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Assessing the resilience of European farming systems to consequences of global peak oil using a dynamic nitrogen flow model

Evaluation de la résilience de systèmes agricoles européens à des conséquences du pic pétrolier mondial à l'aide d'un modèle dynamique de flux d'azote

Thèse de doctorat de l'université Paris-Saclay

École doctorale n°581 : agriculture, alimentation, biologie, environnement, santé (ABIES)
Spécialité de doctorat : Sciences agronomiques
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Référent : AgroParisTech

Thèse préparée dans l'**UMR SAD-APT (Université Paris-Saclay, INRAE, AgroParisTech)**, sous la direction de **François LEGER**, Ingénieur de recherche (ADR), la co-direction de **Sophie MARTIN**, Chargée de recherche (HDR), le co-encadrement de **Francesco ACCATINO**, Chargé de recherche

Thèse soutenue à Paris-Saclay, le 20 mai 2022, par

Corentin PINSARD

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Titre : Evaluation de la résilience de systèmes agricoles européens à des conséquences du pic pétrolier mondial à l'aide d'un modèle dynamique de flux d'azote

Mots clés : Résilience ; Systèmes agricoles européens ; Contraintes sur l'import d'intrants ; Modèle dynamique de flux d'azote ; Analyse multi-mode ; Transition agroécologique

Résumé : Les systèmes agricoles (SA) européens sont actuellement dépendants des énergies fossiles, entre autres pour la synthèse des engrais azotés et l'import de nourriture animale (intrants). Or le pic pétrolier mondial pourrait être atteint d'ici 2030, et entraîner un renchérissement de ces intrants, et une diminution de la capacité des agriculteurs à les acheter. Ainsi, cette dépendance questionne la résilience de ces SAs, c'est-à-dire leur capacité à maintenir la production de nourriture. L'objectif de cette thèse était d'évaluer la résilience de SAs européens à des contraintes sur l'import en intrants. Pour y répondre, j'ai développé un macro-modèle dynamique de bilan d'azote d'un SA constitué de 3 compartiments (cheptel, plante et sol) et de deux usages des sols (prairies permanentes et cultures). J'ai exploré ce modèle pour des SAs en France (élevages de bovins viande extensifs, grandes cultures ou élevages de monogastriques intensifs) et au Portugal (élevages de bovins viande extensifs). J'ai exploré 2 composantes de la résilience: (1) la robustesse, c'est-à-dire leur capacité à maintenir la production de nourriture face à une baisse progressive

de l'import en intrants, en mode simulation, et (2) et le potentiel d'adaptabilité, c'est-à-dire les changements de compositions cultures-cheptel envisageables pour augmenter la robustesse, en mode optimisation multi-objectif. J'ai trouvé que les SAs français spécialisés (grandes cultures ou élevages de monogastriques intensifs) sont moins robustes à court terme que les SAs mixtes. A long terme, les SAs dont la compétition alimentation animale-alimentation humaine (CAH) est élevée sont les plus robustes. En mode optimisation, j'ai montré que la baisse de la CAH est un changement de compositions qui maximise la production de nourriture en l'absence d'import d'intrants. Dans le SA Portugais, j'ai identifié un compromis entre la robustesse de la production de viande et l'atténuation du changement climatique, qui peut être atténué avec la combinaison de pratiques agroécologiques. Ces changements de compositions devraient être mis en place au plus tôt pour prévenir l'insécurité alimentaire face à des contraintes sur l'import en intrants.

Title : Assessing the resilience of European farming systems to consequences of global peak oil using a dynamic nitrogen flow model

Keywords : Resilience; European farming systems; Input import constraints; Dynamic nitrogen flow model; Multi-mode analysis; Agroecological transition

Abstract : European farming systems (FS) are currently dependent on fossil fuels, among other things for the nitrogen fertiliser's synthesis and the feed import (inputs). However, the global peak oil could be reached by 2030, leading to a price increase of these inputs and a decrease in the capacity of farmers to buy them. This dependence raises questions about the resilience of these FSs, *i.e.* their ability to maintain food production. The aim of this thesis was to assess the resilience of European FSs to constraints on input imports. To address it, I developed a dynamic nitrogen balance macro-model of a FS with 3 compartments (livestock, plant and soil) and 2 land-uses (permanent grassland and cropland). I explored this model for FSs in France (extensive beef farms, field crops or intensive monogastric farms) and in Portugal (extensive beef farms). I investigated two components of resilience: (1) robustness, *i.e.* their ability to maintain

food production in the face of a progressive decline in input imports, in simulation mode, and (2) adaptability potential, *i.e.* the changes in crop-livestock compositions that can be envisaged to increase robustness, in multi-objective optimisation mode. I found that specialised French FSs (field crops or intensive monogastric farms) are less robust in the short-term than mixed FSs. In the long-term, the FSs with high feed-food competition (FFC) are the most robust. In optimisation mode, I showed that a decrease in FFC is a compositional change that maximises food production without imported inputs. In the Portuguese FS, I identified a trade-off between beef production robustness and climate change mitigation, which can be alleviated with the combination of agroecological practices. These compositional changes should be implemented as soon as possible to prevent food insecurity in the face of input constraints.

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Résumé substantiel

Aujourd'hui, les principales sources d'énergie de l'agriculture européenne sont les énergies fossiles (pétrole et gaz notamment), par exemple pour la production et l'approvisionnement en intrants tels que les engrais minéraux et les tourteaux d'oléagineux pour l'alimentation animale. L'utilisation de ces intrants permet d'obtenir des rendements agricoles élevés et un excédent agricole important, permettant d'affecter la production céréalière en grande partie à l'élevage afin de satisfaire une proportion historiquement élevée de produits animaux dans les régimes alimentaires. Cependant, la baisse de la production mondiale de pétrole cette décennie, annoncée par l'Agence internationale de l'énergie, pourrait entraîner une hausse des prix des intrants, leur prix étant corrélé à celui du pétrole. Sans changement des politiques macro-économiques au sein de l'Union européenne, cette hausse des prix pourrait entraîner une diminution de l'approvisionnement en intrants des systèmes agricoles européens et, in fine, une baisse de la production agricole qui menacerait la sécurité alimentaire. De même, les énergies fossiles et les intrants étant largement importés dans l'Union Européenne, les instabilités politiques et économiques des pays exportateurs pourraient entraîner des ruptures d'approvisionnement. Ces ruptures pourraient par exemple avoir lieu suite à l'invasion russe de l'Ukraine qui a débuté en février 2022. Ainsi, la résilience de la production agricole européenne face à la hausse des prix et aux pénuries d'approvisionnement en intrants, c'est-à-dire sa capacité à maintenir ou à retrouver un niveau de production satisfaisant les besoins alimentaires face ou pendant ces perturbations, est remise en question.

Dans la littérature des systèmes agricoles, les évaluations de la résilience ont majoritairement concerné la production de nourriture (ou la sécurité alimentaire) face à des perturbations liées au dérèglement climatique. A ma connaissance, il n'y a jamais eu d'évaluation de la résilience de la production agricole à des contraintes d'approvisionnement en intrants pour des systèmes agricoles. Ainsi, dans cette thèse, j'ai cherché à évaluer la résilience de la production agricole de systèmes agricoles européens à des contraintes sur l'approvisionnement en intrants liées au pic pétrolier mondial. J'ai choisi en l'occurrence de me focaliser en matière d'intrants sur les engrais minéraux et la nourriture animale, ces deux intrants intervenant directement dans la croissance des plantes ou des animaux. Pour évaluer la résilience, j'ai adopté une approche de modélisation qui s'avère nécessaire lorsque les perturbations n'ont pas été observées jusqu'alors. Par ailleurs, ce type d'approche est original pour l'évaluation de la résilience étant minoritaire dans la littérature d'évaluation de la résilience de systèmes agricoles, contrairement aux analyses historiques ou qualitatives. J'ai ainsi développé un modèle dynamique de flux d'azote d'un système agricole et eu recours à de la simulation et de l'optimisation pour quantifier deux composantes de la résilience : (1) la robustesse, qui est la capacité d'un système à résister suite ou au cours d'une perturbation, (2) le potentiel d'adaptabilité, c'est-à-dire les adaptations possibles du système pour augmenter la robustesse suite ou au cours d'une perturbation. Dans cette thèse, par système agricole est entendue, une population d'exploitations agricoles situées dans une zone géographique commune et

restreinte, avec des conditions biophysiques, économiques et sociales similaires.

