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

## Supplementary Material C : Description of the models' variables and equations

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# Contents

# 1 Structure of the GOANIM Model

This section reiterates the model description outlined in Gaudaré et al. 2023, updated and translated in python by J.Demay (2024). The model runs in each grid cell independently. Underline is used to highlight any changes to existing constraints or the introduction of new constraints or variables.
These modifications include :

- **Inclusion of processing** : A fraction of crop production can be allocated to processing. Processed crops production is divided between a product (e.g., oil), which is used as food for human, and a co-product (e.g., cake) which is used as feed for livestock.
- **Inclusion of cover crops**. Legume cover crops are not fertilized and entirely used as green manure. Non legume cover crops can be fertilized and used as fodder. They are treated as any fodder crop. Cultivation of non legume cover crops also decreases the fraction of N inputs that is lost via leaching.
- **Inclusion of mixed cropping**. Simultaneous growth of cereals and grain legumes on the same field has been included. Apart from effects on grain yields and cropping intensity, mixed crops are treated as any other crops in GOANIM.
- **Updates on feed requirement and feed use equations.** The proportion of each crop allocated to feed use was explicitly distributed across livestock species. In addition, constraints were added to limit excess of protein or energy allocated to each livestock specie.
- **Updates on crop N budgets**: (i) harvested fodder crops and crop residues production not used for livestock feed can be used as organic fertilizer. (ii) If N fixed by a legume crop is higher than N in the harvested fraction of this crop, the surplus (in non harvested fraction) can be available for other crops.

## Objective function

The objective function estimates the energy (in MJ) in crop products, including food products from processing, and livestock products dedicated to human consumption. The optimization procedure aims at maximising this function.

$$\max \sum_{c=1}^{64} Y_{FoodSubYield}(c)[E]_{grain}(c,h)A(c) + \sum_{c=1}^{64} Y_{ProcessSubYield}(c)[E]_{product}(c)A(c) + \sum_{l=1}^{8} SLH(l)Prod(l)[E]_{prod}(l) \qquad (1)$$

Where $Y_{FoodSubYield}(c)$ , $Y_{ProcessSubYield}(c)$ and $SLH(l)$ are optimized variables.

## Constraints relative to cropland soils

**Maximum Yield** $[tDM.ha^{-1}]$. For each crop specie, the total yield cannot exceed a maximum organic yield:

$$\forall c, Y_{Tot}(c) \leq Y_{max}(c) \qquad (2)$$

**Yield response curve** $[tDM.ha^{-1}]$. For each crop, total yield is computed as a linear function of N in the grain or the harvested part of the plant:

$$\forall c, Y_{Tot}(c) \leq \frac{N_{grain}(c)}{[N]_{grain}(c)} \qquad (3)$$

**Division of crop yield** $[tDM.ha^{-1}]$. The production of each crop is allocated between different uses, by splitting the total yields into subyields variables.
For grain crops that can be processed (oilseeds and cereals), the total yield is divided between a fraction that is consumed directly as food, a fraction that is consumed as feed, and a fraction that is processed (Eq. 4). For the other grain crops, the total yield is divided between food and feed subyields (Eq. 5). Lastly, fodder crops cannot be consumed as food. The yield of a fodder crops is split between feed (for each livestock specie) and a fraction that is not used as feed. The latter is assumed to be collected and can be used as organic fertilizer (Eq. 6).

$$\forall c \in list\ process\ crops, Y_{Tot}(c) = Y_{FoodSubYield}(c) + \sum_{l=1}^{8} Y_{FeedSubYield}(c,l) + Y_{ProcessSubYield}(c) \tag{4}$$

$$\forall c \in list\ grain\ crops \notin list\ process\ crops, Y_{Tot}(c) = Y_{FoodSubYield}(c) + \sum_{l=1}^{8} Y_{FeedSubYield}(c,l) \tag{5}$$

$$\forall c \in list\ fodder\ crops, Y_{Tot}(c) \geq \sum_{l=1}^{8} Y_{FeedSubYield}(c,l) + Y_{RecySubYield(c)} \tag{6}$$

**Maximum fraction of crop yield used for feed** $[tDM.ha^{-1}]$. For each crop, the fraction of the total yield that can be allocated to feed is limited. This limitation is specific to each crop and is based on current trends because we consider that, in organic farming systems, it is unlikely that the share of the crops production dedicated to feed increases.

$$\forall c, \sum_{l=1}^{8} Y_{FeedSubYield}(c,l) \leq Y_{Tot}(c) f_{feed,max}(c) \tag{7}$$

**Maximum fraction of crop yield processed** $[tDM.ha^{-1}]$. For each processable crop, the fraction of the total yield that can be allocated to processing can be limited. This limitation is specific to each crop and is based on current trends.

$$\forall c \in list\ process\ crops, Y_{ProcessSubYield}(c) \leq Y_{Tot}(c) f_{process,max}(c) \tag{8}$$

**Stover yield** $[tDM.ha^{-1}]$. Stover yields are computed from crop yield and crop specific residues production ratios $(RPR)$.

$$\forall c, Y_{stover}(c) = Y_{Tot}(c) RPR(c) \tag{9}$$

**Division of stover yield** $[tDM.ha^{-1}]$. A fixed fraction of crop residues is harvested and exported (10), the remaining part is assumed to be left on fields.
The harvested fraction is divided between a fraction used as feed (for each livestock specie) and a fraction not used as feed (11). The latter is assumed to be collected and can be used as organic fertilizer.

$$\forall c, Y_{stover,out}(c) = Y_{stover}(c) f_{Exported} \tag{10}$$

$$\forall c, Y_{stover,out}(c) = \sum_{l=1}^{8} Y_{stover,feed}(c,l) + Y_{stover,recy}(c) \tag{11}$$

**N budget** $[tN.ha^{-1}]$. For each crop, a N budget is performed:

$$\forall c, N_{grain}(c) + N_{stover,out}(c) + N_{Pool}(c) = N_{BNF}(c) + N_{cyano}(c) + N_{fert,veg}(c) + N_{fert,ani}(c) + N_{dep} \tag{12}$$

Where $N_{grain}$ refers to N output in the grain or harvested part of the plant; $N_{stover,out}$ to N output in crop residues (Eq. 13); $N_{Pool}$ stores N surplus, if any; $N_{BNF}$ refers to input from biological N fixation (Eq. 15); $N_{cyano}$ refers to N fixation from free living cyanobacteria; $N_{fert,veg}$ refers to organic fertilization from plant materials (Eq. 17); $N_{fert,ani}$ stands for animal manure (Eq. 22). Losses via leaching and volatilization following application to soils have already been accounted for. $N_{dep}$ refers to atmospheric deposition.

