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1 Robustness to import declines of three 2 types of European farming systems 3 assessed with a dynamic nitrogen flow 4 model

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14 Abstract

15 Context

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

23 Objective

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

27 Methods

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

37 Results and conclusions

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

46 Significance

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

55 **Keywords**

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

57 oil

58 1 Introduction

59 European agriculture heavily depends on inputs (fertilisers, water, fuel, pesticides) and
60 feed imports (Harchaoui and Chatzimpiros, 2019), as a result of the technical-
61 economic paradigm prevailing after World War II, characterised by genetic
62 improvements, motorisation, use of chemicals, and industrial rationalisation of
63 techniques. This led to a huge increase in crop yields and food production, but at the
64 cost of significant environmental and health impacts (Bassil et al., 2007; Beketov et al.,
65 2013; Guo and Gifford, 2002; Montgomery, 2007; Smith, 1998). In addition, the
66 development of transport and free trade enabled agricultural regions to specialise,
67 taking advantage either of their soil and climate conditions (cereal basins, vineyards or
68 olive groves) or existing infrastructures (for example port trade for intensive
69 monogastric farming in France in Brittany) (European commission, 2021a; Roguet et
70 al., 2015). The consumption of fossil fuels by the agricultural sector increased
71 massively (Food and Agriculture Organization of the United Nations (FAO), n.d.).
72 Agriculture is one of the main greenhouse gas emitters of the European Union,
73 because of methane and nitrous oxide emissions from ruminant enteric fermentation
74 and from soil and effluent management (European commission, 2020b). The
75 production and transport of feed has also a large environmental impact. In 2013,
76 Europe imported more than 21 million tons of soybeans from South America (EEA,
77 2017). The International Energy Agency claimed in its World Energy Outlook in 2018
78 that, without an increase in the shale oil production capacity of the United States, global
79 peak oil production might be reached by 2025. A global peak oil production could lead
80 to increased oil prices and, consequently, increased price of nitrogen fertiliser and
81 associated agricultural commodities prices (Ramírez and Worrell, 2006; Tadasse et
82 al., 2016). As a result, the farmer purchase capacity of agricultural inputs could be
83 reduced, impacting on food security (Irz et al., 2013).

84 The extent to which the European farming systems (FS) would be able to provide food
85 during an oil crisis must be considered. In other words, it must be explored whether
86 the European FS are resilient to potential reductions in input availability. A FS is
87 defined as a population of individual farms located over a common geographical area
88 that have broadly similar resource bases, enterprise patterns, household livelihoods,
89 and constraints and for which similar development strategies would be appropriate
90 (Dixon et al., 2001; Giller, 2013). Meuwissen et al. (2019) define the resilience of a FS

91 as its ability to provide functions facing shocks and stresses. Furthermore, they
92 distinguish three resilience capacities: robustness (the ability to absorb a disturbance
93 without changing configuration), adaptability (the ability of adapting the composition of
94 inputs and production in response to disturbances without changing the structure), and
95 transformability (the ability to change the internal structure and feedback mechanisms
96 in response to disturbances). In this paper we address the robustness to the
97 progressive decrease in imported feed and synthetic fertilisers to determine the
98 capacity of the FS to provide food in face of the perturbation without configurational
99 changes. Such analysis would make it possible to investigate whether there are crop-
100 grassland-livestock compositions more robust than others.

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

124 model, inspired by previous ones, to quantify the food production robustness of FS to
125 a decline in feed and synthetic fertiliser imports.

126 Modelling makes it possible to both simulate previously unobserved challenges and to
127 overcome a lack of data over long periods, which is relevant for studying resilience.
128 Our time-dynamic model focuses on nitrogen flows on a FS scale. Modelling nitrogen
129 flows consists of performing nitrogen mass balances to quantify the exchanges
130 between crops, grasslands, livestock, and soil. Nitrogen is an essential nutrient for
131 living organisms, being a fundamental element of proteins. Additionally, its cycle is
132 already well documented and modelled (Robertson and Vitousek, 2009). The FS scale
133 is essential for integrating crops and livestock (Lemaire et al., 2014; Moraine et al.,
134 2017), and is suitable for predicting FS performance (Billen et al., 2014). There were
135 two main reasons for making our model time-dynamic. First, resilience is a dynamic
136 property (Gunderson, 2000; Holling, 1973; Martin et al., 2011), and the impact of
137 disturbances can be different over the long vs short term. Second, the quantity of
138 organic nitrogen in soil evolves over time and is affected by the quantity of the previous
139 years.

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

149 2 Material and Methods

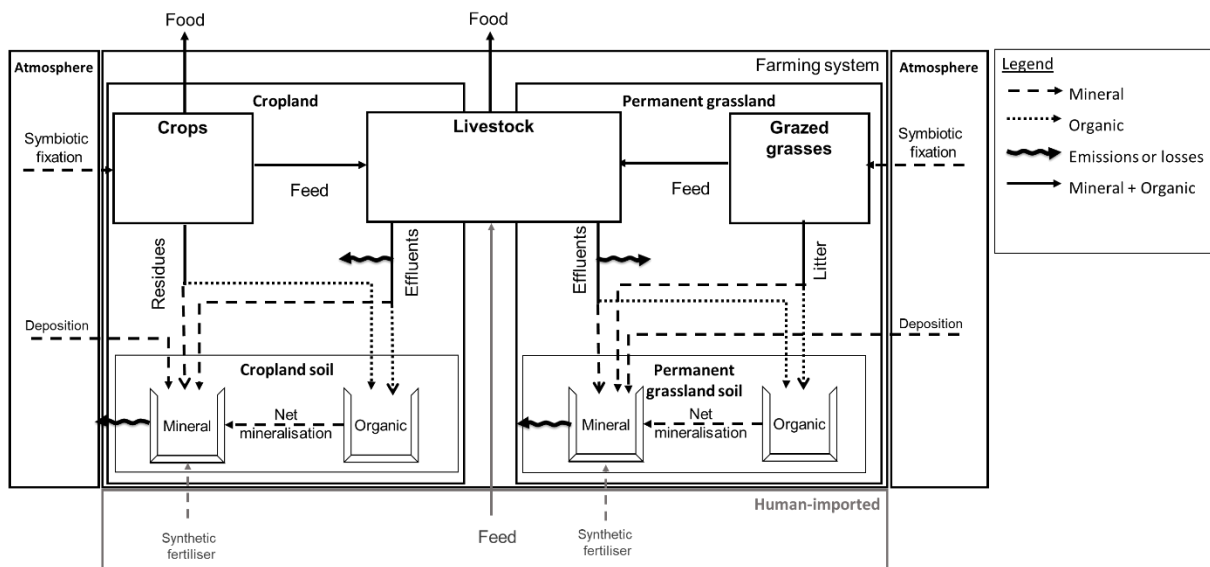
150 The FS nitrogen flow model we developed can be used to simulate a variety of
151 scenarios for any FS.