J'ai exploré la robustesse en mode simulation avec des scénarios de baisse progressive d'approvisionnement en intrants sur 30 années jusqu'à zéro sans changements de pratiques ou de compositions souhaités (Chapitre 1 et 2) puis avec (Chapitre 4). Ces scénarios de contraintes sur les intrants reposent sur l'hypothèse d'un renchérissement continu des énergies fossiles et des intrants pour les agriculteurs dans un contexte de politiques macroéconomiques libérales invariantes (politiques de marchés) et de pic pétrolier mondial, qui impacte l'approvisionnement en intrants. J'ai détaillé la robustesse en deux sous-composantes : (1) la capacité à résister face aux perturbations que j'ai nommé « fenêtre de robustesse » et (2) la capacité à absorber les perturbations que j'ai nommé « intensité de robustesse » (Chapitre 2). J'ai ensuite exploré le potentiel d'adaptabilité utilisant le modèle en mode optimisation avec deux scénarios de maximisation de la production de nourriture et de minimisation des intrants et en faisant varier de manière systématique les compositions du cheptel, et de la sole cultivée (Chapitre 3). Cette évaluation de la résilience s'est par ailleurs inscrite dans le cadre de l'évaluation quantitative intégrée de la résilience future de systèmes agricoles européens du projet Horizon 2020 SURE-Farm et dans le cadre des recherches sur l'optimisation de la production agricole et de l'impact environnemental de systèmes agricoles face à des pressions environnementales de l'institut de convergence Cland.

Le modèle développé décrit les flux et stocks de biomasse au sein d'un système agricole avec un pas de temps annuel et les comptabilise en masse d'azote. Dans le modèle, le système agricole est considéré comme une seule ferme, constituée de deux usages des sols : cultures et prairies permanentes. Chaque usage des sols comporte un compartiment de plantes et un compartiment de sol. Un compartiment du bétail chevauche les deux usages des sols, puisque les animaux, au cours d'une année, pâturent les prairies permanentes ou bien sont gardés en bâtiments. Dans ce dernier cas, leurs effluents peuvent être utilisés pour fertiliser les cultures. Le compartiment du bétail est composé d'espèces animales ayant des besoins alimentaires et des niveaux de productivité différents. Le compartiment du sol consiste en un stock d'azote organique et un bilan d'azote minéral (le modèle ne considère pas de résidus d'azote minéral). Le compartiment de plantes est considéré comme une seule parcelle par usage des sols mais qui est composée de plusieurs espèces de plantes. La production végétale par espèce de plante est proportionnelle à la disponibilité d'azote minéral dans le sol, supposant l'azote comme seul facteur limitant. Cette production végétale sature pour un rendement maximal correspondant au rendement moyen observé ces dernières années dans le système agricole. Tandis que la production animale est fonction de la nourriture animale disponible, localement puis à l'import. Le taux d'azote organique du sol est fonction des apports d'azote organique (résidus des plantes ou effluents d'élevages) et des sorties (minéralisation de la matière organique). L'engrais synthétique, la déposition atmosphérique, la fixation biologique du diazote par les légumineuses, l'azote du sol minéralisé et les parts minérales des

amendements organiques contribuent à la fertilisation minérale des plantes. La production végétale est, selon la plante, allouée aux humains et/ou aux animaux. Des pertes d'azote ont lieu lors de la gestion des effluents et la gestion du sol vers l'air ou les eaux. Les apports d'engrais synthétique et l'import de nourriture animale par les humains sont les deux flux perturbés dans les simulations.

Dans le chapitre 1, j'ai exploré la robustesse pour trois petites régions agricoles françaises avec des compositions cultures-prairies-cheptel distinctes (« grandes cultures » – Plateau Picard, « élevage de monogastriques et de bovins laits intensifs » – Bretagne Centrale, et « élevages de ruminants semi-extensifs » – Bocage Bourbonnais). J'ai assimilé le système agricole à une petite région agricole qui est un ensemble de communes avec une certaine homogénéité biophysique, pédologique et agricole et partageant un même contexte historique (superficie moyenne de 770 km²). J'ai trouvé des trajectoires distinctes de la production agricole totale pour les trois systèmes agricoles français face aux perturbations. Les élevages de ruminants semi-extensifs étaient les plus robustes à court terme (plus de 10 années) tandis que les élevages de monogastriques et de bovins laits intensifs observaient une baisse de la production agricole totale dès le début de la simulation. A long terme, les deux systèmes agricoles d'élevages étaient plus robustes (~50%) que les grandes cultures, mais restaient en absolu moins productifs. Dans le chapitre 2, pour les petites régions agricoles françaises avec une superficie agricole utile qui représente plus de 15% de la superficie totale (652 sur 713), j'ai estimé une fenêtre de robustesse de 8 années en médian et une intensité de robustesse de 31%. Néanmoins, les niveaux de robustesse étaient hétérogènes, notamment spatialement, et dépendaient d'un côté de la composition cultures-prairies-cheptel, qui détermine par ailleurs la dépendance aux intrants, et d'un autre côté de l'intégration entre culture-élevage, que j'ai explorée avec les niveaux d'autosuffisance en nourriture animale par catégorie. Les systèmes agricoles avec peu d'élevage étaient les moins robustes pour les deux métriques (dans les bassins parisien et aquitain par exemple). Les systèmes agricoles avec des élevages de ruminants étaient plus robustes que ceux avec des élevages de monogastriques, en raison de la forte production animale et dépendance à l'import de concentrés de ces derniers. La part de prairies permanentes et temporaires dans l'assolement comme la part de concentrés dans les régimes des ruminants expliquaient moins les niveaux de robustesse des systèmes agricoles avec des élevages que la densité animale et la part d'engrais de synthèse dans la fertilisation. Ces résultats montrent l'intérêt à mettre en place des changements de compositions et de pratiques qui diminuent la dépendance aux intrants, en raison du compromis entre l'usage d'intrants et la production agricole, afin d'améliorer la robustesse à des contraintes sur l'approvisionnement en intrants. Dans le chapitre 3, j'ai confirmé le compromis entre la maximisation des productions agricoles d'origine végétale et d'origine animale, et la minimisation de l'usage d'engrais de synthèse et d'import de nourriture animale pour les trois systèmes agricoles français du chapitre 1. Ce compromis dépendant néanmoins de la composition cultures-prairies-cheptel du système agricole. Un remplacement des élevages de ruminants par des élevages de monogastriques permettaient, ces derniers ayant une efficacité de l'usage de l'azote plus

élevée, de légèrement baisser le recours aux intrants tout en maximisant un peu la production agricole. Sans recours aux intrants, la maximisation de la production agricole était possible et significative avec une baisse de nombre d'animaux (~-90%), aussi bien monogastriques et ruminants, s'ils sont actuellement nombreux, et également en une augmentation des surfaces d'oléoprotéagineux pour l'alimentation animale et de légumes secs pour l'alimentation humaine, augmentant ainsi le flux de fixation biologique de l'azote. Ces changements donnaient un nombre de ruminants supérieur au nombre de monogastriques dans les trois systèmes agricoles. Ainsi, des changements de compositions et de pratiques qui diminuent la dépendance aux intrants sont une augmentation des surfaces de légumineuses, une intégration des cultures à l'élevage, une baisse du besoin en azote minéral des cultures c'est-à-dire des rendements agricoles objectifs, une baisse des concentrés dans les régimes des animaux. Ces changements sont des éléments nécessaires d'une transition agroécologique et constitueraient une déspecialisation des systèmes agricoles. Dans le dernier chapitre, j'ai identifié dans un système agricole Portugais d'élevages de bovins viande extensifs (région agricole Alentejo) un fort compromis entre la robustesse de la production de viande et l'atténuation du dérèglement climatique. Néanmoins, ce compromis (entre intensité de robustesse et atténuation du règlement climatique surtout) pouvait être atténué au maximum avec la combinaison de toutes les pratiques d'adaptation ou d'atténuation du dérèglement climatique considérées (et aujourd'hui déjà partiellement mises en place): augmentation de la surface de prairies permanentes biodiverses riches en légumineuses et plus productives, engraissement à l'herbe des bouvillons plutôt qu'aux concentrés, réduction de la taille du troupeaux et d'augmentation de la productivité animale dans le cadre de la feuille de route du gouvernement Portugais. La réduction de la taille du troupeau est inévitable pour atteindre les objectifs de réduction de gaz à effet de serre fixés par le gouvernement Portugais mais s'avérait seule délétère pour la robustesse (fenêtre et intensité).

