slovenia, Albania, Bosnia and Herzegovina, the Republic of Macedonia, Montenegro, Andorra, Cyprus, Malta, Monaco, San Marino, Gibraltar, Holy See.
East Europe	Serbia, Bulgaria, Hungary, Romania
Central Europe	Switzerland, Austria, Czech Republic, Slovakia
Rest of Europe	Norway; Denmark, Sweden; Finland, Estonia, Ireland, Latvia, Liechtenstein, Lithuania, Netherlands, Belgium, Luxembourg
Non-European regions	
Canada, USA	Canada, USA
Brazil, Argentina	Brazil, Argentina
Rest of America	Antigua and Barbuda, Bahamas, Barbados, Bermuda, Bolivia (Plurinational State of), Aruba, Belize, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela (Bolivarian Republic of), British Virgin Islands, United States Virgin Islands, Anguilla, Falkland Islands (Malvinas), French Guiana, Guadeloupe, Martinique
Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
China	China
India	India
Rest of Asia	Afghanistan, Bangladesh, Bhutan, British Indian Ocean Territory, Brunei Darussalam, Myanmar, Sri Lanka, Cook Islands, Indonesia, Japan, Cambodia, Democratic People's Republic of Korea, Republic of Korea, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Nepal, Pakistan, Philippines, Timor-Leste, Singapore, Thailand, Viet Nam
Near and Middle East	Israel, Jordan, Lebanon, Syrian Arab Republic, Occupied Palestinian Territory, Bahrain, Iran (Islamic Republic of), Iraq, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Yemen, Western Sahara
North Africa	Algeria, Egypt, Libya, Morocco, Tunisia
West Africa	Cabo Verde, Benin, Gambia, Guinea-Bissau, Guinea, Côte d'Ivoire, Mali, Niger, Senegal, Togo, Burkina Faso, Ghana, Liberia, Nigeria, Sierra Leone
ECS Africa (East, Central and South)	Angola, Botswana, Burundi, Cameroon, Central African Republic, Chad, Comoros, Congo, Equatorial Guinea, Djibouti, Gabon, Kenya, Lesotho, Madagascar, Malawi, Mauritanie, Mauritius, Mozambique, Namibia, Eritrea, Zimbabwe, Rwanda, Saint Helena, Ascension and Tristan da Cunha, Sao Tome and Principe, Seychelles, Somalia, South Africa, Swaziland, United Republic of Tanzania, Uganda, Ethiopia, Democratic Republic of the Congo, Zambia, Mayotte, Sudan, South Sudan
Oceania	American Samoa, Australia, Solomon Islands, Christmas Island, Cocos (Keeling) Islands, Fiji, French Polynesia, Kiribati, Guam, Marshall Islands, Micronesia (Federated States of), Nauru, New Caledonia, Vanuatu, New Zealand, Niue, Norfolk Island, Northern Mariana Islands, Papua New Guinea, Pitcairn Islands, Palau, Tokelau, Tonga, Tuvalu, Wake Island, Wallis and Futuna Islands, Samoa
Rest of the world	French Southern and Antarctic Territories, Iceland, Republic of Moldova, Faroe Islands, Greenland, Saint Pierre and Miquelon, Channel Islands, Svalbard and Jan Mayen Islands, Isle of Man

3.4 Parameterization of quantitative input data in the GlobAgri-CLINOrg model



Legend: Input variables (yellow), Input variables from GOANIM (purple),
Output variables (green), Endogenous feedbacks on trade structure (red dotted lines)

Figure S15 - Framework in the GlobAgri-CLINOrg model to achieve equilibrium between resources and uses for each product, in each region. Purple color is used to highlight variables that are exchanged with GOANIM. Red color is used to highlight the model’s feedback on regional export shares and import ratios (i.e. export shares and import ratios are endogenously adjusted, when necessary, to meet constraints on maximum cultivable area, organic crop rotations, and requirement for nitrogen from organic livestock manure). CI : cropping intensity. Adapted from Forslund et al. (2023)