**N output relative to crop residues** $[tN.ha^{-1}]$ is calculated as the sum of N in the harvested crop residues and N losses from residues left on fields.

$$\forall c, N_{stover,out}(c) = Y_{Tot}(c) RPR(c) [N]_{stover}(c) [f_{Exported} + (1 - f_{Exported}) k_{losses}] \tag{13}$$

Where $k_{losses}$ refers to the fraction of the N in crop residues left on fields that is lost via $N_2O$ emissions and leaching :

$$k_{losses} = 0.01 + (1 - N_{not\_leached}) \tag{14}$$

**BNF** $[tN.ha^{-1}]$

$$\forall c, N_{BNF}(c) = Y_{Tot}(c) N_{fixed}(c) \tag{15}$$

Where $N_{fixed}$ is the N fixation rate (in $tN.tDM^{-1}$) computed as :

$$N_{fixed}(c) = NiC(c) \frac{1}{NHI(c)} Proot(c) Ndfa(c) \tag{16}$$

$NiC(c)$ refers to the N content of above ground biomass ($tN.tDM^{-1}$). $NHI(c)$ refers to the N harvest index, i.e., the ratio between the N content in the harvested biomass and the total N amount in the above-ground biomass. $Proot(c)$ refers to the amount of N fixed in the roots as a proportion of N fixed in the shoots. $Ndfa(c)$ refers to the ratio between the amount of symbiotically fixed N and the total N content in the crop biomass.

**N from organic fertilization from plant materials** $[tN.ha^{-1}]$. Total N available for fertilization with plant materials is computed at the grid cell level. The sum of N distributed to the different crops must be equal or lower to total N available in the grid cell.

$$\sum_{c=1}^{64} N_{fert,veg}(c) A(c) \leq N_{fert,veg}(Tot) \tag{17}$$

Where $N_{fert,veg}(Tot)$ includes N from legume cover crops used as green manure, N left in legume crop residues left on field and N from exported crop residues and fodder that are used as fertilizing material (Equations 18 to 20)

**N from legume cover crops** $[tN]$. $N_{cc}(Tot)$ refers to N fixed by leguminous cover crops used as green manure, after subtracting the fraction lost through $N_2O$ emissions and leaching.
With:

$$N_{cc}(Tot) = A(cc)N_{BNF}(cc)(1 - k_{losses}) \tag{18}$$

**N left in legume crop residues left on field** $[tN]$. We assumed that N fixed by a legume crop is first used as the source for itself. If N fixed is higher than the harvested N, the surplus is computed in $N_{pool}(c)$ to balance the crop N budget.
We suppose that this surplus (called $N_{lef}(tot)$) is available to other crops.
With:

$$N_{lef}(Tot) = \sum_{c \in list\ N-fixing\ Crops} \min(0, N_{surplus}(c))A(c)Y_{tot}(c)(1 - k_{losses}) \tag{19}$$

Where $N_{surplus}(c)$ is the difference between N fixed and harvested N, in $tN.tDM^{-1}.ha^{-1}$

**N from crop residues and fodder not used as feed** $[tN]$. Harvested crop residues and fodders that are not used as animal feed can be collected and returned to soils
With:

$$N_{recy}(Tot) = (1-k_{losses})(\sum_{c=1}^{64}(Y_{stover,recy}(c)[N]_{stover}(c)A(c)+ \sum_{c \in list\ fodder\ crops}(Y_{RecySubyield}(c)[N]_{grain}(c)A(c)) \tag{20}$$

**N from animal manure** $[tN]$ Based on the optimized numbers of each livestock specie $(SLH)$ , the total N in animal manure that can be used to fertilize cropland soils is computed in each grid cell :

$$N_{manure}^{org,tot} = \sum_{l=1}^{8} SLH(l)N_{manure}^{soil}(l) \tag{21}$$

**Distribution of N from animal manure to the different crops** $[tN.ha^{-1}]$. The sum of N allocated to each crop must be equal or lower to total N in manure available in the grid cell. For each crop, $\frac{N_{fert,ani}(c)}{f_{available}(c)}$ refers to the total N applied to that crop.

$$\sum_{c=1}^{64} A(c)\frac{N_{fert,ani}(c)}{f_{available}(c)} \leq N_{manure}^{org,tot} \tag{22}$$

Where the fraction of organic manure available for crop uptake is calculated as 1 minus the losses:

$$f_{available}(c) = 1 - [EF_{org}(c) + 0.0066 + 0.21 + (1 - N_{not\_leached})] \tag{23}$$

Losses include:

- Direct losses of $N_2O$ from nitrification and denitrification: $EF_{org}(c)$

- Denitrification $N_2$: 0.0066
- Volatilization of $NH_3$ and $NO_x$: 0.21
- Leaching losses: $1 - N_{not\_leached}$

## Constraints relative to livestock requirements

The following equations aim at ensuring that the feed allocated to each livestock specie matches livestock energy and protein requirement for each type of intake (forage, grain and co-products, and stover).