La modélisation réalisée au cours de cette thèse n'a pas permis par définition de considérer la complexité d'un système agricole, c'est-à-dire l'ensemble de ses fonctions essentielles, et l'ensemble des perturbations possibles, au risque de tirer des conclusions qui pourraient s'avérer antagonistes pour d'autres ensembles de fonctions et de perturbations. J'ai par exemple identifiés des conclusions antagonistes concernant la robustesse de systèmes agricoles d'élevages de ruminants semi-extensifs ou de grandes cultures face aux conséquences du dérèglement climatique et du pic pétrolier. Ce risque de conclusions antagonistes invite ainsi à coupler la modélisation à d'autres types d'analyses (par exemple des enquêtes, ateliers participatifs ou analyses de la littérature grise) afin de pouvoir élargir les ensembles de fonctions et de perturbations considérés lors de l'évaluation de la résilience. Par ailleurs, les conclusions concernant la robustesse de la production agricole ne s'appliquent qu'aux perturbations simulées, qui s'avèrent être un scénario climatique optimiste et sans recours aux technologies de capture et stockage de carbone qui suppose ainsi la neutralité énergétique de l'agriculture en 2050, et ne peuvent être discutées que de manière comparative. De plus, les conclusions se rapportent aux niveaux de production agricole actuels dans les systèmes agricoles européens, stimulés par l'usage d'engrais

minéraux et l'import de nourriture animale. Cependant, l'interprétation des résultats des simulations réalisées dans cette thèse changerait avec un niveau de production agricole objectif fixé à partir des besoins alimentaires d'une population, et des choix d'exportations. Enfin, j'ai réalisé des analyses de sensibilité des variables de sortie en mode simulation (Chapitres 1 et 4) aux paramètres et aux valeurs initiales des variables d'états du modèle. J'ai trouvé des intervalles de sensibilité quasi-invariants au cours du temps signifiant que les phénomènes inertiels comme la dynamique de la matière organique des sols n'impactent.

Cette thèse a montré, dans les systèmes agricoles étudiés, qu'une baisse d'approvisionnement en engrais de synthèse et nourriture animale entraînerait une baisse significative de la production agricole, avec ou sans changements de pratiques et de compositions des systèmes agricoles. Néanmoins, certains changements, comme la baisse de la compétition alimentation humaine-alimentation animale, l'intégration cultures-élevages, la baisse des rendements agricoles et l'augmentation des surfaces de légumineuses, permettraient de contenir la baisse de la production agricole tout en contribuant à l'atténuation du dérèglement climatique. La mise en place de changements ferait néanmoins face à des verrous sociotechniques qu'il serait nécessaire de lever. Les recherches menées au cours de cette thèse ont ainsi ouvert la voie à l'évaluation de la résilience des systèmes agricoles européens à des contraintes d'approvisionnement en intrants. Elles montrent à quel point une évaluation de la résilience est complexe et longue, et les enjeux dont il est question sont urgents. Ils incitent ainsi à mettre en œuvre des démarches collectives ambitieuses au sein de systèmes agricoles européens pour évaluer la résilience de manière complète et rapide. Ces recherches ouvrent également sur de nombreuses perspectives, dans un premier temps à partir du modèle dans sa version actuelle. A titre d'exemples, les analyses réalisées dans cette thèse pourraient être appliquées à d'autres systèmes agricoles européens. On pourrait aussi calculer d'autres composantes de la résilience avec d'autres modes d'analyses comme l'adaptabilité à l'aide de la théorie de la viabilité ou encore explorer l'impact de changements d'usages des sols et de l'amélioration du taux de recyclage des nutriments sur la robustesse de la production agricole. Dans un second temps, le périmètre du modèle pourrait être élargi, que cela soit les perturbations, les fonctions ou les pratiques considérées, tout en adaptant les relations modélisées entre perturbations et fonctions. Par exemple, on pourrait simuler des scénarios de ruptures d'approvisionnements en intrants liés à des instabilités politiques et économiques comme l'invasion de l'Ukraine par la Russie à l'hiver 2022 ou encore considérer des perturbations liées au dérèglement climatique. Enfin, la modélisation pourrait être raffinée en intégrant des dynamiques culturelles intra-annuelles comme les cultures associées et les cultures intermédiaires.

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Glossary

C	Carbon
EFESE	French Evaluation of Ecosystems and Ecosystem Services (Evaluation Française des Écosystèmes et des Services Écosystémiques)
FS	Farming system
GHG	Greenhouse gas
GWP* or GWP₁₀₀	Global warming potential star or over 100 years
LU	Livestock unit
N	Nitrogen
SAR	Small Agricultural Region
UAA	Utilised Agricultural Area

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I General introduction

Current agriculture is very intensive in inputs (water, fuel, pesticides, and fertilisers). As a result, it is very vulnerable and not very resilient to the depletion and cost increase of non-renewable resources (e.g. fossil fuels, phosphorus) as well as environmental issues (climate change, biodiversity loss). In the scientific literature, assessments of the resilience of farming systems mainly focus on the issue of climate change and quantitative analyses of resilience using a model are quite rare. The aim of this PhD thesis is to contribute to the assessment of the resilience of European farming systems to input constraints related to global issues and more particularly to the increase in energy costs linked to the occurrence of global peak oil. A dynamic macro-model of nitrogen flows of a farming system was designed to meet this ambition.

I.1 Global and societal context - An European agriculture vulnerable to environmental, energetic and economic challenges

I.1.1 The birth of an industrialised European agriculture

From Roman times to the 18th century, European farming worlds changed little. The industrial and scientific revolution slowly penetrated these worlds and set them in motion on all levels, namely on technical, economic and social levels. In the second half of the 19th century, the development of agronomic sciences, the appearance of collective animal selection schemes (*herd books*) and professional seed companies, the industrial production of machinery, the appearance of mineral fertilisers (e.g. phosphates, guano, potash) and the first crop treatments (e.g. Bordeaux mixture), the rapid development of railways and river and sea transport reconfigured agricultural activity. A growing number of farmers entered the modern world by becoming real economic agents, active on the markets beyond the local scale where they had previously been largely confined.

This phenomenon increased after the First World War, with the outbreak of motorisation and the industrial production of synthetic nitrogen fertilisers by the Haber-Bosch process, using atmospheric nitrogen and natural gas. These two innovations had a major direct impact on farming systems and rural landscapes, sounding the end of the crop-livestock association, which had previously been essential both for work (animal traction) and for land fertility management (manure being the main source of nitrogen fertiliser). It accelerated even more after the Second World War, when national and then European policies made the modernisation of agricultural techniques and structures the basis of the project to rebuild food sovereignty and provide the population with abundant food at low prices. The development of motorisation, the generalisation of the use of synthetic fertilisers, high-potential varieties and breeds, chemical products for treating crops and livestock, the scientific rationalisation of cultivation and

breeding techniques, and the specialisation of production basins according to the comparative advantages offered by their pedoclimatic potential have produced spectacular results.

