



HAL
open science

European agriculture's robustness to input supply declines: A French case study

Corentin Pinsard, Francesco Accatino

► **To cite this version:**

Corentin Pinsard, Francesco Accatino. European agriculture's robustness to input supply declines: A French case study. *Environmental and Sustainability Indicators*, 2023, 17 (100219), 10.1016/j.indic.2022.100219 . hal-03996528

HAL Id: hal-03996528

<https://hal.inrae.fr/hal-03996528>

Submitted on 21 Jul 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 European agriculture's robustness to 2 input supply declines: A French case 3 study

4 Abstract

5 European farming systems (FSs) are currently dependent on oil to transport feed and
6 to synthesise fertilisers. Disturbances, such as reaching global peak oil by 2030, can
7 therefore result in supply shortages. It is necessary to investigate the robustness of
8 European FSs, i.e., their capacity to maintain agricultural production with their current
9 crop–grassland–livestock composition. The aims were to (1) assess the robustness
10 of French FSs to a joint decline in the input supplies and (2) explore the links
11 between robustness and crop–grassland–livestock compositions. We simulated a
12 progressive 30-year decline of synthetic fertiliser use and feed imports with a time-
13 dynamic FS nitrogen flow model. We then clustered the FSs according to their
14 robustness levels and examined at the national scale the relationships between
15 these clusters and compositional indicators. French FSs maintained agricultural
16 production for a median of 8 years before experiencing a 69% drop in agricultural
17 production after 30 years. The most-specialised FSs (vineyards, intensive
18 monogastrics and field crops) were least robust in the short term (4–7 years), as they
19 were the most dependent on inputs to meet their needs; however, they were the
20 most robust in the long term (60% reduction), except for field crops (~75% reduction).
21 Mixed FSs were the most robust in the short term (8–19 years). However, the
22 robustness levels depended on the degree of crop–livestock integration. Changes in
23 compositions that decrease supply dependency, such as a reduction in feed–food
24 competition, should be implemented as soon as possible to increase the FSs
25 resilience.

26 Keywords

27 Peak oil; Time-Dynamic nitrogen mass flow balance; Farming system typology; Feed
28 import; Synthetic fertilizer

29 Abbreviations

30 FS: Farming System

31 SAR: Small Agricultural Region

32 UAA: Utilised Agricultural Area

33 1 Introduction

34 Modern European agriculture depends on certain inputs to maintain high productivity,
35 including synthetic fertilisers and imported feed (EEA, 2017; European Commission,
36 2019). This dependency originated during the second modern agricultural revolution
37 after the Second World War, through the specialisation, industrialisation and
38 intensification of farming systems (FSs) (Mazoyer and Roudart, 2002). Consequently,
39 European agriculture grew dependent on fossil fuels for feed transportation and
40 fertiliser synthesis (Barbier et al., 2019) and became vulnerable to market price
41 variability and input supply shortages. In 2018, the International Energy Agency
42 estimated that world oil production could peak within the following decade (IEA,
43 2018), implying the volatility and possible rise of oil prices and, therefore, fossil fuels
44 and agricultural commodities (Irz et al., 2013; Naylor and Falcon, 2010; Vatsa and
45 Miljkovic, 2021). This variability in prices and production could lead to supply
46 shortages and threaten European food security without rapid and effective
47 interventionist public policies.

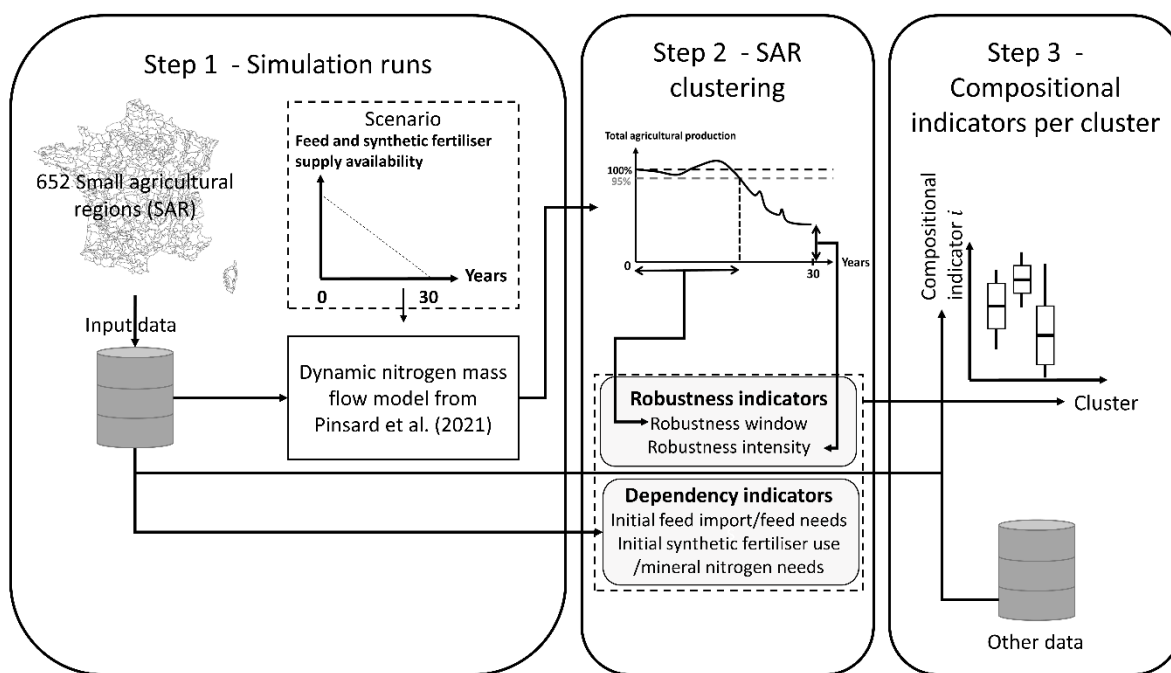
48 In the face this threat, we must question the robustness of European FSs: *with their*
49 *current composition*, what is their capacity to maintain production? Following Giller
50 (2013), we defined an FS as a population of farms with similar biophysical, economic
51 and social conditions located in a common and restricted geographical area. If input
52 availability decreases, European FSs will very likely adapt their compositions,
53 especially in the long term. Nevertheless, studying and mapping the capacity of
54 European FSs to resist change *with their current compositions* is critical to identifying
55 the most vulnerable compositions. Other studies have defined *robustness* as the
56 capacity to withstand disturbances without compositional changes (Accatino et al.,
57 2014; Meuwissen et al., 2019; Mumby et al., 2014; Urruty et al., 2016). Resilience
58 components such as adaptability and transformability, which imply compositional
59 changes, were not addressed in this study. Studying and quantifying FS robustness
60 can help guide public policies on agroecological transition.

61 To our knowledge, systematic quantitative assessments of the robustness, resilience
62 and related properties (e.g., vulnerability and sustainability) of European FSs have
63 mainly analysed statistically historical or ad hoc data specifying in some cases
64 disturbances such as climate change–related extreme weather events, food import
65 shocks (Béné et al., 2019; Dardonville et al., 2020; Das et al., 2020; Fraser et al.,
66 2015; Hannaford, 2018; Kahiluoto et al., 2019; Marchand et al., 2016; Seekell et al.,
67 2017; Smith and Edwards, 2021; Suweis et al., 2015). While no systematic analysis
68 of the robustness of European FSs to future consequences of peak oil (i.e., input
69 supply shock or decline) has been conducted.

70 This study’s objectives were to define and map robustness indicators in France and
71 describe the links between robustness levels and indicators of crop–grassland–
72 livestock composition. France is a suitable case study as it presents a diverse range
73 of FSs (Jouven et al., 2018; Ministère de l’Agriculture et de l’Alimentation, 2010)
74 corresponding to diverse dependencies on synthetic fertilisers and feed imports. To
75 achieve the objectives, we first defined and calculated robustness indicators for all
76 French FSs using the nitrogen (N) mass flow balance model developed by Pinsard et
77 al. (2021). This time-dynamic model allows for the exploration of robustness via
78 simulations of model output trajectories. Pinsard et al. (2021) showed that different
79 crop–grassland–livestock compositions present different levels of robustness. We
80 divided FSs into clusters using robustness indicators, defined from simulated
81 trajectories, and indicators of supply dependency. We then explored how different
82 clusters were linked to indicators of FS crop–grassland–livestock composition. This
83 analysis enabled a discussion of French agricultural vulnerability to supply declines.

84 2 Material and Methods

85 The methodology (Figure 1) involved defining and calculating *robustness indicators*
86 for all French FSs using a dynamic N mass flow balance model (step 1). One FS was
87 identified, as in previous studies (see Accatino et al., 2019), as one *small agricultural*
88 *region* (SAR), a spatial unit of the French administrative system characterised by
89 agronomic and soil homogeneity with an average surface area of 76,800 ha. We
90 considered SARs with an utilised agricultural area (UAA) over 15% of the total area
91 and cropland over 1% of the UAA, for a total of 652 SARs. We calculated the
92 robustness indicators for each SAR based on the simulated temporal dynamics of
93 agricultural production under a 30-year scenario of linear decline in the availability of
94 synthetic fertiliser and feed supplies. In Pinsard et al. (2021), three SARs faced with
95 such constraints showed a decline in agricultural production, though to varying
96 extents according to their robustness. The robustness indicators, which serve to
97 distinguish the forms of agricultural production decline and allow comparison among
98 the SARs, were used as inputs for building a typology of SARs via cluster analysis
99 (step 2) along with two other indicators signifying the level of input dependency. We
100 identified indicators for the crop–grassland–livestock composition (*compositional*
101 *indicators*) of a SAR and studied the relationships between these indicators and the
102 clusters (step 3). The model is broadly described in the next section, and further
103 details are provided in both the Supplementary Material and Pinsard et al. (2021). In
104 the next sections, details are also given for the indicator definitions (Table 1) and
105 cluster analysis. In the remainder of the article, robustness, without specifying ‘of
106 what to what’, refers to that of total agricultural production to input availability decline.



107

108 *Figure 1 Scheme describing the methodology. Step 1 consists of running a dynamic nitrogen (N) mass flow model*
 109 *(defined in Pinsard et al., 2021) for 652 small agricultural regions (SARs) of France under a simulated scenario of*
 110 *declining feed and synthetic fertiliser supply availability over 30 years. Step 2 involves clustering (hierarchical*
 111 *agglomerative classification) two model outputs (the robustness indicators) with two indicators: the percentage of*
 112 *imported feed out of the total feed needs and the percentage of synthetic fertiliser applied out of the total mineral*
 113 *N input. Step 3 generates a compositional indicators boxplot for each SAR cluster.*

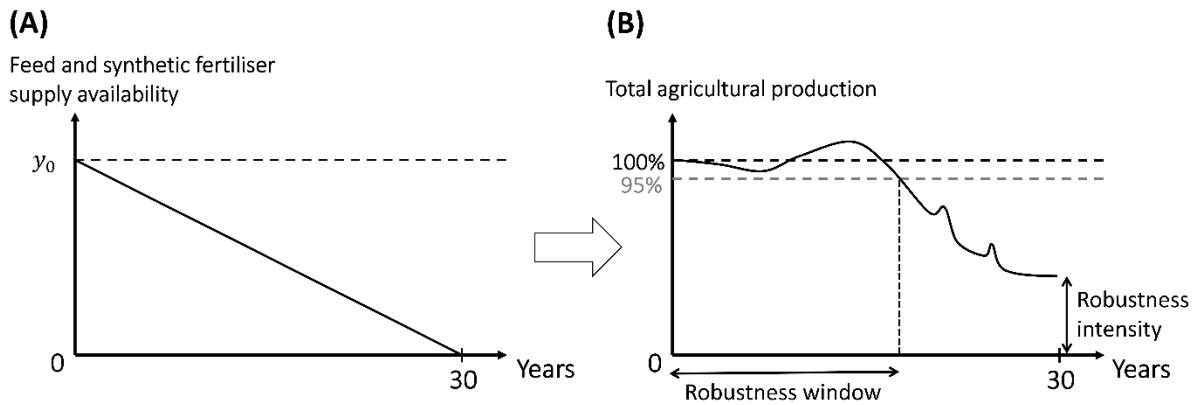
114 2.1 General model description

115 The dynamic N flow model of Pinsard et al. (2021) conceptualises an FS as having
 116 two land uses (cropland and permanent grassland) and a livestock compartment.
 117 Each land use has separate plant and soil compartments; livestock either graze
 118 permanent grasslands or are kept in housing facilities. Manure is allocated to
 119 permanent grasslands or housing facilities proportionally to the time the livestock
 120 spend in each, and the fraction excreted in housing facilities is further redistributed to
 121 crops. The soil compartment consists of an organic N stock and a mineral N balance
 122 (mineral N residues are not considered). The plant compartment is conceptualised as
 123 a single plot per land use but is composed of several surfaces allocated to different
 124 plant species. Plant production is proportional to the availability of soil mineral N
 125 (assuming that N is the only limiting factor), and animal-sourced agricultural
 126 production is a function of the available local and imported feed (quantified as N).
 127 The active soil organic N stock and the livestock herd sizes are updated and the
 128 agricultural production levels (plant and livestock) are calculated at each 1-year

129 increment. The active soil organic N stock increases with organic N inputs (plant
130 residues or livestock effluents) and decreases with outputs (organic matter
131 mineralisation). Synthetic fertiliser, atmospheric deposition, biological N fixation by
132 legumes, mineralised soil N and the mineral parts of organic amendments contribute
133 to the plants' mineral fertilisation. Plant production is allocated to humans and/or
134 livestock, depending on the species. N losses to air or water occur during effluent
135 management and soil management. The number of livestock decreases when feed
136 availability is lower than their needs. The plants' mineral N needs are estimated from
137 the typical yield in each SAR in recent years. The plant yield is a piecewise linear
138 function of mineral N: the yield increases linearly with mineral N availability from 0 to
139 a maximum yield, corresponding to the mineral N needs of the plant. Above the
140 mineral N needs of the plant, the yield is considered saturating at the maximum.

