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Abstract

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

Keywords

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

Abbreviations

FS: Farming System

SAR: Small Agricultural Region

UAA: Utilised Agricultural Area

1 Introduction

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

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

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

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

2 Material and Methods

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

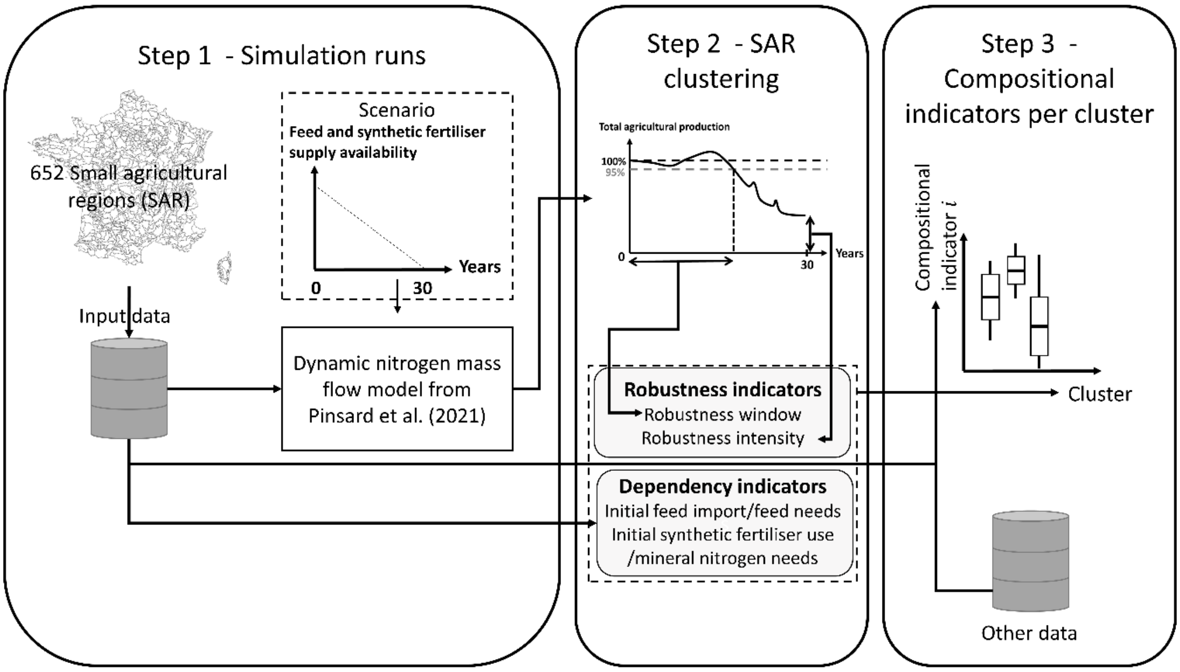


Figure 1 Scheme describing the methodology. Step 1 consists of running a dynamic nitrogen (N) mass flow model (defined in Pinsard et al., 2021) for 652 small agricultural regions (SARs) of France under a simulated scenario of declining feed and synthetic fertiliser supply availability over 30 years.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

2.1 General model description

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

The active soil organic N stock and the livestock herd sizes are updated and the agricultural production levels (plant and livestock) are calculated at each 1-year increment. The active soil organic N stock increases with organic N inputs (plant residues or livestock effluents) and decreases with outputs (organic matter mineralisation). Synthetic fertiliser, atmospheric deposition, biological N fixation by legumes, mineralised soil N and the mineral parts of organic amendments contribute to the plants' mineral fertilisation. Plant production is allocated to humans and/or livestock, depending on the species. N losses to air or water occur during effluent management and soil management. The number of livestock decreases when feed availability is lower than their needs. The plants' mineral N needs are estimated from the typical yield in each SAR in recent years. The plant yield is a piecewise linear function of mineral N: the yield increases linearly with mineral N availability from 0 to a maximum yield, corresponding to the mineral N needs of the plant. Above the mineral N needs of the plant, the yield is considered saturating at the maximum.