**Energy, grain** [$Metabolisable\ MJ$]

$$\forall l, SLH(l)EReq_{grain}(l) \leq EFeed_{grain}(l) \tag{24}$$

**Energy, forage** [$Metabolisable\ MJ$]

$$\forall l, SLH(l)EReq_{forage}(l) \leq EFeed_{forage}(l) \tag{25}$$

**Energy, stover** [$Metabolisable\ MJ$]

$$\forall l, SLH(l)EReq_{stover}(l) \leq EFeed_{stover}(l) \tag{26}$$

**Protein, grain** [$t\ protein$]

$$SLH(l)\frac{ProtReq_{grain}(l)}{1000} \leq ProtFeed_{grain}(l) \tag{27}$$

**Protein, forage** [$t\ protein$]

$$\forall l, SLH(l)\frac{ProtReq_{forage}(l)}{1000} \leq ProtFeed_{forage}(l) \tag{28}$$

**Protein, stover** [$t\ protein$]

$$\forall l, SLH(l)\frac{ProtReq_{stover}(l)}{1000} \leq ProtFeed_{stover}(l) \tag{29}$$

Where $EFeed$, the Energy allocated to specie $l$ (energy 'consumed', which is compared to the requirement $Ereq$) is computed as :

$$\begin{aligned}\forall l, EFeed_{grain}(l) = &\sum_{c \in list\ crop\ feed\ grain} A(c)Y_{FeedSubYield}(c,l)1000[E]_{grain}(c,l) \\ &+ \sum_{c \in list\ process\ crops} A(c)Y_{ProcessSubYield}(c,l)1000[E]_{co-product}(c,l)\end{aligned} \tag{30}$$

$$\forall l, EFeed_{forage}(l) = \sum_{c \in list\ fodder\ crops} A(c) * Y_{FeedSubYield(c,l)} * 1000 * [E]_{forage}(c,l) + Prod(pp) * [E]_{PP} * f_{pp}(l) \quad (31)$$

Where $Prod(pp)$ refers to the total biomass from permanent grasslands in the grid cell, in $tDM$. $[E]_{PP}$ is the energy content of permanent grasslands and $f_{pp}(l)$ the share of the biomass allocated to specie $l$.

$$\forall l, EFeed_{stover}(l) = \sum_{c \in list\ crop\ feed\ stover} A(c) Y_{stover,feed}(c,l) 1000 [E]_{stover}(c) \quad (32)$$

Protein allocated to $l$ is computed as :

$$\forall l, ProtFeed_{grain}(l) = \sum_{c \in list\ crop\ feed\ grain} A(c) Y_{FeedSubYield}(c,l) [Prot]_{grain}(c) + \sum_{c \in list\ process\ crops} A(c) Y_{ProcessSubYield}(c,l) [Prot]_{co-product}(c) \quad (33)$$

$$\forall l, ProtFeed_{forage}(l) = \sum_{c \in list\ fodder\ crops} A(c) * Y_{FeedSubYield(c,l)} * [Prot]_{forage}(c) + Prod(pp) * [Prot]_{PP} * f_{pp}(l) \quad (34)$$

$$\forall l, ProtFeed_{stover}(l) = \sum_{c \in ListCropFeedStover} A(c) Y_{stover,feed}(c,l) [Prot]_{stover}(c) \quad (35)$$

**Limiting surplus consumption** As animal requirements are expressed in terms of energy and protein, GOANIM may allocate an excess of protein to meet the energy requirement of livestock $l$ (and vice versa). The following constraints limit the surplus of protein or energy allocated to each specie. This is done to ensure that the excess of protein or energy does not result in unrealistic DM intakes per head. In a follow-up procedure, output DM intakes are checked against livestock diets data used to compute energy and protein requirements.

**Energy surplus constraint** $[Metabolisable\ MJ]$

$$\forall l, SLH(l) EReq_{tot}(l) Max_E \geq EFeed_{grain}(l) + EFeed_{forage}(l) + EFeed_{stover}(l) \quad (36)$$

**Protein surplus constraint** $[t\ protein]$

$$\forall l, SLH(l) \frac{ProtReq_{tot}(l)}{1000} Max_P \geq ProtFeed_{grain}(l) + ProtFeed_{forage}(l) + ProtFeed_{stover}(l) \quad (37)$$

# 2 Variables used in the GOANIM model

## Output variables

| Var | Description | Unit | Constraints | Number |
|---|---|---|---|---|
| $Y_{Tot}(c)$ | Total yield of crop $c$ | $tDM.ha^{-1}$ | Eq(2:9, 13,15,19) | 64 |
| $Y_{FoodSubYield}(c)$ | Yield of crop $c$ allocated to human (food) consumption | $tDM.ha^{-1}$ | Eq(4, 5) | 64 |
| $\underline{Y_{ProcessSubYield}(c)}$ | Yield of crop $c$ allocated to processing | $tDM.ha^{-1}$ | Eq(4 , 8 , 30 , 33) | 17 |
| $\underline{Y_{FeedSubYield}(c,l)}$ | Yield of crop $c$ allocated to livestock $l$ as feed | $tDM.ha^{-1}$ | Eq(4-4,7 ,30-34) | 64*8 |
| $\underline{Y_{RecySubYield}(c)}$ | Yield of fodder crop $c$ not used as feed that can be returned to soils | $tDM.ha^{-1}$ | Eq(6 , 20) | 10 |
| $Y_{stover}(c)$ | Residues production of crop $c$ | $tDM.ha^{-1}$ | Eq(9 , 10) | 64 |
| $Y_{stover,out}(c)$ | Harvested residues production of crop $c$ | $tDM.ha^{-1}$ | Eq(10 , 11) | 64 |
| $\underline{Y_{stover,feed}(c,l)}$ | Harvested residues production of crop $c$ allocated to livestock $l$ as feed | $tDM.ha^{-1}$ | Eq(11 , 32 , 35) | 64*8 |
| $\underline{Y_{stover,recy}(c)}$ | Harvested stover production of crop $c$ not used as feed that can be returned to soils | $tDM.ha^{-1}$ | Eq(11 , 20) | 64 |
| $SLH(l)$ | Number of standing heads for livestock specie $l$ | Heads | Eq(21,24-29 , 36 , 37) | 8 |
| $N_{grain}(c)$ | N in the grain or harvested part of the plant for crop $c$ | $tN.ha^{-1}$ | Eq(3,12) | 64 |
| $N_{stover,out}(c)$ | N in the residues of crop $c$ that is exported from the field or lost when residues are returned to the soil. | $tN.ha^{-1}$ | Eq(13,12) | 64 |
| $N_{BNF}(c)$ | N inputs though biological N fixation for crop $c$ | $tN.ha^{-1}$ | Eq(15,12) | 64 |
| $N_{Pool}(c)$ | Variable that stores N surplus, if any, for crop $c$ | $tN.ha^{-1}$ | Eq(12) | 64 |
| $\underline{N_{fert,veg}(c)}$ | N from recycled plant materials allocated to crop $c$ (after correction for losses) | $tN.ha^{-1}$ | Eq(12, 17) | 64 |
| $\underline{N_{fert,veg}(Tot)}$ | Total N from recycled plant materials available in the grid cell to fertilize croplands | $tN$ | Eq(17) | 1 |