3.4.1 Organic production data

We used the following GOANIM outputs, aggregated at the regional level and at the level of GlobAgri’s crop and animal products groups, as inputs for running GlobAgri-CLINOrg: (i) organic crop yields (tDM.ha-1 in GOANIM, converted to t.ha-1 using species-specific DM coefficients from Barbieri et al., (2021), except for forages, which are expressed in tDM.ha-1 in GlobAgri). Note that forage crops yield in GlobAgri correspond to the simulated yield in GOANIM minus the fraction recycled back to the field (since this fraction cannot be used as feed); (ii) N input from livestock manure to organic croplands (tN.ha-1); (iii) composition of the organic livestock population; and (iv) organic livestock feed-to-output ratios (kg feed ingredient per kg of animal product). Crop rotations were explicitly considered in organic cropping systems by allocating a share of the total harvested organic area to the different crop groups (Supplementary Material C:

Description of the models' variables and equations). These shares are given in Table S1. The correspondence of crop and animal products between the two models is provided in Table S11.

Table S11 - Correspondence between GlobAgri and GOANIM plant and animal products

GlobAgri product	**Corresponding GOANIM products**
Plant products	
Wheat	Wheat
Maize	Maize (grain)
Rice	Rice
Other cereals	Barley, buckwheat, millet, oats, rye, sorghum, triticale, Cer2 mix
Sugar plant and products	Sugar beet, sugar cane
Fruits and vegetables	Apple, banana, cabbage, fruit nes, grape, mango, onion, orange, plantain, tomato, vegetable nes, watermelon
Pulses	Bean, broadbean, chickpea, cowpea, lentil, pea, pigeonpea, pulse nes, pulses mix
Roots and tubers	Cassava, potato, sweetpotato, yam
Rape and mustard seeds	Rapeseed
Soyabeans	Soybean
Sunflower seeds	Sunflower seed
Other oil crops	Coconut, groundnut, linseed, sesame
Fibers	Cotton, rubber
Other plant products	Cashew, cocoa, coffee, tea, tobacco
Grass	Grass from permanent grasslands
Grass-like forages	Clover, grass nes, mixedgrass
Other forages	Alfalfa fornes, legume nes, maize (fodder), oilseed forages, vetch
Animal products	
Dairy	Cow milk, sheep milk, goat milk
Eggs	Eggs
Pork meat	Pork meat
Poultry meat	Poultry meat
Bovine meat	Beef meat
Small ruminant meat	Sheep meat

3.4.2 Other input data

For most input data, we used the data developed in previous modelling exercises with GlobAgri to parameterize GlobAgri-CLINOrg. More specifically, we used data from the reference scenario in the European Chemical Pesticide Free-Agriculture in 2050 foresight (Mora et al., 2023) for (i) conventional agriculture in Europe and outside Europe, (ii) maximum cultivable areas in 2050, (iii) population growth, (iv) human diets. Here, we provide a brief summary of these data and underlying assumptions. They are described in detail in Tibi et al. (2020) and Mora et al. (2023).

The initial equilibrium of GlobAgri was calibrated for year 2010 based on FAOStat data (2009-2011 average).

Change in total food consumption between 2010 and 2050 in each region results from both change in population and change in food diets. Population in 2050 is the median projection of the United Nations World Population Prospect (UN, 2017) (+40% between 2010 and 2050 at the global level, but stagnation in Europe). Data for human diets were retrieved from Mora et al. (2023), in which the authors built upon FAO business-as-usual (BAU) projections (FAO, 2018) to compute regional BAU diets and Eat lancet diets to compute regional flexitarian, vegetarian and vegan diets. The composition of the diets variants for Europe is given in Figure S16 (average of European sub-regions). Outside Europe, we assumed that diets follow the BAU option in every scenario.