In France, labour productivity increased by a factor of 3 between 1950 and 1970, and 6 between 1970 and 2018¹. Production has risen considerably thanks to increased yields. For example, maize yields tripled and soft wheat and potato yields doubled between 1961 and 2013 on a European scale (FAO, 2021). Over the same period, meat production increased from 20 to 45 million tonnes (or around 88 kg of meat per capita) and milk production from 120 to 160 million litres. This increase reflects the development of increasingly intensive monogastric and ruminant breeding systems, raised in buildings. These intensive breeding systems have high levels of productivity that require a diet based on high consumption of energy concentrates (cereals) and protein concentrates (e.g. soya and oilseed cakes), a large proportion of which is imported. As a result, the share of cereal production allocated to livestock increased, reaching 68% in 2013 (FAO, 2021) and the forage areas in the crop rotation decreased (Huyghe, 2009).

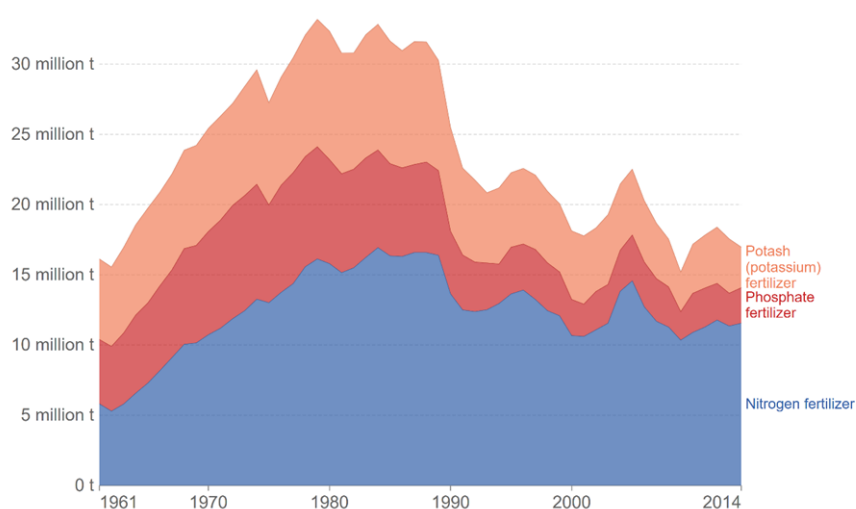


Figure I.1 “[Fertilizer production by nutrient in the European Union in million tons per year from 1961 to 2014](#)” by [OurWorldInData.org](#). Data originates from (FAO, 2021). CC BY

¹ Unless otherwise indicated, the key figures in this paragraph and the following one come from Service études références et prospective (2019) from the French Food and Agriculture Ministry.

However, this production increase has been accompanied by a parallel increase in the quantity of intermediate consumption. Thus, from 1961 to 2014, the production of synthetic nitrogen fertilisers more than doubled in Europe (Figure I.1). The production of phosphate and potash fertilisers reached a peak in the 1980s before decreasing below the 1961 level as the soils have accumulated them since then (Le Noë et al., 2020). Over the course of the 20th century, European agriculture went from being energy self-sufficient to being heavily dependent on fossil fuels (Harchaoui and Chatzimpiros, 2019) (Figure I.2). Between 2008 and 2013, agricultural production in France required an average of nearly 8.4 million tonnes of oil equivalent (mtoe) for agricultural production and almost 10 mtoe for the transport of food upstream or downstream of agricultural production (Barbier et al., 2019). This represents about 15% of France's current fossil fuel consumption (Service des données et études statistiques, 2021). A significant part of the indirect energy in agricultural production is used to extract and synthesise fertilisers (~3 mtoe in France).

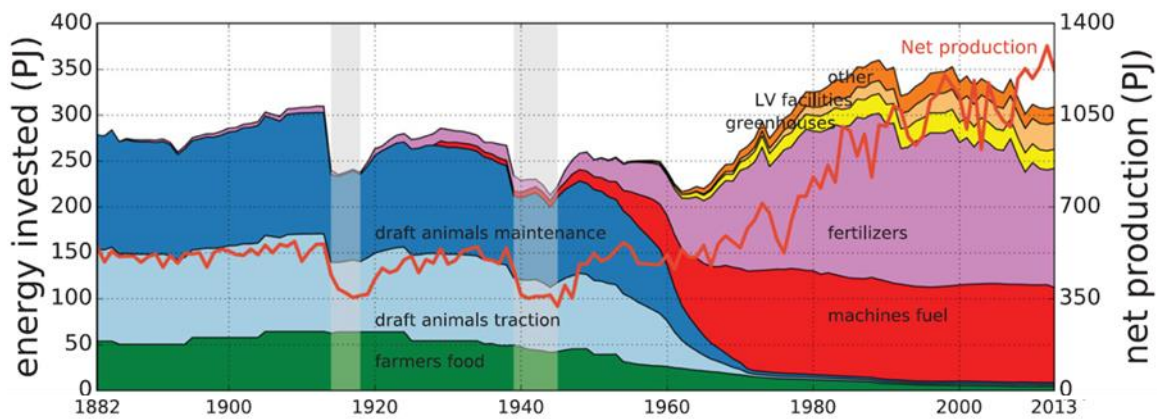


Figure I.2 Energy invested per source in PJ and net production in PJ of agriculture from 1882 to 2013 in France. “Other” includes energy for irrigation and embodied energy in pesticides and imported feed. Subfigure 5a from Chatzimpiros et al (2019)

I.1.2 Environmental and social impacts of the European agriculture: source of global challenges

The evolution of European agriculture in the second half of the 20th century has led to the emergence of environmental and social negative consequences. Environmentally, it has led to deforestation, eutrophication of aquatic ecosystems, degradation of agricultural soils, loss of wild biodiversity and greenhouse gas emissions. Socially, it has led to a decline in the number of farmers, an increase in farm debt, and social isolation of farmers, among others.

I.1.2.1 Social impacts

The modernisation of technical systems has certainly led to a massive increase in labour productivity, but this has been accompanied by a considerable increase in production costs. The need for investment in ever more powerful farm machinery and more sophisticated equipment could only be made profitable through a significant change in scale. The least endowed and most financially vulnerable farmers disappeared. Thus, France had 1.6 million farms in 1970, but fewer than 400,000 in 2017 (Desriers, 2007; Ministère de l'Agriculture et de l'Alimentation, 2022). The active population has fallen from 3 million to less than 650,000. This demographic collapse can only get worse: 40% of the working population was over 55 years old in 2016, and the rate of takeovers by heirs has never been so low. Moreover, expansion is far from always synonymous with economic efficiency. The average income of farmers, which increased rapidly until 1970, remained constant for the next 20 years. The introduction of direct aids during the 1992 Common Agricultural Policy reform led to a sharp increase (almost 60%) in average farm income between 1992 and 1995. Since then there has been a very slight upward trend. However, incomes are increasingly variable, due to the instability of agricultural commodity prices, which have become the object of financial speculation since the 2007 crisis, and also due to the increasing number of climatic extreme events throughout the world, which are having an ever greater impact on production and are fuelling price volatility on markets that are under constant pressure. Farmers' concerns and dissatisfaction are fuelled by another reality: Common Agricultural Policy subsidies now account for just over 25% of the agricultural sector's net added value. They can represent three quarters of farmers' income, and without them, 18% of farms would have a negative income. One third of farmers have a monthly income of less than 600€. However, this is not for lack of effort to adapt. Investments have never ceased, at the cost of a sometimes excessive debt that is constantly increasing, reaching an average of nearly 43% of the assets value in 2017, even though interest rates were at their lowest (APCA 2019).

The disappearance of farms has been general throughout the country. Initially, it massively affected the areas with the least favourable soil and climate conditions, leading to the abandonment of large areas of farmland to fallow land or reforestation. It now affects all French regions, including the most dynamic. However, today it is the expansion of urbanisation that is the main cause of the shrinking of agricultural area in France, but also in Europe: from 1960 to 2016, the agricultural area fell from 342 to 286 million hectares (mha), whereas at the beginning of the 20th century it was 308 mha (Klein, Goldewijk et al., 2017).