152 2.1 General model description

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

162 The model is time-dynamic, with a discrete one-year time step. It describes the time
163 evolution of the quantity of soil organic nitrogen in both land uses according to organic
164 nitrogen inputs (mostly plant residues and livestock effluents) and outputs (mostly net
165 mineralisation). The mineral nitrogen in the soil originates from soil organic nitrogen
166 net mineralisation, synthetic fertiliser, atmospheric deposition and the mineral portions
167 of organic amendments. For each crop or grazed grass, yield is modelled as a function
168 of available soil mineral nitrogen and of symbiotic nitrogen fixation for legumes,
169 assuming nitrogen the only yield-limiting factor. Symbiotic fixation is a function of plant
170 yield. Part of the yield goes to human consumption, whereas another part of the yield
171 is used as feed. Crops and grazed grasses provide the soil with residues (parts of the
172 plant not edible by humans or livestock or that are not harvested or grazed). The
173 livestock number is adjusted depending on feed availability (imported and locally
174 produced). Livestock provides mineral and organic nitrogen to the soil via effluents.
175 Effluents go to permanent grassland soil when livestock are grazing, or in effluent
176 management systems when livestock are in housing facilities. The quantity of effluents
177 in effluent management systems is available to fertilise cropland soil. The fraction of
178 effluents on permanent grasslands is proportional to the fraction of grazed grass in
179 livestock diet, which is assumed as a proxy of the time spent on pasture (see details
180 in Supplementary Material). Nitrogen losses occur during effluent and soil

181 management. The state variables (soil organic nitrogen stocks, livestock numbers, and
 182 crop residues quantities) describe the system state, and their current values are used
 183 to determine the subsequent values. Imported feed and synthetic fertilisers represent
 184 external human-imported nitrogen inputs to the FS.
 185



186
 187 *Figure 1 Conceptual scheme of our model formed by nitrogen compartments (boxes) and flows (arrows). Nitrogen*
 188 *flows are mineral (dashed lines), organic (dotted lines), or a mix (unbroken lines). The external flows that enter the*
 189 *FS come either from the atmosphere or are imported by humans (in grey)*

190 2.2 Mathematical description by compartment

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

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

198 2.2.1 Soil compartments

199 Soil compartments contain the pools of organic (n_t^C for cropland and n_t^G for permanent
 200 grasslands [kg/ha]) and mineral nitrogen. They are considered to be one plot of land
 201 on which different crops or grazed grasses are grown. For the sake of simplification,
 202 we assume only one homogeneous average soil type per soil compartment. We
 203 assume that soil mineral nitrogen ($f_{i,t}^C$ and $f_{i,t}^G$ [kg/ha]) does not accumulate in the soil

204 (it is either consumed by plants or lost at each time step). Organic amendments
 205 (livestock effluents, crop residues, and human sewage sludge – for cropland only) are
 206 homogeneously applied to all crops or grazed grasses for the land use concerned.
 207 Plant residues include both aerial and root residues and their application or
 208 decomposition is assumed homogeneous.

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

220 *Organic nitrogen dynamics*

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

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

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

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

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

238 *Mineral nitrogen flows and losses*

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

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

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

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

253 *2.2.2 Plant compartments*

254 Plant compartments are composed of surfaces cultivated with different crops or grazed
 255 grasses. The areas of these surfaces are assumed constant, and their sum gives the
 256 total utilised agricultural area (UAA) of the FS. Each crop or grazed grass is
 257 parameterised differently. Each crop or grazed grass (i) is assigned a set of traits: area
 258 (A_i [ha]), fresh matter yield of the harvested or grazed organ ($y_{i,t}$ [kg/ha]), harvest

259 index, shoot-to-root ratio and nitrogen contents. All these coefficients make it possible
260 to calculate the nitrogen in plant production.

261 *Plant yield*

262 For each crop or grazed grass (i), the harvested or grazed organ yield ($y_{i,t}$ [kg of fresh
263 matter/ha], the quantity of biomass harvested or grazed from the edible parts of the
264 plants), is a piece-wise linear function of the available soil mineral nitrogen ($f_{i,t}^{A,C}$ or
265 $f_{i,t}^{A,G}$) that saturates at a constant maximum yield (y_i^{MAX}), consistently with previous
266 studies (de Wit, 1992). Below the maximum yield, the mineral nitrogen availability of
267 the soil is limiting. Above the maximum yield, the plant no longer assimilates the
268 mineral nitrogen available in the soil, and the excess is considered lost to water or air
269 (Garnier et al., 2016).

270 *Plant and residues production*

271 Total nitrogen quantities of the harvested or grazed organ ($H_{i,t}$), of the aerial residues
272 ($R_{i,t}^{A,C}$ 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
273 from the AMG model (Clivot et al., 2019).

274 *2.2.3 Livestock compartment*

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

279 *Feed*

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

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

285 The feed shortage ($M_{j,k,t}$) per species (j) and per feed category (k) [kg], i.e. the
286 proportion of feed lacked for feed category (k) and species (j), is defined as $M_{j,k,t} =$

$$287 \max\left(0, \frac{B_{j,k,t}^L - A_{j,k,t}^{FEED,TOT}}{B_{j,k,t}^L}\right).$$

288 *Livestock population dynamics*

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

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

294 *Animal-sourced food production*

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

298 *Livestock effluents*

299 The nitrogen quantity of livestock excretion (E_t^l [kg]) is the difference between the total
300 quantity of ingested feed (B_t^l) and the total animal-sourced food production (P_t) (INRA
301 et al., 2018). Some of these excretions (E_t) occur in housing facilities (E_t^{LB}), and others
302 are deposited during grazing (by ruminants) (E_t^{LG}). Part of these excretions are lost
303 either to the air or to the water. The portion of excretions in housing facilities after
304 losses is available for application on cropland the following year.