141 2.2 Scenario and simulations

142 The species considered are poultry, pigs, sheep, goats and cattle. The feed
143 categories are energy concentrates, protein concentrates and forages. The feed
144 subcategories are cereal and co-products (energy concentrates), oilseed and oilseed
145 cakes (protein concentrates) and fodder and grazed grass (forages). Permanent
146 grasslands are assumed to be synthetically fertilised (Service de l'observation et des
147 statistiques, 2013). Only pure legumes are not considered to be fertilised with
148 synthetic fertiliser. The quantity of effluents applied to cropland cannot exceed 170
149 kgN/ha/year, following the EU Nitrates Directive (European Commission, 2010).
150 Livestock are assumed to graze only on permanent grassland. Both livestock diets
151 and the surface area allocated to each crop or grassland are assumed to be constant
152 over time.



153

154 *Figure 2 (A) Trajectory of joint linear decline over 30 years of the supply availability of synthetic fertiliser and feed.*
 155 *y_0 is worth 70% of the total plant mineral N fertilisation need of areas fertilised with synthetic fertiliser per SAR for*
 156 *synthetic fertiliser and 100% of the total need for livestock per feed subcategory per SAR for imported feed. (B)*
 157 *Example total agricultural production trajectory over time for a SAR from a model simulation of agricultural*
 158 *production under input supply availability decline. The two robustness indicators are obtained from this trajectory.*
 159 *The robustness window is the consecutive number of years during which the agricultural production of the farming*
 160 *system (FS) does not fall below 95% of the initial agricultural production. The robustness intensity is the share of*
 161 *the initial total agricultural production at year 30.*

162 We simulated a scenario of declining input availability for each SAR. Specifically, we
 163 imposed a trajectory of joint linear decline in the supply availability of synthetic
 164 fertiliser and feed import (any feed flow that enters the FS) over 30 years, whatever
 165 their geographical origin (neighbouring regions or another continent). We have
 166 assumed that the synthetic fertiliser used is totally imported, the gas needed for its
 167 synthesis being almost 100% imported (SDES, 2021) and despite the fact that a part
 168 of synthetic fertilizer is produced in France (FAO, 2021). At time zero, the availability
 169 of synthetic fertiliser supplies is imposed as 70% of the total plant mineral N
 170 fertilisation needs of areas fertilised with synthetic fertiliser by SAR, whereas the
 171 availability of imported feed per feed subcategory corresponds to the total needs of
 172 livestock for that feed subcategory per SAR. For both synthetic fertiliser and feed
 173 supplies, the trajectory is imposed as 0 at 30 years with a linear decrease over time
 174 (Figure 2A).

175 2.3 Indicators of robustness to input supply availability declines

176 Declining input availability always results in a gradual agricultural production decline
 177 (Pinsard et al. 2021); the typical trajectory (depicted in Figure 2B) shows an initial
 178 maintenance of agricultural production (even after input availability starts to decline)
 179 and then a gradual decrease until the end of the simulation. However, some FSs

180 start to decline later than others and to different extents. Based on the typical
181 trajectory, we defined two robustness indicators (Figure 2B): the *robustness window*
182 and *robustness intensity*. The robustness window is the initial period in which the
183 system can maintain its current level of agricultural production even after the initial
184 decline in input availability. We defined a threshold of 95% of the initial agricultural
185 production, below which we considered agricultural production to decline. The
186 robustness intensity is the percentage of agricultural production compared to the
187 initial quantity at the end of the 30-year simulation. The robustness window and
188 intensity shed light on short- and long-term robustness, respectively.

189 These indicators, which depend on the disturbance scenario, characterise the
190 various trajectories to compare the SARs' robustness to input availability decline. The
191 results undoubtedly differ for different supply availability decline trajectories;
192 however, the SARs in this study can be compared as the simulated scenario is the
193 same for each of them.

194 No sensitivity analysis was conducted on the robustness indicators because of the
195 high computational time required for this and the subsequent clustering for all the
196 SARs. A sensitivity analysis of the model was conducted in Pinsard et al. (2021),
197 which showed near invariance for total agricultural production over the 30-year
198 simulation using the same scenario as this study.

199 2.4 Clustering indicators

200 The cluster analysis aimed to create a typology of SARs according to their
201 robustness and dependency on external input. We selected four indicators (hereafter
202 *clustering indicators*): (1) the robustness window (years), (2) the robustness intensity
203 (%), (3) the *percentage of imported feed* out of the total feed needs (%) and (4) the
204 *percentage of synthetic fertiliser applied* out of the total mineral N input (%). Indicator
205 (3) is calculated as the ratio of imported feed to the total feed needs considering all
206 the feed categories, expressed as the mass of N. Indicator (4) corresponds to the
207 percentage of mineral N from synthetic fertiliser compared to the total mineral N input
208 (including organic amendments, deposition and biological N fixation). The clustering
209 indicators were chosen based on the conclusions drawn by Pinsard et al. (2021) after
210 simulating input availability decline for 3 SARs. We added indicators (3) and (4) to
211 the clustering indicators because the robustness indicators may be similar for two

212 distinct SARs with different uses of imported feed and synthetic fertiliser, thus
213 requiring finer distinction (e.g., in Pinsard et al. [2021], the robustness intensity was
214 similar for an extensive ruminant FS and an intensive monogastric FS).

215 We implemented a hierarchical agglomerative classification to maximise the variance
216 between groups and minimise the variance within groups (Murtagh and Legendre,
217 2013). Before classification, we manually clustered the SARs with vineyard areas
218 over 50% of the UAA to distinguish them from field crop SARs with similar robustness
219 levels. Clustering was performed using Ward's method (option ward.D2) in the hclust
220 function of the stats package in R (R Core Team, 2020). The optimal number of
221 clusters was estimated graphically with the Hubert and D indicators of R's NbClust
222 package (Charrad et al., 2014).

Table 1 Indicator descriptions by type. UAA: utilised agricultural area, LU: livestock unit, FS: farming system, N: nitrogen.

Type	Name	Description	Unit
Robustness and clustering indicators	<i>Robustness window</i>	Consecutive number of years during which the agricultural production of the FS does not fall below 95% of the initial agricultural production	Years
	<i>Robustness intensity</i>	Share of the initial total agricultural production at year 30	%
	<i>Percentage of imported feed out of the total feed needs</i>	Ratio of imported feed to feed needs considering all feed categories together expressed in mass of N	%
Clustering indicators	<i>Percentage of synthetic fertiliser applied out of the total mineral N input</i>	Ratio of mineral N from synthetic fertiliser to total mineral N input (including organic amendments, deposition and biological N fixation)	%
	<i>Number of monogastrics</i>	Number of poultry and pigs	LU/haUAA
	<i>Number of ruminants</i>	Number of cattle, goats and sheep	LU/haUAA
	<i>Total livestock count</i>	Sum of monogastric and ruminant numbers	LU/haUAA
	<i>Percentage of permanent grassland area in the UAA</i>	Ratio of permanent grassland area to UAA	%
	<i>Percentage of temporary grassland area in the UAA</i>	Ratio of temporary grassland area to UAA	%
	<i>Percentage of cereal and oilseed areas in the UAA (i.e., field crops)</i>	Ratio of cereals and oilseeds area to UAA	%
Compositional indicators	<i>Self-sufficiency in energy concentrates</i>	Ratio of livestock needs to local availability allocated to livestock for energy concentrates	%
	<i>Self-sufficiency in protein concentrates</i>	Ratio of livestock needs to local availability allocated to livestock for protein concentrates	%
	<i>Self-sufficiency in forages</i>	Ratio of livestock needs to local availability allocated to livestock for forages	%
	<i>Biological N fixation by legumes</i>	Natural flow of N to crops from the air	kgN/haUAA/year
	<i>Cropland mineral N fertilisation need</i>	N needs of the crops plus losses to water and air from fertilisation	kgN/ha/year
	<i>Active soil organic N stock in cropland</i>	Amount of soil organic N from which mineralised N is derived	kgN/ha

225

226

2.5 Compositional indicators

227 Three compositional indicators describe the livestock numbers: (i) *number of*
228 *monogastrics* (livestock units [LU]/haUAA), (ii) *number of ruminants* (LU/haUAA) and
229 (iii) *total livestock number* (LU/haUAA). The total livestock number is the sum of the
230 monogastrics and ruminants. Three indicators describe the agricultural areas: (iv) the
231 *percentage of permanent grassland area* in the UAA (%), (v) the *percentage of*
232 *temporary grassland area* in the UAA (%) and (vi) the *percentage of cereal and*
233 *oilseed areas* (i.e., field crops) in the UAA (%). These three indicators also indirectly

234 specify the percentage of other crop species in the UAA, i.e., vineyards, industrial
235 crops (beets and tubers) and fruit and vegetable crops. Three indicators describe
236 feed self-sufficiency (lack or surplus) by category: *self-sufficiency (%)* (vii) in *energy*
237 *concentrates*, (viii) *protein concentrates* and (ix) *forages*. Feed self-sufficiency for a
238 feed category is the ratio of livestock needs to the local availability of the feed
239 category allocated to livestock. This indicator allows for specifying the source of
240 dependency on feed imports, which may concern one feed category or all of them. It
241 also describes the integration between crops, grasslands and livestock, i.e., the
242 extent to which the composition of the livestock herd is fitted to the permanent
243 grassland and cropland of the FS. Finally, three indicators describe the N inflow, crop
244 N needs and soil N stock of the FS: (x) *legume biological N fixation*
245 (kgN/haUAA/year), (xi) *cropland mineral N fertilisation needs* (kgN/ha/year) and (xii)
246 *active soil organic N stock in the cropland* (kgN/ha). Biological N fixation by legumes
247 represents the natural flow of N to crops, the intensity of which depends on cropping
248 practices (in contrast to the deposition of N oxides from the air on the soil which
249 comes from industry and transport fossil fuel combustion). The cropland needs for
250 mineral N fertilisation correspond to the N needs of the crops plus the N losses from
251 fertilisation to water and air. Finally, the amount of active soil organic N in the
252 cropland corresponds to the amount of soil organic N from which mineralised N is
253 derived (calculated in the model). The higher this amount, the higher the natural N
254 fertility of the soil (modulated by the mineralisation rate, which depends on the
255 latitude).

256 2.6 Correlation matrix

257 We calculated a correlation matrix of the robustness and compositional indicators
258 using the Spearman correlation index ρ , which ranges from -1 (perfect negative
259 correlation) to $+1$ (perfect positive correlation). In this study, correlations higher than
260 0.7 in absolute value were considered strong. A correlation matrix of all the
261 compositional indicators calculated for this study is available in the appendix.
262 Although we considered other indicators in this study, we excluded them from the
263 matrix as they were highly correlated with at least one selected compositional
264 indicator.