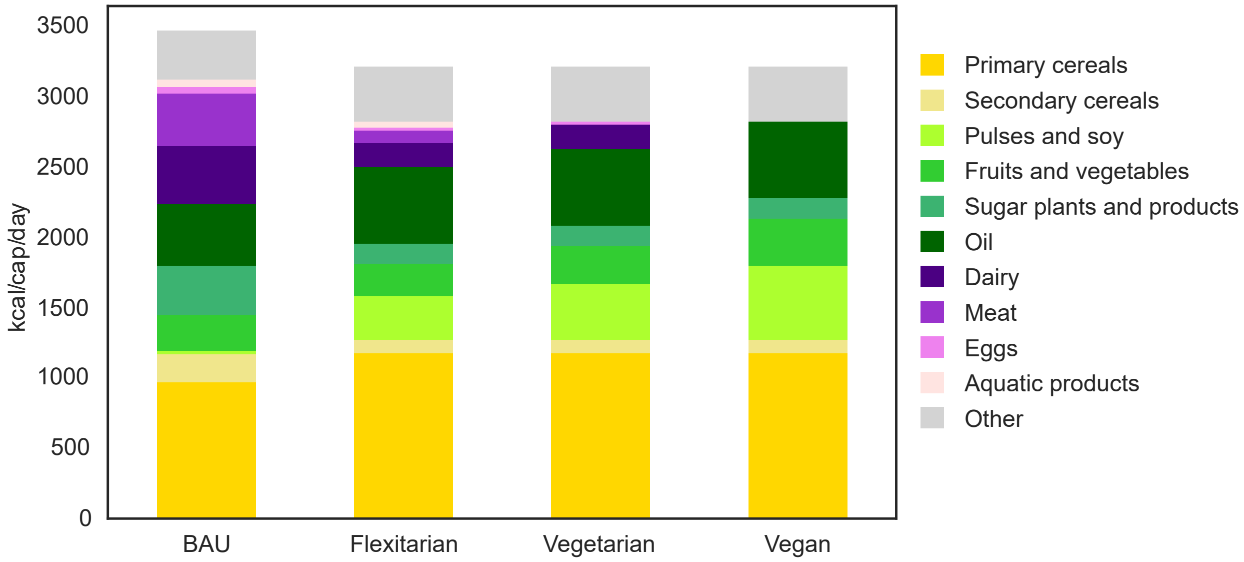


Figure S16 - Average European diets in the different options for human diets, in kcal per person per day. The reported values include wastes at the household level. BAU : buisiness-as-usual (current trends diets). Source : Mora et al. (2023).

Conventional crop and livestock parameters are also unchanged across scenarios both within and outside Europe. Crop yields projection are those of the ‘low’ variant described in Tibi et al. (2020), which combined effects of climate changes (RCP 6.0 climate scenario with no fertilization from CO_2 (Makowski et al., 2020)), with moderate technological advancements assumption from FAO (2018).

For maximum cropland areas in each region in 2050, we used the variant ‘without forests and shrubs’ from Mora et al. (2023) (Table S12). Regional potentially cultivable areas in 2050 include croplands, grasslands and fallows with a projected suitability index > 40% (moderately suitable) under a RCP 6.0 climate scenario in GAEZ-v4 database. Note that this does not mean that our scenarios are “zero deforestation” scenarios : unlike croplands, permanent grasslands can expand on shrublands and forests.

Table S12 - Regional cropland areas in the initial situation (2010) and maximum cultivable areas in 2050 , in 1000ha. Source: Mora et al. (2023).

	Croplands 2010 (1000ha)	Cultivable lands without forests & shrubs in 2050 (1000ha)
France	19 292	30 674
Germany	12 088	19 946
United Kingdom	6 072	16 152
Poland	11 715	16 966
South Europe	35 972	37 753
East Europe	20 260	27 002
Central Europe	6 517	8 354
Rest of Europe	15 175	36 834
Europe	127 091	193 681
Canada, USA	193 234	415 280
Brazil, Argentina	116 143	206 917
Rest of America	68 767	152 857
Former Soviet Union	201 947	352 168
China	122 537	157 215
India	169 442	178 835
Rest of Asia	171 957	155 680
Near and Middle East	57 183	41 158
North Africa	28 283	12 457
West Africa	98 490	130 050
ECS Africa	134 134	354 146
Oceania	47 919	68 245
Rest of World	2 273	2 671
World	1 539 400	2 421 360

3.5 Calculation of greenhouse gas emissions from agriculture

This section describes the calculations of GHG emissions from agriculture (that is, crop and livestock production).

We followed Tier 1 guidelines from the IPCC. When our calculations include default parameters or emissions factors from the IPCC, the same defaults values are applied to both organic and conventional systems, unless we specify otherwise.

All emissions calculated in N_2O-N were converted in N_2O using molar mass ratio of (44/28). All N_2O and CH_4 emissions were converted to CO_2 equivalent (CO_2eq) using GWP100 potential of 265 and 28, respectively (IPCC, 2013).

3.5.1 N_2O emissions from animal manure management, application and left on pasture

For each livestock specie, N excretion rates were computed on the basis of an input-output balance between N intake and N retained in live weight and in animal products (milk or eggs). The procedure included non-producing animals, as described in section S3.1.2.

