Robustness to import declines of three types of European farming systems assessed with a dynamic nitrogen flow model

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Abstract

Context

Agriculture in Western Europe is predominantly input-intensive (fertilisers, water, fuel, pesticides) and relies on feed imports. As a result, it is dependent on oil, which may start to decline in production in the 2020s, thus exposing the agricultural sector to potential economic stress, including increased input prices and decreased farmer purchase capacities. Therefore, it is necessary to assess the capacity of European farming systems (FS) to maintain production levels despite a decline in oil production (i.e., robustness).

Objective

We aimed to model and compare the time variations in the animal- and crop-sourced production of three French FS under three scenarios of decreased availability of feed and synthetic fertiliser imports.

Methods

We developed a FS-scale dynamic model that considers nitrogen flows between livestock, plant, and soil compartments. Plant production is a function of soil mineral nitrogen levels, and livestock numbers depend on feed availability. The three FS are characterised by different crop-grassland-livestock balances: (i) field crop (Plateau Picard), (ii) intensive monogastric (Bretagne Centrale), and (iii) extensive ruminant (Bocage Bourbonnais). The three scenarios consist of different combinations of synthetic nitrogen fertilisers and feed import availability declines until 2050: a decrease in synthetic fertilisers only (*Synth-*), a decrease in feed imports (*Feed-*), and a decrease in both external inputs (*Synth-Feed-*).

Results and conclusions

The first two scenarios highlight the positive role of livestock effluents and permanent grasslands on the robustness of food production. In the *Synth-Feed-* scenario, the extensive ruminant FS exhibits robustness (no decline in food production) for 13 years, whereas the field crop FS exhibits robustness for 4 years. In contrast, the intensive monogastric FS shows decreased food production within the first year. The difference between the two crop-livestock FS can be explained by livestock density, herd composition but also plant cover composition. In the long term, all three FS show a decrease in food production between 45–60%.

Significance

Our modelling work shed some light on the role of ruminants and permanent grasslands in making FS more robust to decreases in synthetic fertiliser and feed import availability, increasing the time with no production decline after the perturbation starts. For longer-time resilience, configurational changes are still necessary, however a greater robustness gives opportunity to implement them, therefore facilitating adaptation and transformation. Our model paves the way to the study of resilience of FS from the point of view of their crop-grassland-livestock configuration and their dependence on external inputs.

Keywords

Dynamic model; Farming system; Resilience; Robustness; Nitrogen flows; Global peak oil

1 Introduction

European agriculture heavily depends on inputs (fertilisers, water, fuel, pesticides) and feed imports (Harchaoui and Chatzimpiros, 2019), as a result of the technical-economic paradigm prevailing after World War II, characterised by genetic improvements, motorisation, use of chemicals, and industrial rationalisation of techniques. This led to a huge increase in crop yields and food production, but at the cost of significant environmental and health impacts (Bassil et al., 2007; Beketov et al., 2013; Guo and Gifford, 2002; Montgomery, 2007; Smith, 1998). In addition, the development of transport and free trade enabled agricultural regions to specialise, taking advantage either of their soil and climate conditions (cereal basins, vineyards or olive groves) or existing infrastructures (for example port trade for intensive monogastric farming in France in Brittany) (European commission, 2021a; Roguet et al., 2015). The consumption of fossil fuels by the agricultural sector increased massively (Food and Agriculture Organization of the United Nations (FAO), n.d.). Agriculture is one of the main greenhouse gas emitters of the European Union, because of methane and nitrous oxide emissions from ruminant enteric fermentation and from soil and effluent management (European commission, 2020b). The production and transport of feed has also a large environmental impact. In 2013, Europe imported more than 21 million tons of soybeans from South America (EEA, 2017). The International Energy Agency claimed in its World Energy Outlook in 2018 that, without an increase in the shale oil production capacity of the United States, global peak oil production might be reached by 2025. A global peak oil production could lead to increased oil prices and, consequently, increased price of nitrogen fertiliser and associated agricultural commodities prices (Ramírez and Worrell, 2006; Tadasse et al., 2016). As a result, the farmer purchase capacity of agricultural inputs could be reduced, impacting on food security (Irz et al., 2013).

The extent to which the European farming systems (FS) would be able to provide food during an oil crisis must be considered. In other words, it must be explored whether the European FS are resilient to potential reductions in input availability. A FS is defined as a population of individual farms located over a common geographical area that have broadly similar resource bases, enterprise patterns, household livelihoods, and constraints and for which similar development strategies would be appropriate (Dixon et al., 2001; Giller, 2013). Meuwissen et al. (2019) define the resilience of a FS as its ability to provide functions facing shocks and stresses. Furthermore, they distinguish three resilience capacities: robustness (the ability to absorb a disturbance without changing configuration), adaptability (the ability of adapting the composition of inputs and production in response to disturbances without changing the structure), and transformability (the ability to change the internal structure and feedback mechanisms in response to disturbances). In this paper we address the robustness to the progressive decrease in imported feed and synthetic fertilisers to determine the capacity of the FS to provide food in face of the perturbation without configurational changes. Such analysis would make it possible to investigate whether there are crop-grassland-livestock compositions more robust than others.

Scientific literature on resilience of agricultural systems identifies the importance of using local resources and reducing external inputs (Cabell and Oelofse, 2012; Moraine et al., 2014). However, the risk of input supply disruptions or decreased agricultural production is not systematically investigated (Cabell and Oelofse, 2012; Darnhofer et al., 2008; Stave and Kopainsky, 2014), and the assessment of robustness has not yet been the subject of quantitative analyses. Existing models could be adapted to this aim, e.g., models based on biophysical factors, including static nutrient flow balances at the regional level, soil-crop models with nutrient sub-models at the plot level, and agent-based nutrient flow models between farms with an annual time step. The Generic Representation of Agro-Food Systems (GRAFS) consists of static material flow balances accounted for in energy or nutrient mass (carbon, nitrogen, phosphorus) (Billen et al., 2019; Domingues et al., 2019). The GRAFS approach has recently been made time-dynamic to evaluate the evolution of carbon stock in agricultural soils following theoretical soil improvement practices at regional scale (Le Noë et al., 2019). The dynamic macro-nutrient models simulate biogeochemical processes between the atmosphere, plants, and soil (Parton, 1996; Brisson et al., 2003). In these models, the time step varies from 1 hour to 1 month, and the spatial resolution is at least the size of the plot (i.e., several hectares). An example of a micro-nutrient model is the one developed by Fernandez-Mena et al. (2020), a material flow balance on a FS scale with an annual time step. The abovementioned models evaluate the current and future environmental impacts of FS as well as their production capacities according to climate scenarios. However, they do not quantitatively investigate the robustness of FS in their current configurations to the decreased input availability. Thus, here we develop a model, inspired by previous ones, to quantify the food production robustness of FS to a decline in feed and synthetic fertiliser imports.

Modelling makes it possible to both simulate previously unobserved challenges and to overcome a lack of data over long periods, which is relevant for studying resilience. Our time-dynamic model focuses on nitrogen flows on a FS scale. Modelling nitrogen flows consists of performing nitrogen mass balances to quantify the exchanges between crops, grasslands, livestock, and soil. Nitrogen is an essential nutrient for living organisms, being a fundamental element of proteins. Additionally, its cycle is already well documented and modelled (Robertson and Vitousek, 2009). The FS scale is essential for integrating crops and livestock (Lemaire et al., 2014; Moraine et al., 2017), and is suitable for predicting FS performance (Billen et al., 2014). There were two main reasons for making our model time-dynamic. First, resilience is a dynamic property (Gunderson, 2000; Holling, 1973; Martin et al., 2011), and the impact of disturbances can be different over the long *vs* short term. Second, the quantity of organic nitrogen in soil evolves over time and is affected by the quantity of the previous years.

The aim of this study was to develop a model and quantify the robustness of FS characterised by different relative proportions of crops, grasslands, and livestock to declines in the imports of feed and synthetic fertilisers from a nitrogen cycle perspective. As a first step, we present our model of nitrogen flows at the FS level. Second, we present scenarios of the progressive decrease of synthetic fertilisers and feed imports over time. We then apply the model to three French FS, each one representative of a different FS type, characterised by different crop-grassland-livestock compositions. By addressing this aim, we investigated the roles of soil organic nitrogen stocks and crop-grassland-livestock balances for enhanced FS robustness.

2 Material and Methods

The FS nitrogen flow model we developed can be used to simulate a variety of scenarios for any FS.

2.1 General model description

The model conceives the FS as consisting of soil, plant, and livestock compartments. The plant and soil compartments are distributed in two land uses: permanent grasslands and cropland (which includes temporary grasslands) (Figure 1). The livestock compartment is composed by livestock species (with different dietary needs) which are either kept in housing facilities or grazing on permanent grasslands. The soil compartment is composed of a stock of active organic nitrogen and a pool of mineral nitrogen assimilated by crops or permanent grasses. Depending on the species and on the share of grazed grass in livestock diet, effluents from the livestock compartment are applied to cropland or permanent grasslands.

The model is time-dynamic, with a discrete one-year time step. It describes the time evolution of the quantity of soil organic nitrogen in both land uses according to organic nitrogen inputs (mostly plant residues and livestock effluents) and outputs (mostly net mineralisation). The mineral nitrogen in the soil originates from soil organic nitrogen net mineralisation, synthetic fertiliser, atmospheric deposition and the mineral portions of organic amendments. For each crop or grazed grass, yield is modelled as a function of available soil mineral nitrogen and of symbiotic nitrogen fixation for legumes, assuming nitrogen the only yield-limiting factor. Symbiotic fixation is a function of plant yield. Part of the yield goes to human consumption, whereas another part of the yield is used as feed. Crops and grazed grasses provide the soil with residues (parts of the plant not edible by humans or livestock or that are not harvested or grazed). The livestock number is adjusted depending on feed availability (imported and locally produced). Livestock provides mineral and organic nitrogen to the soil via effluents. Effluents go to permanent grassland soil when livestock are grazing, or in effluent management systems when livestock are in housing facilities. The quantity of effluents in effluent management systems is available to fertilise cropland soil. The fraction of effluents on permanent grasslands is proportional to the fraction of grazed grass in livestock diet, which is assumed as a proxy of the time spent on pasture (see details in Supplementary Material). Nitrogen losses occur during effluent and soil management. The state variables (soil organic nitrogen stocks, livestock numbers, and crop residues quantities) describe the system state, and their current values are used to determine the subsequent values. Imported feed and synthetic fertilisers represent external human-imported nitrogen inputs to the FS.