1.1.2.2 Environmental impacts

The development of tools for capturing and storing water makes it possible to tap into deep aquifers and build up water reserves. For irrigated areas, water is no longer the limiting factor for plant growth. In 2016, the surface area of irrigated crops was 10 mha in Europe, *i.e.* a little over 3% of the agricultural surface area (Eurostat, 2019). This area increased by 6% between 2005 and 2016. Although the irrigated area is small, irrigation accounts for half of France's water needs (Ariane Blum, 2005). This poses increasingly important problems given the consequences of climate change and increased competition for water resources.

Cultivated ecosystems have been simplified and homogenised, in particular to facilitate the crossing of agricultural machinery. Plots have become larger (Flatrès and Flatrès, 1997), hedges, wetlands and permanent grasslands have partly disappeared (Huyghe and Peeters, 2015; Pointereau, 2002), and rotations have been shortened (Schaller, 2012). For example, in France, only 0.6 million kilometres of hedges remained in 2000, compared to 2 million kilometres in 1900 (Pointereau, 2002) and the proportion of arable land with a crop rotation of 2 years or less has increased considerably since 1970 (Schaller, 2012). These trends, which continue to grow, have important negative consequences for the biodiversity of agroecosystems (Le Roux et al., 2008) and contribute to the pest pressure on crops and therefore to the use of crop protection products (Schaller, 2012).

European industrialised agriculture has contributed and still contributes massively to the deforestation of tropical forests, particularly in South America, due to soy imports (Figure I.3). At the global level, the expansion of agricultural land is responsible for 80% of deforestation, mainly of tropical forests (Kissinger et al., 2012). However, the expansion of agricultural land is increasingly due to foreign demand: between 26% and 39% of tropical deforestation is linked to international trade, mainly in beef and oilseeds, thus representing one sixth of the carbon footprint of European agriculture (Pendrill et al., 2019). Soya cake, used exclusively for feed, generates a quarter of the total traffic in foodstuffs to France and 86% of that by sea (Barbier et al., 2019).

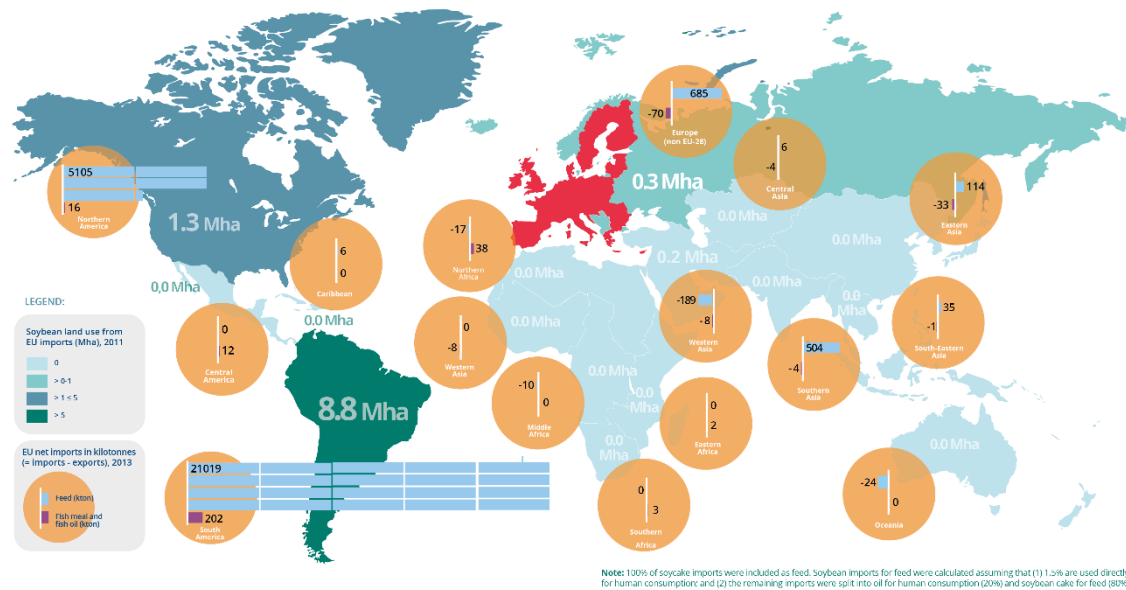


Figure 1.3 European Union feed imports and land dependency. Infographics from the European Environmental Agency published in 2017 and based on data from 2011 and 2013 (EEA, 2017).

The increase in the use of mineral nitrogen and phosphate fertilisers has led to an increase in the concentration of nitrogen and phosphorus in downstream watercourses, when fields are leached, and hence to an increasing eutrophication of aquatic environments (Smith, 1998). This increase favours the proliferation of photosynthetic organisms (algae or bacteria). The death and decomposition of these organisms progressively deprives the aquatic environment of oxygen and thus leads to the death of other organisms (including fish) in this environment (e.g. green tides on the sea coast). Approximately 6 kilotonnes of nitrogen per year, mainly of anthropogenic origin and resulting from livestock production, are leached into the waters of the European Union (Leip et al., 2015). The coastal areas most affected by this phenomenon are the Baltic Sea, the Adriatic Sea, the English Channel, the west coast of the Black Sea, the south-east continental coast of the North Sea (Billen et al., 2011).

The use of increasingly powerful and heavy motorised agricultural machinery has contributed to the degradation of agricultural soils (Keller et al., 2019), *i.e.* a degradation of their fertility, which is mainly indicated by the soil organic matter content (Ferreira et al., 2022). Indeed, soil organic matter favours the biological action of soils, the retention and progressive release of nutrients and the infiltration and storage of rainwater (Lefroy et al., 1995). However, the weight of machinery compacts the soil, and the tools used to work the soil deteriorate the soil structure. As a result, erosion and the loss of nutrients and organic matter accelerate (Rodriguez Eugenio et al., 2018). For example, 40% of arable land in France had soil with a deficit of organic matter between 1990 and 1994 (Roussel and Bourmeau, 2001). However, the increase in crop yields through the use of synthetic fertilisers and the increase in livestock production have contributed during the 20th century to an increase in soil organic matter stocks (Le Noë et al., 2019). This has probably compensated for the above-mentioned consequences on soil fertility.

Pesticide use and the reduction of hedgerows have contributed to a decrease in habitat and wild biodiversity in agroecosystems (Beketov et al., 2013; Brühl and Zaller, 2019; Richard, 2010). A 67% drop in insect biomass has been observed over 10 years in Germany in permanent grasslands (Seibold et al., 2019). In France, a 33% decline in the number of birds dependent on agricultural environments has been observed over the last 30 years (Commissariat général au développement durable, 2018).

Pesticide use has also contributed to water pollution (Mohaupt et al., 2020) and impacts human health through water pollution, air pollution or ingestion of food containing pesticide residues (Bassil et al., 2007; Bjørling-Poulsen et al., 2008; Fantke et al., 2012). They contribute to anti-biological resistance (García et al., 2020; Rangasamy et al., 2018), are endocrine disruptors (Combarrous, 2017; Mnif et al., 2011) or are carcinogenic (Bassil et al., 2007).

The increase in livestock populations, the use of mineral fertilisers and the use of motorised agricultural machinery, have contributed to the increase in greenhouse gas emissions, thereby contributing to human-induced climate change. They accounted for about 10% of the European Union's greenhouse gas emissions in 2015, or about 0.5 GtCO₂-e (European commission, 2020; Lamb et al., 2021) (Figure I.4). The main emissions are methane from ruminant enteric, and nitrous oxide from the management and application of organic or mineral nitrogen fertilisers on crops.