To estimate the share of animal manure that was excreted on pasture/free range in conventional systems, we used regional default values from the IPCC (2019a, Tables 10.A.6 to 10.A.9). For organic systems, we assumed that the share of manure excreted on pasture or free range was equal to the share of the time spent outdoor defined in each scenario (Tables S3-S7). The remaining fraction was distributed among different manure management systems, also according to IPCC default values (Tables 10.A.6 to 10.A.9). For organic laying hens, litter was assumed to be the only system for indoor manure management. We considered that all N excreted indoor, minus the fraction lost during manure management, was collected and applied on agricultural soils. We considered no exchanges of animal manure between organic and conventional farms.

We used IPCC default emissions factors, in kg N_2O -N.kg N^{-1}, to calculate direct emissions from manure left on pasture, application, and manure management (Table 10.21 in IPCC (2019a) and Table 11.1 in IPCC (2019b)). We accounted for differences between wet and dry climates and used specific emissions factor for each type of manure management system. We calculated indirect emissions using default values provided in Table 11.3 in IPCC (2019b) for N volatilization and redeposition and N leaching, expressed in kg N_2O –N (kg NH3–N + NO_X–N volatilized)-1 and kg N_2O -N.kg N^{-1}, respectively. We used default values for leaching and volatilization fractions (Tables 10.22 and 11.3), except for leaching fraction of manure applied to organic croplands which was corrected to account for non-leguminous cover crops soil cover.

3.5.2 N_2O emissions from plant material recycled on croplands

In organic systems, plant materials applied or left on croplands included crop residues and biomass from cover crops and forage crops used as green manure. The amount of N retrieved from these sources was computed by GOANIM. In conventional systems, only crop residues were considered. The fraction of crop residues returned to soils in conventional systems was retrieved from Barbieri et al. (2021). Direct N_2O losses were computed using IPCC defaults emissions factors (in kg N_2O -N.kg N^{-1}), distinguishing wet and dry climate (Table 11.1 in IPCC (2019b)). For conventional systems, we used default fractions for N leaching, and the associated emission factor (Table 11.3 in IPCC (2019b)). For organic systems, the fraction lost through leaching depended on the crop rotation option.

3.5.3 N_2O emissions from synthetic fertilizers application

For conventional systems, the amount of N from synthetic fertilizers was computed in order to balance croplands N budget at the regional level. With:

$$N_{synth}(r) = (N_{harvest}(r) + N_{loss}(r)) - (N_{fert,ani}(r) + N_{fix}(r) + N_{dep}(r))$$

Where $N_{synth}(r)$ stands for N input from synthetic fertilizers in region r, $N_{harvest}(r)$ for N harvested in crops and crop residues, $N_{fert,ani}(r)$ for N from livestock manure application, $N_{fix}(r)$ for N from legumes BNF and free cyanobacteria fixation, $N_{dep}(r)$ for N from atmospheric deposition, and $N_{loss}(r)$ for N lost to the environment, as gaseous N_2O, N_2, NH_3 or NO_3^- leaching.

The total amount of N applied on soils was then:

$$N_{tot}(r) = N_{synth}(r) \,/\, (1 - kloss(r))$$

With kloss, the loss coefficient, calculated as:

$$kloss(r) = Fgas(r) + Fleach(r) + Dirloss(r)$$

Where Fgas is the fraction lost via volatilization, Fleach is the fraction lost via leaching and Dirloss are direct gaseous losses following synthetic fertilizers application (in in kg N_2O -N.kg N-1, 0.005 or 0.016 in dry and wet climates, respectively). Emissions factors and default values for fraction lost through volatilization and leaching were retrieved from Table 11.1 and 11.3 in IPCC guidelines (IPCC, 2019b).

3.5.4 CH_4 from enteric fermentation

We estimated CH_4 from enteric fermentation based on animal live weight (LW) and IPCC Tier 1 default emissions factor (in kg CH_4 per head) (IPCC, 2019a). As suggested in the guidelines, we adapted the default emissions factor ($EF_{default}$) by scaling with live weight ratios raised to the 0.75 power. Thus, the adapted emission factor (EF) is as follows:

$$EF = EF_{default} * (LW/LW_{default})^{0.75}$$

We accounted for the entire livestock population by adding CH_4 from non-producing animals, calculated following the same procedure, and corrected using the number of non-producing animals per producing animals in LU equivalent (Ratio total LU / producing LU). Table S13 reports the default values for emissions factors and associated default live weight used in this work. Live weights and coefficients of non-producing animals for organic production systems are available in Tables S3-S7.