2.2 Scenario and simulations

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

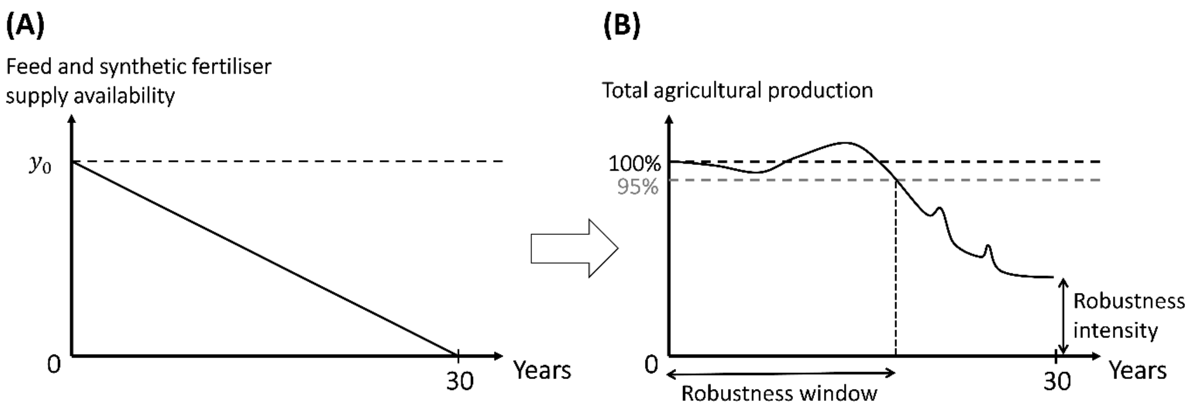


Figure 2 (A) Trajectory of joint linear decline over 30 years of the supply availability of synthetic fertiliser and feed. y_0 is worth 70% of the total plant mineral N fertilisation need of areas fertilised with synthetic fertiliser per SAR for synthetic fertiliser and 100% of the total need for livestock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

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

2.3 Indicators of robustness to input supply availability declines

Declining input availability always results in a gradual agricultural production decline (Pinsard et al. 2021); the typical trajectory (depicted in Figure 2B) shows an initial maintenance of agricultural production (even after input availability starts to decline) and then a gradual decrease until the end of the simulation. However, some FSs start to decline later than others and to different extents. Based on the typical trajectory, we defined two robustness indicators (Figure 2B): the *robustness window* and *robustness intensity*. The robustness window is the initial period in which the system can maintain its current level of agricultural production even after the initial decline in input availability. We defined a threshold of 95% of the initial agricultural production, below which we considered agricultural production to decline. The robustness intensity is the percentage of agricultural production compared to the initial quantity at the end of the 30-year simulation. The robustness window and intensity shed light on short- and long-term robustness, respectively.

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

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

2.4 Clustering indicators

The cluster analysis aimed to create a typology of SARs according to their robustness and dependency on external input. We selected four indicators (hereafter *clustering indicators*): (1) the robustness window (years), (2) the robustness intensity (%), (3) the *percentage of imported feed* out of the total feed needs (%) and (4) the *percentage of synthetic fertiliser applied* out of the total mineral N input (%). Indicator (3) is calculated as the ratio of imported feed to the total feed needs considering all the feed categories, expressed as the mass of N. Indicator (4) corresponds to the percentage of mineral N from synthetic fertiliser compared to the total mineral N input (including organic amendments, deposition and biological N fixation). The clustering indicators were chosen based on the conclusions drawn by Pinsard et al. (2021) after simulating input availability decline for 3 SARs. We added indicators (3) and (4) to the clustering indicators because the robustness indicators may be similar for two distinct SARs with different uses of imported feed and synthetic fertiliser, thus requiring finer distinction (e.g., in Pinsard et al. [2021], the robustness intensity was similar for an extensive ruminant FS and an intensive monogastric FS).

We implemented a hierarchical agglomerative classification to maximise the variance between groups and minimise the variance within groups (Murtagh and Legendre, 2013). Before classification, we manually clustered the SARs with vineyard areas over 50% of the UAA to distinguish them from field crop SARs with similar robustness levels. Clustering was performed using Ward’s method (option ward.D2) in the hclust function of the stats package in R (R Core Team, 2020). The optimal number of clusters was estimated graphically with the Hubert and D indicators of R’s NbClust 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	*Robustness window*	Consecutive number of years during which the agricultural production of the FS does not fall below 95% of the initial agricultural production	Years
	Robustness intensity	Share of the initial total agricultural production at year 30	%
Clustering indicators	*Percentage of imported feed* out of the total feed needs	Ratio of imported feed to feed needs considering all feed categories together expressed in mass of N	%
	Percentage of synthetic fertiliser applied out of the total mineral N input	Ratio of mineral N from synthetic fertiliser to total mineral N input (including organic amendments, deposition and biological N fixation*)*	%
Compositional indicators	*Number of monogastrics*	Number of poultry and pigs	LU/haUAA
	Number of ruminants	Number of cattle, goats and sheep	LU/haUAA
	Total livestock count	Sum of monogastric and ruminant numbers	LU/haUAA
	Percentage of permanent grassland area in the UAA	Ratio of permanent grassland area to UAA	%
	Percentage of temporary grassland area in the UAA	Ratio of temporary grassland area to UAA	%
	Percentage of cereal and oilseed areas in the UAA (i.e., field crops)	Ratio of cereals and oilseeds area to UAA	%
	Self-sufficiency in energy concentrates	Ratio of livestock needs to local availability allocated to livestock for energy concentrates	%
	Self-sufficiency in protein concentrates	Ratio of livestock needs to local availability allocated to livestock for protein concentrates	%
	Self-sufficiency in forages	Ratio of livestock needs to local availability allocated to livestock for forages	%
	Biological N fixation by legumes	Natural flow of N to crops from the air	kgN/haUAA/year
	Cropland mineral N fertilisation need	N needs of the crops plus losses to water and air from fertilisation	kgN/ha/year
	Active soil organic N stock in cropland	Amount of soil organic N from which mineralised N is derived	kgN/ha