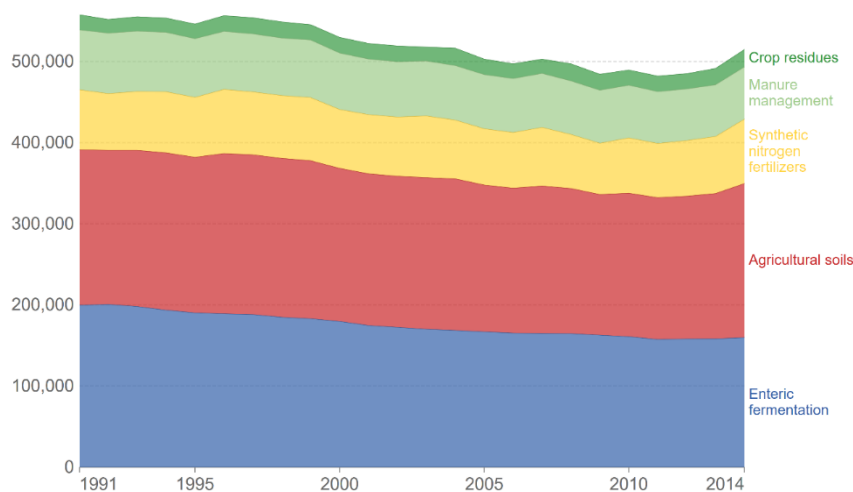


Figure I.4 “[Greenhouse gas emissions from agriculture by source in the European Union from 1991 to 2014](#)” in GtCO₂-e per year by [OurWorldInData.org](#). Data originates from (FAO, 2021). CC BY.

I.1.3 Trade-offs or synergies between functions in the industrialised European agriculture

The modernisation of agriculture in developed countries and the 'green revolution' that has spread throughout the world have focused exclusively on the function of producing 'marketable biomass', with the environmental and social consequences just mentioned. However, agriculture can provide a variety of functions, some of which can be linked to ecosystem services, which can be divided into private or public (Darnhofer et al., 2008; Meuwissen et al., 2019) as well as provided to or accessible by a variety of social groups beyond the farming world. Non-exhaustively, the private or market functions are the production of biomass for human consumption and other uses (feed, seeds, fiber, materials, medicine and cosmetics, energy, etc.), and also the contribution to the quality of life of farmers which depends, among other things, on the work ergonomics, the income level, the pleasantness of the living environment. Public functions are the quality of biodiversity (e.g. habitats, wild and cultivated species, genetics), the quality of abiotic resources, the animal welfare, and the recreational quality of the agricultural landscape. These functions are available to any human or livestock living in the farming system.

This diversity of functions is the subject of measurements or modelling to explore the relationships between them. As part of the EU's Biodiversity 2020 strategy, the Joint Research Centre (European Commission Research Centre) (Maes et al., 2016) has mapped the provision of ecosystem services at the EU level over time (European commission et al., 2011; Maes et al., 2015). This work can be used as a basis for statistical analyses of the relationships between ecosystem services and the impacts of changes in practices or uses on the provision of these services. The analysis of these relationships can be used as a decision support tool for the development of public policies and the evaluation of their impact (Maes et al., 2012 - Table 5.1).

Different types of relationships between the functions of agriculture are possible. They can be in trade-off, when an increase in the level of provision of one function leads to a decrease in the level of provision of another function, or in synergy, when an increase in the level of provision of one function leads to an increase in the level of provision of another function, or neutral (Bennett et al., 2009). For example, at the European Union level, Jopke et al. (2015) have shown that arable land area is in trade-off with water quality and that it is the ecosystem service at the European scale with the most trade-offs with the other ecosystem services selected in this study. Balbi et al. (2015) demonstrated in a cropping system in the Basque Country that improving air quality and water quality by reducing manure use necessarily implies a decrease in crop productivity. In the UK, Field et al. (2016) showed that changes in agricultural and land use practices on a farm would lead to a decrease in crop production but would increase the number of breeding birds and decrease greenhouse gas emissions. In France, Deguines et al. (2014) have shown

that for 54 crops from the 1990s to the 2010s intensification of pollination-dependent crops does not lead to the expected gains in productivity because the pollination service is degraded by this intensification. More broadly, the modernisation of agriculture and the green revolution have led to an increase in the functions of biomass production at the expense of public goods-type functions (e.g. water and air pollution, soil degradation, loss of biodiversity, homogenisation of the agricultural landscape) but also of certain aspects of the quality of life of farmers (social isolation, level of debt)

A relationship between two functions can evolve depending on the farming system. Indeed, changes in agricultural practices, biomass use, land use, or even socio-economic changes impact the supply levels of the functions of a farming system and possibly the intensity of the relationships between the functions or even the type of relationship (trade-off or synergy). For example, simultaneous polyculture (diversification of crops in a plot at a given time) can increase biomass productivity as well as the pest control services (Iverson et al., 2014), just as an increase in the area of permanent grassland can, in some regions, increase the feed production and the provision of other ecosystem services (e.g. carbon storage) (Accatino et al., 2019).

I.1.4 Vulnerabilities of the industrialised European agriculture to the global challenges

The evolution of European agriculture in the second half of the 20th century made it vulnerable to various global challenges, to which it has partly contributed: depletion of fossil and mineral resources, climate change and global warming, loss of wild and cultivated biodiversity, and economic and political instabilities. These global challenges have two types of consequences for the functions of European agriculture: (i) gradual and predictable degradations; (ii) crisis situations, *i.e.* exceptional degradations, limited in time, unpredictable, and important.

I.1.4.1 Two threatening resources peaks: Oil and Phosphorus

The production and consumption of a finite resource (whether fossil or mineral) follows a bell curve (Gaussian curve) over time, *i.e.* it starts from zero, peaks and then falls back to zero (Auzanneau and Chauvin, 2021). Depending on the growth rate of consumption of this resource, and the amount of resource available, the peak may take the form of a longer or shorter plateau and occur more or less soon after the start of production. As explained in paragraph I.1.1, European agriculture has become dependent on fossil and mineral resources. Two resources on which European agriculture is dependent are oil and phosphate rock. Oil powers the farm machinery, the trucks that transport inputs and foodstuffs, and the machines that extract the phosphate rock that supports crop growth. However, these two resources could reach their peak production in the next two decades (2020-2040), which would most likely threaten food security in Europe.

Oil

Oil supply could start to decline in the short term, *i.e.* in the decade 2020-2030, in the face of a demand that continues to grow due to an increasing population and economic development (IEA, 2018). Indeed, conventional oil supply has reached a plateau since 2008 (75% of all liquid fuel production), and was 4% lower than 2008 in 2019 (Auzanneau and Chauvin, 2021). This decline is inexorable due to the decrease in both conventional oil discoveries (since the mid-1960s and despite increasing investment since then) and remaining reserve levels. In the geological sense, the notion of "reserve" refers to the recoverable volumes or quantities of a resource under the contemporary technical and economic conditions in deposits that have been or are in the process of being exploited. While the notion of "resource" refers to all the volumes or quantities contained in the earth's subsoil (IFP Energies nouvelles, 2013). The technologies for discovering oil have never been so sophisticated. However, the International Energy Agency (IEA) considers that the discovery of significant reserves of conventional oil or a technological breakthrough that would significantly increase the extraction of conventional resources is highly unlikely. Since 2008, it is the supply of US unconventional (shale) oil that has mostly

met the increase in oil demand (13.9 million barrels per day (mb/d) in 2019). Increased production of heavy unconventional oil such as Canadian oil sands or Venezuelan "extra-heavy" oil is struggling to grow and will only account for 7 mb/d in 2021. To meet growing future demand, production would have to triple by 2025 (*i.e.* 30mb/d) (IEA, 2018). However, the COVID-19 pandemic has put a stop to US unconventional shale oil production, leading to a general freeze on investment. Thus, during the decade 2020-2030, oil supply (conventional and unconventional) could no longer meet global oil demand (IEA, 2018), specifically the European Union oil demand (Figure I.5).