3.5.5 CH_4 from manure management

CH_4 emissions from manure management and storage were defined based on default emission factor from Table 10.14 in IPCC guidelines (in g CH_4 per kg volatile solid (VS) excretion) (IPCC, 2019a). VS excretion rate were calculated using IPCC default values for VS excretion rate (in KG vs (1000 kg animal mass)-1 day-1).

3.5.6 Paddy rice (CH4) and crop residues burning (N_2O and CH_4)

To calculate emissions from paddy rice cultivation and crop residues burning, we used regional emission coefficients retrieved from Mora et al., (2023). These coefficients are derived from FAOStat emissions data. We used the same coefficients for organic and conventional systems. There are evidences suggesting that emissions from paddy rice are higher in organic systems (Seufert & Ramankutty, 2017). However, these evidences are very limited and we considered that, given the small contribution of these emissions on GHG emissions from agriculture in our calculations, this simplification would not affect the overall results.

Table S13 - Default emission factors for enteric fermentation used in this work (in kg CH$_4$/head), retrieved from IPCC (2019a) at the scale of large world regions. The numbers in parentheses represent the default live weight associated with the emission factor for each animal in the IPCC tables (IPCC, 2019a). Note that for dairy organic cattle, we used the value for Eastern Europe because the milk productivity (5000 kg/head) was closest to our assumptions. Broilers and laying hens are not associated with emissions from enteric fermentation. EEU : Eastern Europe. WEU: Western Europe. NAM : North America. IND : Indian sub-continent. LAC : Latin America. MEA : Middle East. OCE : Oceania

		EEU	WEU	NAM	Africa	Asia	IND	LAC	MEA	OCE
Dairy cattle	Mature animals	93 (550)	126 (600)	138 (650)	High productivity 86 (250)	High productivity 96 (485)	High productivity 70 (350)	High productivity 103 (520)	High productivity 94 (510)	93 (488)
					Low productivity 66 (270)	Low productivity 71 (355)	Low productivity 74 (265)	Low productivity 78 (500)	Low productivity 62 (270)	
	Non mature animals (calves on forages)	46 (180)	32 (230)	59 (215)	31 (82)	26 (90)	29 (72)	39 (160)	46 (115)	43 (185)
Beef cattle	Mature animals	65 (600)	81 (600)	98 (820)	79 (540)	72 (501)	53 (309)	81 (582)	75 (519)	64 (467)
	Non mature animals (calves on forages)	46 (180)	32 (230)	59 (215)	31 (82)	26 (90)	29 (72)	39 (160)	46 (115)	43 (185)
Sheep	Liveweight > 40	9 (40)								
	Liveweight < 40	5 (31)								
Goats	Liveweight > 50	9 (50)								
	Liveweight < 50	5 (28)								
Pigs	Liveweight > 72	1.5 (72)								
	Liveweight < 72	1 (52)								

4 Supplementary references

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R. M., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology*, *25*(8), 2530-2543. https://doi.org/10.1111/gcb.14644

Arvalis. (2020). *Flux et calculs intermédiaires pour obtenir les pertes en azote et en matière organique des animaux d'élevage*. https://www.arvalis.fr/sites/default/files/imported_files/4-3-2587189502817534782.pdf

Barbieri, P., Pellerin, S., & Nesme, T. (2017). Comparing crop rotations between organic and conventional farming. *Scientific Reports*, *7*(1), Article 1. https://doi.org/10.1038/s41598-017-14271-6

Barbieri, P., Pellerin, S., Seufert, V., & Nesme, T. (2019). Changes in crop rotations would impact food production in an organically farmed world. *Nature Sustainability*, *2*(5), Article 5. https://doi.org/10.1038/s41893-019-0259-5

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

Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E. S., Prieur, L., & Justes, E. (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agronomy for Sustainable Development*, *35*(3), 911-935. https://doi.org/10.1007/s13593-014-0277-7

Benoit, M., & Veysset, P. (2021). Calcul des Unités Gros Bétails : Proposition d'une méthode basée sur les besoins énergétiques pour affiner l'étude des systèmes d'élevage. *INRAE Productions Animales*, *34*(2), Article 2. https://doi.org/10.20870/productions-animales.2021.34.2.4855