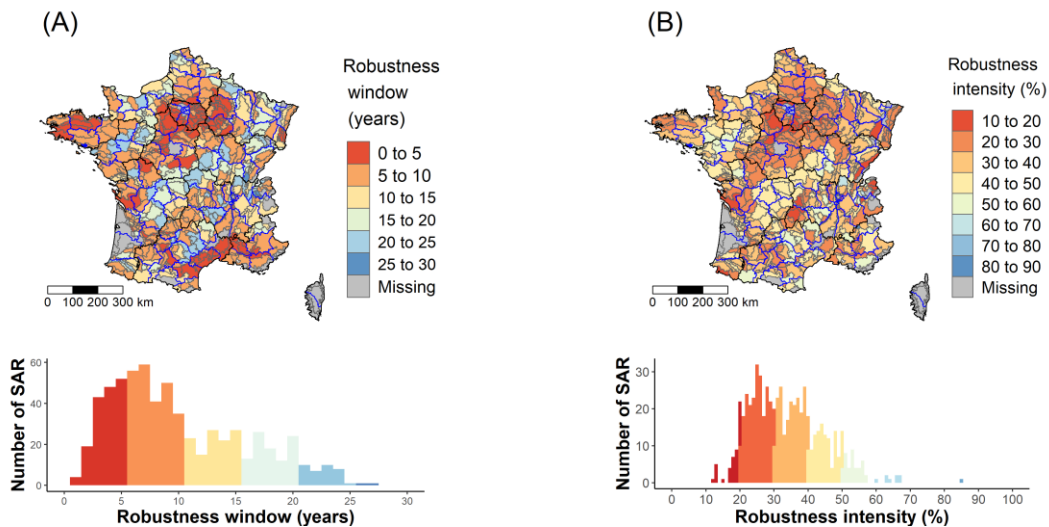
265 2.7 Input data

266 The data on cultivated and grazed land were retrieved from the *Registre Parcellaire*
267 *Graphique* for 2016 (IGN, 2016). The livestock number, diet, and productivity per
268 livestock product were gathered from the 2010 agricultural census (Therond et al.,
269 2017). The input data for all the French SARs and details on the metadata and R
270 code are available in a Zenodo repository (<https://doi.org/10.5281/zenodo.6350666>).
271 As some data were missing for some SARs (~50, including Corse), we interpolated
272 the missing values. For missing biophysical data, such as the soil carbon (C):N ratio
273 or organic matter mineralisation rate, we used values from neighbouring SARs with
274 similar environmental conditions. Values of individual N feed needs per species and
275 individual N productivity per product and species that were extreme compared with
276 the national average (i.e., extreme values were worth ~0 or several hundred
277 kgN/LU/year) were also replaced with the national average. As in Pinsard et al.
278 (2021), the active soil organic N stock was initialised with the spin-up method,
279 assuming constant organic amendments for 30 years. However, in contrast to
280 Pinsard et al. (2021), we assumed an initial active soil organic C stock in permanent
281 grassland soils of 20,000 kgC. We used the humification coefficients and C:N ratios
282 of organic amendments (effluents and residues) from Le Noë et al. (2017). We
283 assumed that the C:N ratio of permanent grassland soils is twice that of cropland
284 soils (i.e., ~20) (Leifeld et al., 2008). Finally, we assumed the biological N fixation per
285 plant to be constant over time and a function of the typical fresh matter plant yield.

286 **3 Results**

287 The spatial distributions of the robustness indicators and clusters were described
288 according to their geographical locations (north, west, south, east, and their
289 combinations), department and region (a division adopted in 2016) and climate
290 (typology based on Joly et al., 2010) (see especially Table 2).

291 **3.1 Robustness indicators**



292
293 *Figure 3 Maps of the robustness indicators (elaborated from the model output trajectories) with their frequency*
294 *distribution histograms at the small agricultural region (SAR) level in France. Simulations were run for a scenario*
295 *of linear decline in synthetic fertiliser and feed supply availability. (A) Robustness window (in years), i.e., the*
296 *period during which agricultural production does not fall below 95% of the initial total agricultural production. (B)*
297 *Robustness intensity (%), i.e., the percentage of the initial total agricultural production after 30 years.*

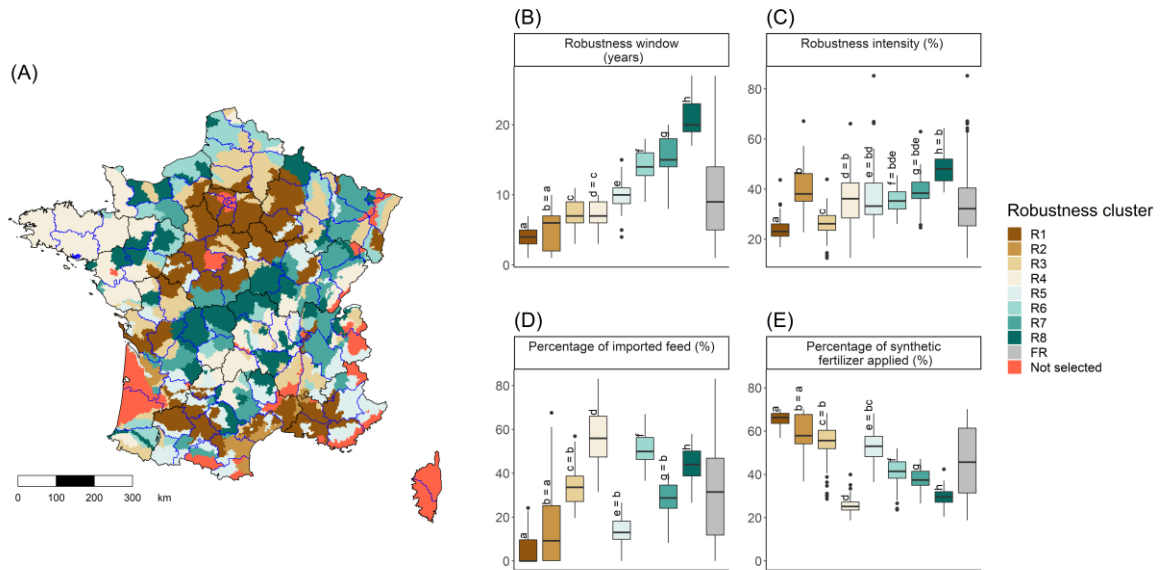
298 The levels of the robustness indicators varied across France (Figure 3). The median
299 robustness window of the selected SARs was 9 years, with values ranging from 1 to
300 27 years (Figure 3A). The median robustness intensity of the SARs was 32%, with
301 values ranging from 12% to 85% (Figure 3B).

302 SARs with similar robustness windows appear spatially aggregated (Figure 3A). The
303 114 SARs with a robustness window of less than 5 years were mostly located in the
304 centre-north (around the Paris region), south (Languedoc-Roussillon) and west
305 (Brittany) of France. The 38 SARs with a robustness window of more than 20 years
306 were mainly located in oceanic or semi-continental climates in the centre of France.
307 The spatial distribution of the robustness intensity appeared less aggregated than
308 that of the robustness windows (Figure 3B). The 9 SARs with the highest robustness

309 intensity (60%–85%) were located in the centre (Auvergne-Rhône-Alpes) and south
310 (Occitanie). The lowest robustness intensities (10%–20%) were mainly in Ile-de-
311 France, the centre-southeast and the centre (Auvergne-Rhône-Alpes in mountain
312 climates and Centre-Val de Loire in oceanic climates).

313 3.2 Relationship between robustness clusters and compositional indicators

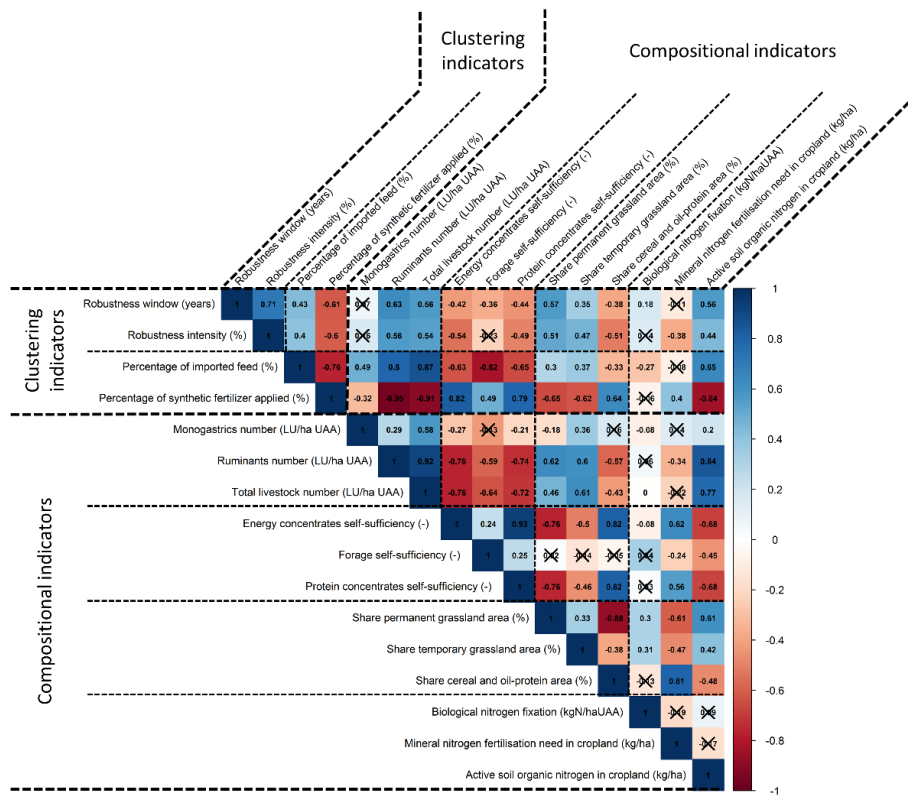
314



315

316 *Figure 4 Robustness typology for French small agricultural regions (SARs). (A) Spatial representation of the*
 317 *clusters. (B)–(E) Boxplots of the four clustering indicators: (B) Robustness window (years); (C) Robustness*
 318 *intensity (%); (D) Percentage of imported feed compared to the total feed needs (%); (E) Percentage of synthetic*
 319 *fertiliser applied compared to the total mineral nitrogen (N) input (%). The line in the boxplots represents the*
 320 *median value. Statistical difference (via t-test) is described with a letter code: the first letter identifies the cluster*
 321 *(a–h for clusters R1–R8); the letters after the equal sign refer to clusters with a median that is not statistically*
 322 *different.*

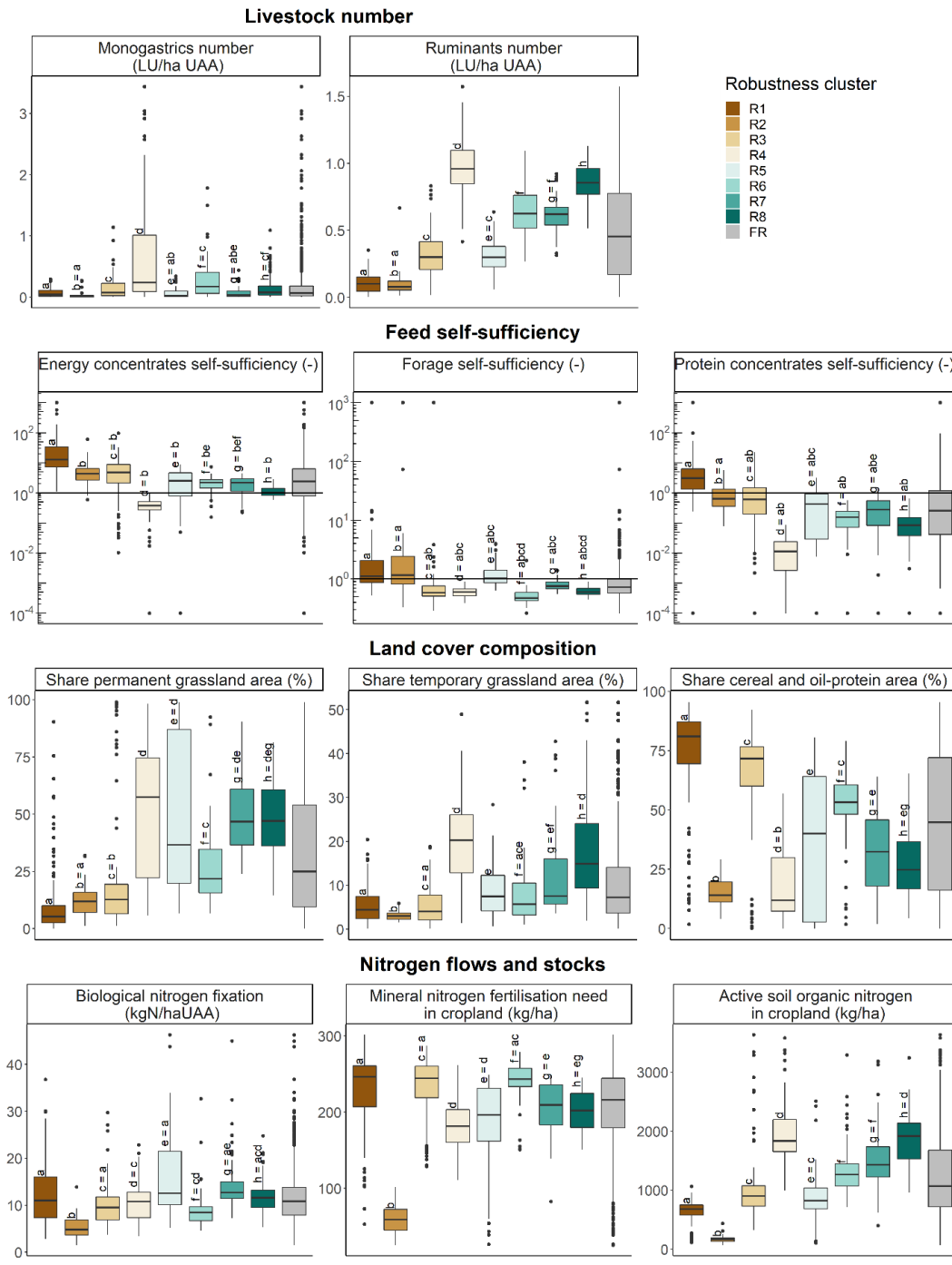
323 We found that the optimal number of clusters was 8, producing a rather aggregated
 324 spatial distribution (Figure 4A). The clusters were ordered (R1–R8) by the
 325 (significantly different) increasing medians of their robustness windows and then of
 326 their robustness intensity (Figure 4B and C). For benchmarking, the France-wide
 327 distribution (i.e., all the considered SARs) of each indicator was also visualised (grey
 328 in Figure 4). R2 included 20 SARs and R1 almost 150 SARs; the others had fewer
 329 than 100 SARs. The considered SARs had a median percentage of imported feed
 330 less than 32% of livestock needs, with values ranging from 12% to 83% (Figure 4D).
 331 The median percentage of synthetic fertiliser applied was 46%, and values ranged
 332 between 19% and 70% (Figure 4E).