**Table 1: Description of the optimized variables in the GOANIM model**

| Var | Description | Unit | Constraints | Number |
|---|---|---|---|---|
| $\underline{N_{cc}(Tot)}$ | N from BNF in legume cover crops | $tN$ | Eq(18) | 1 |
| $\underline{N_{lef}(Tot)}$ | N from BNF in crop residues of legumes that are left on field. | $tN$ | Eq(19) | 1 |
| $\underline{N_{recy}(Tot)}$ | Total N from fodder and crop residues collected and used as organic fertilizers. | $tN$ | Eq(20) | 1 |
| $N_{manure}^{org,tot}$ | Total N in animal manure available in the grid cell to fertilize cropland soils | tN | Eq(21,22) | 1 |
| $N_{fert,ani}(c)$ | N in animal manure applied to crop $c$ and that is available for uptake. | $tN.ha^{-1}$ | Eq(12,22) | 64 |
| $\underline{EFeed_{grain}(l)}$ | Total Energy from grain and grain co-product allocated to livestock $l$. | $ME\ MJ$ | Eq(24, 30) | 8 |
| $\underline{EFeed_{forage}(l)}$ | Total Energy from forage allocated to livestock $l$. | $ME\ MJ$ | Eq(25, 31) | 8 |
| $\underline{EFeed_{stover}(l)}$ | Total Energy from crop residues allocated to livestock $l$. | $ME\ MJ$ | Eq(26, 32) | 8 |
| $\underline{ProtFeed_{grain}(l)}$ | Total protein from grain and grain co-product allocated to livestock $l$. | $t\ protein$ | Eq(27, 33) | 8 |
| $\underline{ProtFeed_{forage}(l)}$ | Total protein from forages allocated to livestock $l$. | $t\ protein$ | Eq(28, 34) | 8 |
| $\underline{ProtFeed_{stover}(l)}$ | Total protein from crop residues allocated to livestock $l$. | $t\ protein$ | Eq(29, 35) | 8 |
| $\underline{f_{pp}(l)}$ | Share of permanent grasslands biomass allocated to livestock $l$. | No unit | Eq(25, 28) | 8 |

**Table 1 continued**

## Input variables

| Var | Description | Unit | Resolution | Source |
|---|---|---|---|---|
| $Prod(l)$ | Productivity of organic livestock animals | kg meat or milk or eggs per Standing heads. | Specie specific | Computed, see Supplementary Material A |
| $[E]_{prod}(l)$ | Energy content of livestock products | $MJ.kg^{-1}$ | Specie-specific | Barbieri et al. 2021 |
| $N^{soil}_{manure}(l)$ | N excreted by livestock specie $l$ and available for application on cropland soils. Has been corrected for N losses during storage and for N excreted on permanent pasture | $tN.SH^{-1}$ | Specie and grid cell-specific | Computed, see Supplementary Material A |
| $ProtReq_{grain}(l)$ | Annual protein requirement as grain or co-product for livestock specie $l$ | $kg\ prot.SH^{-1}$ | Specie specific | Computed, see Supplementary Material A |
| $ProtReq_{forage}(l)$ | Annual protein requirement as forage for livestock specie $l$ | $kg\ prot.SH^{-1}$ | Specie specific | Computed, see Supplementary Material A |
| $ProtReq_{stover}(l)$ | Annual protein requirement as stover for livestock specie $l$ | $kg\ prot.SH^{-1}$ | Specie specific | Computed, see Supplementary Material A |
| $EReq_{grain}(l)$ | Annual energy requirement as grain for livestock specie $l$ | $ME\ MJ.SH^{-1}$ | Specie specific | Computed, see Supplementary Material A |
| $EReq_{forage}(l)$ | Annual energy requirement as forage for livestock specie $l$ | $ME\ MJ.SH^{-1}$ | Specie specific | Computed, see Supplementary Material A |
| $EReq_{stover}(l)$ | Annual energy requirement as stover for livestock specie $l$ | $ME\ MJ.SH^{-1}$ | Specie specific | Computed, see Supplementary Material A |
| $\underline{Max_E}$ | Maximum Energy that can be allocated to a livestock specie. Expressed as ratio of requirement. Set as 1.25 | No unit | Europe | Experts communication |
| $\underline{Max_P}$ | Maximum protein that can be allocated to a livestock specie. Expressed as ratio of requirement. Set as 1.5 | No unit | Europe | Experts communication |