305 **2.3 Simulated scenarios**

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

317 Regarding the availability of synthetic fertiliser imports, the initial value (S_0^A)
318 corresponds to 70% of the total initial mineral nitrogen needs of the plants (see
319 Supplementary Material) so that the simulation is started without a synthetic fertiliser
320 shortage, as the synthetic fertilisation needs never exceeds 70% of the plant nitrogen
321 needs. Regarding the availability of feed imports, the initial value for each feed
322 category ($I_{k,0}^A$) corresponds to the initial import needs per feed category (k). If the initial
323 import needs for a feed category are less than 1,000 tons of nitrogen, then a value of
324 1,000 tons is assigned to the import availability for that feed category.

325 In these scenarios, the considered livestock species are cattle, goats and sheep
326 (ruminants), pigs and poultry (monogastrics). Diet is concentrate-only for the
327 monogastrics and contains at least 70% fodder for ruminants (Hou et al., 2016;
328 Therond et al., 2017). The nominal value of the management rate (T_j^M) is zero. The
329 considered animal-sourced food products are eggs, milk, and meat. The plant
330 categories considered are a subset of the categories used in the *Registre Parcellaire*
331 *Graphique* (RPG) (IGN, 2016), inspired by the French agricultural census (Ministère
332 de l'Agriculture et de l'Alimentation, n.d.). The main categories of crops considered are
333 cereals, oil and protein crops, sugar crops, industrial crops, tuber crops, fruit and
334 vegetables, and fodder. Within the fodder category, we differentiate temporary
335 grasslands (harvested or grazed grasslands less than 6 years old composed of 100%
336 or partly of grasses), artificial grasslands (temporary grasslands composed of 100%
337 legumes) and annual forage crops. Crops consisting of 100% legumes are not fertilised
338 with synthetic fertiliser (Service de l'observation et des statistiques, 2013), as well as
339 low-productive permanent grasslands. The feed categories for the different plants are
340 cereals, oil-protein, fodder, grazed grass, co-products, and oilseed meal. We also
341 considered a category labelled 'other' that includes fruits, vegetables, and tubers
342 (classification based on the French National Ecosystem Assessment (Therond et al.,
343 2017)). Only permanent grasslands are used for livestock grazing. Oilseed meals are
344 derived from the processing of oilseeds into oil. Co-products come from the processing
345 of cereals, fruit and vegetables for human consumption. More details about plant and
346 feed classifications are available in the Supplementary Material. The nitrogen needs of
347 a plant are estimated for a maximum yield equal to a typical regional yield. The
348 fertilisation needs are equal to the nitrogen needs of the plant before fertilisation losses.
349 The synthetic nitrogen needs of a plant are the nitrogen needs of the plant minus the

350 natural and organic nitrogen flows. Imported synthetic nitrogen is distributed
351 proportionally to the plant synthetic nitrogen needs. Crop residues are not fed to
352 livestock, but 35% of aerial residues are exported as livestock bedding. The share
353 $\xi_{FSS,t}$ is a function of the total feed needs and the total local feed availability. The
354 remaining crop residues are buried in cropland soil. Livestock consume local feed as
355 a priority. The share of feed pairs is constant in the livestock diet, while for a same pair,
356 the share of one feed category may vary to the detriment of the other. Feed pairs
357 include fodder and grazed grass, cereals and co-products, meals and oil-protein crops.
358 In the case of a feed surplus, feed categories that are also edible by humans (i.e.,
359 cereals and oil-protein crops) are reallocated for human consumption. Constant
360 practices (crop area, maximum yield of each crop, emission factors) and biophysical
361 conditions are assumed constant. More details on the repartition rules implemented for
362 these scenarios are in the Supplementary Material.

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

374 2.4 Case studies

375 We applied this model to three FS types characterised by distinct proportions of
376 livestock numbers and plant areas. We chose three French small agricultural regions
377 (SAR, *Petite Region Agricole* in French). The SAR (average area of 76,800 ha) is an
378 ideal representation of a FS, as already used in other studies (Accatino et al., 2019;
379 Mouysset et al., 2012; Teillard et al., 2017). Jouven et al. (2018) grouped SAR to reflect
380 the adequacy between local plant production and livestock consumption. We picked
381 three SAR (Table 1) from different groups of the classification by Jouven et al. (2018):
382 (i) an *extensive ruminant* FS (Bocage Bourbonnais), taken from the group '*balanced*

383 *livestock and plant production with surplus concentrates*’ consisting of mainly ruminant
 384 farms; (ii) an *intensive monogastric* FS (Bretagne Centrale), taken from the group
 385 *‘dependent livestock production’* consisting of mainly monogastric farms with more
 386 than a 30% dependence on dry matter imports; (iii) a *field crop* FS (Plateau Picard),
 387 characterised by the prominent presence of crops and a very low livestock stocking
 388 rate and therefore not considered in the clustering by Jouven et al. (2018). In summary,
 389 the choice of the scenarios was aimed at exploring the roles of the stressors, and the
 390 choice of the SAR was aimed at exploring the roles of the FS configuration in terms of
 391 crops, grasses and livestock.