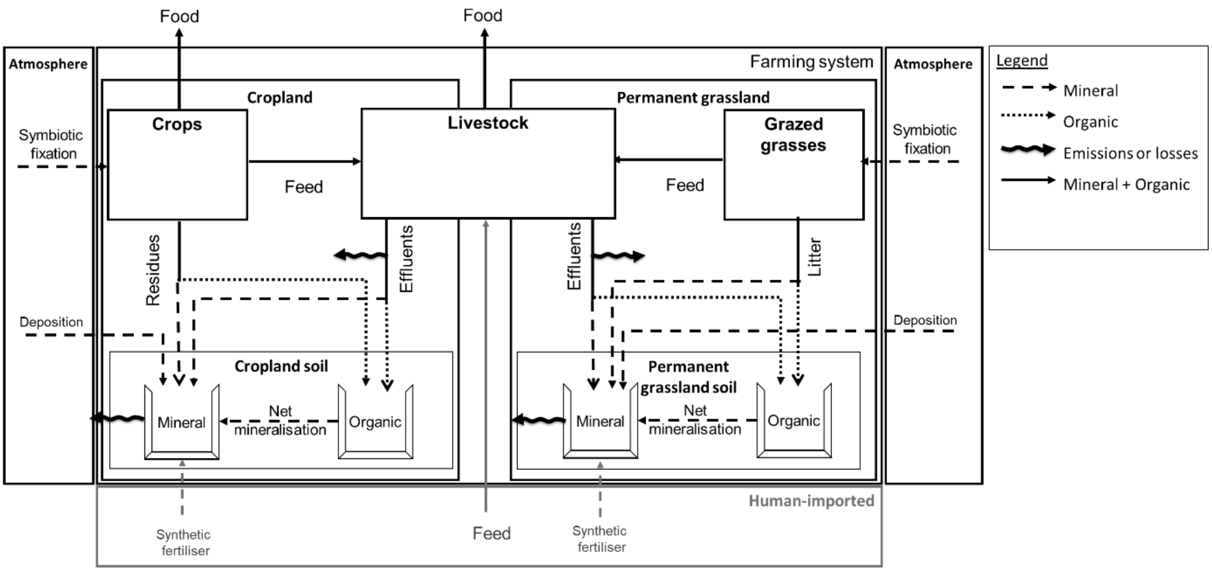

Figure 1 *Conceptual scheme of* our *model* formed by nitrogen compartments (boxes) and flows (arrows). Nitrogen flows are mineral (dashed lines), organic (dotted lines), or a mix (unbroken lines). The external flows that enter the FS come either from the a*tmosphere* or are imported by humans (in grey)

2.2 Mathematical description by compartment

Each compartment is characterised by variables dependent on parameters of the compartment itself, variables of other compartments, and exogenous variables. These compartments also serve to calculate output variables.

Unless otherwise stated, mass flows are nitrogen and annual values. The model has been coded in R language and solved using the “deSolve” package. The code and the list of data to be collected as input are available in table format upon request. More explanations and equations can be found in the Supplementary Material.

2.2.1 Soil compartments

Soil compartments contain the pools of organic (n_t^C for cropland and n_t^G for permanent grasslands [kg/ha]) and mineral nitrogen. They are considered to be one plot of land on which different crops or grazed grasses are grown. For the sake of simplification, we assume only one homogeneous average soil type per soil compartment. We assume that soil mineral nitrogen ($f_{i,t}^C$ and $f_{i,t}^G$ [kg/ha]) does not accumulate in the soil (it is either consumed by plants or lost at each time step). Organic amendments (livestock effluents, crop residues, and human sewage sludge – for cropland only) are homogeneously applied to all crops or grazed grasses for the land use concerned. Plant residues include both aerial and root residues and their application or decomposition is assumed homogeneous.

Organic amendments of year *t* are applied on cropland as well as on permanent grasslands in year *t+1*. Concerning aerial residues for cropland, a share (ξ_{EXP} [-]) is exported as livestock bedding, and a share ($\xi_{FSS,t}$ [-]) of the exported crop residues is reapplied in year *t+1* with the effluents. The human sewage sludge (E^H [kg]), the human population, and the share of recovered human excretion are assumed constant. The organic amendments both fill the soil organic and mineral nitrogen stocks. The organic nitrogen content of an organic amendment is known using its humification coefficient (Φ [-]) and C:N ratios (organic amendment over soil C:N ratios [-]). Synthetic fertiliser only consists of mineral nitrogen and it is only applied to crops or grazed grasses that are fertilised by chemicals, *i.e.* plant cover types that are composed by less than 100% of legumes.

Organic nitrogen dynamics

The dynamics of soil organic nitrogen correspond to the dynamics of soil carbon (see the AMG model (Clivot et al., 2019)) transposed to nitrogen and are described by a mass balance equation (Equations (1) and (2) below). We replaced the quantity of carbon by the quantity of nitrogen using C:N ratios. The mineralised soil organic nitrogen is immobilised to humify the carbon in the input biomass flow when there is not enough nitrogen in the flow to do so (i.e., when the C:N ratio of the input flow is high compared to that of the soil and when the humification coefficient is high) (Trinsoutrot et al., 2000). Plant residues have generally higher C:N ratios than livestock effluent (Fuchs et al., 2014).

$$n_{t+1}^{C} = n_t^{C} + (\hat{e}^{H} + \hat{e}_t^{L^B} + \hat{r}_t^{A,C} * (1 - (\xi_{EXP} * \xi_{FSS,t})) + \hat{r}_t^{R,C}) - (\mu^{C} * n_t^{C} - i_{t+1}^{M,C}) \quad (1)$$

$$n_{t+1}^{G} = n_t^{G} + (\hat{e}_t^{L^G} + \hat{r}_t^{A,G} + \hat{r}_t^{R,G}) - (\mu^{G} * n_t^{G} - i_{t+1}^{M,G}) \quad (2)$$

Equations (1) and (2) represent a nitrogen balance in cropland and permanent grasslands, whose inputs are the organic parts of aerial residues ($\hat{r}_t^{A,C}$ and $\hat{r}_t^{A,G}$

[kg/ha]), root residues ($\hat{r}_t^{R,C}$ and $\hat{r}_t^{R,G}$ [kg/ha]), livestock effluents ($\hat{e}_t^{LB}$ and $\hat{e}_t^{LG}$ [kg/ha]), and human sewage sludge for cropland only ($\hat{e}^H$ [kg/ha]). The model does not assume any nitrogen losses in the organic form to water. Output terms are the net mineralisation of organic nitrogen, which is equal to the mineralised flow ($\mu * n_t$) minus the immobilisation flow ($i_{t+1}^{M,C}$ and $i_{t+1}^{M,G}$ [kg/ha]), being μ^C and μ^G constant mineralisation rates.

Mineral nitrogen flows and losses

Soil mineral nitrogen ($f_{i,t+1}^{C}$ for cropland and $f_{i,t+1}^{G}$ for permanent grasslands) available for each crop or grazed grass (i) is the sum of the input flows of mineral nitrogen applied to the soil and the flow coming from the soil organic nitrogen (Equations (3) and (4) below). Components of this pool are the net mineralisation from the soil organic nitrogen pool, the synthetic fertiliser ($s_{i,t+1}$ [kg/ha]) per crop or grazed grass (i), the atmospheric deposition (d, assumed constant over time), and the mineral portions of organic amendments: aerial residues ($\check{r}_t^{A,C}$ and $\check{r}_t^{A,G}$), root residues ($\check{r}_t^{R,C}$ and $\check{r}_t^{R,G}$), livestock effluents ($\check{e}_t^{LB}$ and $\check{e}_t^{LG}$), and human sewage sludge for cropland only ($\check{e}^H$). Although the organic nitrogen is assumed uniform throughout the soil, the mineral nitrogen assumes different values for each crop or grazed grass because it is affected by the synthetic fertiliser tailored for each crop or grazed grass.

$$f_{i,t+1}^{C} = (\check{e}^H + \check{e}_t^{LB} + \check{r}_t^{A,C} * (1 - (\xi_{EXP} * \xi_{FSS,t})) + \check{r}_t^{R,C}) + (\mu^C * n_t^C - i_{t+1}^{M,C}) + s_{i,t+1} + d \qquad (3)$$

$$f_{i,t+1}^{G} = (\check{e}_t^{LG} + \check{r}_t^{A,G} + \check{r}_t^{R,G}) + (\mu^G * n_t^G - i_{t+1}^{M,G}) + s_{i,t+1} + d \qquad (4)$$

The mineral nitrogen effectively available for plant uptake ($f_{i,t+1}^{A,C}$ or $f_{i,t+1}^{A,G}$ [kg/ha]) corresponds to the quantity of soil mineral nitrogen reduced by the emissions and enriched by the atmospheric nitrogen fixed by the crops, if applicable.

2.2.2 Plant compartments

Plant compartments are composed of surfaces cultivated with different crops or grazed grasses. The areas of these surfaces are assumed constant, and their sum gives the total utilised agricultural area (UAA) of the FS. Each crop or grazed grass is parameterised differently. Each crop or grazed grass (i) is assigned a set of traits: area (A_i [ha]), fresh matter yield of the harvested or grazed organ ($y_{i,t}$ [kg/ha]), harvest index, shoot-to-root ratio and nitrogen contents. All these coefficients make it possible to calculate the nitrogen in plant production.

Plant yield

For each crop or grazed grass (i), the harvested or grazed organ yield ($y_{i,t}$ [kg of fresh matter/ha], the quantity of biomass harvested or grazed from the edible parts of the plants), is a piece-wise linear function of the available soil mineral nitrogen ($f_{i,t}^{A,C}$ or $f_{i,t}^{A,G}$) that saturates at a constant maximum yield (y_i^{MAX}), consistently with previous studies (de Wit, 1992). Below the maximum yield, the mineral nitrogen availability of the soil is limiting. Above the maximum yield, the plant no longer assimilates the mineral nitrogen available in the soil, and the excess is considered lost to water or air (Garnier et al., 2016).

Plant and residues production

Total nitrogen quantities of the harvested or grazed organ ($H_{i,t}$), of the aerial residues ($R_{i,t}^{A,C}$ and $R_{i,t}^{A,G}$) and of the root residues ($R_{i,t}^{R,C}$ and $R_{i,t}^{R,G}$) are obtained using equations from the AMG model (Clivot et al., 2019).

2.2.3 Livestock compartment

The livestock compartment is composed of different species. Each species (j) is characterised by an average annual number ($L_{j,t}$ [LU], i.e., the average number of livestock present daily in the FS). The livestock numbers follow a dynamic dependent on feed availability and herd management.

Feed

A livestock species (j) is characterised by its diet (*i.e.*, the individual annual feed needs ($\beta_{j,k,t}$ [kg/LU]) per feed category (k)). For each feed category (k) and species (j), the total feed needs ($B_{j,k,t}^{L}$ [kg]) in the FS are defined by $B_{j,k,t}^{L} = L_{j,t} * \beta_{j,k,t}$.

The total available feed for livestock ($A_{j,k,t}^{FEED,TOT}$ [kg]) is equal to the sum of the locally available quantity ($A_{j,k,t}^{FEED,LOC}$ [kg]) and the imported quantity ($I_{j,k,t}$ [kg]).

The feed shortage ($M_{j,k,t}$) per species (j) and per feed category (k) [kg], i.e. the proportion of feed lacked for feed category (k) and species (j), is defined as $M_{j,k,t} = \max(0, \frac{B_{j,k,t}^{L} - A_{j,k,t}^{FEED,TOT}}{B_{j,k,t}^{L}})$.

Livestock population dynamics

The time evolution of livestock populations is ruled by a dynamic model. The livestock number ($L_{j,t}$) for a species (j) changes with the management rate ($\tau_{j,t}^{M}$ [-]) (Equation (5) below). A positive value of the management rate corresponds to the willingness of the farmer to increase the herd size, whereas a negative value corresponds to the willingness of the farmer to decrease the herd size.

$$L_{j,t+1} = \left(1 + \tau_{j,t+1}^{M}\right) * L_{j,t} \qquad (5)$$

Animal-sourced food production

Animal-sourced food production ($P_{j,t}^{l}$) per species (j) and per livestock product (l) is obtained by $P_{j,t}^{l} = c_{j}^{l} * L_{j,t}$, where the coefficients (c_{j}^{l}) represent the unitary production and are assumed constant.

Livestock effluents

The nitrogen quantity of livestock excretion (E_{t}^{L} [kg]) is the difference between the total quantity of ingested feed (B_{t}^{L}) and the total animal-sourced food production (P_{t}) (INRA et al., 2018). Some of these excretions (E_{t}) occur in housing facilities ($E_{t}^{L^B}$), and others are deposited during grazing (by ruminants) ($E_{t}^{L^G}$). Part of these excretions are lost either to the air or to the water. The portion of excretions in housing facilities after losses is available for application on cropland the following year.