**Table 2:** Description of input variables relative to livestock systems in the GOANIM model

| Var | Description | Unit | Resolution | Source |
|---|---|---|---|---|
| $A(c)$ | Area occupied by crop $c$. | $ha$ | Crop- and grid cell-specific. | Computed, see Supplementary Material A |
| $\underline{A(cc)}$ | Area occupied by legume cover crops. | $ha$ | grid cell-specific. | Computed, see Supplementary Material A |
| $\underline{Y_{max}(c)}$ | Maximum organic yield. Computed by Barbieri et al. 2021 based on the conventional yields at circa year 2000 and corrected to take into account yield losses from biotic stresses. Projected to 2050 using coefficients from Mora et al. 2023 | $tDM.ha^{-1}$ | Crop- and grid cell-specific | Barbieri et al. 2021; Mora et al. 2023 |
| $[N]_{grain}(c)$ | N concentration of the grain or harvested part of the plant | $tN.tDM^{-1}$ | Crop-specific | Barbieri et al. 2019 |
| $[E]_{grain}(c,h)$ | Metabolizable energy of the grain for humans | $MEMJ.kgDM^{-1}$ | Crop-specific | Barbieri et al. 2019 |
| $\underline{[E]_{product}(c)}$ | Metabolizable energy of the human edible product after processing | $MEMJ.kgDM^{-1}$ | Crop-specific | England 2002 |
| $\underline{[E]_{grain}(c,l)}$ | Metabolizable energy of the grain for livestock $l$ | $MEMJ.kgDM^{-1}$ | Crop and livestock specific | feedipedia[a] INRAE-CIRAD-AFZ Feed tables[b] |
| $\underline{[E]_{co-product}(c,l)}$ | Metabolizable energy of the livestock edible product after processing | $MEMJ.kgDM^{-1}$ | Crop and livestock specific | feedipedia INRAE-CIRAD-AFZ Feed tables |
| $[Prot]_{grain}(c)$ | Protein content of the grain | $tprot.tDM^{-1}$ | Crop-specific | Barbieri et al. 2019 |
| $\underline{[Prot]_{co-product}(c)}$ | Protein content of the livestock edible co-product after processing | $tprot.tDM^{-1}$ | Crop-specific | feedipedia INRAE-CIRAD-AFZ Feed tables |
| $\underline{[E]_{fodder}(c,l)}$ | Metabolizable energy of the plant for livestock $l$ | $MEMJ.kgDM^{-1}$ | Crop and livestock specific | feedipedia INRAE-CIRAD-AFZ Feed tables |
| $[Prot]_{fodder}(c)$ | Protein content of the plant | $tprot.tDM^{-1}$ | Crop-specific | Barbieri et al. 2019 |
| $f_{feed,max}(c)$ | Maximum fraction of total yield that can be allocated to feed | No unit | Crop-specific | Barbieri et al. 2021 |
| $\underline{f_{process,max}(c)}$ | Maximum fraction of total yield that can be allocated to processing | No unit | Crop-specific | FAOStat[c] |
| $RPR(c)$ | Factor to convert grain yield to stover yield. It is null for fodder crops. For wheat for example it is 1.56 | No unit | Crop-specific | Barbieri et al. 2021 |
| $[N]_{stover}(c)$ | N content of crop residues | $tN.tDM^{-1}$ | Crop-specific | Barbieri et al. 2021 |
| $[E]_{stover}(c)$ | Metabolizable energy of stover | $MEMJ.kgDM^{-1}$ | Crop-specific | Barbieri et al. 2021 |
| $[Prot]_{stover}(c)$ | Protein content of stover | $tprot.tDM^{-1}$ | Crop-specific | Barbieri et al. 2021 |
| $f_{Exported}$ | Fraction of the crop residues exported from the field under organic management (36% or 51%) | No unit | Region-specific | Barbieri et al. 2021 |
| $N_{BNF}(cc)$ | N fixation from leguminous cover crops | $tN.ha^{-1}$ | grid cell specific | Computed, see Supplementary Material A |

**Table 3:** Description of input variables relative to crops in the GOANIM model

[a] https://feedipedia.org/
[b] https://feedtables.com/
[c] https://www.fao.org/faostat/

| Var | Description | Unit | Resolution | Source |
| --- | --- | --- | --- | --- |
| $N_{dep}$ | Atmospheric N deposition. Leaching losses have already been accounted for. | $tN.ha^{-1}$ | grid cell-specific | Dentener et al. 2006 |
| $N_{cyano}(c)$ | Free living cyanobacteria N fixation | $tN.ha^{-1}$ | Crop-specific | Barbieri et al. 2021 |
| $N_{not\_leached}$ | Fraction of N available after leaching. Where leaching occurs, the fraction of N lost through leaching is 0.24 (IPCC 2019). It can be corrected on basis of the share of cropland areas covered with non leguminous cover crops | No unit | grid cell-specific | Computed, see Supplementary Material A |
| $EF_{org}(c)$ | Fraction lost via direct losses of $N_20$-N - For all species it is 0.006 or 0.005. Only exception is rice for which we use a value of 0.003 that also includes volatilization of $NH_3$ and $NO_x$ and denitrification of $N_2$ | No unit | Crop- and grid cell-specific | Barbieri et al. 2021 |
| $Prod(pp)$ | Permanent grasslands biomass available for grazing. | $tDM$ | grid cell-specific | Computed, see Supplementary Material A |

**Table 4:** Description of input variables relative to other inputs in the GOANIM model

# 3 Structure of the GlobAgri-CLINOrg Model

## Objective function

The objective function computes the sum of the square values of $\lambda_{low}^{rot}(i,r)$. These variables are set to 0 in the initial equilibrium, but can activate when the equilibrium between resources and uses is not feasible because of insufficient share of a crop group in organic crop rotation compared to the region's required production to compile with domestic consumption and exports. Activation of $\lambda_{low}^{rot}$ reduces regional export shares for all crops $i$ included in crop group $g$ (46). Therefore, the optimization procedure aims at minimizing the decrease in export shares that can be imputed to organic crop rotations.

$$\min \sum_{r=1}^{21} \sum_{g=1}^{8} \lambda_{low}^{rot}(g,r)^2 \tag{38}$$

## Constraints relative to resources/uses balances

**Balance between resources and uses** [1000$t$] for each product $i$ in each region $r$

$$\begin{aligned}\forall i, \forall r, Prod_{tot}(i,r) + Impt(i,r) - Expt(i,r) = Food(i,r) + Feed(i,r) \\ +Oth(i,r) + Waste(i,r) + Varstock(i,r)\end{aligned} \tag{39}$$

**Production is divided between organic and conventional production** in European regions [1000$t$]

$$\forall i, \forall r \in r_{org}, Prod_{tot}(i,r) = Prod_{org}(i,r) + Prod_{conv}(i,r) \tag{40}$$

Where $r_{org}$ is a subset of regions with a fixed share of land under organic farming. In this work, $r_{org}$ refers to the 8 European regions.