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

Variable	Extensive ruminants	Intensive monogastr ics	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

396 **daily protein requirement of 80g/person*
397 ***except permanent grasslands*
398 ****not fertilised by synthetic nitrogen in the model*
399

400 2.5 Parameters

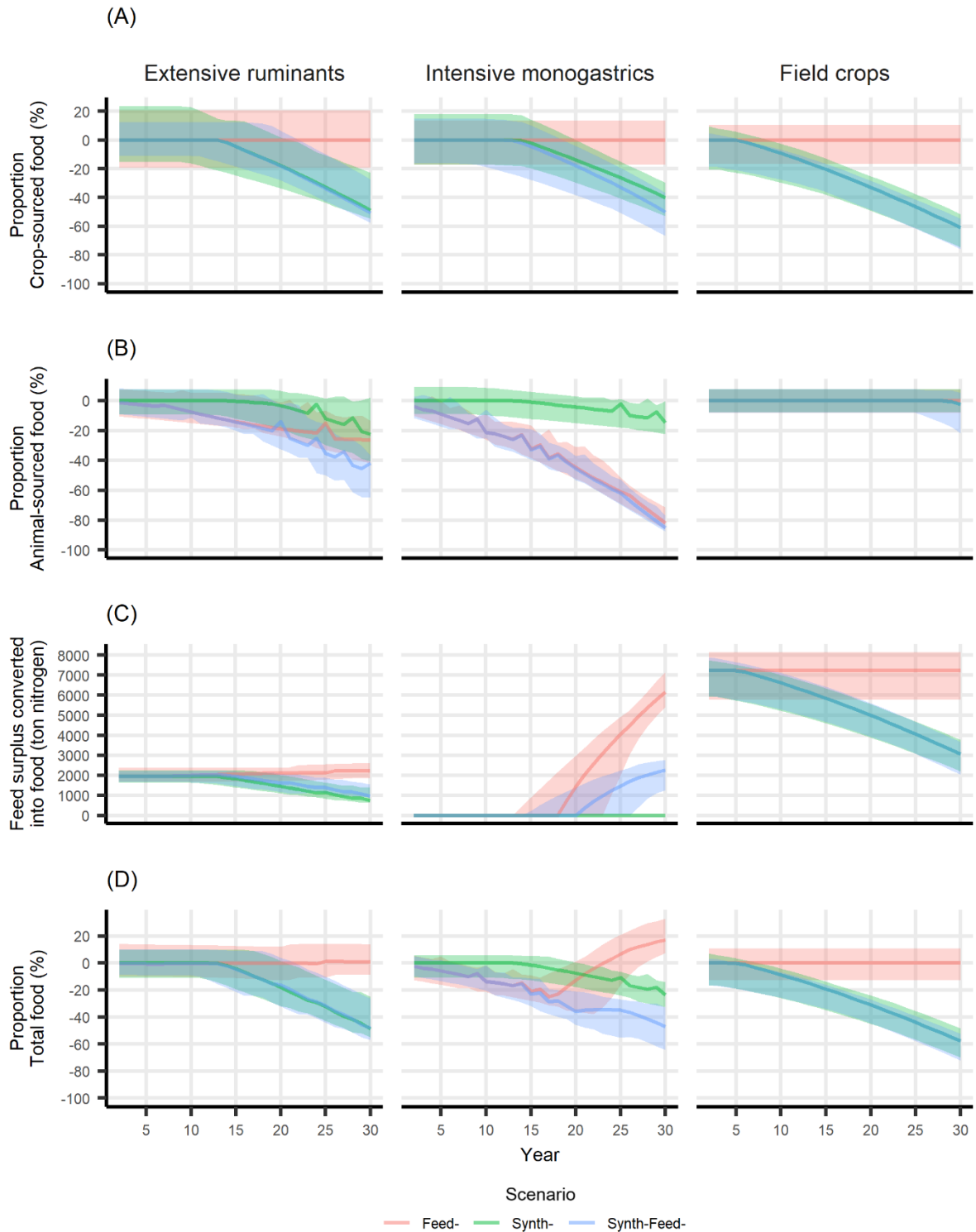
401 We collected from the literature the most recent parameter values for the considered
402 SAR. A list of the parameters with their sources and nominal values is available in the
403 Supplementary Material. We performed a global sensitivity analysis using the R "FME"
404 package. We considered an interval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