333

334 *Figure 5 Correlation matrix of robustness and compositional indicators in France at the small agricultural region*
 335 *(SAR) level, obtained with the Spearman method of the stats package in R. Robustness indicators (robustness*
 336 *window and intensity) are defined in Figure 2. A cross means that the correlation is not significant (p-value >*
 337 *0.01).*

338 The correlation matrix revealed that biological N fixation and forage self-sufficiency
 339 were the indicators least correlated with other indicators (Figure 5). The strongest
 340 negative correlation ($\rho = -0.95$) was between the number of ruminants and the
 341 percentage of synthetic fertiliser applied. There were also strong negative
 342 correlations between the share of permanent grassland area and the share of cereal
 343 and oilseed areas ($\rho = -0.88$) and the synthetic fertiliser applied and the active soil
 344 organic N in cropland ($\rho = -0.84$). The strongest positive correlations were between
 345 the number of ruminants and the total livestock count and between self-sufficiency in
 346 energy concentrates and self-sufficiency in protein concentrates ($\rho > 0.9$ for both).
 347 The positive correlation between the percentage of imported feed and the total
 348 number of livestock was also strong ($\rho = 0.87$) (Figure 5). Furthermore, the
 349 percentage of synthetic fertiliser applied was moderately negatively correlated with
 350 the percentage of permanent grassland area ($\rho = -0.65$). The biological N fixation by
 351 leguminous plants appeared only weakly positively correlated with the robustness
 352 window ($\rho = 0.18$) (the correlation was not significant for the robustness intensity).



353

354 *Figure 6* Boxplots showing the distribution of 11 compositional indicators within each robustness cluster and for all
 355 of France (in grey): number of monogastrics (LU/haUAA); number of ruminants (LU/haUAA); self-sufficiency in
 356 energy concentrates (-); self-sufficiency in forages (-); self-sufficiency in protein concentrates (-); percentage of
 357 permanent grassland area in the UAA (%); percentage of temporary grassland area in the UAA (%); percentage
 358 of cereal and oilseed area in the UAA (%); biological N fixation from the air by legumes (kgN/haUAA/year);
 359 mineral N fertilisation needs of cropland (kgN/ha/year); active soil organic N of cropland (kgN/ha). The total
 360 livestock number is not plotted as it showed correlations similar to those between the number of ruminants and
 361 the other indicators. In the boxplots, the line corresponds to the median value. The letters above the boxplots
 362 describe the statistical t-tests between clusters and by indicator. The first letter identifies the cluster (a–h for
 363 clusters R1–R8); the letters after the equal sign refer to clusters with a median that is not statistically different.

364 Combinations of compositional indicator distributions are significantly different among
365 the eight robustness clusters (Figure 6). The median number of ruminants is higher
366 than that of monogastrics for all SARs considered (0.45 vs. 0.07 LU/haUAA,
367 respectively) (Figure 6). Furthermore, the median self-sufficiency in protein
368 concentrates did not exceed 30%. For all SARs considered, the median biological N
369 fixation was 11 kgN/haUAA/year and the median active soil organic N in cropland
370 was just over 1000 kgN/ha.

371 3.3 Cluster description

372 Each robustness cluster was composed of specific clustering and compositional
373 indicator values that allowed us to label them. Table 2 presents an overview of the
374 characteristics of the robustness clusters, including their geographical positions. The
375 median values (M) are reported in the following descriptions.

376 The R1 SARs presented the lowest values of the robustness indicators (Figure 4B
377 and C). R1's percentage of imported feed was close to 0 (Figure 4D), but it had the
378 highest percentage of applied synthetic fertiliser of all the clusters (Figure 4E). The
379 SARs in this cluster had among the lowest ruminant numbers, making them the only
380 SARs with self-sufficiency in all three feed categories (Figure 6). The percentages of
381 permanent and temporary grassland areas were among the lowest in France,
382 whereas the percentage of cereal and oilseed areas (80%) and the need for mineral
383 N fertilisation of cropland (M≈250 kgN/ha/year) were the highest in France. Finally,
384 the quantity of active soil organic N in cropland was one of the lowest (M≈690
385 kgN/ha). The SARs of R1 can be labelled *intensive field crop regions with few*
386 *livestock*.

387 The SARs of R2 also had some of the lowest robustness window values (M=6 years)
388 (Figure 4B) but some of the highest robustness intensity values as well (M≈40%)
389 (Figure 4C). The percentage of synthetic fertiliser applied was the highest (M≈60%),
390 and both the need for mineral N fertilisation of cropland and the amount of active soil
391 organic N in cropland were the lowest (M=60 kgN/ha and M≈170 kgN/ha,
392 respectively) (Figure 6). Finally, there was almost no import of feed and livestock in
393 these SARs, which can be labelled *wine-producing regions* (see Figure A.1 in the
394 appendix).

395 The robustness window values for the SARs in R3 were low but significantly higher
396 than those of R1 (Figure 4B). The percentage of synthetic fertilisers applied was
397 among the highest (M=56%), and the percentage of imported feed was 34% (Figure
398 4D and E). These SARs had quantities of ruminants or monogastrics lower than or
399 close to the national median values (M=0.3 and 0.07 LU/haUAA, respectively)
400 (Figure 6). The percentages of permanent and temporary grasslands were among
401 the lowest (M≈13% and 4%, respectively), and the percentage of cereal and oilseed
402 areas (M≈72%) and mineral N fertilisation needs for cropland (M≈245 kgN/ha/year)
403 were the highest. The amount of active soil organic N in cropland was among the
404 lowest (M≈900 kgN/ha). These SARs can be labelled *intensive field crop regions with*
405 *low-density intensive ruminant farming*.

406 The SARs in R4 had small robustness windows (M≈7 years) (Figure 4B) and average
407 robustness intensity (M=36%) (Figure 4C). The percentage of imported feed was the
408 highest (M≈56%) (Figure 4D) for one of the lowest percentages of synthetic fertiliser
409 applied (M=25%) (Figure 4E). They had a high number of monogastrics compared
410 with the other clusters (M≈0.24 LU/haUAA) (Figure 6). The number of ruminants was
411 also among the highest (M=0.96 LU/haUAA). The R4 SARs were the only ones that
412 lacked self-sufficiency in all three feed categories simultaneously. The percentage of
413 temporary grassland area was the highest (M≈21%), as was the amount of active soil
414 organic N in cropland (M≈1800 kgN/ha). The SARs of R4 can be labelled *intensive*
415 *monogastric and ruminant farming regions with crops for livestock*.

416 The values of the robustness indicators in R5 SARs were slightly higher than the
417 national median value (Figure 4B and C). The percentage of imported feed was
418 among the lowest (M≈13%) (Figure 4D). These SARs also had among the lowest
419 monogastric numbers (M≈0.02 LU/haUAA) and a median ruminant number of 0.3
420 LU/haUAA (Figure 6). They had the highest self-sufficiency in forages and energy
421 concentrates. The percentage of permanent grassland was one of the highest
422 (M≈37%) for one of the lowest needs of mineral N fertilisation of cropland (M≈197
423 kgN/ha/year). The SARs of R5 can thus be labelled *extensive or semi-extensive low-*
424 *density ruminant farming regions*.

425 The robustness intensity of the R6 SARs was slightly higher than the national median
426 value (M≈35%) (Figure 4C), and the robustness window was among the highest
427 (M=14 years) (Figure 4B). The percentage of imported feed was the second highest

428 (M≈50%) (Figure 4D). These SARs had more ruminants than the national median
429 and had one of the highest numbers of monogastrics (M≈0.17 LU/haUAA) (Figure 6).
430 R6 SARs had the lowest self-sufficiency in forages and protein concentrates. The
431 percentage of cereal and oilseed areas was among the highest (M≈53%). Finally, the
432 need for mineral N fertilisation of cropland was the highest (M≈243 kgN/ha/year), and
433 the percentage of synthetic fertiliser applied was close to the national median. The
434 SARs of R6 can be labelled *intensive monogastric and ruminant farming regions with*
435 *intensive crops for humans*.

436 The R7 SARs had among the longest robustness windows (M≈15 years) (Figure 4B).
437 They had the lowest percentage of cereal and oilseed areas and the lowest number
438 of monogastrics (Figure 6). The percentage of permanent grassland area was one of
439 the highest (M≈47%). The number of ruminants was slightly higher than the national
440 median value (M≈0.62 LU/haUAA). The median values of the other compositional
441 indicators were close to the national median. The SARs of R7 can be labelled
442 *extensive average-density ruminant farming regions*.

443 The SARs of R8 had the highest values of the two robustness indicators (M=20 years
444 and 48%) (Figure 4B and C) despite having among the highest percentages of
445 imported feed (Figure 4D). These SARs had the highest number of ruminants (M≈0.9
446 LU/haUAA) and the highest percentages of permanent and temporary grassland
447 areas (M=47% and 15%, respectively) (Figure 6). The need for mineral N fertilisation
448 of cropland, the percentage of synthetic fertiliser applied and the self-sufficiency in
449 protein concentrates and forages were lower than the national medians. The amount
450 of active soil organic N in cropland was the highest (M≈1900 kgN/ha). The R8 SARs
451 can be labelled *semi-extensive high-density ruminant farming regions*.

Table 2 Characteristics of the eight robustness clusters (columns). The letters indicate, for each indicator (robustness, clustering and compositional indicators) that the median of the distribution of the indicator for the considered cluster is significantly one of the lowest (L) or highest (H) values or is close to the national median value (M) (approx. \pm 25%). + and - indicate that the cluster median value is higher or lower than the national median value, respectively.