**Feed is computed as a linear function of the production of livestock products** [1000$t$]. Where $\beta(i, iani, r)$ are feed to output coefficients for animal production. $iani$ is a subset of $i$, including all livestock products.

$$\forall i, \forall r, Feed(i,r) = \sum_{iani=1}^{7} Prod_{org}(iani,r)\beta^{org}(i,iani,r) + \sum_{iani=1}^{7} Prod_{conv}(iani,r)\beta^{conv}(i,iani,r) \tag{41}$$

**Wastes are computed as a linear function of domestic uses** [1000$t$]. $Waste(i,r)$ covers losses during storage, transport, and distribution. Food waste at the household level is included in $Food(i,r)$

$$\forall i, \forall r, Waste(i,r) = \gamma_{(i,r)}[Food(i,r) + Feed(i,r) + Oth(i,r) + Varstock(i,r)] \tag{42}$$

**Organic production of animal products** [1000$t$] is computed on the basis of the amount of N from animal manure per ha of organic cropland simulated in GOANIM. This procedure was developed to ensure consistency regarding N budget between organic crop yield levels simulated in GOANIM (for a given area), and new organic cropland areas simulated in GlobAgri-CLINOrg.

$$\forall r \in r_{org}, \sum_{i \in iani} Prod_{org}(i,r) N_{manure}^{soil}(i,r) = N_{manure}^{tot}(r) \sum_{i \in icrop} A_{org}(i,r) \tag{43}$$

Where *icrop* includes all crop products in $i$ and *iani* includes animal products in $i$. The total N input from organic livestock to organic croplands is computed as the sum of the organic production of each animal product ($Prod_{org}(i,r)$) multiplied by their excretion rate of N, corrected to account only for the portion of N that is available for fertilizing croplands ($N^{soil}_{manure}(i,r)$). This total N input must be equal to the N inputs from animal manure per harvested ha computed in GOANIM, multiplied by the organic harvested area $A_{org}$.

**Division of N manure between ruminant and monogastric animals** [$1000tN$] is constrained to compile with the composition of livestock population from GOANIM.

$$\forall r \in r_{org}, \sum_{i \in irumi} Prod_{org}(i,r) N^{soil}_{manure}(i,r) = f_{rumi}(r) N^{tot}_{manure}(r) \sum_{i \in icrop} A_{org}(i,r) \tag{44}$$

**Imports are a share of domestic uses** [$1000t$]. Imports ratios can be endogenously adjusted through a set of variables $\sigma$, that each activate under specific conditions described in 3. Fodders are not traded products.

$$\begin{aligned}\forall i, \forall r, Impt(i,r) = &impratio(i,r)[Food(i,r) + Feed(i,r) + Oth(i,r) + Waste(i,r)] \\ &*(1 + \sigma^{rot}_{low}(r,i))(1 + \sigma^{rot}_{up}(r,i))(1 + \sigma^{N}_{up}(r,i))(1 + \sigma^{N}_{low}(r,i))(1 + \sigma^{land}_{up}(r))\end{aligned} \tag{45}$$

**Exports are a share of the global market size of each product** [$1000t$]. Export shares can be endogenously adjusted through a set of variables $\lambda$, which each activate under specific conditions described in 3.

$$\begin{aligned}\forall i, \forall r, Expt(i,r) = expshare(i,r) \sum_{r=1}^{21} Impt(i,r) \\ *(1 + \lambda^{rot}_{low}(r,i))(1 + \lambda^{rot}_{up}(r,i))(1 + \lambda^{N}_{up}(r,i)) * (1 + \lambda^{N}_{low}(r,i))(1 + \lambda^{land}_{low}(r))\end{aligned} \tag{46}$$

**Equilibrium equation for global trade** [$1000t$]. At the global level, the sum of regional exports of product $i$ must be equal to the sum of regional imports.

$$\forall i, \sum_{r=1}^{21} Expt(i,r) = \sum_{r=1}^{21} Impt(i,r) \tag{47}$$

## Constraints relative to land use

**Harvested area of conventional crops** [$1000ha$].

$$\forall i \in icrop, \forall r, A_{conv}(i,r) = \frac{PROD_{conv}(i,r)}{Y_{conv}(i,r)} \tag{48}$$

**Harvested area of organic crops** [$1000ha$].

$$\forall i \in icrop, \forall r \in r_{org}, A_{org}(i,r) = \frac{PROD_{org}(i,r)}{Y_{org}(i,r)} \tag{49}$$

**Permanent grasslands area** [$1000ha$].

$$\forall r, A_{(pp,r)} = \frac{Feed_{org}(pp,r)}{Y_{(pp,r)}} + \frac{Feed_{conv}(pp,r)}{Y_{(pp,r)}} \tag{50}$$

Where $Y_{(pp,r)}$ refers to yields of permanent grasslands corrected to account for maximum grazing intensity threshold. For consistency with GOANIM, we used yields computed at the grid cell level (see Supplementary Material A) aggregated at the regional level. Therefore, these values correspond to the area hypothetically grazed if land was used at its maximum, sustainable intensity.

**Constraint on the share of organic farming**.
The share of organically managed croplands ($f_{\%org}$) over the total cropland areas in each region is fixed, with :

$$\forall r \in r_{org}, \sum_{i \in icrop} A_{org}(i,r) = f_{\%org} \sum_{i \in icrop} [A_{org}(i,r) + A_{conv}(i,r)] \tag{51}$$

**Constraint on maximum cultivable area** [$1000ha$].

$$\forall r, \frac{\sum_{i \in icrop} A_{org}(i,r)}{\kappa_{org}(r)} + \frac{\sum_{i \in icrop} A_{conv}(i,r)}{\kappa_{conv}(r)} \leq Max_{culti}(r) \tag{52}$$

Where $\kappa_{org}(r)$ and $\kappa_{conv}(r)$ stand for the cropping intensity of organic and conventional cropping, respectively. Cropping intensity is defined as the ratio of harvested area over cultivated area (representing the number of crops cultivated on a single field during one year).