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

413 3 Results

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

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

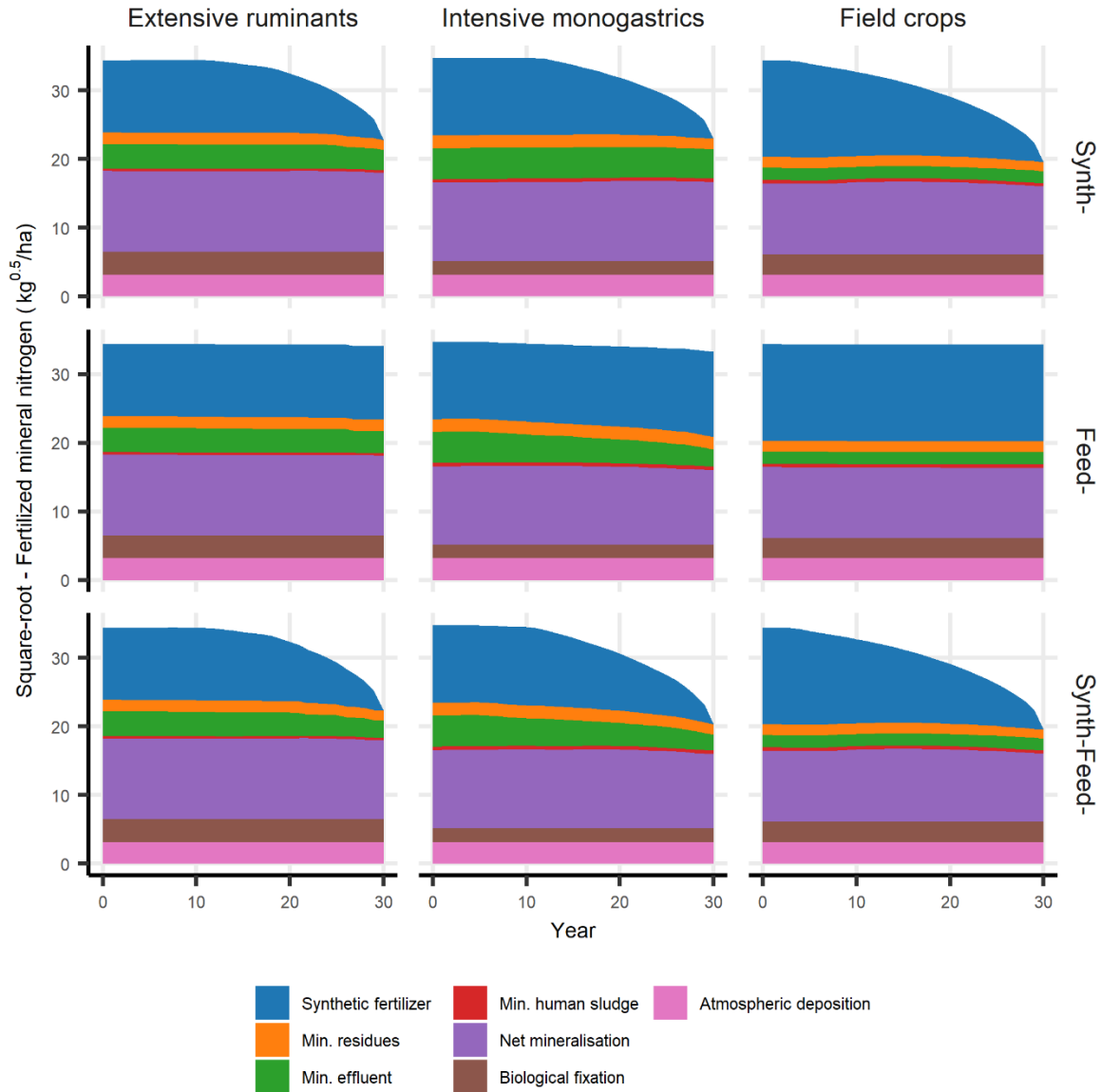


425

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

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

436



437

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

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

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

445 3.1 Extensive ruminant FS results

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

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

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

468 The *Synth-Feed-* scenario exhibits curves similar to those of the *Synth-* scenario for
469 crop-sourced food production and feed surplus converted into food. However, animal-
470 sourced food production decreases, nearly reaching -33% in year 30 and experiencing
471 three local production peaks (Figure 2B). The averaged net mineralisation flow shows
472 trends similar to those of the *Synth-* scenario, despite a larger decline in animal-
473 sourced food production, reaching -5% in year 30 (Figure 3). Total food production

474 reaches -50% in year 30, after remaining almost constant for the first 13 years (Figure
475 2D).

476 Further analyses show that mainly monogastric populations are declining, especially
477 in the short term, in scenarios with a decrease in feed imports (see Appendices). They
478 also show that the cropland soil organic nitrogen stock decreases by a maximum of
479 13%, and the permanent grassland soil organic nitrogen stock by 7% after 30 years.
480 Natural and organic nitrogen flows represent for cropland and for permanent
481 grasslands approximately 70% and 56% respectively of the mineral nitrogen needs
482 before losses.

483 3.2 Intensive monogastric FS results

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

490 In the *Synth-* scenario, crop-sourced food production is not affected until year 13. It
491 then decreases linearly until year 30, reaching -40% (Figure 2A). For animal-sourced
492 food production, it is almost constant until year 13, before declining to -13% in year 30
493 (Figure 2B). It experiences two local meat production peaks linked to livestock
494 destocking during feed shortages. The averaged net mineralisation flow varies little
495 (Figure 3). The feed surplus value remains at 0 (Figure 2C). Total food production is
496 constant for the first 13 years, before declining linearly to approximately -25% in year
497 30 (Figure 2D).

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

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

514 Further analyses show that mainly monogastric populations are declining, especially
515 in the short term (see Appendices). Ruminant populations only decrease after more
516 than 20 years when there is a decrease in feed imports. They also show that the
517 cropland soil organic nitrogen stock decreases by a maximum of 20% from its initial
518 value, whereas the permanent grassland soil organic nitrogen stock by a maximum of
519 9%. Natural and organic nitrogen flows represent for cropland and for permanent
520 grasslands approximately 70% and 56% respectively of the mineral nitrogen needs
521 before losses.

522 3.3 Field crops FS results

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

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

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

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

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

550

551 4 Discussion

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

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

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

576 The main assumptions of our modelling approach are that parameters of the FS that
577 are considered constant over time (maximum yield, livestock diet, herd size, plant
578 cover composition etc.). The results and their implication are only valid in relation to
579 the forms of perturbations considered and the rules specified for the distribution of
580 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

613 due to the decline in animal-sourced food production in the first year. This difference
614 is less pronounced for the extensive ruminant FS. The reason is that part of the
615 ruminant effluents occur on permanent grasslands, which do not contribute to crop
616 production. The use of livestock effluents as a substitute for synthetic fertilisers has
617 already been largely implemented in crop-livestock farms, thus promoting synergy
618 between livestock and crop compartments and enhancing nutrient self-sufficiency (see
619 Li et al., (2021)). Nevertheless, at the FS level this synergy is not systematically
620 promoted today in France (Loyon, 2017).

621 4.1.2 Cropland soil organic nitrogen as an essential source of mineral 622 nitrogen

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

629 To our knowledge, the scientific literature studies the soil processes of nutrient supply
630 through mineralisation, but it does not specifically mention the contribution of the net
631 mineralisation flow to the robustness of plant production at the farm or FS levels (e.g.,
632 Fuchs et al., 2014). The increase in the application of organic amendments is
633 considered a contributor to the increase in soil organic matter and carbon stocks, and
634 it may play a key role in climate change mitigation. The 4-per-1000 initiative is an
635 example of an identified action that consists of using currently unrecycled sources of
636 organic matter (such as household organic waste) to increase the carbon stocks of
637 agricultural soils and thus offset the net flow of CO₂ emissions into the atmosphere
638 (Chabbi et al., 2017; Minasny et al., 2017). The literature emphasizes that organic
639 amendments indirectly contribute to crop yield stability as sources of microorganisms
640 and sometimes antagonists, and therefore regulators, of plant diseases (Gis Sol,
641 2011). They also contribute to crop yield stability by increasing the long-term soil
642 structural stability, thus increasing the ability of the soil to retain water, preventing soil
643 erosion, and stimulating the growth and activity of soil organisms.