2.5 Compositional indicators

Three compositional indicators describe the livestock numbers: (i) *number of monogastrics* (livestock units [LU]/haUAA), (ii) *number of ruminants* (LU/haUAA) and (iii) *total livestock number* (LU/haUAA). The total livestock number is the sum of the monogastrics and ruminants. Three indicators describe the agricultural areas: (iv) the *percentage of permanent grassland area* in the UAA (%), (v) the *percentage of temporary grassland area* in the UAA (%) and (vi) the *percentage of cereal and oilseed areas* (i.e., field crops) in the UAA (%). These three indicators also indirectly specify the percentage of other crop species in the UAA, i.e., vineyards, industrial crops (beets and tubers) and fruit and vegetable crops. Three indicators describe feed self-sufficiency (lack or surplus) by category: *self-sufficiency* (%) (vii) in *energy concentrates*, (viii) *protein concentrates* and (ix) *forages*. Feed self-sufficiency for a feed category is the ratio of livestock needs to the local availability of the feed category allocated to livestock. This indicator allows for specifying the source of dependency on feed imports, which may concern one feed category or all of them. It also describes the integration between crops, grasslands and livestock, i.e., the extent to which the composition of the livestock herd is fitted to the permanent grassland and cropland of the FS. Finally, three indicators describe the N inflow, crop N needs and soil N stock of the FS: (x) *legume biological N fixation* (kgN/haUAA/year), (xi) *cropland mineral N fertilisation needs* (kgN/ha/year) and (xii) *active soil organic N stock in the cropland* (kgN/ha). Biological N fixation by legumes represents the natural flow of N to crops, the intensity of which depends on cropping practices (in contrast to the deposition of N oxides from the air on the soil which comes from industry and transport fossil fuel combustion). The cropland needs for mineral N fertilisation correspond to the N needs of the crops plus the N losses from fertilisation to water and air. Finally, the amount of active soil organic N in the cropland corresponds to the amount of soil organic N from which mineralised N is derived (calculated in the model). The higher this amount, the higher the natural N fertility of the soil (modulated by the mineralisation rate, which depends on the latitude).

2.6 Correlation matrix

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

2.7 Input data

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

3 Results

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

3.1 Robustness indicators

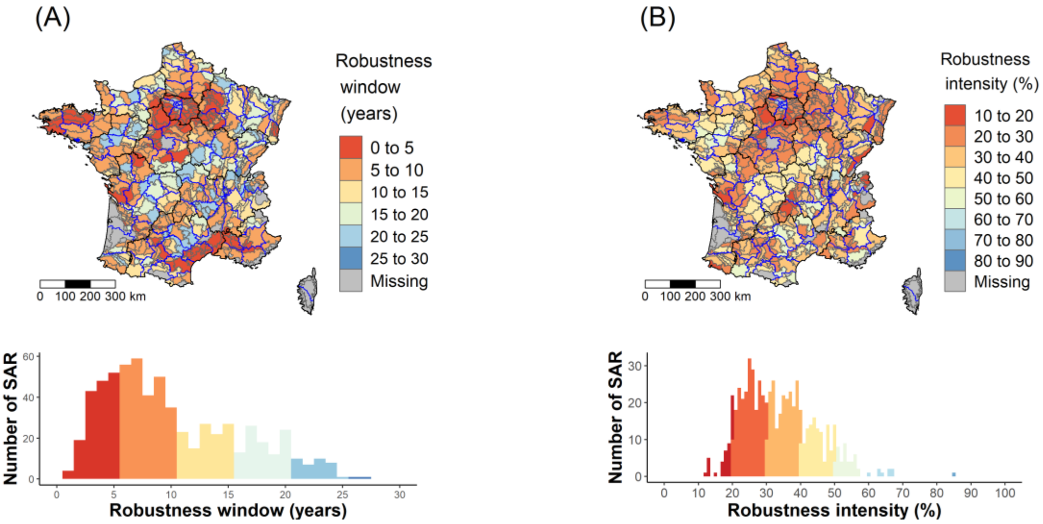


Figure 3 Maps of the robustness indicators (elaborated from the model output trajectories) with their frequency distribution histograms at the small agricultural region (SAR) level in France. Simulations were run for a scenario of linear decline in synthetic fertiliser and feed supply availability. (A)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