Bonnefous, C., Collin, A., Guilloteau, L. A., Germain, K., Ravon, L., Bordeau, T., Chartrin, P., Godet, E., Cailleau-Audouin, E., Couroussé, N., Raynaud, E., Mignon, S. V., Reverchon, M., Mattioli, S., Castellini, C., Angelucci, E., Guesdon, V., Calandreau, L., Berri, C., & Le Bihan-Duval, E. (2024). Performance, meat quality and blood parameters in four strains of organic broilers differ according to range use. *Scientific Reports*, *14*(1), 30854. https://doi.org/10.1038/s41598-024-81672-9

Brossard, L., Nieto, R., Charneca, R., Araujo, J. P., Pugliese, C., Radović, Č., & Čandek-Potokar, M. (2019). Modelling Nutritional Requirements of Growing Pigs from Local Breeds Using InraPorc. *Animals*, *9*(4), Article 4. https://doi.org/10.3390/ani9040169

Candek-Potokar, M., Linan, R. M. N., Candek-Potokar, M., & Linan, R. M. N. (2019). *European Local Pig Breeds—Diversity and Performance. A study of project TREASURE*. https://doi.org/10.5772/intechopen.83749

Denoual, P. (2022). *Efficience d'utilisation des aliments dans des scénarios prospectifs d'évolution de l'élevage de porcs biologiques* (p. 74). Institut Agro.

Dourmad, J.-Y., Étienne, M., Valancogne, A., Dubois, S., van Milgen, J., & Noblet, J. (2008). InraPorc : A model and decision support tool for the nutrition of sows. *Animal Feed Science and Technology*, *143*(1), 372-386. https://doi.org/10.1016/j.anifeedsci.2007.05.019

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. *Nature Communications*, *7*(1), Article 1. https://doi.org/10.1038/ncomms11382

FAO. (2018). *The future of food and agriculture – Alternative pathways to 2050.* (p. 224).

Fendrich, A. N., Matthews, F., Van Eynde, E., Carozzi, M., Li, Z., d'Andrimont, R., Lugato, E., Martin, P., Ciais, P., & Panagos, P. (2023). From regional to parcel scale : A high-resolution map of cover crops across Europe combining satellite data with statistical surveys. *Science of The Total Environment*, *873*, 162300. https://doi.org/10.1016/j.scitotenv.2023.162300

Fetzel, T., Havlik, P., Herrero, M., Kaplan, J. O., Kastner, T., Kroisleitner, C., Rolinski, S., Searchinger, T., Van Bodegom, P. M., Wirsenius, S., & Erb, K.-H. (2017). Quantification of uncertainties in global grazing systems assessment. *Global Biogeochemical Cycles*, *31*(7), 1089-1102. https://doi.org/10.1002/2016GB005601

Fischer, G. (2021). *Global Agro-Ecological Zones v4 – Model documentation*. FAO. https://doi.org/10.4060/cb4744en

Forslund, A., Tibi, A., Schmitt, B., Marajo-Petitzon, E., Debaeke, P., Durand, J.-L., Faverdin, P., & Guyomard, H. (2023). Can healthy diets be achieved worldwide in 2050 without farmland expansion? *Global Food Security*, *39*, 100711. https://doi.org/10.1016/j.gfs.2023.100711

García-Gudiño, J., N. T. R. Monteiro, A., Espagnol, S., Blanco-Penedo, I., & Garcia-Launay, F. (2020). Life Cycle Assessment of Iberian Traditional Pig Production System in Spain. *Sustainability*, *12*(2), Article 2. https://doi.org/10.3390/su12020627

Gaudaré, U., Kuhnert, M., Smith, P., Martin, M., Barbieri, P., Pellerin, S., & Nesme, T. (2023). Soil organic carbon stocks potentially at risk of decline with organic farming expansion. *Nature Climate Change*, 1-7. https://doi.org/10.1038/s41558-023-01721-5

Gaudaré, U., Pellerin, S., Benoit, M., Durand, G., Dumont, B., Barbieri, P., & Nesme, T. (2021). Comparing productivity and feed-use efficiency between organic and conventional livestock animals. *Environmental Research Letters*, *16*(2), Article 2. https://doi.org/10.1088/1748-9326/abd65e

Guerder, F., Debut, M., & Vialter, S. (2009). *PREMIERE APPROCHE DE LA CARACTERISATION DE LA QUALITE TECHNOLOGIQUE DE LA VIANDE DE POULE*. 5.