644 The spin-up method misestimated the value and the dynamics of active soil organic
645 nitrogen stocks and net mineralisation flows. In the Plateau Picardie SAR (the field

646 crop FS), active soil organic nitrogen stocks (for a soil C:N ratio equal to 10 and at 10
647 cm soil depth) have been reported to range from 1,400–1,750 kg/ha (Martin, 2019);
648 however, we estimated between 115%-145% this quantity using the spin-up method.
649 Depending on the soil type, crop, and sowing period, the net mineralisation flow can
650 realistically range from 30–85 kg/ha nitrogen in the same SAR (Groupe régional
651 d'expertise nitrates Picardie, 2015); however, we estimated an initial net mineralisation
652 flow of about 100 kg/ha nitrogen. These overestimations seem to be due to a
653 predominant immobilisation phenomenon in the model. The strong uncertainties
654 regarding the humification coefficients of organic amendments, especially crop
655 residues, may be one possible explanation for this overestimated flow (Fuchs et al.,
656 2014). However, the global sensitivity analysis showed that uncertainties and
657 overestimates of soil parameters did not drastically change the trends in terms of food
658 production, although they did change the active soil organic nitrogen stocks.

659 4.1.3 Extensive ruminants: a type of crop-livestock farming system 660 more coupled to local resources

661 Of the two FS with high stocking rates, the extensive ruminant FS has lower import
662 needs than the intensive monogastric FS (see Supplementary Material). The feed
663 surplus converted into food flow is an indicator of this low import. On the contrary, the
664 extensive ruminant FS depends proportionally more on local production. This explains
665 the higher robustness of animal-sourced food production of the extensive ruminant FS
666 in the *Feed-* scenario compared to the intensive monogastric FS. Moreover, in the
667 *Synth-* scenario, the decline in food production remains low for extensive ruminants
668 despite their dependence on local production. This last result can be explained by the
669 high share of organic and natural flows in the mineral fertilisation of permanent
670 grasslands (which represents 50% of the UAA in this FS). In other words, according to
671 the model results and from a nitrogen point of view, permanent grasslands are less
672 fertilised synthetically (Service de l'observation et des statistiques, 2013). Furthermore,
673 permanent grasslands are also larger carbon pools than cropland (Martin, 2019) and
674 on the farm scale, other studies showed that the presence of grasslands used to feed
675 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

709 production was to decline, either current local protein consumption or food export
710 would decline. If maintaining consumption and/or export levels is desired, then it would
711 be necessary to invest in configuration changes that promote both productivity and
712 robustness to declining imports. In such cases, it seems necessary to increase the
713 area of legumes to reduce the dependence on synthetic nitrogen fertilisers (Billen et
714 al., 2018). This would at the same time reduce the environmental impact due to high
715 mineral nitrogen inputs.

716 4.3 Decisive capacity of robustness for adaptability and 717 transformability

718 Of the three resilience capacities presented by Meuwissen et al. (2019), we only
719 considered robustness (the capacity to absorb challenges without configurational
720 changes). However, conclusions regarding robustness put into perspective the
721 importance of FS adaptations and transformations to minimise the imports of feed and
722 synthetic fertilisers in addition to reducing environment losses. The time period during
723 which food production does not decline can be seen as a “robustness window” in which
724 other adaptive or transformative actions can be implemented. Two adaptive actions
725 are already largely implemented in Europe: enhancing nitrogen use efficiency at the
726 plot level and by livestock. We also identified three other complementary actions at the
727 FS level : (i) reducing losses during the management of organic amendments (Oenema
728 et al., 2007); (ii) maximising the input of new nitrogen molecules by nitrogen-fixing
729 plants to minimise the use of synthetic fertilisers and maintain a certain crop
730 productivity (Billen et al., 2018); (iii) increasing productivity and reducing losses at the
731 FS level for crop-livestock FS by reducing feed-food competition (Van Zanten et al.,
732 2018).

733 4.4 Study and model limits

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

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

755 5 Conclusion

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

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

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

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

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

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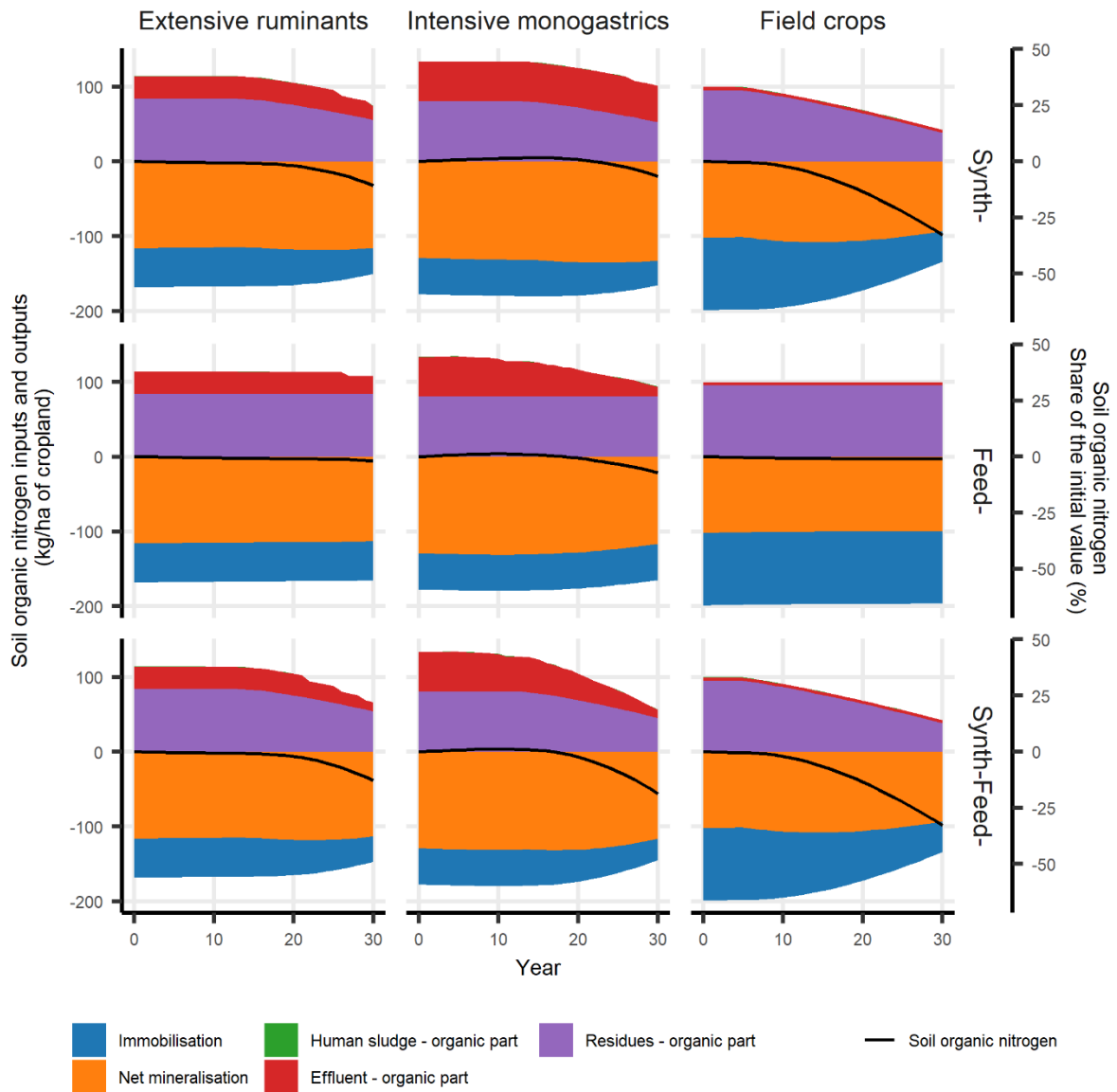
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1055 8 Appendices