**Organic crop rotations** [$1000ha$]. Crop rotations are explicitly considered by allocating a share of the total organic area at the crop group level. The assumption here is that the distribution of crop groups is representative of the temporal sequence of the crop rotation. Conversely, there is no rotation constraint to conventional production.

$$\forall g, \forall r \in r_{org}, \frac{\sum_{i \in g} A_{org}(i,r)}{\sum_{i \in icrop} A_{org}(i,r)} = f_{rot}(g,r) \tag{53}$$

## Constraints relative to import and export adjustments

The following equations aim at enabling the set of variables $\sigma$ and $\lambda$ to activate only under specific conditions.

**Particular case 1. A region reaches its constraint on land** ($Max_{culti}(r)$). The model resolution follows two steps:
(i) - A proportional reduction is applied to all export shares. Equation 54 ensures that $\lambda_{low}^{land}(r)$ activates only if the region reaches its constraint on land.

(ii) - If the constraint on land is still exceeded even when the exports of all products fall to zero, then regional import ratios increase. Equation 55 ensures that $\sigma_{up}^{land}(r)$ activates only when exports are down to zero.

$$\forall r, \frac{\sum_{i \in icrop} A_{org}(i,r)}{\kappa_{org}(r)} + \frac{\sum_{i \in icrop} A_{conv}(i,r)}{\kappa_{conv}(r)} = \lambda_{low}^{land}(r) Max_{culti} \tag{54}$$

$$\forall r, \sigma_{up}^{land}(r) \sum_{i} Expt(i,r) = 0 \tag{55}$$

**Particular case 2. Trade adjustment of a crop group is required to respect constraints on organic crop rotations.**
(i) - If the organic production of a crop group $g$ needed to respect the rotation constraint is higher than domestic uses and exports, first conventional production will decrease by natural adjustment of the balance equation (Eq 39). If not sufficient, import ratios of $g$ are reduced through the activation of $\sigma_{low}^{rot}$ (Eq 56). The same $\sigma$ apply to all crops within a group (Eq 45). If not sufficient, then the regional export shares for all crops belonging to $g$ increase through the activation of $\lambda_{up}^{rot}(i,r)$. Eq.58 ensures that export shares increase only after import ratios fall to zero.

$$\forall i \in g, \forall r \in r_{org}, 0 \leq \sigma_{low}^{rot}(i,r)[\frac{\sum_{i \in g} A_{org}(i,r)}{\sum_{i \in icrop} A_{org}(i,r)} - f_{rot}(g,r)] \tag{56}$$

With :

$$\sigma_{low}^{rot}(i,r) Prod_{conv}(i,r) = 0 \tag{57}$$

$$\forall i \in g, \lambda_{up}^{rot}(i,r) \sum_{i} Impt(i,r) = 0 \tag{58}$$

(ii) - Opposite situation. Organic production of a crop group $g$ needed to respect the rotation constraint is lower than domestic uses and exports. In this case, conventional production of $g$ will increase. If the region reaches its maximum cultivable area, regional export shares of $g$ decrease through the activation of $\lambda_{low}^{rot}$. Then, if necessary, $\sigma_{up}^{rot}$ activates to increase the import ratios.

$$\forall i \in g, \forall r \in r_{org}, 0 \geq \lambda_{low}^{rot}(i,r)[\frac{\sum_{i \in g} A_{org}(i,r)}{\sum_{i \in icrop} A_{org}(i,r)} - f_{rot}(g,r)] \tag{59}$$

With :

$$\forall r, \frac{\sum_{i \in icrop} A_{org}(i,r)}{\kappa_{org}(r)} + \frac{\sum_{i \in icrop} A_{conv}(i,r)}{\kappa_{conv}(r)} = \lambda_{low}^{rot}(r) Max_{culti}(r) \tag{60}$$

$$\forall i \in g, \sigma_{up}^{rot}(i,r) \sum_{i} Expt(i,r) = 0 \tag{61}$$

**Particular case 3. Trade adjustment of a livestock product is required to respect constraints on organic animal production**. These adjustments take place in a similar manner than what is described for organic crops in the former paragraph, except that the coefficients that adjust import ratios and export shares activate when the constraint on N input from animal manure is incompatible with the regions uses (43)