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

SARs with similar robustness windows appear spatially aggregated (Figure 3A). The 114 SARs with a robustness window of less than 5 years were mostly located in the centre-north (around the Paris region), south (Languedoc-Roussillon) and west (Brittany) of France. The 38 SARs with a robustness window of more than 20 years were mainly located in oceanic or semi-continental climates in the centre of France. The spatial distribution of the robustness intensity appeared less aggregated than that of the robustness windows (Figure 3B). The 9 SARs with the highest robustness intensity (60%–85%) were located in the centre (Auvergne-Rhône-Alpes) and south (Occitanie). The lowest robustness intensities (10%–20%) were mainly in Ile-de-France, the centre-southeast and the centre (Auvergne-Rhône-Alpes in mountain climates and Centre-Val de Loire in oceanic climates).

3.2 Relationship between robustness clusters and compositional indicators

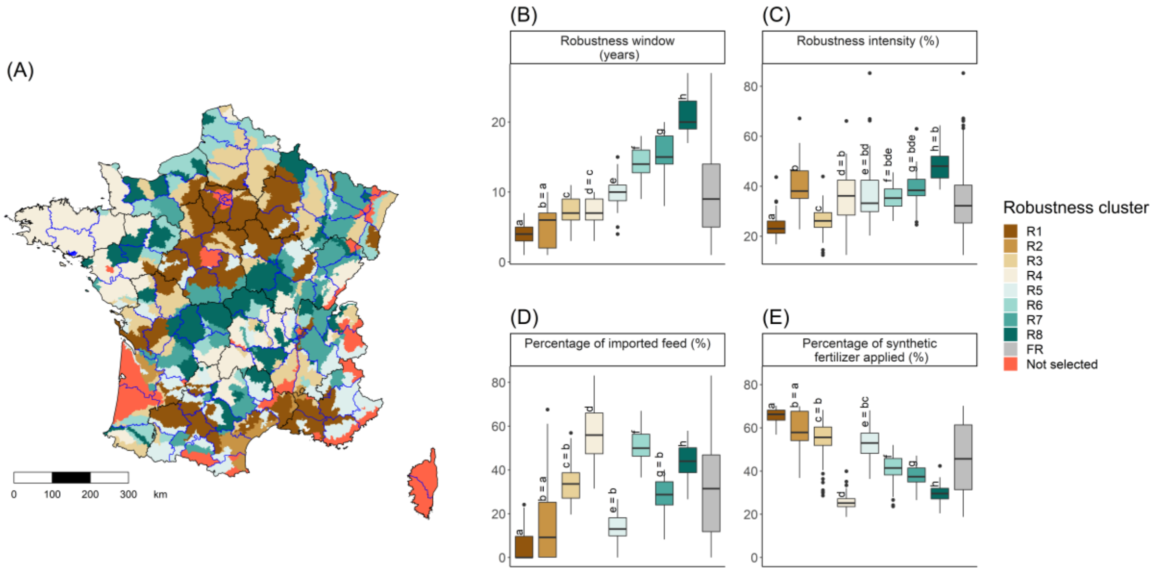
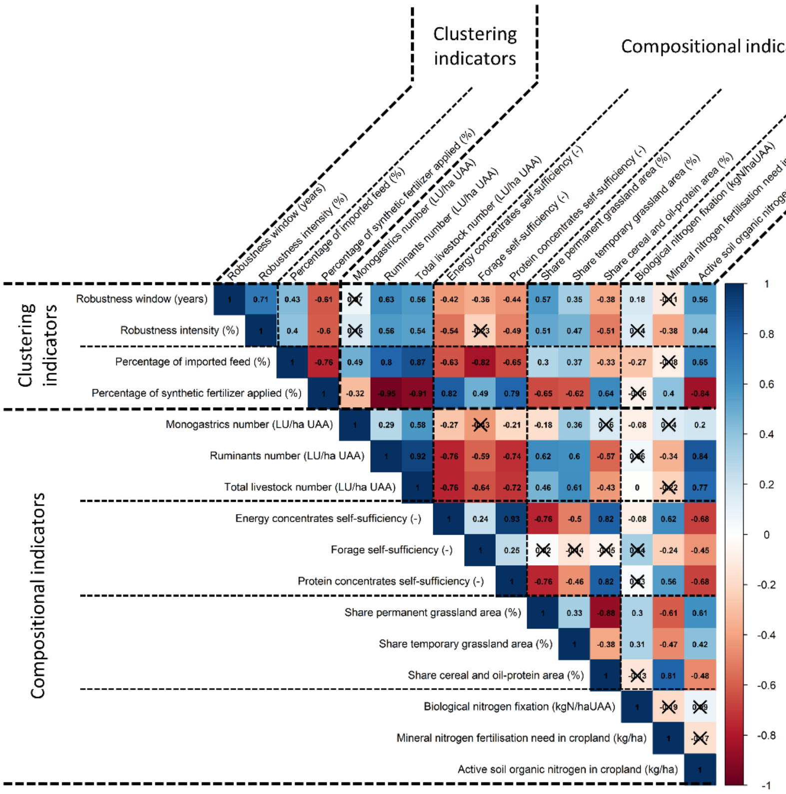