Robustness cluster	R1	R2	R3	R4	R5	R6	R7	R8
Label	Intensive field crop regions with few livestock	Wine-producing regions	Intensive field crop regions with low-density intensive ruminant farming	Intensive monogastric and ruminant farming regions with crops for livestock	Extensive or semi-extensive low-density ruminant farming regions	Intensive monogastric and ruminant farming regions with intensive crops for humans	Extensive average-density ruminant farming regions	Semi-extensive high-density ruminant farming regions
Number of SARs	146	20	95	97	72	68	76	78
Location and climate	Around the Paris region (Centre-Val de Loire and Ile-de-France), east-northeast (Grand-Est) and south-southwest (Occitanie), in the degraded oceanic climate of the lowlands	Centre-southwest (Bordeaux vineyards, altered oceanic climate) and south-southwest (Languedoc-Roussillon vineyards, clear Mediterranean climate)	Oceanic or mountain climates in the centre-southwest (Nouvelle-Aquitaine), north (Hauts-de-France) or centre-southeast (Auvergne-Rhône-Alpes)	Western regions (Bretagne and Pays de la Loire) and centre-southeast (Auvergne-Rhône-Alpes) regions with oceanic or mountain climates	Mainly the south and southeast (Occitanie and Provence-Alpes-Côte d'Azur) regions with predominantly oceanic or mountain climates	North (Hauts-de-France), northwest (Normandy) and southwest (Nouvelle-Aquitaine), mostly in regions with an oceanic climate	Centre-east (Bourgogne-Franche-Comté), centre-southwest (Nouvelle-Aquitaine), centre (Auvergne-Rhône-Alpes) and east-northeast (Grand-Est), in semi-continental, mountain or oceanic climates	East (Grand-Est), centre (Auvergne-Rhône-Alpes) and south-southwest (Occitanie), mostly in regions with oceanic or mountain climates
Clustering indicators								
Robustness window (Year)	L	L	M-	M-	M+	H	H	H
Robustness intensity (%)	L	M+	M-	M+	M+	M+	M+	H
Percentage of imported feed (%)	L	L	M+	H	L	H	M-	H
Percentage of synthetic fertiliser applied (%)	H	M+	M+	L	M+	M-	M-	L
Compositional indicators								
Number of monogastrics (LU/haUAA)	M-	L	M+	H	L	H	L	M+
Number of ruminants (LU/haUAA)	L	L	M-	H	M-	M+	M+	H
Self-sufficiency in energy concentrates (-)	H	H	H	L	M+	M-	M-	L
Self-sufficiency in forages (-)	H	H	M-	M-	H	L	M+	M-
Self-sufficiency in protein concentrates (-)	H	H	H	L	H	L	M+	L
Percentage of permanent grassland area (%)	L	L	L	H	H	M-	H	H
Percentage of temporary grassland area (%)	L	L	L	H	M+	M-	M+	H
Percentage of area under cereals and oilseeds (%)	H	L	H	L	M-	M+	L	L
Biological N fixation by legumes (kgN/haUAA/year)	M+	L	M-	M-	M+	M-	M+	M+
Active soil organic N from cropland (kgN/ha)	L	L	M-	H	M-	M+	H	H
Mineral N fertilisation needs of cropland (kgN/ha/year)	M+	L	M+	M-	M-	M+	M-	M-

456 4 Discussion

457 Our first objective was to define robustness indicators, calculate them from the
458 simulations of a dynamic N mass flow balance model, map them for the majority of
459 French SARs and identify SAR clusters according to their robustness properties. Our
460 second objective was to study the relationship between robustness clusters and
461 indicators of crop–grassland–livestock composition. The results show that without
462 compositional changes, the majority of SARs would experience a decrease in
463 agricultural production due to progressive input decline. The clusters obtained show
464 statistically significantly different values of compositional indicators, suggesting that
465 crop–grassland–livestock compositions are key determinants of the robustness of
466 FSs.

467 4.1 Crop–grassland–livestock compositions associated with robustness and 468 input imports

469 4.1.1 Crop-specialised SARs: A high dependency on synthetic fertilisers implies a 470 small robustness window

471 More than 75% of agricultural production is crop-sourced in the crop-specialised
472 SARs (R1, R2 and R3). These SARs are poor in livestock and, therefore, in manure
473 and active soil organic N, causing the highest levels of synthetic fertiliser dependency
474 and further resulting in small robustness windows.

475 *4.1.1.1 Intensive field crop SARs with few or low-density intensive ruminant farming*
476 Intensive field crop SARs with few livestock (R1 and R3) had among the lowest short-
477 and long-term robustness values. Low livestock density implies almost-reached feed
478 self-sufficiency and, consequently, the robustness of animal-sourced agricultural
479 production. However, animal-sourced agricultural production only accounts for 20%
480 of the total agricultural production at most (see Figure A.1 in the appendix), therefore
481 minimally contributing to the overall robustness. Moreover, their low livestock density
482 implies low effluent input to crops ($M=3$ and 9 kgN/ha/year for R1 and R3,
483 respectively; see Figure A.1 in the appendix), which contributes to low levels of active
484 soil organic N and, indirectly, soil organic N mineralisation. For these SARs, we
485 estimated active soil organic N stocks to be below the national median. This, along
486 with the highest crop needs for mineral N, further increased the dependency of these
487 clusters on synthetic fertilisers, causing agricultural production to be immediately

488 impacted when the availability of imported synthetic fertilisers dropped. These results
489 generalise those presented by Pinsard et al. (2021) for the Plateau Picard, an
490 intensive field crop SAR with some livestock production belonging to this study's R3
491 cluster.

492 *4.1.1.2 Wine-producing SARs*

493 The wine-producing SARs (R2) had among the lowest robustness windows due to
494 the higher percentages of synthetic fertilisers applied. Despite the relatively low need
495 for mineral N fertiliser on vineyards, the dependency on synthetic fertiliser remained
496 high because of the near absence of livestock. The amount of effluents applied on
497 croplands (including vineyards) was the lowest (M=1 kgN/ha/year), as was the active
498 soil organic N stock, indicating low levels of soil organic N mineralisation, which
499 supports soil sampling data in these SARs from a previous study (Martin, 2019).
500 However, these SARs presented a higher robustness intensity than those of R1, R3
501 and the national median. This result can be explained by the lower percentage of
502 concentrates in ruminant diets (see Figure A.1 in the appendix), improving the
503 robustness of animal-sourced agricultural production. This and the livestock number
504 are the main differences between R2 and the R1 and R3 clusters.

505 *4.1.2 Regions with livestock: The level of integration between crops, grasslands and* 506 *livestock determines the robustness*

507 The analysis was more complex for SARs with livestock (R4, R5, R6, R7 and R8)
508 than for crop-specialised SARs. For clusters R5–R8, the percentage of synthetic
509 fertiliser applied explained the levels of robustness: from R5 to R8, the robustness
510 levels increased significantly (or were not significantly different) as the percentage of
511 synthetic fertiliser applied decreased significantly. However, the percentage of
512 synthetic fertiliser depended not only on the livestock number but also on the land
513 cover composition.

514 In contrast, the robustness levels of R4, which were the lowest among the livestock
515 SARs, were not explained by the percentage of synthetic fertiliser applied as it was
516 also the lowest among these SARs. The percentage of imported feed was the
517 highest; however, only those of R6 and R8 were higher than the national median
518 value, whereas those of R5 and R7 were lower than the national median. This
519 difference should be investigated through the details of the integration between

520 crops, grasslands and livestock, including other indicators such as herd composition
521 and the levels of self-sufficiency by feed category.

522 *4.1.2.1 Percentage of synthetic fertiliser applied was not only explained by livestock* 523 *number*

524 Livestock effluents (strongly positively correlated to the livestock number) contribute
525 to cropland fertilisation with mineral N and (unlike synthetic fertiliser) fill the active soil
526 organic N stocks in cropland. Effluents on monogastric farms (mainly off-ground) and
527 some effluents from ruminants are available for crop fertilisation (Service de
528 l'observation et des statistiques, 2013). Thus, livestock effluents and the
529 mineralisation of soil organic N in cropland reduce the dependency on imported N
530 synthetic fertiliser (Le Noë et al., 2019; Li et al., 2021). This corroborates our findings:
531 the total livestock number was strongly negatively correlated with the percentage of
532 synthetic fertiliser applied and positively correlated with the active soil organic N in
533 cropland.

534 However, the N contents of the plants also determined the percentage of synthetic
535 fertiliser applied. For example, the R6 and R7 SARs had similar levels of mineral N
536 from livestock manure applied to croplands and active soil organic N in cropland, but
537 the plant mineral N needs were higher in R6 than in R7; therefore, the percentage of
538 synthetic fertiliser applied was higher in R6 than in R7. These differences can be
539 explained by the land cover composition and crop rotation: the percentage of cereal
540 and oilseed areas was higher in R6 than in R7 and the percentage of permanent
541 grassland area was lower in R6 than in R7, whereas the percentage of temporary
542 grassland area was similar in both clusters. Yet, permanent grasslands require less
543 mineral N than cereal and oilseed crops (Service de l'observation et des statistiques,
544 2013).

545 *4.1.2.2 Intensive monogastric and ruminant farming regions with crops for livestock*

546 The SARs specialised in intensive monogastric and ruminant farming with crops for
547 feed (R4) presented the lowest robustness levels among the livestock regions as the
548 high livestock numbers led to a high percentage of imported feed, resulting in low
549 short-term robustness of animal-sourced agricultural production. As the crop-sourced
550 food share was low, the total agricultural production was quickly impacted. In
551 contrast, the SARs of R8 had a similar composition but were the most robust. This
552 difference (and the low robustness of the R4 cluster) can be explained by the herd

553 composition, which was mainly monogastric in R4, unlike in R8. The model considers
554 monogastric animals to only consume concentrates, and self-sufficiency in energy
555 and protein concentrates was much lower in R4 than in the other livestock regions.
556 Thus, the decrease in livestock numbers (and animal-sourced agricultural production)
557 came earlier.

558 Moreover, these SARs had a robustness intensity not significantly different from
559 those in R5, R6 and R7, although the concentrates self-sufficiency was much lower
560 in R4. This can also be explained by herd composition. In these SARs, feed–food
561 competition for biomass use is high ($M=75\%$, see Figure A.1 in the appendix), i.e.,
562 the area of cereal and oilseed crops allocated for livestock consumption is
563 considerable. Consequently, the decrease in monogastrics increased the quantity of
564 crops (cereals and oilseeds) allocated for human consumption (Pinsard et al., 2021).
565 The results obtained for R4 generalised those obtained by Pinsard et al. (2021) for
566 Bretagne Centrale, a SAR of intensive monogastric farms belonging to this cluster.

567 4.2 Biological N fixation and robustness levels

568 We showed that biological N fixation by legumes was not correlated or only weakly
569 positively correlated with the robustness indicators. Biological N fixation currently
570 represents no more than 15% of fertilised mineral N flows at the French scale (~12–
571 17 kgN/haUAA/year, according to estimates in the literature) (Harchaoui and
572 Chatzimpiros, 2019; Le Noë et al., 2017; Solagro, 2017), which is why correlations
573 with the robustness indicators were weak. In this study, the SARs had a median
574 biological N fixation of 11 kgN/haUAA/year. During the 19th century, biological N
575 fixation oscillated between 10 and 20 kgN/haUAA/year but, together with
576 atmospheric deposition, accounted for 60% of mineral N inputs early in the century
577 (Harchaoui and Chatzimpiros, 2019). If such a high percentage of mineral N from
578 biological N fixation existed in French FSs today, we argue that the positive
579 correlation between biological N fixation and the two robustness indicators would be
580 much stronger.

581 4.3 Specialisation of French FSs in the second half of the 20th century

582 The typology of the robustness of French SARs can be seen as the result of a
583 historical process of FS evolution (in practices and composition) in the context of the
584 second modern agricultural revolution, which took place in the second half of the 20th

585 century. The current specialisation of FSs in France, particularly for those with the
586 shortest robustness window (except wine-producing regions), took place during the
587 industrialisation of agriculture to increase food productivity and was based on the
588 attributes of each territory (Mazoyer and Roudart, 2002). The increase in productivity
589 initially intended to cope with food shortages after the Second World War. In the first
590 half of the 20th century, French FSs were mostly mixed (Mazoyer and Roudart,
591 2002). The emergence of regions specialising in intensive field crops (R1 and R3)
592 took place during a process called 'cerealisation' that began in the 1970s with a
593 decrease in the forage area and then decreased the ruminant numbers from the
594 2000s onward (Perrot et al., 2015). This process aimed to assign crops to the best
595 lands and use ruminant farming to valorise surfaces with low agronomic potential
596 (Domingues et al., 2019). The emergence of intensive livestock farming SARs (R4)
597 took place from the 1960s and began with the dairy intensification of the dominant
598 mixed crop farms with maize silage and temporary grasslands (Domingues et al.,
599 2018). Consequently, the R4 SARs have one of the highest percentages of
600 temporary grassland areas in the UAA. Off-farm poultry and pig farms were
601 developed to increase farmers' income and modernise farming practices. This
602 development has largely benefited from the joint presence of slaughtering and feed
603 manufacturing industries but also the large, nearby seaports, which are a
604 considerable asset for the agri-food industry. The density of monogastric livestock
605 has thus grown sixfold between 1938 and 2010 in the western regions of France
606 (Domingues et al., 2018).