2.3 Simulated scenarios

We designed scenarios of progressive declines in the availability of synthetic fertiliser and feed imports over thirty years. This time horizon made it possible to observe the consequences of the perturbations on the food production with sufficient hindsight, and to simulate a decline in oil availability that could be possible in the event of a global oil peak in the 2020s. The first scenario (*Synth*-) corresponds to a linear decrease in the availability of imported synthetic fertilisers (S_{t}^{A}) with no feed imports decrease. The second scenario (*Feed*-) corresponds to a linear decrease in the availability of feed imports ($I_{k,t}^{A}$) for each feed category (k) with no synthetic fertiliser import decrease. The third scenario (*Synth-Feed*-) corresponds to a joint linear decrease in the availability of the two external human imported inputs (S_{t}^{A} and $I_{k,t}^{A}$). The trajectories of input decreases start from an initial value decrease linearly until zero at the time horizon.

Regarding the availability of synthetic fertiliser imports, the initial value (S_0^A) corresponds to 70% of the total initial mineral nitrogen needs of the plants (see Supplementary Material) so that the simulation is started without a synthetic fertiliser shortage, as the synthetic fertilisation needs never exceeds 70% of the plant nitrogen needs. Regarding the availability of feed imports, the initial value for each feed category ($I_{k,0}^A$) corresponds to the initial import needs per feed category (k). If the initial import needs for a feed category are less than 1,000 tons of nitrogen, then a value of 1,000 tons is assigned to the import availability for that feed category.

In these scenarios, the considered livestock species are cattle, goats and sheep (ruminants), pigs and poultry (monogastrics). Diet is concentrate-only for the monogastrics and contains at least 70% fodder for ruminants (Hou et al., 2016; Therond et al., 2017). The nominal value of the management rate (T_j^M) is zero. The considered animal-sourced food products are eggs, milk, and meat. The plant categories considered are a subset of the categories used in the *Registre Parcellaire Graphique* (RPG) (IGN, 2016), inspired by the French agricultural census (Ministère de l'Agriculture et de l'Alimentation, n.d.). The main categories of crops considered are cereals, oil and protein crops, sugar crops, industrial crops, tuber crops, fruit and vegetables, and fodder. Within the fodder category, we differentiate temporary grasslands (harvested or grazed grasslands less than 6 years old composed of 100% or partly of grasses), artificial grasslands (temporary grasslands composed of 100% legumes) and annual forage crops. Crops consisting of 100% legumes are not fertilised with synthetic fertiliser (Service de l'observation et des statistiques, 2013), as well as low-productive permanent grasslands. The feed categories for the different plants are cereals, oil-protein, fodder, grazed grass, co-products, and oilseed meal. We also considered a category labelled 'other' that includes fruits, vegetables, and tubers (classification based on the French National Ecosystem Assessment (Therond et al., 2017)). Only permanent grasslands are used for livestock grazing. Oilseed meals are derived from the processing of oilseeds into oil. Co-products come from the processing of cereals, fruit and vegetables for human consumption. More details about plant and feed classifications are available in the Supplementary Material. The nitrogen needs of a plant are estimated for a maximum yield equal to a typical regional yield. The fertilisation needs are equal to the nitrogen needs of the plant before fertilisation losses. The synthetic nitrogen needs of a plant are the nitrogen needs of the plant minus the natural and organic nitrogen flows. Imported synthetic nitrogen is distributed proportionally to the plant synthetic nitrogen needs. Crop residues are not fed to livestock, but 35% of aerial residues are exported as livestock bedding. The share $\xi_{FSS,t}$ is a function of the total feed needs and the total local feed availability. The remaining crop residues are buried in cropland soil. Livestock consume local feed as a priority. The share of feed pairs is constant in the livestock diet, while for a same pair, the share of one feed category may vary to the detriment of the other. Feed pairs include fodder and grazed grass, cereals and co-products, meals and oil-protein crops. In the case of a feed surplus, feed categories that are also edible by humans (i.e., cereals and oil-protein crops) are reallocated for human consumption. Constant practices (crop area, maximum yield of each crop, emission factors) and biophysical conditions are assumed constant. More details on the repartition rules implemented for these scenarios are in the Supplementary Material.

For quantifying the robustness of FS in these scenarios we considered the changes (expressed as the fraction of the initial value) in crop- and animal-sourced and total food production, and feed surplus converted into food. Total food production is the sum of crop- and animal-sourced food and feed surplus converted into food. Robustness is the capacity to maintain the initial food production levels in response to a disturbance without changing configuration. Therefore, the smaller the decline in food production, the higher the robustness of the FS (Bullock et al., 2017). In particular, in the short term, the longer food production is maintained without decline, the more robust the FS is, and in the long term, the higher the food production, the more robust the FS is. Finally, we evaluated the mineral nitrogen flows for plant fertilisation to explain the variations in crop-sourced food production.

2.4 Case studies

We applied this model to three FS types characterised by distinct proportions of livestock numbers and plant areas. We chose three French small agricultural regions (SAR, *Petite Region Agricole* in French). The SAR (average area of 76,800 ha) is an ideal representation of a FS, as already used in other studies (Accatino et al., 2019; Mouysset et al., 2012; Teillard et al., 2017). Jouven et al. (2018) grouped SAR to reflect the adequacy between local plant production and livestock consumption. We picked three SAR (Table 1) from different groups of the classification by Jouven et al. (2018): (i) an *extensive ruminant* FS (Bocage Bourbonnais), taken from the group '*balanced* *livestock and plant production with surplus concentrates*' consisting of mainly ruminant farms; (ii) an *intensive monogastric* FS (Bretagne Centrale), taken from the group '*dependent livestock production*' consisting of mainly monogastric farms with more than a 30% dependence on dry matter imports; (iii) a *field crop* FS (Plateau Picard), characterised by the prominent presence of crops and a very low livestock stocking rate and therefore not considered in the clustering by Jouven et al. (2018). In summary, the choice of the scenarios was aimed at exploring the roles of the stressors, and the choice of the SAR was aimed at exploring the roles of the FS configuration in terms of crops, grasses and livestock.

Table 1 Indicators of the three selected FS types (UAA, utilised agricultural area; LU, livestock unit). 'Extensive ruminants' refers to Bocage Bourbonnais, 'Intensive monogastrics' refers to Bretagne Centrale, and 'Field crops' refers to Plateau Picard. The initial stocks of active soil organic nitrogen are results from simulations with the nominal parameter set.

Variable	Extensive ruminants	Intensive monogastrics	Field crops
Number of inhabitants in 2017 [person]	103,150	210,844	188,749
Protein requirement of the local FS population in nitrogen* [kg/ha UAA]	2	4	4.1
Livestock density [LU/ha UAA]	0.62	1.75	0.11
Share of ruminants [-]	0.95	0.14	0.76
Total utilised agricultural area [ha]	234,941	237,592	207,642
Share of fodder area** [-]	0.30	0.41	0.05
of which artificial grassland area	0.03	0.01	0.14
of which temporary grassland area	0.10	0.50	0.71
of which annual fodder area	0.87	0.49	0.15
Share of permanent grassland area [-]	0.48	0.06	0.06
of which low-productivity permanent grassland area	0.02	0.08	0
Share of cereals area [-]	0.18	0.47	0.60
Share of oil and protein crop area [-]	0.03	0.05	0.16
Share of sugar crop area [-]	0	0	0.09
Share of 100% legume crop area*** [-]	0.02	0.01	0.05
Initial stock of soil organic nitrogen in the 30cm soil depth in agricultural land [kg/ha UAA]	8,010	6,206	7,464

Initial stock of cropland active soil organic nitrogen in the 30cm soil depth n_0^C [kg/ha]	2,707	2,554	2,260
Initial stock of permanent grassland active soil organic nitrogen in the 30cm soil depth n_0^G [kg/ha]	2,625	2,179	2,055
Mineralisation rate of the soil organic matter in agricultural land [-]	0.06	0.07	0.09

**daily protein requirement of 80g/person*
***except permanent grasslands*
****not fertilised by synthetic nitrogen in the model*

2.5 Parameters

We collected from the literature the most recent parameter values for the considered SAR. A list of the parameters with their sources and nominal values is available in the Supplementary Material. We performed a global sensitivity analysis using the R "FME" package. We considered an interval of ±20% of the nominal values for the repartition coefficients, humification factors, and C:N ratios as well as an interval of ±10% of the nominal values for nitrogen content, yield, harvest index, shoot-to-root ratio, livestock diet, and livestock production coefficients. We did not apply uncertainties to the initial livestock numbers and plant areas.

More details regarding the estimation of parameters, estimation methods and data for the initialisation of state variables, the year of parameter values, nominal values of parameters, parameter uncertainty intervals are available in the Supplementary Material.

3 Results

Time evolution of food production (Figure 2), and mineral nitrogen fertilisation flows (Figure 3), per FS and per scenario are examined.

Food production decreases over time because of the decreased input availability (Figure 2). However, two things should be noted: (i) in some FS it starts to decline earlier than others; (ii) in some cases, the total food production is little or not affected, and in one case (the *Feed-* scenario for the intensive monogastric FS), it even increases. Local peaks in animal-sourced food production correspond to the destocking of livestock (and consequent meat production) during feed shortages. An initially positive feed surplus decreases in the event of a synthetic fertiliser shortage (in the extensive ruminant and field crop FS). However, an initially null feed surplus increases when livestock destocking takes place (in the intensive monogastric FS).