Figure 4 Robustness typology for French small agricultural regions (SARs). (A) Spatial representation of the clusters. (B)–(E) Boxplots of the four clustering indicators: (B) Robustness window (years); (C) Robustness intensity (%); (D) Percentage of imported feed compared to the total feed needs (%);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

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



	Robustness window (years)	Robustness intensity (%)	Percentage of imported feed (%)	Percentage of synthetic fertilizer applied (%)	Monogastrics number (LU/ha UAA)	Ruminants number (LU/ha UAA)	Total livestock number (LU/ha UAA)	Energy concentrates self-sufficiency (-)	Forage self-sufficiency (-)	Protein concentrates self-sufficiency (-)	Share permanent grassland area (%)	Share temporary grassland area (%)	Share cereal and oil-protein area (%)	Biological nitrogen fixation (kgN/haUAA)	Mineral nitrogen fertilisation need in cropland (kg/ha)	Active soil organic nitrogen in cropland (kg/ha)
Robustness window (years)	1	0.71	0.43	-0.61	0.07	0.63	0.56	-0.42	-0.36	-0.44	0.57	0.35	-0.38	0.18	-0.01	0.56
Robustness intensity (%)		1	0.4	-0.6	0.06	0.56	0.54	-0.54	-0.03	-0.49	0.51	0.47	-0.51	0.04	-0.38	0.44
Percentage of imported feed (%)			1	-0.76	0.49	0.8	0.87	-0.63	-0.82	-0.65	0.3	0.37	-0.33	-0.27	-0.08	0.65
Percentage of synthetic fertilizer applied (%)				1	-0.32	-0.95	-0.91	0.82	0.49	0.79	-0.65	-0.62	0.64	-0.06	0.4	-0.84
Monogastrics number (LU/ha UAA)					1	0.29	0.58	-0.27	-0.03	-0.21	-0.18	0.36	0.06	-0.08	0.04	0.2
Ruminants number (LU/ha UAA)						1	0.92	-0.76	-0.59	-0.74	0.62	0.6	-0.57	0.06	-0.34	0.84
Total livestock number (LU/ha UAA)							1	-0.76	-0.64	-0.72	0.46	0.61	-0.43	0	-0.02	0.77
Energy concentrates self-sufficiency (-)								1	0.24	0.93	-0.76	-0.5	0.82	-0.08	0.62	-0.68
Forage self-sufficiency (-)									1	0.25	0.02	-0.04	-0.05	0.04	-0.24	-0.45
Protein concentrates self-sufficiency (-)										1	-0.76	-0.46	0.82	0.03	0.56	-0.68
Share permanent grassland area (%)											1	0.33	-0.88	0.3	-0.61	0.61
Share temporary grassland area (%)												1	-0.38	0.31	-0.47	0.42
Share cereal and oil-protein area (%)													1	-0.03	0.81	-0.48
Biological nitrogen fixation (kgN/haUAA)														1	-0.09	0.09
Mineral nitrogen fertilisation need in cropland (kg/ha)															1	-0.07
Active soil organic nitrogen in cropland (kg/ha)																1