607 4.4 Protein self-sufficiency under threat in 2050

608 We estimated that without any compositional changes, agricultural production for the
609 652 considered SARs will be 12.6 kgN/haUAA/year in 30 years, in which time the
610 French population should reach 74 million (Blanpain and Buisson, 2016) and the N
611 need (80 g protein/capita/day) of the population should be 12.2 kgN/haUAA/year
612 (constant UAA). Thus, assuming constant agricultural and food waste (~30%) and
613 exports, the protein needs of France will not be met in 2050 in the case of a
614 progressive decline in input supply without changes in the compositions and
615 practices of French FSs. This conclusion is in line with that of Barbieri et al. (2021) on
616 a global scale and confirms the need for compositional changes to increase protein

617 self-sufficiency in France in the context of input supply constraints, i.e., to improve
618 the robustness of French FSs.

619 4.5 Strategies for improving robustness: Despecialising agricultural regions?

620 We argue that French SARs could increase their robustness in the short and long
621 term by facilitating an agroecological transition through adaptive or transformative
622 actions (Caquet et al., 2020) aimed at increasing their food self-sufficiency. These
623 actions should include increasing legume-cultivated areas (Billen et al., 2021; Poux
624 and Aubert, 2018; Solagro, 2017), adapting livestock numbers to local crops and
625 grasslands and reducing feed–food competition for biomass use by reducing
626 ruminants' consumption of concentrates. The increase of legume area should be
627 agronomically relevant, avoiding increasing disease and pest pressure (Ratnadass et
628 al., 2012; Siddique et al., 2012). In short, these actions would contribute to crop–
629 grassland–livestock integration and allocating crops to humans first (Van Zanten et
630 al., 2019). We also argue that the longer the robustness window, the greater the
631 opportunity to implement adaptations or transformations, and the higher the
632 robustness intensity, the fewer adaptations or transformations will be necessary
633 because the structure of the system allows for some time to cope with the input
634 decline.

635 It was possible to identify actions to be carried out within each cluster to improve their
636 robustness. The SARs of R1–R4 would benefit from 'despecialisation'. For SARs
637 specialised in intensive livestock farming (R4), reducing the livestock number would
638 reduce feed import needs and feed–food competition for biomass use. For example,
639 the number of monogastric livestock could be reduced to adapt to the local
640 production of co-products. Conversely, for intensive field crop SARs with few or low-
641 density intensive ruminant farming (R1 and R3), an increase in the livestock number
642 would enhance the use of locally-produced feed that does not compete with food
643 (i.e., co-products or fodder) (Poux and Aubert, 2018) and simultaneously increase
644 the amount of livestock effluents used for cropland. Furthermore, a decrease in the
645 need for mineral N fertilisation would reduce the need for synthetic fertilisers. For the
646 wine-producing SARs (R2), systematic inter-row plant cover would help increase the
647 stock of active soil organic N and reduce synthetic fertiliser needs (Payen et al.,
648 2021). Finally, for SARs with permanent grasslands and livestock (R5–R8), a joint
649 decrease in the crop yield, i.e., in the need for mineral N fertilisation, and livestock

650 number is necessary to reduce input imports. This should be done alongside the
651 integration of crops with the needs of the livestock. More specifically, a decrease in
652 the need for protein concentrates in the ruminant diet (Poux and Aubert, 2018;
653 Solagro, 2017) would reduce the need for imported concentrates. However, there
654 may be trade-offs: for example, a decrease in concentrate consumption by ruminants
655 would decrease milk yield (Solagro, 2017). For R6, an increased percentage of
656 permanent and temporary grassland areas would contribute to the integration of
657 crops, grasslands and livestock.

658 Other adaptive actions that could increase food self-sufficiency include increasing the
659 N use efficiency of crops and livestock (Morais et al., 2021) and improving the
660 recycling of human and livestock excreta (Barbieri et al., 2021; Billen et al., 2021;
661 Morais et al., 2021). Finally, failure to implement the above adaptive actions in time
662 to maintain agricultural production in the face of input constraints could lead to an
663 increase in agricultural area at the expense of forested areas, as occurred in the 18th
664 century (Ramankutty and Foley, 1999). This would harm biodiversity (Barlow et al.,
665 2016), soil carbon stocks (Guo and Gifford, 2002) and local water cycles (Sterling et
666 al., 2013).

667 4.6 Study limitations

668 4.6.1 Feed import perturbations considered independent of their geographical origin

669 We considered the decline of feed import availability to be linear over time,
670 irrespective of geographical origin and transport mode. In the context of peak oil and
671 increasing transport costs for agricultural commodities, imports of protein
672 concentrates from Latin America would likely slow more rapidly than would imports
673 from neighbouring French regions due to the higher price and distance. Thus,
674 robustness levels may have been underestimated for regions with feed imports from
675 neighbouring regions in France.

676 4.6.2 A nutritional and mono-nutrient approach

677 We assessed biomass fluxes in terms of N, but this may cause some distortions. For
678 example, the relationship between livestock numbers and feed availability would
679 imply different levels of feed self-sufficiency, if accounted in mass of dry matter. This
680 difference can be seen by comparing France's spatial distribution of feed self-
681 sufficiency at the SAR level computed in dry-matter mass (Jouven et al. 2018) with

682 that computed in mass of N (see supplementary material). Furthermore, N is not the
683 only limiting factor for plant growth. Phosphorus, another limiting factor (Plaxton and
684 Lambers, 2015) derived solely from rock mining in few and limited geographical
685 areas around the globe (Cordell and White, 2011), would also face supply disruptions
686 in the context of peak oil. Decreased availability of phosphate mineral fertiliser
687 imports could further decrease the availability of soil mineral N (Ågren et al., 2012;
688 Ringeval et al., 2019).

689 4.6.3 Robustness levels to be qualified in the face of climate change

690 Extensive or semi-extensive ruminant FSs (characterised by grazing primarily of
691 permanent grasslands, mainly in R4, R5, R7 and R8) may be less robust to the
692 consequences of climate change than intensive ruminant FSs (mainly in R3 and R6).
693 Increasing drought frequency results in a greater decline in forage self-sufficiency for
694 extensive or semi-extensive than intensive livestock systems based on crop systems
695 (Dardonville et al., 2020). In other words, what is most robust to input availability
696 decline might not be to climate change.

697 4.7 Quality of estimates

698 For some regions (Bretagne, Picardie and Eure-et-Loire), we compared our
699 estimations (feed imports, synthetic fertiliser applied to cropland, livestock effluents
700 applied to cropland and active soil organic N in cropland) with those of Le Noë et al.
701 (2018) and Le Noë et al. (2019). The estimates were comparable, although some of
702 our estimates were lower (active soil organic N in cropland) and others were higher
703 (feed imports). For the total amount of synthetic fertiliser applied, we estimated
704 almost 2.6 million tons N, i.e., 15% more than the amount delivered during the 2017–
705 2018 campaign in France (Ministère de la transition écologique et solidaire, 2019).
706 This overestimation is partly linked to the assumption that all permanent grassland
707 areas are fertilised with synthetic fertilisers, as only 50% are in reality (Service de
708 l'observation et des statistiques, 2013).

709 5 Conclusion

710 This study confirmed that declining availability of imported feed and synthetic
711 fertilisers would have a significant negative impact on the agricultural production of
712 French FSs if their current compositions and practices are maintained. Our analysis
713 also shows the heterogeneity of the robustness of French FSs. Specialised FSs –
714 vineyards, field crops and livestock – were the least robust in the short term. Mixed
715 FSs were the most robust in the short term, and their crop–livestock integration
716 determined their levels of robustness.

717 Implementing changes in composition and practices towards ‘despecialization’ and
718 agroecological transition would increase robustness in the context of global peak oil
719 and enhance protein self-sufficiency. For some SARs, a decrease in the use of
720 synthetic fertilisers would lead to decreases in plant productivity and therefore in total
721 agricultural production; for others, a decrease in feed–food competition for biomass
722 use would increase total agricultural production, even without inputs. Such changes
723 in composition and practices would also contribute to climate change adaptation and
724 mitigation. Future modelling could help to address possible trade-offs between
725 climate change mitigation and food security objectives over time.

726 6 Acknowledgements

727 CP and FA were supported by the French state aid managed by the National
728 Research Agency (ANR) under the Investissements d'avenir Programme and
729 reference number ANR-16-CONV-0003. The funding source had no influence on the
730 content or submission of the article.

731 7 References

- 732 Accatino, F., Sabatier, R., Michele, C.D., Ward, D., Wiegand, K., Meyer, K.M., 2014.
733 Robustness and management adaptability in tropical rangelands: a viability-
734 based assessment under the non-equilibrium paradigm. *animal* 8, 1272–1281.
735 <https://doi.org/10.1017/S1751731114000913>
- 736 Accatino, F., Tonda, A., Dross, C., Léger, F., Tichit, M., 2019. Trade-offs and
737 synergies between livestock production and other ecosystem services.
738 *Agricultural Systems* 168, 58–72. <https://doi.org/10.1016/j.agsy.2018.08.002>
- 739 Ågren, G.I., Wetterstedt, J.Å.M., Billberger, M.F.K., 2012. Nutrient limitation on
740 terrestrial plant growth – modeling the interaction between nitrogen and
741 phosphorus. *New Phytologist* 194, 953–960. <https://doi.org/10.1111/j.1469-8137.2012.04116.x>
- 743 Barbier, C., Couturier, C., Pourouchottamin, P., Cayla, J.-M., Sylvestre, M.,
744 Pharabod, I., 2019. Energy and carbon footprint of food in France from
745 production to consumption. IDDR - Club Ingénierie Prospective Energie et
746 Environnement, Paris.
- 747 Barbieri, P., Pellerin, S., Seufert, V., Smith, L., Ramankutty, N., Nesme, T., 2021.
748 Global option space for organic agriculture is delimited by nitrogen availability.
749 *Nat Food* 2, 363–372. <https://doi.org/10.1038/s43016-021-00276-y>
- 750 Barlow, J., Lennox, G.D., Ferreira, J., Berenguer, E., Lees, A.C., Nally, R.M.,
751 Thomson, J.R., Ferraz, S.F. de B., Louzada, J., Oliveira, V.H.F., Parry, L.,
752 Ribeiro de Castro Solar, R., Vieira, I.C.G., Aragão, L.E.O.C., Begotti, R.A.,
753 Braga, R.F., Cardoso, T.M., de Oliveira, R.C., Souza Jr, C.M., Moura, N.G.,
754 Nunes, S.S., Siqueira, J.V., Pardini, R., Silveira, J.M., Vaz-de-Mello, F.Z.,
755 Veiga, R.C.S., Venturieri, A., Gardner, T.A., 2016. Anthropogenic disturbance
756 in tropical forests can double biodiversity loss from deforestation. *Nature* 535,
757 144–147. <https://doi.org/10.1038/nature18326>
- 758 Béné, C., Prager, S.D., Achicanoy, H.A.E., Toro, P.A., Lamotte, L., Bonilla, C.,
759 Mapes, B.R., 2019. Global map and indicators of food system sustainability.
760 *Sci Data* 6, 279. <https://doi.org/10.1038/s41597-019-0301-5>
- 761 Billen, G., Aguilera, E., Einarsson, R., Garnier, J., Gingrich, S., Grizzetti, B.,
762 Lassaletta, L., Noë, J.L., Sanz-Cobena, A., 2021. Reshaping the European
763 agro-food system and closing its nitrogen cycle: The potential of combining
764 dietary change, agroecology, and circularity. *One Earth* 4, 839–850.
765 <https://doi.org/10.1016/j.oneear.2021.05.008>
- 766 Blanpain, N., Buisson, G., 2016. Projections de population à l'horizon 2070 (No.
767 1619), INSEE Première. INSEE, Paris.
- 768 Caquet, T., Gascuel, C., Tixier-Boichard, M., 2020. Agroécologie : des recherches
769 pour la transition des filières et des territoires. éditions Quae.
770 <https://doi.org/10.35690/978-2-7592-3130-0>
- 771 Charrad, M., Ghazzali, N., Boiteau, V., Niknafs, A., 2014. NbClust : An R Package for
772 Determining the Relevant Number of Clusters in a Data Set. *Journal of*
773 *Statistical Software* 61. <https://doi.org/10.18637/jss.v061.i06>
- 774 Cordell, D., White, S., 2011. Peak Phosphorus: Clarifying the Key Issues of a
775 Vigorous Debate about Long-Term Phosphorus Security. *Sustainability* 3,
776 2027–2049. <https://doi.org/10.3390/su3102027>
- 777 Dardonville, M., Urruty, N., Bockstaller, C., Therond, O., 2020. Influence of diversity
778 and intensification level on vulnerability, resilience and robustness of