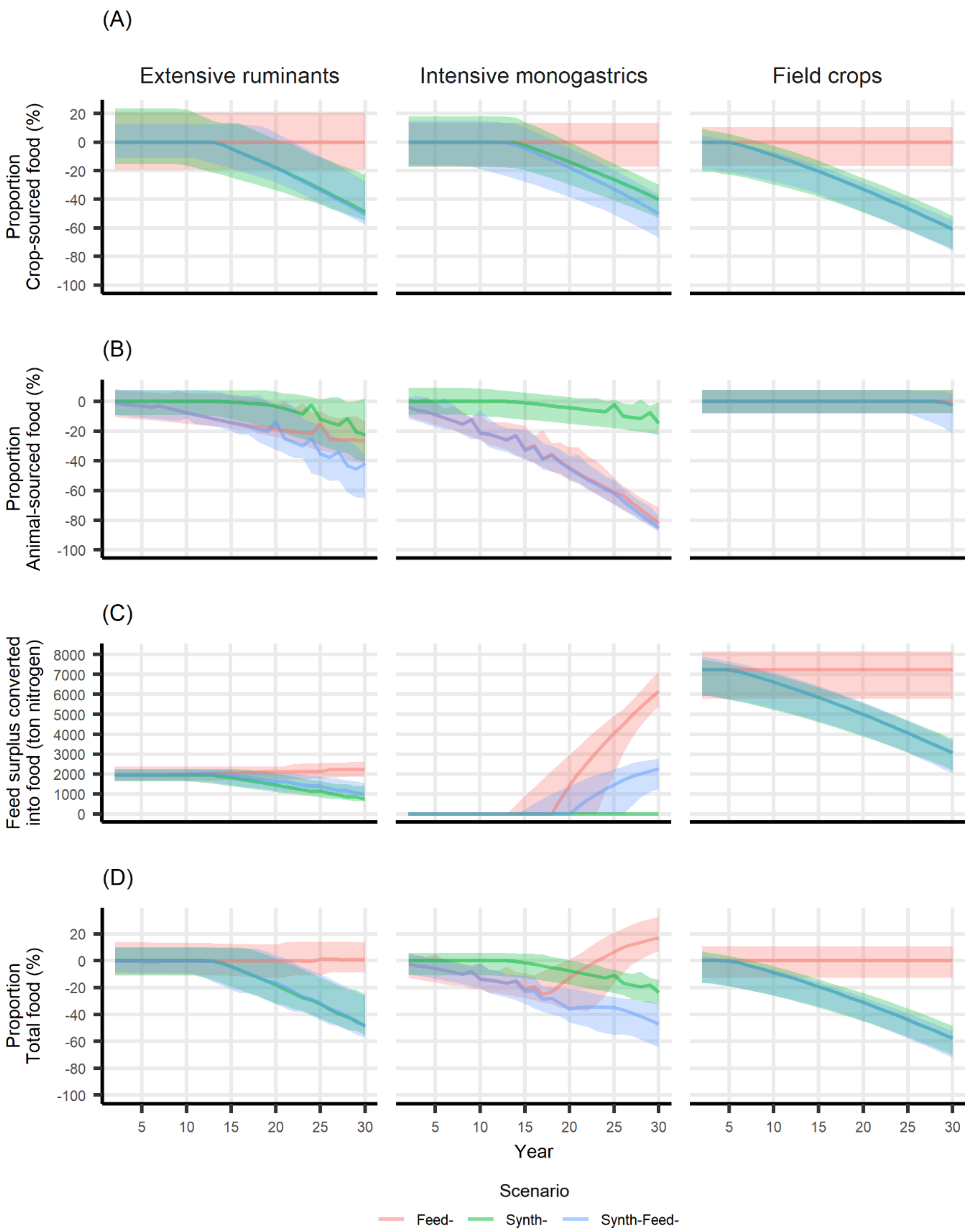

Figure 2 Simulated evolution of food production over time for the nominal parameter set as a percentage of the initial quantity or in tons of nitrogen for the three scenarios (colours) according to FS (columns). (A) Crop-sourced food production. (B) Animal-sourced food production (meat, milk, eggs). (C) Feed surplus converted into food in tons of nitrogen. (D) Total food production (aggregated crop- and animal-sourced food production and feed surplus converted into food). For the field crops FS, trajectories in the Synth- and Synth-Feed- scenarios overlap. The coloured ribbons correspond to the intervals of the minimum and maximum values from the global sensitivity analysis.

Uncertainty ribbons overlap the first years for all the outputs and in the three scenarios. The uncertainty ribbons are narrower for animal-sourced food production than for crop-sourced production.

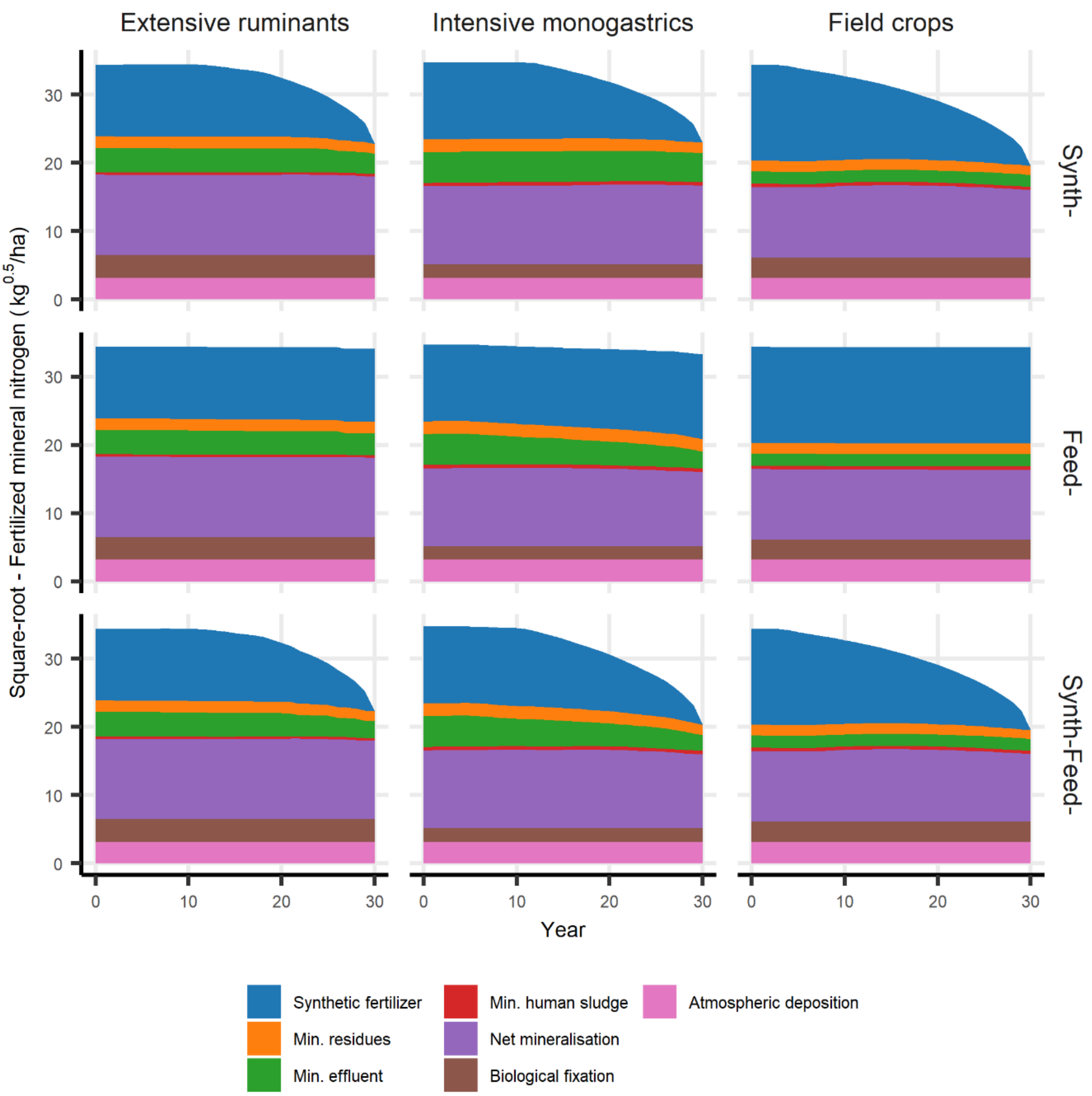

Figure 3 Area diagram of the averaged quantity of mineral nitrogen fertilised for both land uses per unit area of UAA ($kg^{0.5}$/ha) over time (in years) according to scenario (rows) and FS (columns) for the nominal parameter set. Y axis is put on a square root scale to facilitate the reading of the diagram.

The proportion of the different fertiliser sources changes over time in all the simulations (Figure 3). In the scenarios where the availability of synthetic fertilisers decreases

(*Synth-* and *Synth-Feed-*), the FS eventually arrives at a fertiliser deficit at different times during the different simulations. This point is not reached in the *Feed-* scenario.

3.1 Extensive ruminant FS results

In the *Synth-* and *Feed-* scenarios for the extensive ruminant FS, the crop-sourced food production remains constant for the first 13 years and then it decreases linearly. However, when comparing by scenario, it is the most robust FS in the short term in all the scenarios, regarding total food production (Figure 2). Natural and organic nitrogen flows represent approximately 175 kg/ha (i.e., ~60% of the total mineral nitrogen needs before losses) (Figure 3).

In the *Synth-* scenario, crop-sourced food production is constant until year 13. Then it decreases linearly (Figure 2A), reaching -50% of the initial production. The production of animal-sourced food remains almost constant until year 15 and then decreases reaching -20% of its initial production in year 30 (Figure 2B). Feed surplus decreases linearly from year 13 to year 30, reaching 1,000 tons (Figure 2C). A decrease in crop-sourced food production and the destocking of livestock cause a decrease in the quantity of crop residues and livestock effluents applied to the soil but have little impact on the net mineralisation of soil organic nitrogen in cropland or permanent grasslands (Figure 3). Total food production is constant for the first 13 years, before nearly declining linearly to -50% in year 30 (Figure 2D).

In the *Feed-* scenario, crop-sourced food production does not decrease throughout the entire simulation (Figure 2A). Animal-sourced food production declines from the first year to approximately -25% in year 30, and it experiences one local peak (Figure 2B). The averaged net mineralisation flow also decreases very little as in the previous scenario (Figure 3). The total food production slightly increases from year 13 on because of the feed surplus converted into food (Figure 2C and D).

The *Synth-Feed-* scenario exhibits curves similar to those of the *Synth-* scenario for crop-sourced food production and feed surplus converted into food. However, animal-sourced food production decreases, nearly reaching -33% in year 30 and experiencing three local production peaks (Figure 2B). The averaged net mineralisation flow shows trends similar to those of the *Synth-* scenario, despite a larger decline in animal-sourced food production, reaching -5% in year 30 (Figure 3). Total food production reaches -50% in year 30, after remaining almost constant for the first 13 years (Figure 2D).

Further analyses show that mainly monogastric populations are declining, especially in the short term, in scenarios with a decrease in feed imports (see Appendices). They also show that the cropland soil organic nitrogen stock decreases by a maximum of 13%, and the permanent grassland soil organic nitrogen stock by 7% after 30 years. Natural and organic nitrogen flows represent for cropland and for permanent grasslands approximately 70% and 56% respectively of the mineral nitrogen needs before losses.

3.2 Intensive monogastric FS results

In the intensive monogastric FS, the total food production is the least affected among FS in the *Synth-* scenario in the long term (after year 15), but it is the most affected in the *Feed-* and *Synth-Feed-* scenarios in the short term (Figure 2). In this FS, natural and organic flows represent approximately 57% of total mineral nitrogen needs before losses (Figure 3). The quantity of mineral nitrogen from livestock effluents applied to cropland is the highest among the three FS (~20 kg/ha).

In the *Synth-* scenario, crop-sourced food production is not affected until year 13. It then decreases linearly until year 30, reaching -40% (Figure 2A). For animal-sourced food production, it is almost constant until year 13, before declining to -13% in year 30 (Figure 2B). It experiences two local meat production peaks linked to livestock destocking during feed shortages. The averaged net mineralisation flow varies little (Figure 3). The feed surplus value remains at 0 (Figure 2C). Total food production is constant for the first 13 years, before declining linearly to approximately -25% in year 30 (Figure 2D).

In the *Feed-* scenario, crop-sourced food production does not decrease throughout the entire simulation (Figure 2A). Animal-sourced food production nearly declines linearly from the first year, reaching -80% in year 30 and experiencing five local production peaks (Figure 2B). The averaged net mineralisation flow decreases to -9% from the initial value in year 30 (Figure 3). The feed surplus increases from year 18, reaching approximately 6,000 tons in year 30 (Figure 2C). Finally, total food production decreases linearly until year 17, reaching -25% (Figure 2D). It then increases linearly until year 30, reaching +20%.

The *Synth-Feed-* scenario exhibits curves similar to those of the *Feed-* scenario until year 13. However, from that year on, crop-sourced food production decreases linearly, reaching approximately -50% (Figure 2A), and animal-sourced food production is slightly lower in the long term compared with the *Feed-* scenario (-85%) (Figure 2B). It experiences five local production peaks. The averaged net mineralisation flow decreases from year 15 on reaching -10% in year 30 (Figure 3). The feed surplus increases from year 20 on, reaching approximately 2,200 tons in year 30 (Figure 2C). Total food production decreases, reaching more than -45% in year 30 (Figure 2D).

Further analyses show that mainly monogastric populations are declining, especially in the short term (see Appendices). Ruminant populations only decrease after more than 20 years when there is a decrease in feed imports. They also show that the cropland soil organic nitrogen stock decreases by a maximum of 20% from its initial value, whereas the permanent grassland soil organic nitrogen stock by a maximum of 9%. Natural and organic nitrogen flows represent for cropland and for permanent grasslands approximately 70% and 56% respectively of the mineral nitrogen needs before losses.

3.3 Field crops FS results

When a fertiliser shortage is simulated (*Synth-* and *Synth-Feed-* scenarios), total food production decreases linearly in the field crops FS due to a lower presence of livestock. The impact of these two scenarios are identical, the trajectories overlap (Figure 2). Natural and organic flows represent approximately 40% of the total mineral nitrogen needs before losses, the lowest share among the FS (Figure 3).