1056 8.1 Cropland soil organic nitrogen balance

1057 In all the scenarios and FS, cropland soil organic nitrogen inputs decrease over time
1058 (Figure 4). In the scenarios with a synthetic fertiliser decline, the quantity of crop
1059 residues applied decreases, and the quantity of livestock effluents applied also
1060 decreases, especially in scenarios with a decline in feed imports. A decrease in crop
1061 residues lead to a decrease in immobilisation flow, whereas a decrease in livestock
1062 effluents does not impact the immobilisation flow. Organic amendment decreases lead
1063 to decreases in the soil organic nitrogen stock and net mineralisation flow in different
1064 proportions, depending on the FS. However, decreases in crop residues and
1065 immobilisation flow contribute in the short term to containing or even slightly increasing
1066 the net mineralisation flow. They also lead to shifting the date when the net
1067 mineralisation flow decreases, with respect to the soil organic nitrogen stock.



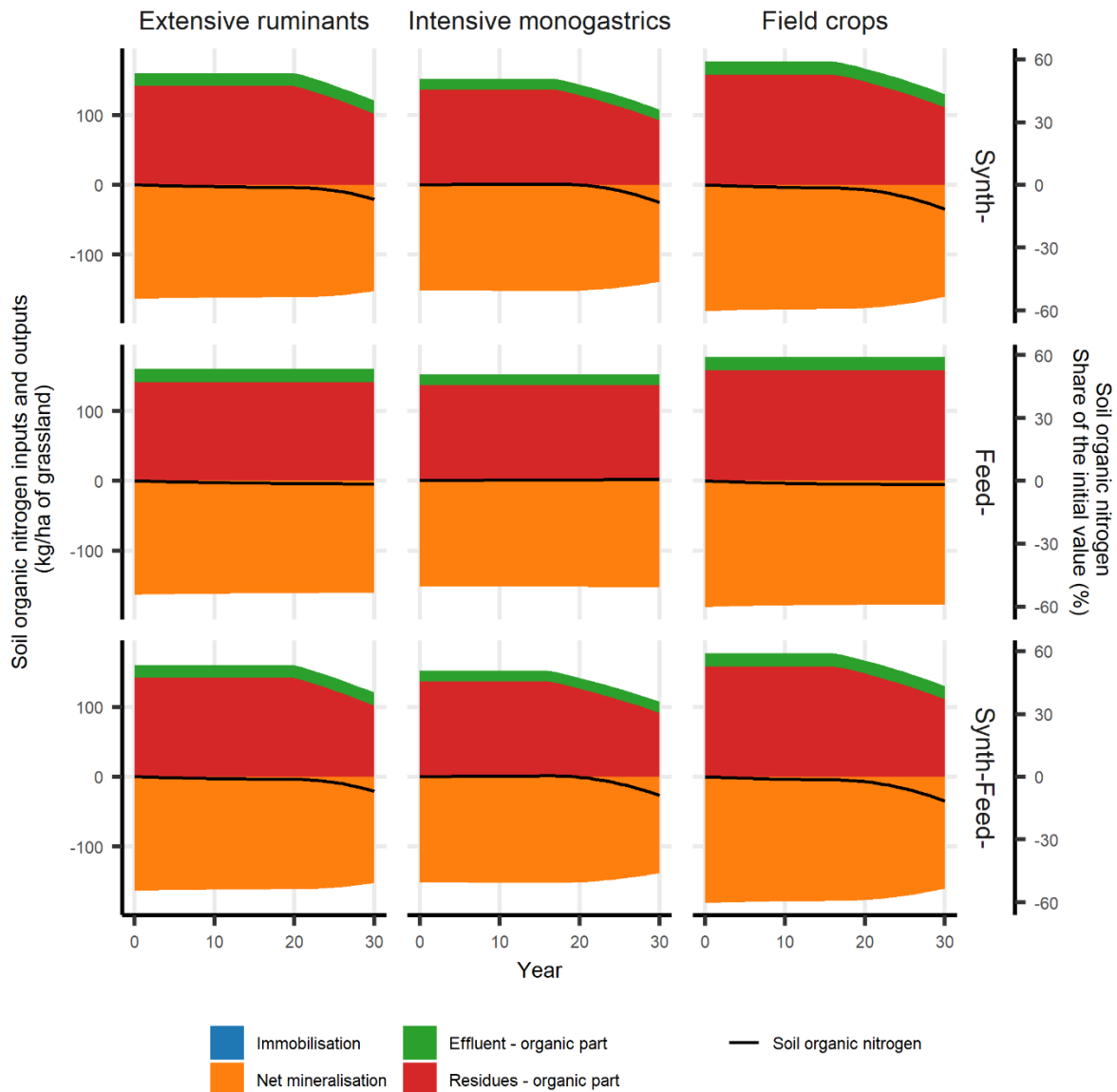
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Figure 4 Area diagram of the quantity for cropland of soil organic nitrogen inputs and outputs per unit area (kg/ha) over time (in years) according to scenario (rows) and FS (columns) for the nominal parameter set. Cropland soil organic nitrogen stock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



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1074

Figure 5 Area diagram of the quantity for permanent grassland of soil organic nitrogen inputs and outputs per unit

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area (kg/ha) over time (in years) according to scenario (rows) and FS (columns) for the nominal parameter set.