779 agricultural systems. *Agricultural Systems* 184, 102913.
780 <https://doi.org/10.1016/j.agsy.2020.102913>
781 Das, U., Ghosh, S., Mondal, B., 2020. Resilience of agriculture in a climatically
782 vulnerable state of India. *Theor Appl Climatol* 139, 1513–1529.
783 <https://doi.org/10.1007/s00704-019-03061-x>
784 Domingues, J.P., Bonaudo, T., Gabrielle, B., Perrot, C., Trégaro, Y., Tichitt, M.,
785 2019. Les effets du processus d'intensification de l'élevage dans les
786 territoires. *INRAE Productions Animales* 32, 159–170.
787 <https://doi.org/10.20870/productions-animales.2019.32.2.2506>
788 EEA, 2017. EU animal feed imports and land dependency.
789 European Commission, 2019. Fertilisers in the EU Prices, trade and use (EU
790 Agricultural Markets Briefs No. 15), Agriculture and Rural Development.
791 European Commission.
792 European Commission, 2010. The EU Nitrates Directive.
793 FAO, F. and A.O. of the U.N., 2021. FAOSTAT [WWW Document]. FAOSTAT
794 Database. URL <http://www.fao.org/faostat/en/#data> (accessed 3.26.21).
795 Fraser, E.D.G., Legwegoh, A., KC, K., 2015. Food stocks and grain reserves:
796 evaluating whether storing food creates resilient food systems. *J Environ Stud*
797 *Sci* 5, 445–458. <https://doi.org/10.1007/s13412-015-0276-2>
798 Giller, K.E., 2013. Can We Define the Term 'Farming Systems'? A Question of Scale:
799 Outlook on Agriculture. <https://doi.org/10.5367/oa.2013.0139>
800 Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta
801 analysis. *Global Change Biology* 8, 345–360. <https://doi.org/10.1046/j.1354-1013.2002.00486.x>
802 Hannaford, M.J., 2018. Long-term drivers of vulnerability and resilience to drought in
803 the Zambezi-Save area of southern Africa, 1505–1830. *Global and Planetary*
804 *Change* 166, 94–106. <https://doi.org/10.1016/j.gloplacha.2018.05.001>
805 Harchaoui, S., Chatzimpiros, P., 2019. Energy, Nitrogen, and Farm Surplus
806 Transitions in Agriculture from Historical Data Modeling. France, 1882–2013.
807 *Journal of Industrial Ecology* 23, 412–425. <https://doi.org/10.1111/jiec.12760>
808 IEA, 2018. World Energy Outlook 2018 661.
809 IGN, 2016. Registre parcellaire graphique (RPG) : contours des parcelles et îlots
810 cultureux et leur groupe de cultures majoritaire - data.gouv.fr [WWW
811 Document]. URL [https://www.data.gouv.fr/fr/datasets/registre-parcellaire-
812 graphique-rpg-contours-des-parcelles-et-ilots-cultureux-et-leur-groupe-de-
813 cultures-majoritaire/](https://www.data.gouv.fr/fr/datasets/registre-parcellaire-graphique-rpg-contours-des-parcelles-et-ilots-cultureux-et-leur-groupe-de-cultures-majoritaire/) (accessed 7.17.20).
814 Irz, X., Niemi, J., Liu, X., 2013. Determinants of food price inflation in Finland—The
815 role of energy. *Energy Policy* 63, 656–663.
816 <https://doi.org/10.1016/j.enpol.2013.09.023>
817 Joly, D., Brossard, T., Cardot, H., Cavailles, J., Hilal, M., Wavresky, P., 2010. Les
818 types de climats en France, une construction spatiale. *Cybergeo : European*
819 *Journal of Geography*. <https://doi.org/10.4000/cybergeo.23155>
820 Jouven, M., Puillet, L., Perrot, C., Pomeon, T., Dominguez, J.-P., Bonaudo, T., Tichitt,
821 M., 2018. Quels équilibres végétal/animal en France métropolitaine, aux
822 échelles nationale et « petite région agricole » ? *INRA Productions Animales*
823 31, 353–364. <https://doi.org/10.20870/productions-animales.2018.31.4.2374>
824 Kahiluoto, H., Kaseva, J., Balek, J., Olesen, J.E., Ruiz-Ramos, M., Gobin, A.,
825 Kersebaum, K.C., Takáč, J., Ruget, F., Ferrise, R., Bezak, P., Capellades, G.,
826 Dibari, C., Mäkinen, H., Nendel, C., Ventrella, D., Rodríguez, A., Bindi, M.,
827

828 Trnka, M., 2019. Decline in climate resilience of European wheat. *PNAS* 116,
829 123–128. <https://doi.org/10.1073/pnas.1804387115>

830 Koch, B.M., Pavan, E., Long, N.M., Andrae, J.G., Duckett, S.K., 01:00. Postweaning
831 Exposure to High Concentrates versus Forages Alters Marbling Deposition
832 and Lipid Metabolism in Steers. *Meat and Muscle Biology* 3.
833 <https://doi.org/10.22175/mmb2018.12.0040>

834 Le Noë, J., Billen, G., Esculier, F., Garnier, J., 2018. Long-term socioecological
835 trajectories of agro-food systems revealed by N and P flows in French regions
836 from 1852 to 2014. *Agriculture, Ecosystems & Environment* 265, 132–143.
837 <https://doi.org/10.1016/j.agee.2018.06.006>

838 Le Noë, J., Billen, G., Garnier, J., 2017. How the structure of agro-food systems
839 shapes nitrogen, phosphorus, and carbon fluxes: The generalized
840 representation of agro-food system applied at the regional scale in France.
841 *Science of The Total Environment* 586, 42–55.
842 <https://doi.org/10.1016/j.scitotenv.2017.02.040>

843 Le Noë, J., Billen, G., Mary, B., Garnier, J., 2019. Drivers of long-term carbon
844 dynamics in cropland: A bio-political history (France, 1852–2014).
845 *Environmental Science & Policy* 93, 53–65.
846 <https://doi.org/10.1016/j.envsci.2018.12.027>

847 Leifeld, J., Zimmermann, M., Fuhrer, J., 2008. Simulating decomposition of labile soil
848 organic carbon: Effects of pH. *Soil Biology and Biochemistry* 40, 2948–2951.
849 <https://doi.org/10.1016/j.soilbio.2008.08.019>

850 Li, Y., Sun, Z., Accatino, F., 2021. Satisfying meat demand while avoiding excess
851 manure: Studying the trade-off in eastern regions of China with a nitrogen
852 approach. *Science of The Total Environment* 151568.
853 <https://doi.org/10.1016/j.scitotenv.2021.151568>

854 Marchand, P., Carr, J.A., Dell’Angelo, J., Fader, M., Gephart, J.A., Kummu, M.,
855 Magliocca, N.R., Porkka, M., Puma, M.J., Ratajczak, Z., Rulli, M.C., Seekell,
856 D.A., Suweis, S., Tavoni, A., D’Odorico, P., 2016. Reserves and trade jointly
857 determine exposure to food supply shocks. *Environ. Res. Lett.* 11, 095009.
858 <https://doi.org/10.1088/1748-9326/11/9/095009>

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

861 Mazoyer, M., Roudart, L., 2002. Histoire des agricultures du monde: du néolithique à
862 la crise contemporaine, Nouv. éd. ed, Points. Éd. du Seuil, Paris.

863 Meuwissen, M.P.M., Feindt, P.H., Spiegel, A., Termeer, C.J.A.M., Mathijs, E., Mey,
864 Y. de, Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M.,
865 Zawalińska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W.,
866 Slijper, T., Coopmans, I., Vroege, W., Ciechomska, A., Accatino, F.,
867 Kopainsky, B., Poortvliet, P.M., Candel, J.J.L., Maye, D., Severini, S., Senni,
868 S., Soriano, B., Lagerkvist, C.-J., Peneva, M., Gavrilescu, C., Reidsma, P.,
869 2019. A framework to assess the resilience of farming systems. *Agricultural
870 Systems* 176, 102656. <https://doi.org/10.1016/j.agsy.2019.102656>

871 Ministère de la transition écologique et solidaire, C. général au développement
872 durable, 2019. Les livraisons d’engrais en France [WWW Document].
873 L’environnement en France - Rapport sur l’état de l’environnement. URL
874 <https://ree.developpement-durable.gouv.fr/themes/pressions-exercees-par-les-modes-de-production-et-de-consommation/usages-de-matieres-potentiellement-polluantes/fertilisants/article/les-livraisons-d-engrais-en-france>
875
876 (accessed 10.4.21).
877

878 Ministère de l'Agriculture et de l'Alimentation, 2010. Orientation technico économique
879 des exploitations (Otex) [WWW Document]. Agreste, la statistique agricole.
880 URL [https://agreste.agriculture.gouv.fr/agreste-web/methodon/N-](https://agreste.agriculture.gouv.fr/agreste-web/methodon/N-Otex/methodon/)
881 [Otex/methodon/](https://agreste.agriculture.gouv.fr/agreste-web/methodon/N-Otex/methodon/) (accessed 8.27.21).

882 Morais, T.G., Teixeira, R.F.M., Lauk, C., Theurl, M.C., Winiwarter, W., Mayer, A.,
883 Kaufmann, L., Haberl, H., Domingos, T., Erb, K.-H., 2021. Agroecological
884 measures and circular economy strategies to ensure sufficient nitrogen for
885 sustainable farming. *Global Environmental Change* 69, 102313.
886 <https://doi.org/10.1016/j.gloenvcha.2021.102313>

887 Morales Gómez, J.F., Antonelo, D.S., Beline, M., Pavan, B., Bambil, D.B., Fantinato-
888 Neto, P., Saran-Netto, A., Leme, P.R., Goulart, R.S., Gerrard, D.E., Silva, S.L.,
889 2021. Feeding strategies impact animal growth and beef color and
890 tenderness. *Meat Science* 108599.
891 <https://doi.org/10.1016/j.meatsci.2021.108599>

892 Mumby, P.J., Chollett, I., Bozec, Y.-M., Wolff, N.H., 2014. Ecological resilience,
893 robustness and vulnerability: how do these concepts benefit ecosystem
894 management? *Current Opinion in Environmental Sustainability, Environmental*
895 *change issues* 7, 22–27. <https://doi.org/10.1016/j.cosust.2013.11.021>

896 Naylor, R.L., Falcon, W.P., 2010. Food Security in an Era of Economic Volatility.
897 *Population and Development Review* 36, 693–723.
898 <https://doi.org/10.1111/j.1728-4457.2010.00354.x>

899 Payen, F.T., Sykes, A., Aitkenhead, M., Alexander, P., Moran, D., MacLeod, M.,
900 2021. Soil organic carbon sequestration rates in vineyard agroecosystems
901 under different soil management practices: A meta-analysis. *Journal of*
902 *Cleaner Production* 290, 125736. <https://doi.org/10.1016/j.jclepro.2020.125736>

903 Perrot, C., Gallot, S., Roguet, C., 2015. Evolution de l'élevage français métropolitain
904 au travers des recensements agricoles. Les exploitations se spécialisent
905 moins que les territoires. Presented at the Structures d'exploitation et exercice
906 de l'activité agricole : Continuités, changements ou ruptures?, Rennes,
907 France.

908 Pinsard, C., Martin, S., Léger, F., Accatino, F., 2021. Robustness to import declines
909 of three types of European farming systems assessed with a dynamic nitrogen
910 flow model. *Agricultural Systems* 193, 103215.
911 <https://doi.org/10.1016/j.agsy.2021.103215>

912 Plaxton, W., Lambers, H., 2015. Annual Plant Reviews, Phosphorus Metabolism in
913 Plants. John Wiley & Sons.

914 Poux, X., Aubert, P.-M., 2018. Une Europe agroécologique en 2050 : une agriculture
915 multifonctionnelle pour une alimentation saine. IDDRI.