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

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

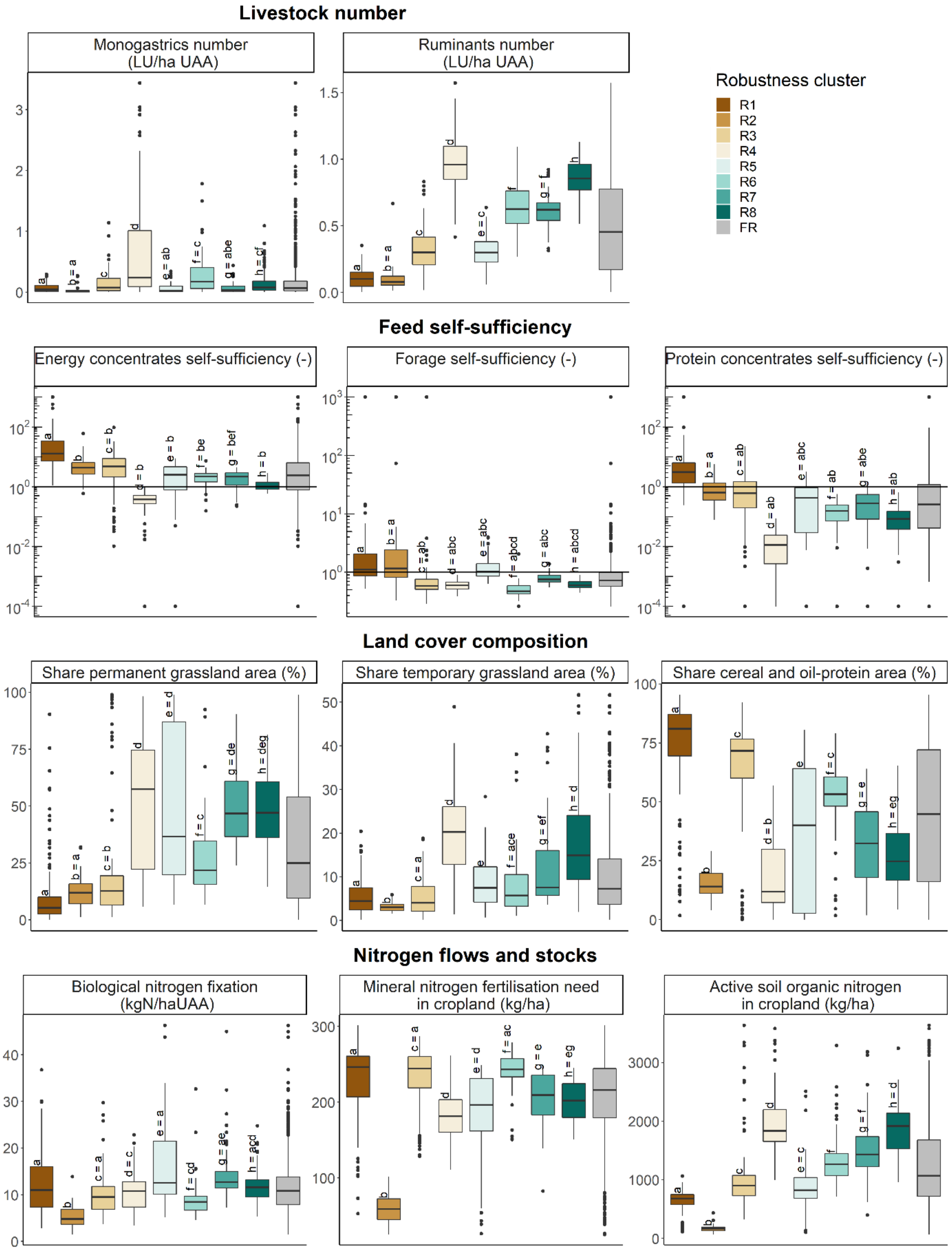


Figure 6 Boxplots showing the distribution of 11 compositional indicators within each robustness cluster and for all of France (in grey): number of monogastrics (LU/haUAA); number of ruminants (LU/haUAA); self-sufficiency in energy concentrates (−); self-sufficiency in forages (−); self-sufficiency in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

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

3.3 Cluster description

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

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

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

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

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

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

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

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

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

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

4 Discussion

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

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

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

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

4.1.1.1 Intensive field crop SARs with few or low-density intensive ruminant farming

Intensive field crop SARs with few livestock (R1 and R3) had among the lowest short- and long-term robustness values. Low livestock density implies almost-reached feed self-sufficiency and, consequently, the robustness of animal-sourced agricultural production. However, animal-sourced agricultural production only accounts for 20% of the total agricultural production at most (see Figure A.1 in the appendix), therefore minimally contributing to the overall robustness. Moreover, their low livestock density implies low effluent input to crops (M=3 and 9 kgN/ha/year for R1 and R3, respectively; see Figure A.1 in the appendix), which contributes to low levels of active soil organic N and, indirectly, soil organic N mineralisation. For these SARs, we estimated active soil organic N stocks to be below the national median. This, along with the highest crop needs for mineral N, further increased the dependency of these clusters on synthetic fertilisers, causing agricultural production to be immediately impacted when the availability of imported synthetic fertilisers dropped. These results generalise those presented by Pinsard et al. (2021) for the Plateau Picard, an intensive field crop SAR with some livestock production belonging to this study’s R3 cluster.