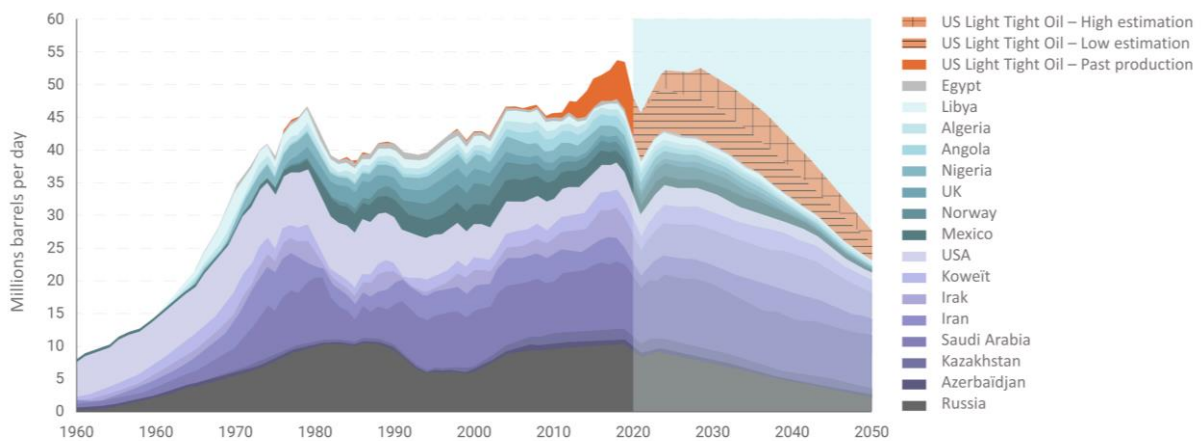


Figure I.5 Past production of conventional and unconventional oil in million barrels per day in the 16 main European Union supplier countries based on Rystad Energy data and post-2020 projections by The Shift Project (Rech and Duterne, 2021).

This near and anticipated decline in oil supply will have political and economic consequences that could ultimately impact the production capacity of European farming systems. Indeed, an increase in the variability of oil prices due to the decline in supply would have the same effect on the price of agricultural commodities as has been observed in the past, notably during the subprime crisis and the Arab Spring (Irz et al., 2013; Lagi et al., 2011; Naylor and Falcon, 2010; Vatsa and Miljkovic, n.d.). In the two oil shocks of 1973 and 1979, constraints on oil supply led to higher prices. The increase in oil prices in 2008 due to the production plateau of conventional oil is discussed as one of the origins that led to the subprime crisis (Auzanneau and Chauvin, 2021; FAO, 2009). Moreover, as oil enables the extraction of mineral resources and the transportation of these and other resources, a peak oil would probably imply a peak in these mineral resources (Auzanneau and Chauvin, 2021; Heinberg, 2010). Furthermore, the risk of supply shortages of primary (e.g. oil, gas), secondary (e.g. fertilisers, pesticides) or final (e.g. food) resources would increase, especially in densely populated geographical areas (Steel, 2013). This is all the more true in the absence of interventionist public policies to prioritise the supply of inputs and foodstuffs. At the end of 2021, the rise in gas prices led to a rise in the price of synthetic

fertilisers and then to a rise in the price of foodstuffs, threatening, as in 2008 and 2011, the food security of the poorest households, of which farmers are a part, especially in developing countries (Christian de Perthuis, 2021).

Phosphorus

Phosphate rock supply could start to decline during the 2030-2040 decade, in the face of a global demand that is expected to continue growing (Cordell and White, 2011). Phosphorus is an essential element for life, and a limiting factor for plant growth. Unlike nitrogen, phosphorus cannot be synthesised and is not present in the atmosphere. It is a non-substitutable resource, derived solely from phosphate rocks, and these rocks are concentrated in few countries in the world. On a global scale, the demand for phosphate rock is growing, while in Europe the demand has been constant for several decades (Food and Agriculture Organization of the United Nations, 2019) because part of the historical inputs (1950-1980s) in excess has accumulated in the soils of arable land and becomes bioavailable to plants each year (e.g. for France see Le Noë et al. (2020) and Ringeval et al. (2014)). Over the past 10 years, the concept of a phosphorus peak has emerged in the scientific literature (Cordell and White, 2011). There is a consensus that there is a decline in the quality and accessibility of reserves, an increase in extraction costs and inefficient use of the resource today, but due to uncertainties in rock reserve data there is no consensus on the date of peak phosphorus yet (Cordell and White, 2011). Based on USGS rock reserve estimates (16,000 million tonnes), which may be underestimated, peak phosphorus could occur in the next decade of 2030-2040 regardless of the impact of peak oil on extraction capacity. As the most concentrated deposits are depleted, the amount of energy needed to obtain the same amount of ore increases, *i.e.* the cost, especially in a world where oil is becoming scarcer and more expensive. In other words, peak oil could precipitate peak phosphorus on a global scale.

As with oil, this future decline would increase the price of phosphate fertilisers and the risk of supply disruptions. Without changes in agricultural practices and farming systems, agricultural yields would decline on a global scale and thus food production. In France, stopping the use of phosphate mineral fertilisers could still allow agricultural yields to be maintained by 2075 with the application of organic fertilisers, as the soils have accumulated phosphorus since the 1950s (Le Noë et al., 2020). Changes in agricultural practices and composition (e.g. by reducing phosphorus losses during livestock effluent management or by recycling human effluent) would contribute to slowing down the depletion of phosphorus stocks in soils and thus to maintaining agricultural yields.

1.1.4.2 Climate change

Climate change is the consequence of the increase in the concentration of greenhouse gases in the atmosphere due to the burning of fossil fuels and the change in land use (mainly deforestation) resulting from human activities. The increase in these greenhouse gases generates an additional greenhouse effect, increasing the amount of energy captured on earth. This increase in energy generates a melting of glaciers and ice caps contributing to the rise in sea level. The global average surface temperature of the continents is increasing, as is the temperature of the oceans. Precipitation patterns are changing, and the frequency and intensity of droughts (Grillakis, 2019), floods, heat waves and storms are increasing (IPCC, 2021). These major gradual degradations but also these crises are sources of variability and progressive decline in agricultural yields (Field et al., 2014). In addition, climate change intensifies pest activity, which is a source of lower agricultural yields (Civantos et al., 2012; Deutsch et al., 2018; Raven and Wagner, 2021) just as the degradation of agricultural soils in Europe increases vulnerability to extreme weather events (Ferreira et al., 2022).

1.1.4.3 Biodiversity loss

Agriculture contributes significantly to the loss of wild biodiversity (Le Roux et al., 2008) which is characterised by a decline in the number of individuals of species, species richness (species number) and consequently functional diversity and response (IPBES, 2018). This loss of wild biodiversity involves three major gradual degradations: a decrease in pollination (IPBES, 2016), a decrease in the regulation of pest (Raven and Wagner, 2021) as well as a decrease in the biological fertility of soils due to the reduction in the activity of soil micro-organisms (Hasan, 2000; Turbé et al., 2010; Williamson and Wardle, 2004). These major gradual degradations have a negative impact on agricultural yields. The declines in agricultural yields can be all the more significant as three quarters of the world's crop species (*i.e.* one third of global production) depend on insects for pollination (Dainese et al., n.d.; Klein et al., 2007).

The decline in intra-varietal and crop-specific diversity during the 'green revolution', (Goffaux et al., 2011; IPBES, 2018) together with the pesticide use and the decrease in hedgerow lineages, have in turn increased vulnerability to both extreme weather events linked to climate change (Bélanger and Pilling, 2019; Raven and Wagner, 2021) and the spread of pathogens, pests or invasive species (Bonneuil et al., 2012; Chateil et al., 2013; Tooker and Frank, 2012) . Such spread is also enhanced by climate change. For example, more virulent strains of wheat rusts, which are diseases caused by fungi of the genus *Puccinia* on straw cereals, have emerged and threaten straw cereal crops (Singh et al., 2011). Low intra-varietal diversity threatens the production of these crops almost entirely in climatic regions favourable to these pathogens. In addition, climate change favours the airborne transport of these pathogens to geographical areas that have been spared for several decades (Lewis et al., 2018; Prank et al., 2019).