In the *Synth-* scenario, crop-sourced food production is constant until year 4. It then decreases linearly until year 30 (Figure 2A), decreasing by 62% of its initial value. This decline occurs as soon as there is a synthetic fertiliser shortage (Figure 3). This implies a decrease in the quantity of crop residues applied to the soil. The averaged net mineralisation flow first slightly increases and then decreases to approximately -8% in year 30 (Figure 3). The feed surplus decreases linearly to approximately 3,000 tons in year 30 (Figure 2C). The trajectory for total food production also has the same shape as the crop-sourced food production curve (Figure 2D). In year 30, total food production decreases by approximately 55% of its initial value.

In the *Feed-* scenario, crop- and animal-sourced food production as well as the feed surplus remain constant throughout the entire simulation, showing that a progressive decline in feed imports does not impair food production in this FS, contrary to what happens in the other FS. Therefore, total food production is also constant over time (Figure 2D).

In the *Synth-Feed-* scenario, all the curves are similar to those of the *Synth-* scenario because this FS is nearly self-sufficient in all of the feed categories (see Supplementary Material).

The cropland soil organic nitrogen stock decreases, reaching approximately -32% in scenarios with a synthetic fertiliser decline, whereas the permanent grassland soil organic nitrogen stock decreases by a maximum of 12% (see Appendices). Natural and organic nitrogen flows represent for cropland and for permanent grasslands approximately 68% and 38% respectively of the mineral nitrogen needs before losses.

4 Discussion

Our objective was to quantify and compare, using a dynamic nitrogen flow model, the food production robustness of three FS to the progressive decrease in the availability of feed and synthetic fertiliser imports over 30 years**.** We assumed nitrogen as the main limiting factor for plant growth but also for animal growth and herd management: a lack of nitrogen, *i.e.* feed, leads to a decrease in the livestock number. Robustness was quantified by comparing the simulated declining trajectories of some key outputs of the FS, *i.e.* the length of the period without decrease in food production and the final value. Scenarios were designed so that the challenges of progressive import availability declines could be simulated either in an isolated manner (scenarios *Synth-* and *Feed-*) or simultaneously (scenario *Synth-Feed-*). With a few exceptions, all the FS showed a decline in food production in all the simulated scenarios However, more or less robustness was observed depending on the FS type and scenario. The date from which food production decline start, but also the extent of decline, varies according to the FS type and scenario.

Uncertainty analysis confirmed the observed trends in food production with the nominal set of parameters, including the conclusions drawn from the comparison of these trends across the FS. Furthermore, this analysis also confirmed that the dates when FS are expected to show decreases in crop- or animal-sourced food production or a conversion of feed surplus into food may vary by ±5 years.

The integration of livestock and local plant production suggested less import needs in a FS and thus promoted food production robustness. Nevertheless, the presence of livestock implied more losses in a FS and resulted in the decreased productivity of a FS. However, the feed consumed by livestock could be transformed into effluents for cropland or permanent grassland fertilisation.

The main assumptions of our modelling approach are that parameters of the FS that are considered constant over time (maximum yield, livestock diet, herd size, plant cover composition etc.). The results and their implication are only valid in relation to the forms of perturbations considered and the rules specified for the distribution of nitrogen flows.

4.1 Interaction of crop-grassland-livestock composition affecting robustness

First, our modelling results suggest that livestock made it possible to delay and attenuate a decline in crop-sourced food production due a synthetic fertiliser shortage because effluents could be used to fertilise cropland. Second, cropland soil organic nitrogen stock significantly contributed to the robustness of crop-sourced food production due to the net mineralisation flow, a non-negligible part of the mineral nitrogen assimilated by crops. Third, extensive ruminants need less feed imports than intensive monogastrics, and consume partly grazed grass of permanent grasslands. This land use is less dependent on synthetic fertilisers than cropland in these FS. Finally, in this model, crop-grassland-livestock balances not only revealed feed surpluses converted into food but also feed-food competition for biomass use. The feed-food competition corresponds to the share of food edible by humans allocated to livestock (livestock are fed in priority). When livestock decreases, the higher the feed-food competition for biomass use is, the higher the feed surplus reallocated for human consumption.

4.1.1 Cropland mineral fertilisation using livestock effluents

Livestock effluents have a similar humification coefficient but lower C:N ratios than crop residues in this model. Consequently, they contributed both to fill soil organic nitrogen stocks and to fertilise crops with mineral nitrogen.

Livestock effluents complemented crop residues in organic amendments. They directly increased the net mineralisation flow of the cropland soil organic nitrogen stock because they did not influence the immobilisation flow. Indirectly, they increased the share of natural and organic flows among mineral nitrogen flows. The two FS with high stocking rates showed higher share of natural and organic flows in the mineral fertilisation balance than the field crop FS. Consequently, in the presence of a progressive synthetic fertiliser shortage, the time at which the FS experiences the effects was delayed. The *Synth-* scenario showed a higher total food production robustness of the crop-livestock FS compared with the field crop FS.

As a mineral fertiliser, livestock effluents also attenuated a decline in crop production. In the *Synth-Feed-* scenario, the intensive monogastric FS exhibited a more prominent decline in crop-sourced food production compared with the *Synth-* scenario. This was due to the decline in animal-sourced food production in the first year. This difference is less pronounced for the extensive ruminant FS. The reason is that part of the ruminant effluents occur on permanent grasslands, which do not contribute to crop production. The use of livestock effluents as a substitute for synthetic fertilisers has already been largely implemented in crop-livestock farms, thus promoting synergy between livestock and crop compartments and enhancing nutrient self-sufficiency (see Li et al., (2021)). Nevertheless, at the FS level this synergy is not systematically promoted today in France (Loyon, 2017).

4.1.2 Cropland soil organic nitrogen as an essential source of mineral nitrogen

The net mineralisation flow of cropland soil organic nitrogen provided an important contribution to the mineral nitrogen fertilisation of crops. They are higher for extensive ruminant and intensive monogastric FS due to higher livestock effluent input quantities than in the field crop FS (see section 4.1.1). In addition, in the *Synth*-Feed scenario, the decrease in soil organic nitrogen stock in cropland is less important for those FS with high organic matter input from livestock.

To our knowledge, the scientific literature studies the soil processes of nutrient supply through mineralisation, but it does not specifically mention the contribution of the net mineralisation flow to the robustness of plant production at the farm or FS levels (e.g., Fuchs et al., 2014). The increase in the application of organic amendments is considered a contributor to the increase in soil organic matter and carbon stocks, and it may play a key role in climate change mitigation. The 4-per-1000 initiative is an example of an identified action that consists of using currently unrecycled sources of organic matter (such as household organic waste) to increase the carbon stocks of agricultural soils and thus offset the net flow of CO_2 emissions into the atmosphere (Chabbi et al., 2017; Minasny et al., 2017). The literature emphasizes that organic amendments indirectly contribute to crop yield stability as sources of microorganisms and sometimes antagonists, and therefore regulators, of plant diseases (Gis Sol, 2011). They also contribute to crop yield stability by increasing the long-term soil structural stability, thus increasing the ability of the soil to retain water, preventing soil erosion, and stimulating the growth and activity of soil organisms.

The spin-up method misestimated the value and the dynamics of active soil organic nitrogen stocks and net mineralisation flows. In the Plateau Picardie SAR (the field crop FS), active soil organic nitrogen stocks (for a soil C:N ratio equal to 10 and at 10 cm soil depth) have been reported to range from 1,400–1,750 kg/ha (Martin, 2019); however, we estimated between 115%-145% this quantity using the spin-up method. Depending on the soil type, crop, and sowing period, the net mineralisation flow can realistically range from 30–85 kg/ha nitrogen in the same SAR (Groupe régional d'expertise nitrates Picardie, 2015); however, we estimated an initial net mineralisation flow of about 100 kg/ha nitrogen. These overestimations seem to be due to a predominant immobilisation phenomenon in the model. The strong uncertainties regarding the humification coefficients of organic amendments, especially crop residues, may be one possible explanation for this overestimated flow (Fuchs et al., 2014). However, the global sensitivity analysis showed that uncertainties and overestimates of soil parameters did not drastically change the trends in terms of food production, although they did change the active soil organic nitrogen stocks.

4.1.3 Extensive ruminants: a type of crop-livestock farming system more coupled to local resources

Of the two FS with high stocking rates, the extensive ruminant FS has lower import needs than the intensive monogastric FS (see Supplementary Material). The feed surplus converted into food flow is an indicator of this low import. On the contrary, the extensive ruminant FS depends proportionally more on local production. This explains the higher robustness of animal-sourced food production of the extensive ruminant FS in the *Feed-* scenario compared to the intensive monogastric FS. Moreover, in the *Synth-* scenario, the decline in food production remains low for extensive ruminants despite their dependence on local production. This last result can be explained by the high share of organic and natural flows in the mineral fertilisation of permanent grasslands (which represents 50% of the UAA in this FS). In other words, according to the model results and from a nitrogen point of view, permanent grasslands are less fertilised synthetically (Service de l'observation et des statistiques, 2013). Furthermore, permanent grasslands are also larger carbon pools than cropland (Martin, 2019) and on the farm scale, other studies showed that the presence of grasslands used to feed ruminants had economic advantages (Ryschawy et al., 2012).

4.1.4 Feed surplus, feed-food competition for biomass use, and robustness

A feed surplus occurs when the local feed for livestock in a feed category exceeds the needs of all livestock species for that feed category (Jouven et al., 2018). According to our modelling assumptions, a feed surplus composed of cereals and oil-protein seeds can be converted into food, like in the extensive ruminant FS and field crop FS. In this case, as livestock are primarily fed in priority, a decrease of the local plant production lead first to a decrease in the feed surplus converted into food which contributes to maintain livestock. In the intensive monogastric FS, where there is no feed surplus converted into food, a decrease in feed import and of the local plant production leads to a decrease in the livestock number and an increase in the feed surplus converted into food.

Feed-food competition for the use of biomass consists of allocating to livestock harvested biomass that could be directly allocated to human consumption (Mottet et al., 2017). In the model, the feed-food competition corresponds to the share of food consumed by livestock. Therefore, the feed-food competition is higher in the intensive monogastric FS than in the two other FS (Jouven et al., 2018). However, when livestock decreases, the greater feed-food competition is, the higher feed surplus can be reallocated for human consumption. These findings suggested that a voluntary decrease in feed-food competition for biomass use by destocking livestock would increase the feed surplus converted into food and thus the food productivity of the FS.

4.2 Interaction between productivity and robustness

The three FS showed heterogeneous productivity levels: ~18 kg/ha UAA (extensive ruminant FS); ~38 kg/ha UAA (intensive monogastric FS); ~67 kg/ha UAA (field crop FS) declining between 45-60% in *Synth-Feed-* scenario. We noted that the most robust FS in the *Synth-Feed-* scenario is the least productive (extensive ruminant FS) from a nitrogen cycle perspective. However, in the context of global peak oil, food imports could also decrease, and the food production of a FS would have to satisfy more and more the local protein needs of humans. Protein is certainly not sufficient to qualify the adequacy between local production and local needs, but it is a necessary condition for the healthy functioning of the body's metabolism (Wu, 2016). In the three FS, total food production is far higher than the protein needs of the local population, without considering losses through food processing and consumption. However, if local protein production was to decline, either current local protein consumption or food export would decline. If maintaining consumption and/or export levels is desired, then it would be necessary to invest in configuration changes that promote both productivity and robustness to declining imports. In such cases, it seems necessary to increase the area of legumes to reduce the dependence on synthetic nitrogen fertilisers (Billen et al., 2018). This would at the same time reduce the environmental impact due to high mineral nitrogen inputs.