4.1.1.2 Wine-producing SARs

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

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

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

In contrast, the robustness levels of R4, which were the lowest among the livestock SARs, were not explained by the percentage of synthetic fertiliser applied as it was also the lowest among these SARs. The percentage of imported feed was the highest; however, only those of R6 and R8 were higher than the national median value, whereas those of R5 and R7 were lower than the national median. This difference should be investigated through the details of the integration between crops, grasslands and livestock, including other indicators such as herd composition and the levels of self-sufficiency by feed category.

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

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

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

4.1.2.2 Intensive monogastric and ruminant farming regions with crops for livestock

The SARs specialised in intensive monogastric and ruminant farming with crops for feed (R4) presented the lowest robustness levels among the livestock regions as the high livestock numbers led to a high percentage of imported feed, resulting in low short-term robustness of animal-sourced agricultural production. As the crop-sourced food share was low, the total agricultural production was quickly impacted. In contrast, the SARs of R8 had a similar composition but were the most robust. This difference (and the low robustness of the R4 cluster) can be explained by the herd composition, which was mainly monogastric in R4, unlike in R8. The model considers monogastric animals to only consume concentrates, and self-sufficiency in energy and protein concentrates was much lower in R4 than in the other livestock regions. Thus, the decrease in livestock numbers (and animal-sourced agricultural production) came earlier.

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

4.2 Biological N fixation and robustness levels

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

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

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

4.4 Protein self-sufficiency under threat in 2050

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

4.5 Strategies for improving robustness: Despecialising agricultural regions?

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

It was possible to identify actions to be carried out within each cluster to improve their robustness. The SARs of R1–R4 would benefit from ‘despecialisation’. For SARs specialised in intensive livestock farming (R4), reducing the livestock number would reduce feed import needs and feed–food competition for biomass use. For example, the number of monogastric livestock could be reduced to adapt to the local production of co-products. Conversely, for intensive field crop SARs with few or low-density intensive ruminant farming (R1 and R3), an increase in the livestock number would enhance the use of locally-produced feed that does not compete with food (i.e., co-products or fodder) (Poux and Aubert, 2018) and simultaneously increase the amount of livestock effluents used for cropland. Furthermore, a decrease in the need for mineral N fertilisation would reduce the need for synthetic fertilisers. For the wine-producing SARs (R2), systematic inter-row plant cover would help increase the stock of active soil organic N and reduce synthetic fertiliser needs (Payen et al., 2021). Finally, for SARs with permanent grasslands and livestock (R5–R8), a joint decrease in the crop yield, i.e., in the need for mineral N fertilisation, and livestock number is necessary to reduce input imports. This should be done alongside the integration of crops with the needs of the livestock. More specifically, a decrease in the need for protein concentrates in the ruminant diet (Poux and Aubert, 2018; Solagro, 2017) would reduce the need for imported concentrates. However, there may be trade-offs: for example, a decrease in concentrate consumption by ruminants would decrease milk yield (Solagro, 2017). For R6, an increased percentage of permanent and temporary grassland areas would contribute to the integration of crops, grasslands and livestock.

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

4.6 Study limitations

4.6.1 Feed import perturbations considered independent of their geographical origin

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

4.6.2 A nutritional and mono-nutrient approach

We assessed biomass fluxes in terms of N, but this may cause some distortions. For example, the relationship between livestock numbers and feed availability would imply different levels of feed self-sufficiency, if accounted in mass of dry matter. This difference can be seen by comparing France’s spatial distribution of feed self-sufficiency at the SAR level computed in dry-matter mass (Jouven et al. 2018) with that computed in mass of N (see supplementary material). Furthermore, N is not the only limiting factor for plant growth. Phosphorus, another limiting factor (Plaxton and Lambers, 2015) derived solely from rock mining in few and limited geographical areas around the globe (Cordell and White, 2011), would also face supply disruptions in the context of peak oil. Decreased availability of phosphate mineral fertiliser imports could further decrease the availability of soil mineral N (Ågren et al., 2012; Ringeval et al., 2019).

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

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

4.7 Quality of estimates

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

5 Conclusion

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

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

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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., 01:00; 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.