Guyot, Y., Blazy, V., & Fontanet, J.-M. (2022). *Refonte méthodologique du bilan réel simplifié volailles*. 883-887. https://www.itavi.asso.fr/publications/

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., & Fischer-Kowalski, M. (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(31), 12942-12947. https://doi.org/10.1073/pnas.0704243104

Herrero et al. (2013). *Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems*. PNAS. https://www.pnas.org/doi/abs/10.1073/pnas.1308149110

Høgh-Jensen, H., Loges, R., Jørgensen, F. V., Vinther, F. P., & Jensen, E. S. (2004). An empirical model for quantification of symbiotic nitrogen fixation in grass-clover mixtures. *Agricultural Systems*, *82*(2), 181-194. https://doi.org/10.1016/j.agsy.2003.12.003

Idele. (2012). *Alimentation des bovins : Rations moyenne et autonomie alimentaire. Compte rendu final 00 12 39 005* (Collection Résultats, p. 46). https://idele.fr/

I.D.M. Gangnat, S. Mueller, R.E. Messikommer, & M. Kreuzer. (2020). Performance, egg quality and resilience to nutritional challenges of Lohmann Dual hens as opposed to layer and traditional dual-purpose types : A preliminary study. *European Poultry Science (EPS)*, *84*. https://doi.org/10.1399/eps.2020.301

IFIP. (2013). *Mémento de l'Eleveur de Porc—Edition 2013*. https://ifip.asso.fr/documentations/4610-memento-de-leleveur-de-porc-edition-2013/

Iger-Centres-de-Gestion. (1989). *Le mot juste. 250 termes et expressions pour analyser les résultats de gestion des exploitations d'élevage*. 168p.

INRA. (2007). *Alimentation des bovins, ovins et caprins. Besoins des animaux. Valeur des aliments.* Éditions Quae.

IPCC. (2013). Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013 : The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA). https://www.ipcc.ch/report/ar5/wg1/

IPCC. (2019a). Chapter 10 : Emissions from livestock and manure management. In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.: Vol. Volume 4 Agriculture, Forestry and Other Land Use*.

IPCC. (2019b). Chapter 11 : N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.: Vol. Volume 4 Agriculture, Forestry and Other Land Use*.

ITAVI. (2013). *Estimation des rejets d'azote, phosphore, potassium, calcium, cuivre et zinc par les élevages avicoles – Mise à jour des références CORPEN Volailles de 2006* (p. 63).

ITAVI. (2022a). *Performances techniques et indicateurs économiques en pouletttes prêtes à pondre et poules pondeuses d'œufs de consommation – résultats 2020 & 2021.* (p. 24). Rapport Service Economie ITAVI.

ITAVI. (2022b). *Performances techniques et résultats économiques des volailles de chair biologiques et sous Label Rouge en 2021* (p. 35). Rapport Service Economie ITAVI.

Jousseins C., Tchakérian E., de Boissieu C., Morin E., Turini T. (2014). *Alimentation des ovins : rations moyennes et niveaux d'autonomie alimentaires. Compte rendu 00 14 301 027.* Idele, collection résultats, 54p.

Latham, J., Cumani, R., Rosati, I., & Bloise, M. (2014). *Global Land Cover SHARE (GLC-SHARE) database Beta-Release Version 1.0—2014* (p. 40). FAO. https://www.fao.org/

Makowski, D., Marajo-Petitzon, E., Durand, J.-L., & Ben-Ari, T. (2020). Quantitative synthesis of temperature, CO2, rainfall, and adaptation effects on global crop yields. *European Journal of Agronomy*, *115*, 126041. https://doi.org/10.1016/j.eja.2020.126041

Méda, B., Jessus, L., Denoual, P., & Garcia-Launay, F. (2023). *Formulation of eco-friendly feeds for conventional and organic poultry to reduce feed-food competition, greenhouse gas emissions, and land use*. 97. https://hal.inrae.fr/hal-04349857

Monfreda, C., Ramankutty, N., & Foley, J. A. (2008). Farming the planet : 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, *22*(1), Article 1. https://doi.org/10.1029/2007GB002947