916 R Core Team, 2020. R: A language and environment for statistical computing.

917 Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover:
918 Croplands from 1700 to 1992. *Global Biogeochemical Cycles* 13, 997–1027.
919 <https://doi.org/10.1029/1999GB900046>

920 Ratnadass, A., Fernandes, P., Avelino, J., Habib, R., 2012. Plant species diversity for
921 sustainable management of crop pests and diseases in agroecosystems: a
922 review. *Agron. Sustain. Dev.* 32, 273–303. [https://doi.org/10.1007/s13593-](https://doi.org/10.1007/s13593-011-0022-4)
923 [011-0022-4](https://doi.org/10.1007/s13593-011-0022-4)

924 Ringeval, B., Kvakić, M., Augusto, L., Ciais, P., Goll, D., Mueller, N.D., Müller, C.,
925 Nesme, T., Vuichard, N., Wang, X., Pellerin, S., 2019. Insights on nitrogen and
926 phosphorus co-limitation in global croplands from theoretical and modelling

927 fertilization experiments. *Biogeosciences Discussions* 1–35.
928 <https://doi.org/10.5194/bg-2019-298>
929 SDES, 2021. Chiffres clés de l'énergie - Edition 2021, Statistique publique. Ministère
930 de la transition écologique.
931 Seekell, D., Carr, J., Dell'Angelo, J., D'Odorico, P., Fader, M., Gephart, J., Kummu,
932 M., Magliocca, N., Porkka, M., Puma, M., Ratajczak, Z., Rulli, M.C., Suweis,
933 S., Tavoni, A., 2017. Resilience in the global food system. *Environ. Res. Lett.*
934 12, 025010. <https://doi.org/10.1088/1748-9326/aa5730>
935 Service de l'observation et des statistiques, 2013. NOPOLU-Agri - Outil de
936 spatialisation des pressions de l'agriculture - Méthodologie et résultats pour
937 les surplus d'azote et les émissions des gaz à effet de serre - Campagne
938 2010-2011 (No. 14). Ministère de l'écologie, du développement durable et de
939 l'énergie.
940 Siddique, K.H.M., Johansen, C., Turner, N.C., Jeuffroy, M.-H., Hashem, A., Sakar,
941 D., Gan, Y., Alghamdi, S.S., 2012. Innovations in agronomy for food legumes.
942 A review. *Agron. Sustain. Dev.* 32, 45–64. [https://doi.org/10.1007/s13593-011-](https://doi.org/10.1007/s13593-011-0021-5)
943 0021-5
944 Smith, S.M., Edwards, E.C., 2021. Water storage and agricultural resilience to
945 drought: historical evidence of the capacity and institutional limits in the United
946 States. *Environ. Res. Lett.* 16, 124020. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/ac358a)
947 9326/ac358a
948 Solagro (Ed.), 2017. Le scénario Afterres2050: version 2016. Solagro, Toulouse.
949 Sterling, S.M., Ducharne, A., Polcher, J., 2013. The impact of global land-cover
950 change on the terrestrial water cycle. *Nature Clim Change* 3, 385–390.
951 <https://doi.org/10.1038/nclimate1690>
952 Suweis, S., Carr, J.A., Maritan, A., Rinaldo, A., D'Odorico, P., 2015. Resilience and
953 reactivity of global food security. *PNAS* 112, 6902–6907.
954 <https://doi.org/10.1073/pnas.1507366112>
955 Therond, O., Tichit M. (coord.), Tibi A. (coord.), Accatino F., Biju-Duval L., Bockstaller
956 C., Bohan D., Bonaudo T., Derocles S., De Sousa L., Domingues Santos J.P.,
957 Dross C., Duru M., Eugène M., Fontaine C., Garcia B., Geijzendorffer I.,
958 Girardin A., Graux A.-I., Jouven M., Langlois B., Le Bas C., Le Bissonnais Y.,
959 Lelièvre V., Lifran R., Maigné E., Martin G., Martin R., Martin-Laurent F.,
960 Martinet V., McLaughlin O., Meillet A., Mignolet C., Mouchet M., Nozières-Petit
961 M.-O., Ostermann O.P., Paracchini M.L., Pellerin S., Peyraud J.-L., Petit-
962 Michaut S., Picaud C., Plantureux S., Poméon T., Porcher, E., Puech T.,
963 Puillet L., Rambonilaza T., Raynal H., Resmond R., Ripoche D., Ruget F.,
964 Rulleau B., Rusch A., Salles J.-M., Sauvans D., Schott C., Tardieu L., 2017.
965 Volet "écosystèmes agricoles" de l'Evaluation Française des Ecosystèmes et
966 des Services Ecosystémiques, Evaluation Française des Ecosystèmes et des
967 Services Ecosystémiques. INRA (France).
968 Urruty, N., Tailliez-Lefebvre, D., Huyghe, C., 2016. Stability, robustness, vulnerability
969 and resilience of agricultural systems. A review. *Agron. Sustain. Dev.* 36, 15.
970 <https://doi.org/10.1007/s13593-015-0347-5>
971 Van Zanten, H.H.E., Van Ittersum, M.K., De Boer, I.J.M., 2019. The role of farm
972 animals in a circular food system. *Global Food Security* 21, 18–22.
973 <https://doi.org/10.1016/j.gfs.2019.06.003>
974 Vatsa, P., Miljkovic, D., 2021. Energy and crop price cycles before and after the
975 global financial crisis: A new approach. *Journal of Agricultural Economics* n/a.
976 <https://doi.org/10.1111/1477-9552.12454>

Appendix A

A.1 Definition of compositional indicators

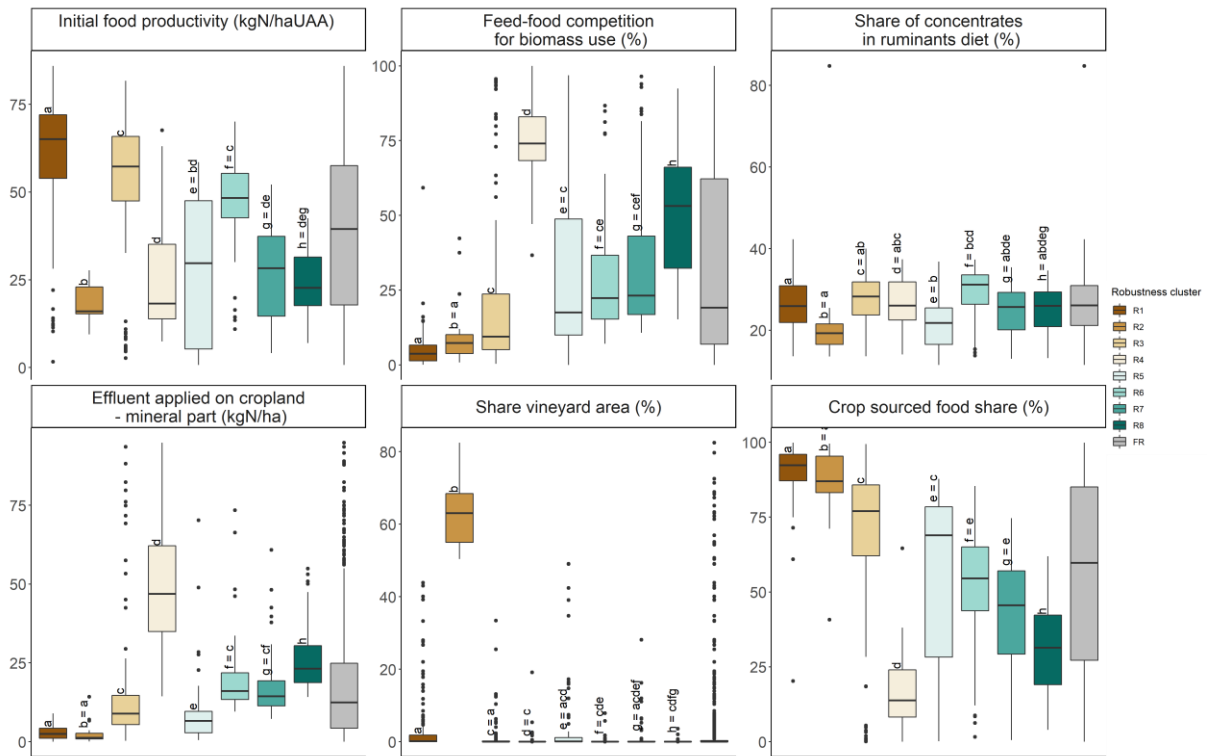
Food productivity corresponds to crop- and animal-sourced food (meat, milk and eggs) allocated to humans (kgN/haUAA/year). According to Pinsard et al. (2021), the trade-off between food productivity and robustness indicators is non-linear. High productivity implies a greater dependency on imported inputs and, thus, lower short- and long-term robustness, but low productivity does not necessarily imply greater short- and long-term robustness; this depends on the degree of integration between livestock, grasslands and crops.

Feed–food competition for biomass use is defined as the local consumption of cereals and oilseeds by livestock (seeds, oils and co-products, the feed subcategories that compete with food) divided by local cereal and oilseed production for both humans and livestock (%). Stronger feed–food competition for biomass use may imply stronger long-term robustness (intensity) (Pinsard et al., 2021).

The percentage of concentrates in the ruminant diet corresponds to ruminant needs for energy and protein concentrates (mass of N) divided by the total ruminant needs (mass of N) (%). The higher this percentage, the more intensive the ruminant farming because the consumption of concentrates by ruminants accelerates the animals' mass gain and, therefore, meat production (Koch et al., 2010; Morales Gómez et al., 2021).

The mineral content of the manure applied to cropland corresponds to the N in the manure in housing facilities that mineralises in the year it is applied to the crops (kgN/ha/year). The higher this amount, the less synthetic fertiliser is needed, depending on the need for mineral N fertilisation of the cropland and the intensity of natural N flows.

The percentage of crop-sourced food is its share in the total agricultural production (animal- and crop-sourced) (%). The lower the percentage, the more food is animal-sourced.



1006

1007 *Figure A.1 Boxplots of six compositional indicators by robustness cluster (in colour) and at the French scale (in*
 1008 *grey): Initial feed productivity (kgN/haUAA/year); feed–food competition for biomass use (%); percentage of*
 1009 *concentrates in ruminant diet in mass of N (%); mineral amount of livestock manure applied to crops*
 1010 *(kgN/ha/year); percentage of vineyard area in UAA (%); percentage of crop-sourced food (%). The letters above*
 1011 *the boxplots are from statistical t-tests between clusters and by indicator. The first letter corresponds to that of the*
 1012 *cluster considered (a–h for clusters R1–R8). Those after the equal sign correspond to clusters with medians not*
 1013 *significantly different from that of the cluster in question. In the boxplots, the line corresponds to the median value.*

1014 A.2.1 Indicators without clear correlations with robustness levels

1015 The results of this study show that the trade-off between productivity and robustness
1016 is not strict: low-productivity SARs can have either low or high robustness.
1017 Nevertheless, high productivity is correlated with low levels of robustness. The results
1018 also show that feed–food competition is a proxy for neither the robustness window
1019 nor intensity. The most robust SARs (R8) had a median feed–food competition for
1020 biomass use of 50%, whereas SARs with low competition had intermediate or low
1021 levels of robustness (R1, R2 and R3). This indicator is a function of the percentage of
1022 cereal and oilseed areas, whose production is allocated to animals, as well as the
1023 livestock number and their diet. Depending on the livestock number, low feed–food
1024 competition can increase feed imports because of the lack of sufficient local
1025 production allocated to animals.

1026 A.2.2 By cluster

1027 Initial food productivity was the highest for R1 ($M \approx 65$ kgN/haUAA/year), but its feed–
1028 food competition for biomass use was the lowest. Initial feed productivity and feed–
1029 food competition were both lowest for the R2 SARs. The percentage of concentrates
1030 in the ruminant diet was also low in R2, as was the amount of mineral N from
1031 livestock manure applied to crops. In these SARs, the percentage of vineyards was
1032 over 60%. The R3 SARs also had high initial food productivity ($M \approx 57$
1033 kgN/haUAA/year). The feed–food competition for biomass use was highest for the R4
1034 SARs ($M \approx 74\%$), which also had the highest percentage of concentrates in ruminant
1035 feed ($M \approx 26\%$) and amount of mineral N from livestock manure applied to crops. The
1036 share of crop-sourced food was less than 15%. For the R5 SARs, the initial feed
1037 productivity ($M \approx 30$ kgN/haUAA/year), the percentage of concentrates in the ruminant
1038 diet and the amount of mineral N from livestock manure applied to crops were among
1039 the lowest. The initial food productivity in the R6 SARs was among the highest; the
1040 percentage of concentrates in the ruminants' diet was the highest in R6 ($M \approx 31\%$). All
1041 the indicators in the R7 SARs had medians close to the national median values
1042 except for initial food productivity, which was lower. The initial food productivity and
1043 the percentage of crop-sourced food for the R8 SARs had medians lower than the
1044 national median. In contrast, the feed–food competition and the amount of mineral N
1045 from livestock effluents applied to crops had medians higher than the national
1046 medians.