1076

Permanent grassland soil organic nitrogen stock variations are also shown as percentages (right y-axis).

1077

In contrast to cropland, decreases in organic nitrogen input flows or soil organic

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nitrogen stock are smaller in all three FS and scenarios for permanent grassland, and

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there is not immobilisation of mineral nitrogen from soil organic nitrogen mineralisation

1080

(Figure 5). In the *Feed-* scenario, there is a slight decrease in soil organic nitrogen

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stock. And in scenarios with decreasing synthetic nitrogen imports, after 15 years, the

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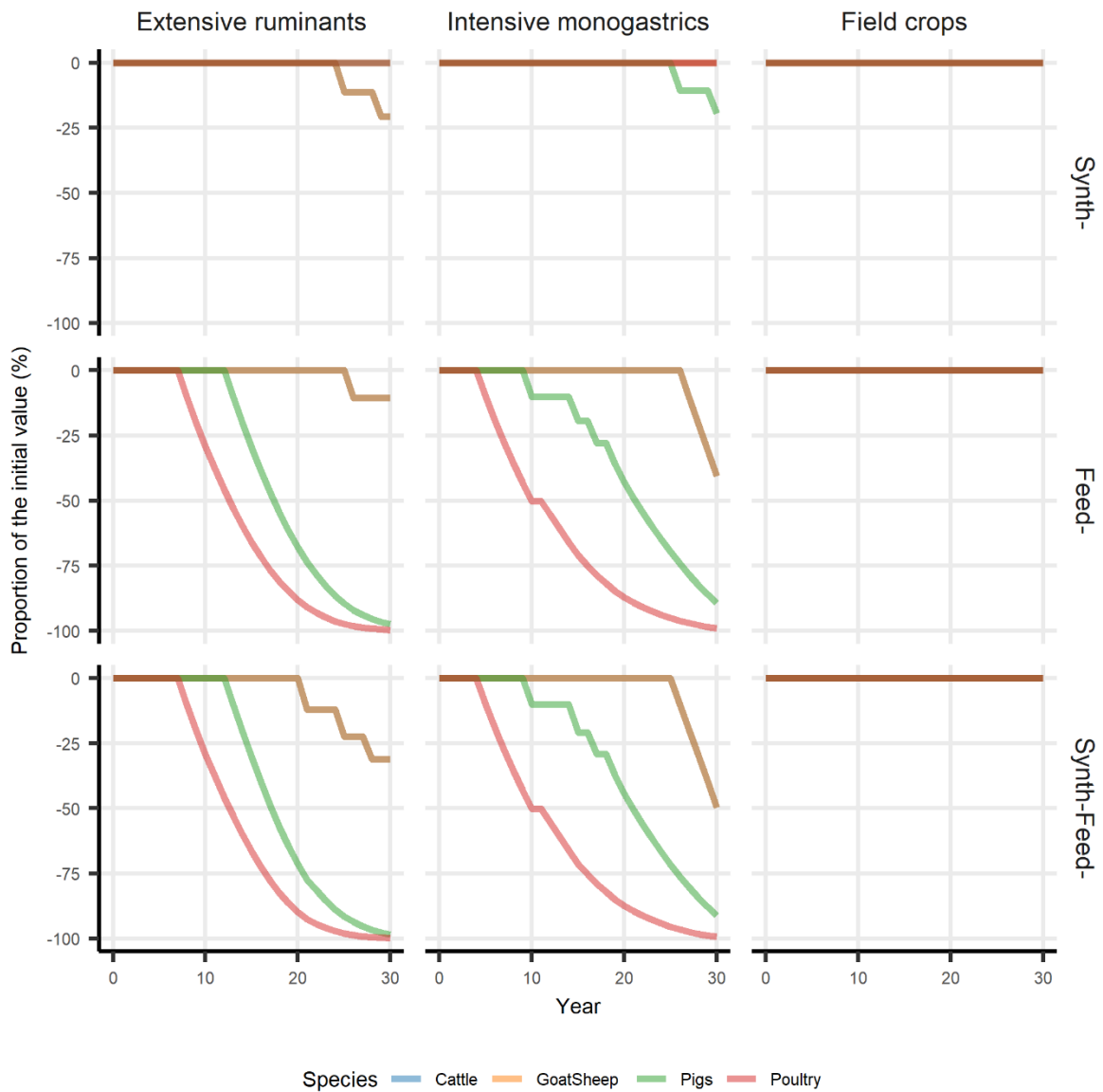
residues input flows decrease and decreases in soil organic nitrogen stock accelerate.

1083 After 30 years, the soil organic nitrogen stock in permanent grasslands has decreased
1084 by 10-15%.

1085 8.3 Livestock number

1086 Depending on the species, the time evolution of the livestock number varies due to
1087 species-specific diets (Figure 6). Species in the monogastric group, fed only on
1088 concentrates, are less robust, especially in the *Feed-* scenarios, in which their numbers
1089 decrease in the short term (less than 15 years). In the long term, their decline can
1090 reach 100%. Ruminant numbers only decrease in the long term and to a lesser extent.

1091 However, in the monogastric intensive FS during the *Synth-Feed-* scenario, livestock
 1092 numbers decrease by 50% in the year 30.



1093

1094 *Figure 6 Time evolution of livestock numbers (%) for the three scenarios (rows) and FS (columns) per species for*
 1095 *the nominal parameter set: cattle, goats and sheep, pigs, poultry. The curves for cattle and sheep/goats overlap*
 1096 *because their diets are identical per FS. Among the monogastrics, poultry numbers tend to decline first. The*
 1097 *decrease in ruminant numbers occurs during year 15, at the soonest, in the Feed- and Synth-Feed- scenarios.*

1098