Monteiro, A. N. T. R., Wilfart, A., Utzeri, V. J., Batorek Lukač, N., Tomažin, U., Costa, L. N., Čandek-Potokar, M., Fontanesi, L., & Garcia-Launay, F. (2019). Environmental impacts of pig production systems using European local breeds : The contribution of carbon sequestration and emissions from grazing. *Journal of Cleaner Production*, *237*, 117843. https://doi.org/10.1016/j.jclepro.2019.117843

Mora, O., Berne, J.-A., Drouet, J.-L., Le Mouël, C., Meunier, C., & et al. (2023). *European Chemical Pesticide-Free Agriculture in 2050. Foresight Report.* (p. 643). INRAE DEPE. https://hal.inrae.fr/hal-04231124v1

Nouri, A., Lukas, S., Singh, S., Singh, S., & Machado, S. (2022). When do cover crops reduce nitrate leaching? A global meta-analysis. *Global Change Biology*, *28*(15), 4736-4749. https://doi.org/10.1111/gcb.16269

Portmann, F. T., Siebert, S., & Döll, P. (2010). MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000 : A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, *24*(1). https://doi.org/10.1029/2008GB003435

Public Health England. (2002). *McCance and Widdowson's The Composition of Foods*. The Royal Society of Chemistry. https://doi.org/10.1039/9781849735551

Ravon, L., Reverchon, M., Berri, C., Barbin, A., Bernard, J., Bordeau, T., Bonnefous, C., Cailleau-Audouin, E., Chartrin, P., Couroussé, N., Desaint, B., Duval, E., Gamain, J.-C., Godet, E., Gorichon, T., Hondelatte, A., Lamothe, E., Le Manach, C., Lombard, S., … Germain, K. (2024). *Evaluation de trois souches à double fin en système biologique comme alternative à l'élimination des poussins*. 355-359. https://www.itavi.asso.fr/publications/evaluation-de-trois-souches-a-double-fin-en-systeme-biologique-comme-alternative-a-l-elimination-des-poussins

Robinson, T. P., Wint, G. R. W., Conchedda, G., Boeckel, T. P. V., Ercoli, V., Palamara, E., Cinardi, G., D'Aietti, L., Hay, S. I., & Gilbert, M. (2014). Mapping the Global Distribution of Livestock. *PLOS ONE*, *9*(5), e96084. https://doi.org/10.1371/journal.pone.0096084

Seufert, V., & Ramankutty, N. (2017). Many shades of gray—The context-dependent performance of organic agriculture. *Science Advances*, *3*(3), Article 3. https://doi.org/10.1126/sciadv.1602638

Thapa, R., Mirsky, S. B., & Tully, K. L. (2018). Cover Crops Reduce Nitrate Leaching in Agroecosystems:A Global Meta-Analysis. *Journal of Environmental Quality*, *47*(6), 1400-1411. https://doi.org/10.2134/jeq2018.03.0107

Tibi, A., Forslund, A., Debaeke, P., Schmitt, B., Guyomard, H., Marajo-Petitzon, E., Ben Ari, T., Bérard, A., Bispo, A., & Durand, J.-L. (2020). *Place des agricultures européennes dans le monde à l'horizon 2050 : Entre enjeux climatiques et défi de la sécurité alimentaire mondiale. Rapport de synthèse de l'étude* (p. 159). https://hal.inrae.fr/hal-02791523

Tribouillois, H., Cohan, J.-P., & Justes, E. (2016). Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring : Assessment combining experimentation and modelling. *Plant and Soil*, *401*(1), 347-364. https://doi.org/10.1007/s11104-015-2734-8

UN. (2017). *World Population Prospects : The 2017 revision*. Department of Economics and Social Affairs. Population division.

van Milgen, J., Valancogne, A., Dubois, S., Dourmad, J.-Y., Sève, B., & Noblet, J. (2008). InraPorc : A model and decision support tool for the nutrition of growing pigs. *Animal Feed Science and Technology*, *143*(1), 387-405. https://doi.org/10.1016/j.anifeedsci.2007.05.020

Zhao, M., Running, S., Heinsch, F. A., & Nemani, R. (2011). MODIS-Derived Terrestrial Primary Production. In B. Ramachandran, C. O. Justice, & M. J. Abrams (Éds.), *Land Remote Sensing and Global Environmental Change : NASA's Earth Observing System and the*

Science of ASTER and MODIS (p. 635-660). Springer. https://doi.org/10.1007/978-1-4419-6749-7_28