4.3 Decisive capacity of robustness for adaptability and transformability

Of the three resilience capacities presented by Meuwissen et al. (2019), we only considered robustness (the capacity to absorb challenges without configurational changes). However, conclusions regarding robustness put into perspective the importance of FS adaptations and transformations to minimise the imports of feed and synthetic fertilisers in addition to reducing environment losses. The time period during which food production does not decline can be seen as a "robustness window" in which other adaptive or transformative actions can be implemented. Two adaptive actions are already largely implemented in Europe: enhancing nitrogen use efficiency at the plot level and by livestock. We also identified three other complementary actions at the FS level : (i) reducing losses during the management of organic amendments (Oenema et al., 2007); (ii) maximising the input of new nitrogen molecules by nitrogen-fixing plants to minimise the use of synthetic fertilisers and maintain a certain crop productivity (Billen et al., 2018); (iii) increasing productivity and reducing losses at the FS level for crop-livestock FS by reducing feed-food competition (Van Zanten et al., 2018).

4.4 Study and model limits

Certain assumptions made for this analysis have limitations. We assumed the parameters of these FS to be constant: plant yield was considered a function of mineral nitrogen fertilisation and was saturated at a fixed value; loss and emission coefficients were assumed to be constant and no improvements in practices that could reduce losses were considered; agricultural area and plant composition were also assumed to be constant. These assumptions seemed appropriate to answer the research question posed. However, in reality, some of these parameters have experienced minor changes since 1960. For example, since the end of the 20th century in France and

Greece, crop nitrogen yields have stagnated at a decreasing nitrogen fertilisation rate. Yet in the Netherlands, they have increased at a constant nitrogen fertilisation rate (Lassaletta et al., 2014). The efficiency of crop nitrogen use is increasing in these three countries, and it is clear that there is still room for improvement in the crop nitrogen use efficiency in Europe (Dobermann, 2005). Moreover, we assumed that nitrogen was the only limiting factor to crop yield, but other factors can be limiting, depending on climatic and soil conditions, for instance, water or other nutrients such as phosphorus (Csathó and Radimszky, 2009; Webber et al., 2015). Finally, we did not considered atmospheric deposition as a function of reactive nitrogen emissions (Liu et al., 2013), and did not take into account the phenomenon of dilution in the plant of the mineral nitrogen taken from the soil (Lemaire et al., 2008). Improvements to the model could include the addition of other nutrient cycles and the refinement of the relationship between yield and soil available mineral nitrogen.

5 Conclusion

The main objective of this study was to quantify and compare the robustness of the three FS to gradual declines in the availability of synthetic fertiliser and feed imports. We developed a dynamic nitrogen flow model on a FS scale. The model allowed quantitatively evaluating robustness and causal links among several plant cover types and livestock species and previously unobserved challenges. The dynamic nature of the model made it possible to consider central causal links in FS: the relationship between fertilised mineral nitrogen and plant yield; the relationship between animal-sourced food production and feed shortages. Simulations provided insights into short-term versus long-term robustness and allowed comparing the robustness of the three FS.

In the short term (10-year horizon), our results suggested that the extensive ruminant FS was the most robust in all scenarios. In the long term, all three FS did not exhibit robustness in the *Synth-Feed-* scenario because they all showed large relative declines in total food production.

Delaying the manifestation of shortages is an important characteristic of robustness for FS. Crop-grassland-livestock balances determine the length of this robustness window. Livestock effluents are a substitute for synthetic fertilisers and contribute to soil organic nitrogen stocks without immobilising mineralised soil organic nitrogen. Additionally, if livestock are ruminants, they can graze permanent grasslands that are more coupled to local natural resources than cropland and thus they enhance animal-source food production robustness. Soil organic nitrogen net mineralisation flows are key for plant production robustness.

The robustness window allows the implementation of actions that could help to close the nitrogen cycle at the FS level by adapting FS configurations e.g., reduce feed-food competition, increase the share of legume crop area and reduce nitrogen losses during the management of livestock effluents.

We believe it is important to explore and quantitatively assess different FS and combinations and trajectories of action that promote increased food production robustness in response to import declines. We also think it is necessary to evaluate other forms and extents of disturbances to provide more insights into the behaviours of FS.

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7 References

Accatino, F., Tonda, A., Dross, C., Léger, F., Tichit, M., 2019. Trade-offs and synergies between livestock production and other ecosystem services. Agricultural Systems 168, 58–72. https://doi.org/10.1016/j.agsy.2018.08.002

Bassil, K.L., Vakil, C., Sanborn, M., Cole, D.C., Kaur, J.S., Kerr, K.J., 2007. Cancer health effects of pesticides: Systematic review. Canadian Family Physician 53, 1704–1711.

Beketov, M.A., Kefford, B.J., Schäfer, R.B., Liess, M., 2013. Pesticides reduce regional biodiversity of stream invertebrates. PNAS 110, 11039–11043. https://doi.org/10.1073/pnas.1305618110

Billen, G., Lassaletta, L., Garnier, J., 2014. A biogeochemical view of the global agro-food system: Nitrogen flows associated with protein production, consumption and trade. Global Food Security, SI: GFS Conference 2013 3, 209–219. https://doi.org/10.1016/j.gfs.2014.08.003

Billen, G., Lassaletta, L., Garnier, J., Le Noë, J., Aguilera, E., Sanz-Cobeña, A., 2019. Opening to Distant Markets or Local Reconnection of Agro-Food Systems? Environmental Consequences at Regional and Global Scales, in: Agroecosystem Diversity. Elsevier, pp. 391–413. https://doi.org/10.1016/B978-0-12-811050-8.00025-X

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

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H., 2003. An overview of the crop model stics. European Journal of Agronomy, Modelling Cropping Systems: Science, Software and Applications 18, 309–332. https://doi.org/10.1016/S1161-0301(02)00110-7

Bullock, J.M., Dhanjal-Adams, K.L., Milne, A., Oliver, T.H., Todman, L.C., Whitmore, A.P., Pywell, R.F., 2017. Resilience and food security: rethinking an ecological concept. Journal of Ecology 105, 880–884. https://doi.org/10.1111/1365-2745.12791

Cabell, J., Oelofse, M., 2012. An Indicator Framework for Assessing Agroecosystem Resilience. Ecology and Society 17. https://doi.org/10.5751/ES-04666-170118

Chabbi, A., Lehmann, J., Ciais, P., Loescher, H.W., Cotrufo, M.F., Don, A., SanClements, M., Schipper, L., Six, J., Smith, P., Rumpel, C., 2017. Aligning agriculture and climate policy. Nature Climate Change 7, 307–309. https://doi.org/10.1038/nclimate3286

Clivot, H., Mouny, J.-C., Duparque, A., Dinh, J.-L., Denoroy, P., Houot, S., Vertès, F., Trochard, R., Bouthier, A., Sagot, S., Mary, B., 2019. Modeling soil organic carbon evolution in long-term arable experiments with AMG model. Environmental Modelling & Software 118, 99–113. https://doi.org/10.1016/j.envsoft.2019.04.004

Csathó, P., Radimszky, L., 2009. Two Worlds within EU27: Sharp Contrasts in Organic and Mineral Nitrogen–Phosphorus Use, Nitrogen–Phosphorus Balances, and Soil Phosphorus Status: Widening and Deepening Gap between Western and Central Europe. Communications in Soil Science and Plant Analysis 40, 999–1019. https://doi.org/10.1080/00103620802693151

Darnhofer, I., Moller, H., Fairweather, J.R., 2008. Farm resilience for sustainable food production: a conceptual framework (Working Paper). Lincoln University.

de Wit, C.T., 1992. Resource use efficiency in agriculture. Agricultural Systems, Systems approaches for agricultural 40, 125–151. https://doi.org/10.1016/0308-521X(92)90018-J

Dixon, J.A., Gibbon, D.P., Gulliver, A., Nations, F. and A.O. of the U., 2001. Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World. Food & Agriculture Org.

Dobermann, A., 2005. Nitrogen Use Efficiency – State of the Art. Presented at the Proceedings of the IFA International Workshop on Enhanced Efficiency Fertilizers, Frankfurt, Germany, pp. 1–16.

Domingues, J.P., Gameiro, A.H., Bonaudo, T., Tichit, M., Gabrielle, B., 2019. Exploring trade-offs among indicators of performance and environmental impact in livestock areas. Reg Environ Change 19, 2089–2099. https://doi.org/10.1007/s10113-019-01538-z

EEA, 2017. EU animal feed imports and land dependency.

European commission, 2021a. Structure of agricultural holdings by NUTS 3 regions - main indicators [WWW Document]. Eurostat. URL https://ec.europa.eu/eurostat/databrowser/view/ef_r_nuts/default/table?lang=en (accessed 3.29.21).

European commission, 2020b. Greenhouse gas emission statistics - emission inventories [WWW Document]. Eurostat. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_emission_inventories#Trends_in_greenhouse_gas_emissions (accessed 3.26.21).

Food and Agriculture Organization of the United Nations (FAO), n.d. FAOSTAT [WWW Document]. FAOSTAT Database. URL http://www.fao.org/faostat/en/#data (accessed 3.26.21).

Fuchs, J., Génermont, S., Houot, S., Jardé, E., Ménasseri, S., Mollier, A., Morel, C., Parnaudeau, V., Pradel, M., Vieublé, L., 2014. Effets agronomiques attendus de l'épandage des Mafor sur les écosystèmes agricoles et forestiers, in: Matières fertilisantes d'origine résiduaire. p. 204.

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

Giller, K.E., 2013. Can We Define the Term 'Farming Systems'? A Question of Scale: Outlook on Agriculture. https://doi.org/10.5367/oa.2013.0139

Gis Sol, 2011. L'état des sols de France. Groupement d'intérêt scientifique sur les sols.

Groupe régional d'expertise nitrates Picardie, 2015. Guide de calcul de la dose d'aote à appaorter sur les cultures et les prairies.

Gunderson, L.H., 2000. Ecological Resilience—In Theory and Application. Annual Review of Ecology and Systematics 31, 425–439. https://doi.org/10.1146/annurev.ecolsys.31.1.425

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8, 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x