A.2 Results

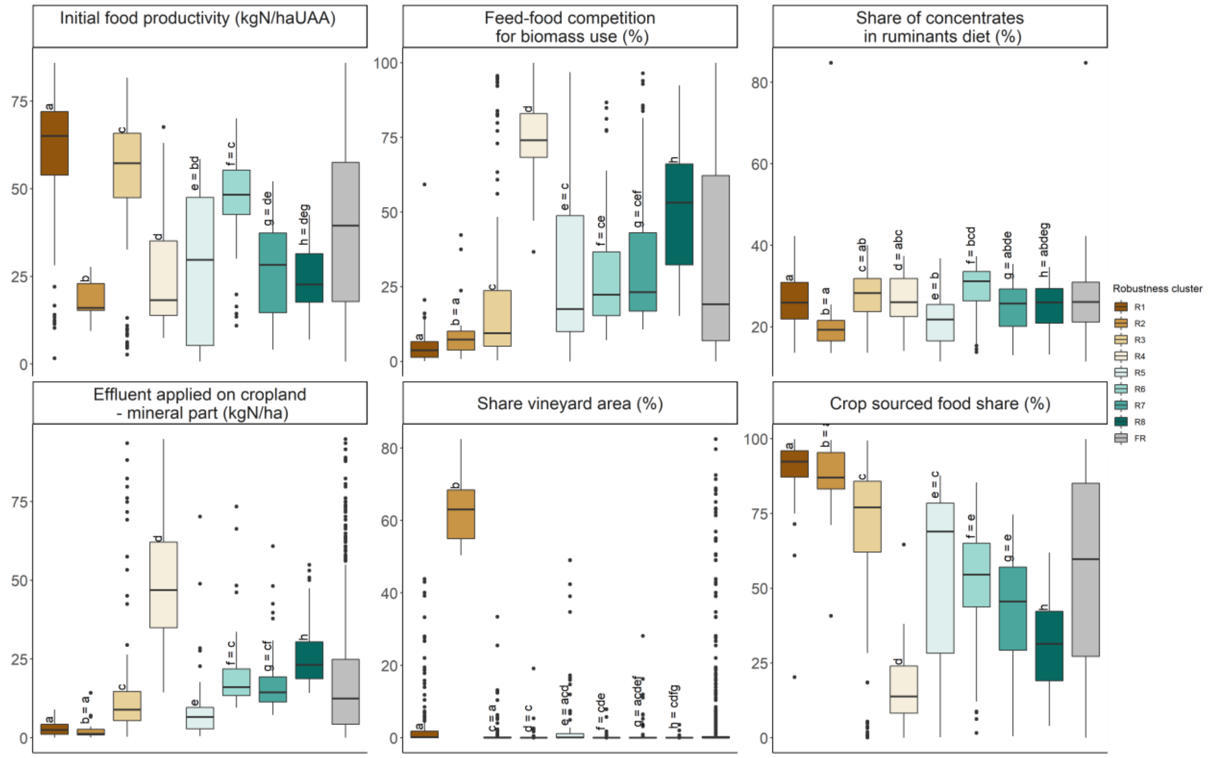

Figure A.1 Boxplots of six compositional indicators by robustness cluster (in colour) and at the French scale (in grey): Initial feed productivity (kgN/haUAA/year); feed–food competition for biomass use (%); percentage of concentrates in ruminant diet in mass of N (%); mineral amount of livestock manure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

A.2.1 Indicators without clear correlations with robustness levels

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

A.2.2 By cluster

Initial food productivity was the highest for R1 (M≈65 kgN/haUAA/year), but its feed–food competition for biomass use was the lowest. Initial feed productivity and feed–food competition were both lowest for the R2 SARs. The percentage of concentrates in the ruminant diet was also low in R2, as was the amount of mineral N from livestock manure applied to crops. In these SARs, the percentage of vineyards was over 60%. The R3 SARs also had high initial food productivity (M≈57 kgN/haUAA/year). The feed–food competition for biomass use was highest for the R4 SARs (M≈74%), which also had the highest percentage of concentrates in ruminant feed (M≈26%) and amount of mineral N from livestock manure applied to crops. The share of crop-sourced food was less than 15%. For the R5 SARs, the initial feed productivity (M≈30 kgN/haUAA/year), the percentage of concentrates in the ruminant diet and the amount of mineral N from livestock manure applied to crops were among the lowest. The initial food productivity in the R6 SARs was among the highest; the percentage of concentrates in the ruminants' diet was the highest in R6 (M≈31%). All the indicators in the R7 SARs had medians close to the national median values except for initial food productivity, which was lower. The initial food productivity and the percentage of crop-sourced food for the R8 SARs had medians lower than the national median. In contrast, the feed–food competition and the amount of mineral N from livestock effluents applied to crops had medians higher than the national medians.