# 4 Variables used in the GlobAgri-CLINOrg model

## Output variables

| Var | Description | Unit | Constraints | Number |
|---|---|---|---|---|
| $Prod_{Tot}(i,r)$ | Production of product $i$ in region $r$ | $1000t$ | Eq(39,40) | 38*21 |
| $Prod_{org}(i,r)$ | Organic production of $i$ in region $r$. Only crops and animal products | $1000t$ | Eq(40, 41, 43, 44, 49) | 21*21 |
| $Prod_{conv}(i,r)$ | Conventional production of product $i$ in region $r$ | $1000t$ | Eq(39,40 , 41, 48, 57) | 21*21 |
| $Feed(i,r)$ | Feed use of product $i$ in region $r$ | $1000t$ | Eq(39, 41, 42, 45) | 38*21 |
| $Expt(i,r)$ | Exports of product $i$ in region $r$ | $1000t$ | Eq(39,46 , 61, 55, 61) | 38*21 |
| $Impt(i,r)$ | Imports of product $i$ in region $r$ | $1000t$ | Eq(39, 45, 47, 58) | 38*21 |
| $Waste(i,r)$ | Waste during storage, transport and distribution. | $1000t$ | Eq(39, 42) | 38*21 |
| $A_{org}(i,r)$ | Organic harvested area of crop $i$ (in $icrop$) in region $r$ | $1000ha$ | Eq( 43 , 44 , 49 : 54 , 56, 59, 60) ) | 15*21 |
| $A_{conv}(i,r)$ | Conventional harvested area of crop $i$ (in $icrop$) in region $r$ | $1000ha$ | Eq(48 , 51 , 53, 54 , 60) | 15*21 |
| $A(pp,r)$ | Permanent grassland areas | $1000ha$ | Eq(50) | 21 |
| $\lambda_{low}^{land}(r)$ , | Coefficients that reduce regional export shares when the maximum cultivable area is reached | No unit | Eq(46, 53 ) | 21 |
| $\lambda_{up}^{rot}(i,r)$ & $\lambda_{low}^{rot}(i,r)$, | Coefficients that change regional export shares of crops in case of incompatibilities between organic rotations and resources-uses balance | No unit | Eq(46 , 58 : 60) | 15*21 |
| $\lambda_{up}^{N}(i,r)$ & $\lambda_{low}^{N}(i,r)$, | Coefficients that change regional export shares of animal products (excluding aquatic products) in case of incompatibilities between constraints on organic production and resources-uses balance | No unit | Eq(46) | 21*6 |
| $\sigma_{up}^{land}(r)$, | Coefficients that increase regional import ratios when the maximum cultivable area is reached | No unit | Eq(45, 55) | 21 |
| $\sigma_{up}^{rot}(i,r)$ &$\sigma_{low}^{rot}(i,r)$, | Coefficients that change regional import ratios of crops in case of incompatibilities between organic rotations and resources-uses balance | No unit | Eq(45, 56 , 57 , 61) | 21*15 |
| $\sigma_{up}^{N}(i,r)$ &$\sigma_{low}^{N}(i,r)$, | Coefficients that change regional import ratios of animal products in case of incompatibilities between constraints on organic production and resources-uses balance | No unit | Eq(45) | 21*15 |

**Table 5:** Description of the output variables from the GlobAgri-CLINOrg model

## Input variables

### Variables used to compute resources-uses balances

| Var | Description | Unit | Resolution | Source |
|---|---|---|---|---|
| $Food_{(i,r)}$ | Food use of product $i$ in region $r$. Includes wastes at the household level. | $1000t$ | Region and product specific | Computed. See Supplementary Material A |
| $Oth_{(i,r)}$ | Other use of product $i$ in region $r$ (e.g., bioenergy). | $1000t$ | Region and product specific | Tibi et al. 2020 |
| $Varstock_{(i,r)}$ | Stock variation | $1000t$ | Region and product specific | Tibi et al. 2020 |
| $\gamma(i,r)$ | Fraction of production lost during storage, transport and retail. | No unit | Region and product specific | Tibi et al. 2020 |
| $impratio_{(i,r)}$ | Initial import ratios. Expressed as a fraction of domestic uses. Is set to zero for fodders. | No unit | Region and product specific | Tibi et al. 2020 |
| $expshare_{(i,r)}$ | Initial export shares. Expressed as a fraction of a product's global market. Is set to zero for fodders. | No unit | Region and product specific | Tibi et al. 2020 |

**Table 6:** Description of input variables relative to resources-uses balances in the GlobAgri-CLINOrg model

### Variables relative to plant production

| Var | Description | Unit | Resolution | Source |
|---|---|---|---|---|
| $Y_{org}(i,r)$ | Organic crop yield | $t.ha^{-1}$ | Region and crop specific | Computed in GOANIM |
| $Y_{conv}(i,r)$ | Conventional crop yields | $t.ha^{-1}$ | Region and crop specific | Tibi et al. 2020 |
| $Y(pp,r)$ | Permanent grassland yields corrected to account for a maximum grazing intensity threshold | $t.ha^{-1}$ | Region specific | Computed. See Supplementary Material A |
| $\kappa_{org}(i,r)$ | Cropping intensity in organic croplands | No unit | Region specific | Computed. See Supplementary Material A |
| $\kappa_{conv}(i,r)$ | Cropping intensity in conventional croplands | No unit | Region specific | Mora et al. 2023 |
| $Max_{culti}(r)$ | Maximum area available for cultivation in 2050. Calculated in Mora et al. (2023) from GAEZ-v4 data (Fischer 2021). | $1000ha$ | Region specific | Mora et al. 2023 |
| $f_{\%org}$ | Fraction of organic area over the total harvested area. | No unit | Only in European regions | Scenario dependant |
| $f_{rot}(g,r)$ | Fraction of organic area occupied by crop group $g$ to align with the crop rotation. | No unit | Region and group specific | Computed. See Supplementary Material A |

**Table 7:** Description of input variables relative to crop production in the GlobAgri-CLINOrg model

### Variables relative to livestock production

| Var | Description | Unit | Resolution | Source |
|---|---|---|---|---|
| $\beta^{org}(i, iani, r)$ | Feed to output coefficients. Number of kg of product $i$ to produced one kg of animal product $iani$ in region $r$ | $kg.kg^{-1}$ | Region, livestock and feed product specific | Computed in GOANIM |
| $\beta^{conv}(i, iani, r)$ | Feed to output coefficients. Number of kg of product $i$ to produced one kg of animal product $iani$ in region $r$ | $kg.kg^{-1}$ | Region, livestock and feed product specific | Mora et al. 2023 |
| $N^{soil}_{manure}(i, r)$ | N excretion of organic livestock $i$, per t product, available for application on organic croplands. Corrected for losses during manure storage and application. | $t.t^{-1}$ | Region and specie specific | Computed. See Supplementary Material A |
| $N^{tot}_{manure}(r)$ | N from livestock manure applied on organic croplands. | $t.ha^{-1}$ | Region specific | Computed in GOANIM |
| $f_{rumi}(r)$ | Fraction of N from livestock manure applied on organic croplands that comes from ruminants. | No unit | Region specific | Computed in GOANIM |

**Table 8:** Description of input variables relative to livestock production in the GlobAgri-CLINOrg model

# 5 Supplementary references


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