Harchaoui, S., Chatzimpiros, P., 2019. Energy, Nitrogen, and Farm Surplus Transitions in Agriculture from Historical Data Modeling. France, 1882–2013. Journal of Industrial Ecology 23, 412–425. https://doi.org/10.1111/jiec.12760
Holling, C.S., 1973. Resilience and Stability of Ecological Systems. Annu. Rev. Ecol. Syst. 4, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245
Hou, Y., Bai, Z., Lesschen, J.P., Staritsky, I.G., Sikirica, N., Ma, L., Velthof, G.L., Oenema, O., 2016. Feed use and nitrogen excretion of livestock in EU-27. Agriculture, Ecosystems & Environment 218, 232–244. https://doi.org/10.1016/j.agee.2015.11.025
IGN, 2016. Registre parcellaire graphique (RPG) : contours des parcelles et îlots culturaux et leur groupe de cultures majoritaire - data.gouv.fr [WWW Document]. URL https://www.data.gouv.fr/fr/datasets/registre-parcellaire-graphique-rpg-contours-des-parcelles-et-ilots-culturaux-et-leur-groupe-de-cultures-majoritaire/ (accessed 7.17.20).
INRA, Sauvant, D., Peyraud, J.-L., Faverdin, P., Noziere, P., 2018. Ecrétion azotée fécale et urinaire, in: Alimentation Des Ruminants. Editions Quae, pp. 237–242.
Irz, X., Niemi, J., Liu, X., 2013. Determinants of food price inflation in Finland—The role of energy. Energy Policy 63, 656–663. https://doi.org/10.1016/j.enpol.2013.09.023
Jouven, M., Puillet, L., Perrot, C., Pomeon, T., Dominguez, J.-P., Bonaudo, T., Tichit, M., 2018. Quels équilibres végétal/animal en France métropolitaine, aux échelles nationale et « petite région agricole » ? INRA Productions Animales 31, 353–364. https://doi.org/10.20870/productions-animales.2018.31.4.2374
Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9, 105011. https://doi.org/10.1088/1748-9326/9/10/105011
Le Noë, J., Billen, G., Mary, B., Garnier, J., 2019. Drivers of long-term carbon dynamics in cropland: A bio-political history (France, 1852–2014). Environmental Science & Policy 93, 53–65. https://doi.org/10.1016/j.envsci.2018.12.027
Lemaire, G., Franzluebbers, A., Carvalho, P.C. de F., Dedieu, B., 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agriculture, Ecosystems & Environment, Integrated Crop-Livestock System Impacts on Environmental Processes 190, 4–8. https://doi.org/10.1016/j.agee.2013.08.009
Lemaire, G., Jeuffroy, M.-H., Gastal, F., 2008. Diagnosis tool for plant and crop N status in vegetative stage: Theory and practices for crop N management. European Journal of Agronomy 28, 614–624. https://doi.org/10.1016/j.eja.2008.01.005
Li, Y., Sun, Z., Accatino, F., Hang, S., Lv, Y., Ouyang, Z., 2021. Comparing specialised crop and integrated crop-livestock systems in China with a multi-criteria approach using the emergy method. Journal of Cleaner Production 127974. https://doi.org/10.1016/j.jclepro.2021.127974
Liu, X., Zhang, Y., Han, W., Tang, A., Shen, J., Cui, Z., Vitousek, P., Erisman, J.W., Goulding, K., Christie, P., Fangmeier, A., Zhang, F., 2013. Enhanced nitrogen deposition over China. Nature 494, 459–462. https://doi.org/10.1038/nature11917
Loyon, L., 2017. Overview of manure treatment in France. Waste Management 61, 516–520. https://doi.org/10.1016/j.wasman.2016.11.040

Martin, M., 2019. La carte nationale des stocks de carbone des sols intégrée dans la carte mondiale de la FAO. https://doi.org/10.15454/JCONRJ

Martin, S., Deffuant, G., Calabrese, J.M., 2011. Defining Resilience Mathematically: From Attractors To Viability, in: Deffuant, G., Gilbert, N. (Eds.), Viability and Resilience of Complex Systems: Concepts, Methods and Case Studies from Ecology and Society, Understanding Complex Systems. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 15–36. https://doi.org/10.1007/978-3-642-20423-4_2

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O’Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Ministère de l’Agriculture et de l’Alimentation, n.d. Agreste, la statistique agricole [WWW Document]. Chiffres et analyses. URL https://agreste.agriculture.gouv.fr/agreste-web/disaron/!searchurl/searchUiid/search/ (accessed 7.17.20).

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. PNAS 104, 13268–13272. https://doi.org/10.1073/pnas.0611508104

Moraine, M., Duru, M., Nicholas, P., Leterme, P., Therond, O., 2014. Farming system design for innovative crop-livestock integration in Europe. Animal 8, 1204–1217. https://doi.org/10.1017/S1751731114001189

Moraine, M., Duru, M., Therond, O., 2017. A social-ecological framework for analyzing and designing integrated crop–livestock systems from farm to territory levels. Renewable Agriculture and Food Systems 32, 43–56. https://doi.org/10.1017/S1742170515000526

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security, Food Security Governance in Latin America 14, 1–8. https://doi.org/10.1016/j.gfs.2017.01.001

Mouysset, L., Doyen, L., Jiguet, F., 2012. Different policy scenarios to promote various targets of biodiversity. Ecological Indicators 14, 209–221. https://doi.org/10.1016/j.ecolind.2011.08.012

Oenema, O., Oudendag, D., Velthof, G.L., 2007. Nutrient losses from manure management in the European Union. Livestock Science, Recycling of Livestock Manure in a Whole-Farm Perspective 112, 261–272. https://doi.org/10.1016/j.livsci.2007.09.007

Parton, W.J., 1996. The CENTURY model, in: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models, NATO ASI Series. Springer, Berlin, Heidelberg, pp. 283–291. https://doi.org/10.1007/978-3-642-61094-3_23

Ramírez, C.A., Worrell, E., 2006. Feeding fossil fuels to the soil: An analysis of energy embedded and technological learning in the fertilizer industry. Resources, Conservation and Recycling 46, 75–93. https://doi.org/10.1016/j.resconrec.2005.06.004

Robertson, G.P., Vitousek, P.M., 2009. Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. Annual Review of Environment and Resources 34, 97–125. https://doi.org/10.1146/annurev.environ.032108.105046

Roguet, C., Gaigné, C., Chatellier, V., Cariou, S., Carlier, M., Chenut, R., Daniel, K., Perrot, C., 2015. Spécialisation territoriale et concentration des productions animales européennes : état des lieux et facteurs explicatifs. INRAE Productions Animales 28, 5–22. https://doi.org/10.20870/productions-animales.2015.28.1.3007

Ryschawy, J., Choisis, N., Choisis, J.P., Joannon, A., Gibon, A., 2012. Mixed crop-livestock systems: an economic and environmental-friendly way of farming? Animal 6, 1722–1730. https://doi.org/10.1017/S1751731112000675

Service de l'observation et des statistiques, 2013. NOPOLU-Agri - Outil de spatialisation des pressions de l'agriculture - Méthodologie et résultats pour les surplus d'azote et les émissions des gaz à effet de serre - Campagne 2010-2011 (No. 14). Ministère de l'écologie, du développement durable et de l'énergie.

Smith, V.H., 1998. Cultural Eutrophication of Inland, Estuarine, and Coastal Waters, in: Pace, M.L., Groffman, P.M. (Eds.), Successes, Limitations, and Frontiers in Ecosystem Science. Springer, New York, NY, pp. 7–49. https://doi.org/10.1007/978-1-4612-1724-4_2

Stave, K.A., Kopainsky, B., 2014. Dynamic thinking about food system vulnerabilities in highly developed countries: Issues and initial analytic structure for building resilience. Presented at the 32nd International Conference of the System Dynamics Society, Delft, The Netherlands.

Tadasse, G., Algieri, B., Kalkuhl, M., von Braun, J., 2016. Drivers and Triggers of International Food Price Spikes and Volatility, in: Kalkuhl, M., von Braun, J., Torero, M. (Eds.), Food Price Volatility and Its Implications for Food Security and Policy. Springer International Publishing, Cham, pp. 59–82. https://doi.org/10.1007/978-3-319-28201-5_3

Teillard, F., Doyen, L., Dross, C., Jiguet, F., Tichit, M., 2017. Optimal allocations of agricultural intensity reveal win-no loss solutions for food production and biodiversity. Reg Environ Change 17, 1397–1408. https://doi.org/10.1007/s10113-016-0947-x

Therond, O., Tichit M. (coord.), Tibi A. (coord.), Accatino F., Biju-Duval L., Bockstaller C., Bohan D., Bonaudo T., Derocles S., De Sousa L., Domingues Santos J.P., Dross C., Duru M., Eugène M., Fontaine C., Garcia B., Geijzendorffer I., Girardin A., Graux A-I., Jouven M., Langlois B., Le Bas C., Le Bissonnais Y., Lelièvre V., Lifran R., Maigné E., Martin G., Martin R., Martin-Laurent F., Martinet V., McLaughlin O., Meillet A., Mignolet C., Mouchet M., Nozières-Petit M-O., Ostermann O.P., Paracchini M.L., Pellerin S., Peyraud J-L., Petit-Michaut S., Picaud C., Plantureux S., Poméon T., Porcher, E., Puech T., Puillet L., Rambonilaza T., Raynal H., Resmond R., Ripoche D., Ruget F., Rulleau B., Rusch A., Salles J-M.,, Sauvant D., Schott C., Tardieu L., 2017. Volet "écosystèmes agricoles" de l'Evaluation Française des Ecosystèmes et des Services Ecosystémiques, Evaluation Française des Ecosystèmes et des Services Ecosystémiques. INRA (France).

Trinsoutrot, I., Recous, S., Bentz, B., Linères, M., Chèneby, D., Nicolardot, B., 2000. Biochemical Quality of Crop Residues and Carbon and Nitrogen Mineralization Kinetics under Nonlimiting Nitrogen Conditions. Soil Science Society of America Journal 64, 918–926. https://doi.org/10.2136/sssaj2000.643918x

Van Zanten, H.H.E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C., De Boer, I.J.M., 2018. Defining a land boundary for sustainable livestock consumption. Global Change Biology 24, 4185–4194. https://doi.org/10.1111/gcb.14321

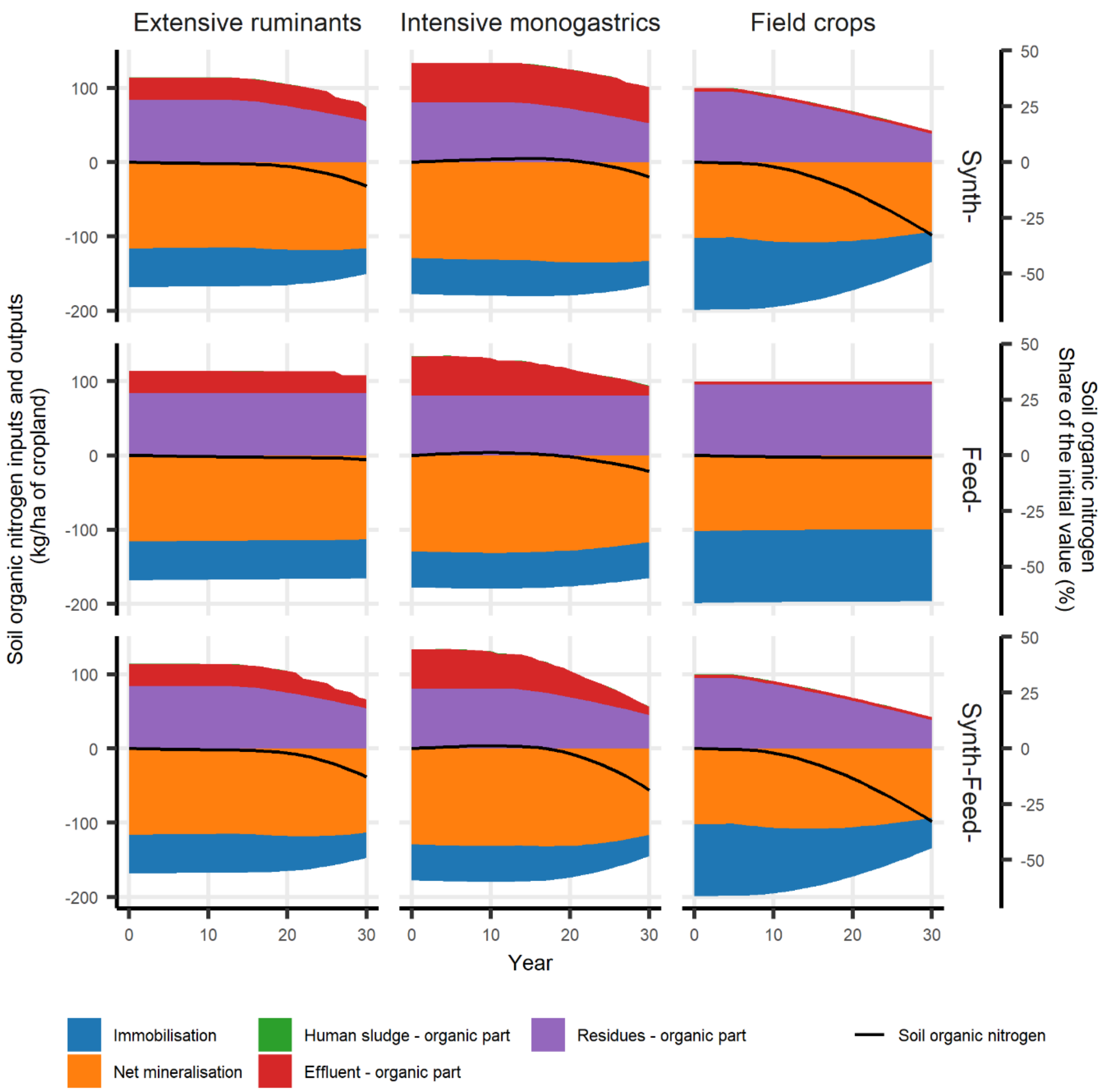
Webber, H., Zhao, G., Wolf, J., Britz, W., Vries, W. de, Gaiser, T., Hoffmann, H., Ewert, F., 2015. Climate change impacts on European crop yields: Do we need to consider nitrogen limitation? European Journal of Agronomy 71, 123–134. https://doi.org/10.1016/j.eja.2015.09.002

Wu, G., 2016. Dietary protein intake and human health. Food & Function 7, 1251–1265. https://doi.org/10.1039/C5FO01530H

8 Appendices

8.1 Cropland soil organic nitrogen balance

In all the scenarios and FS, cropland soil organic nitrogen inputs decrease over time (Figure 4). In the scenarios with a synthetic fertiliser decline, the quantity of crop residues applied decreases, and the quantity of livestock effluents applied also decreases, especially in scenarios with a decline in feed imports. A decrease in crop residues lead to a decrease in immobilisation flow, whereas a decrease in livestock effluents does not impact the immobilisation flow. Organic amendment decreases lead to decreases in the soil organic nitrogen stock and net mineralisation flow in different proportions, depending on the FS. However, decreases in crop residues and immobilisation flow contribute in the short term to containing or even slightly increasing the net mineralisation flow. They also lead to shifting the date when the net mineralisation flow decreases, with respect to the soil organic nitrogen stock.



1068

1069 *Figure 4 Area diagram of the quantity for cropland of soil organic nitrogen inputs and outputs per unit area (kg/ha)*
1070 *over time (in years) according to scenario (rows) and FS (columns) for the nominal parameter set. Cropland soil*
1071 *organic nitrogen stock variations are also shown as percentages (right y-axis).*

8.2 Permanent grassland soil organic nitrogen balance

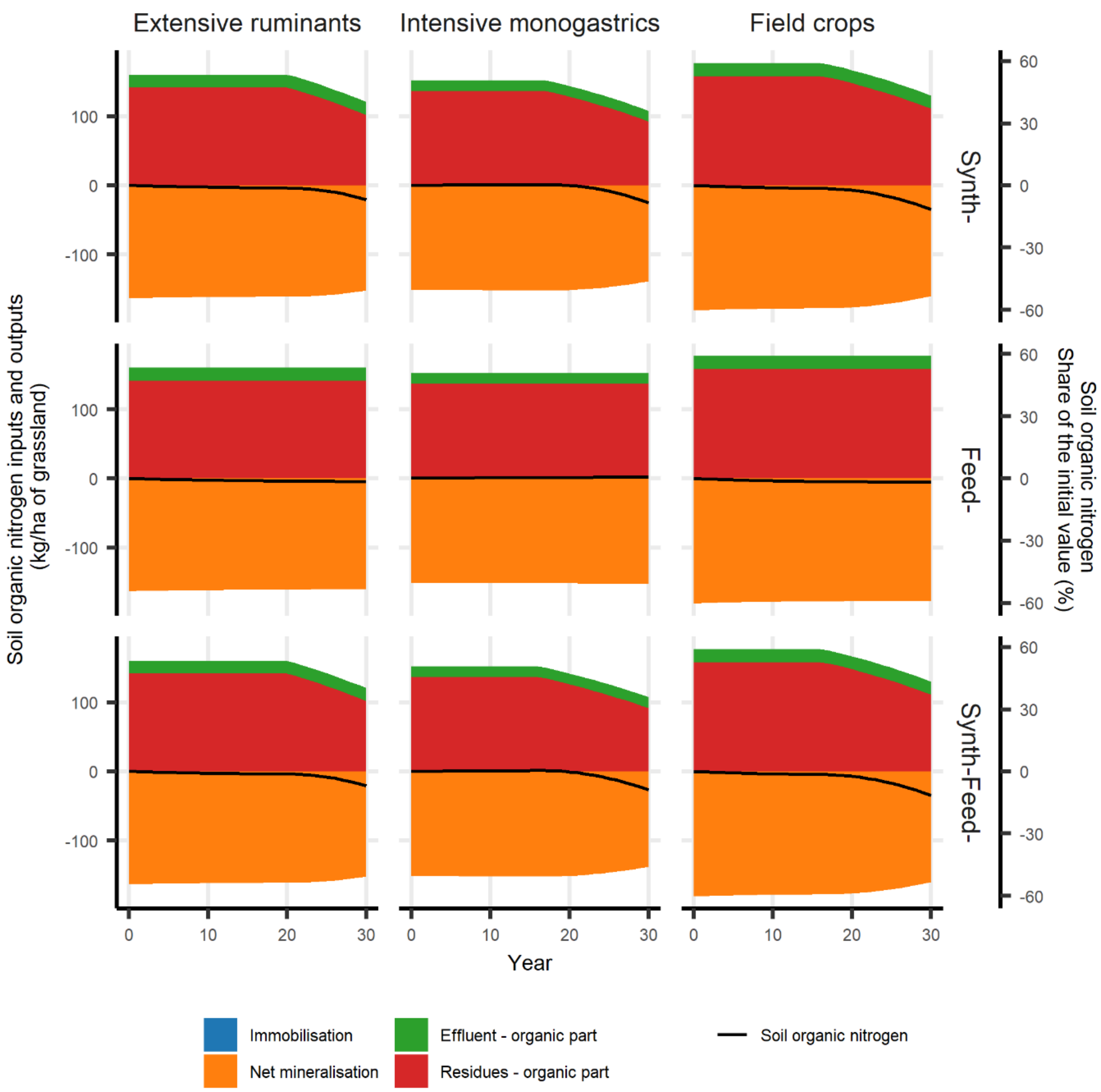


Figure 5 Area diagram of the quantity for permanent grassland of soil organic nitrogen inputs and outputs per unit area (kg/ha) over time (in years) according to scenario (rows) and FS (columns) for the nominal parameter set. Permanent grassland soil organic nitrogen stock variations are also shown as percentages (right y-axis).

In contrast to cropland, decreases in organic nitrogen input flows or soil organic nitrogen stock are smaller in all three FS and scenarios for permanent grassland, and there is not immobilisation of mineral nitrogen from soil organic nitrogen mineralisation (Figure 5). In the *Feed-* scenario, there is a slight decrease in soil organic nitrogen stock. And in scenarios with decreasing synthetic nitrogen imports, after 15 years, the residues input flows decrease and decreases in soil organic nitrogen stock accelerate.

After 30 years, the soil organic nitrogen stock in permanent grasslands has decreased by 10-15%.

8.3 Livestock number

Depending on the species, the time evolution of the livestock number varies due to species-specific diets (Figure 6). Species in the monogastric group, fed only on concentrates, are less robust, especially in the *Feed-* scenarios, in which their numbers decrease in the short term (less than 15 years). In the long term, their decline can reach 100%. Ruminant numbers only decrease in the long term and to a lesser extent.

However, in the monogastric intensive FS during the *Synth-Feed-* scenario, livestock numbers decrease by 50% in the year 30.

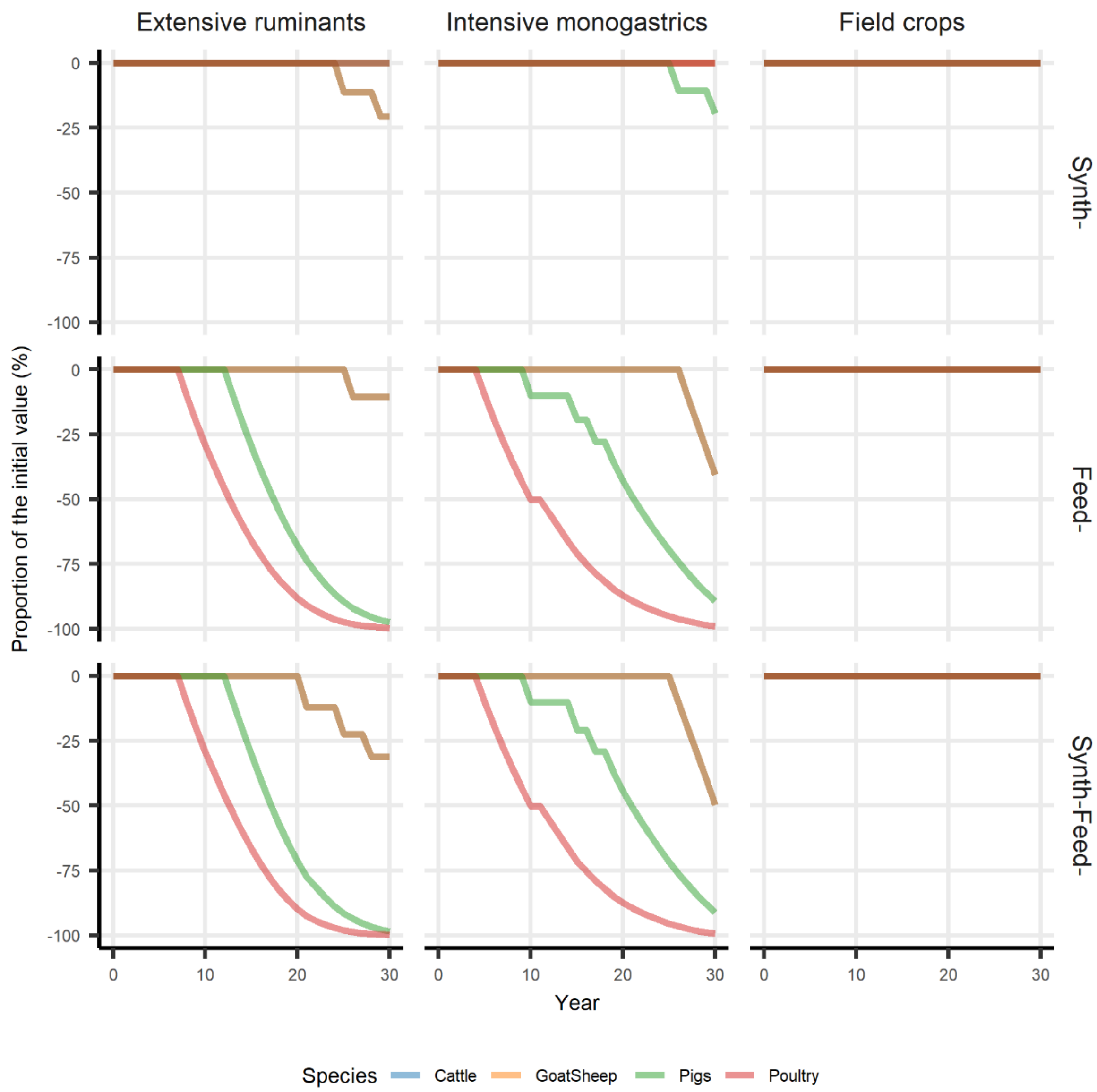


Figure 6 Time evolution of livestock numbers (%) for the three scenarios (rows) and FS (columns) per species for the nominal parameter set: cattle, goats and sheep, pigs, poultry. The curves for cattle and sheep/goats overlap because their diets are identical per FS. Among the monogastrics, poultry numbers tend to decline first. The decrease in ruminant numbers occurs during year 15, at the soonest, in the Feed- and Synth-Feed- scenarios.