I.1.4.4 Political and economic instabilities

For two decades, the debt of private economic actors has been growing faster than economic flows, *i.e.* these actors are increasingly indebted (Vitor Gaspar et al., 2021). This gradual deterioration, together with the increased risk of sudden commodity price inflation due to the approaching global peak oil and more frequent and intense extreme weather events or geopolitical conflict, increases the risk of a global economic crisis, *i.e.* the risk of a default in the repayment of debts by private economic actors (International Monetary Fund, 2020). For households, an economic crisis implies a drop in purchasing power, which can put the weakest social layers, including farmers, in a precarious situation (Atelier paysan, 2021). It would also be a source of social movements that generate political instability (Lagi et al., 2011) (Figure I.6) which could amplify the economic problems. Finally, it could contribute to disruptions in the supply of key goods and services (following bankruptcies), particularly in the food systems. These disruptions would in turn contribute to instabilities in global markets.

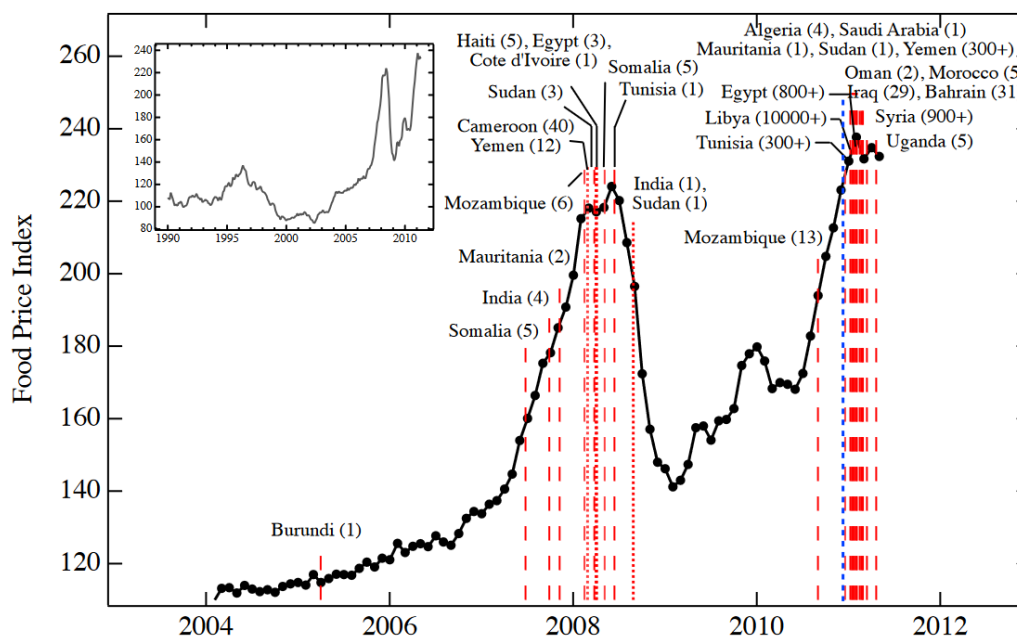


Figure I.6 FAO Food Price Index from 2004 to 2011 and beginning dates of “food riots” and protests in North Africa and in the Middle East (red dashed vertical lines). The numbers in brackets correspond to the number of victims for each conflict. The inset shows FAO Food Price Index from 1990 to 2011. Figure 1 from (Lagi et al., 2011).

I.1.5 Practices or composition changes to decrease vulnerabilities

In the scientific literature, a certain number of changes in practices or compositions are identified and implemented in reality to reduce the vulnerability of European farming systems to the challenges they face. They aim to promote wild or cultivated biodiversity, reduce the use of inputs (water, pesticides, fertilisers and fuel), reduce GHG emissions, increase organic carbon stocks in agricultural soils, adapting cultivated plants and livestock to the consequences of climate change, reduce economic and social inequalities and improve the accounting of agricultural farms. Changes in practices concern, for example, herd management, genetic selection, effluent management, crop fertilisation and food waste. Changes in composition are understood to be all changes in crop area, livestock number and livestock diet. Changes in land cover (e.g. permanent grassland, cropland) are considered as structural changes. In a non-exhaustive way, I list below five actions, specifying the issues they address or the vulnerabilities they reduce, *i.e.* why they are implemented, and to what extent they are and/or can be implemented:

- Re-establish hedgerows around plots to both host biodiversity (Pointereau, 2002) and store carbon in the soil (Pellerin et al., 2020). Nevertheless, for example in France, the trend towards a decrease in the number of kilometres of hedgerows is not currently being reversed (Solagro, 2017).
- Increase the nitrogen use efficiency of both livestock at the individual level, for example, by optimising their diets (Millet et al., 2018), and crops, by optimising the application of nitrogen fertilisers at plot level. This increase would reduce the use of synthetic or organic fertilisers (Bouraoui et al., 2014) as well as GHG emissions (Gu et al., 2017). For crops, since the 2000s, the nitrogen use efficiency in France has changed little and is currently about 70%. However, the possibility of increasing efficiency is limited if we wish to avoid destocking soil nitrogen (Hutchings et al., 2020; Lassaletta et al., 2014a). For livestock, the nitrogen use efficiency in Northern Europe is between 25% and 35% (Hutchings et al., 2020). The possibility of increasing efficiency is also limited (at most +10%) but more important for monogastrics than for ruminants (Hutchings et al., 2020).

- Increase recycling rates of human and animal excreta to reduce the use of synthetic fertilisers and GHG emissions (Peyraud et al. 2014). For human excreta, the recycling rate is low today in Europe. For example, for a city like Paris, the recycling rate of nitrogen from human excreta has gone from 50% at the beginning of the 20th century to less than 10% today (Esculier et al., 2019). The recycling rate of human excreta could be increased by composting organic waste, applying 100% of sewage sludge to agricultural land or separating and collecting urine at source (Esculier et al., 2019). For animal excreta, the recycling rate of nitrogen from livestock effluents was 75% before spreading in 2010 in France (Service de l'observation et des statistiques, 2013). This recycling rate could be increased by technical innovations along the management chain that would also make it possible to significantly reduce the content of undesirable elements, particularly chemical or medicinal residues (Peyraud et al. 2014).
- Diversify crop rotations by adding legumes or adopting legume or legume-associated intercropping practices to reduce the use of synthetic fertilisers and improve soil quality and health (Nemecek et al., 2008; Schaller, 2012; Voisin et al., 2014). Nevertheless, today, for example, in France, the trend is still towards simplifying rotations (Schaller, 2012). Concerning associated crops, the pea-cereal mixture represented less than 100,000 ha (*i.e.* less than 0.3% of the agricultural area) in 2012 in France (Schneider and Huyghe, 2015). Before the 1950s, cereal-legume associations were nevertheless very common in France (Schneider and Huyghe, 2015). The systemisation of intermediate crops would also have a significant effect on reducing the climatic impact of French agriculture (Solagro, 2017).
- Integrate livestock (composition and diets) into cereal systems while decreasing feed-food competition for biomass use to reduce feed imports (Billen et al., 2021a) or reduce the need for agricultural land (Van Zanten et al., 2018). Today, the trend is still towards stagnation in livestock size (Eurostat, 2020) and the content of concentrates in their diet is now several tens of percent for cattle and more particularly for dairy cattle (Hou et al., 2016). The livestock population in Europe should at least be halved to significantly reduce feed imports (Poux and Aubert, 2018).

I.2 Scientific challenge: assessing European farming systems resilience

As we have seen, there are numerous changes in practices and in the composition of European farming systems to reduce their vulnerability to the challenges they face. The scientific challenge is then to evaluate and therefore measure the effectiveness of these actions to reduce vulnerabilities. The concept of resilience is one of the measures that make it possible to evaluate the effectiveness of actions to reduce vulnerability (Prosperi et al., 2016; Urruty et al., 2016). This measurement requires the collection and statistical analysis of qualitative and/or quantitative data and can be also done through modelling (quantitative method) which consists of the mathematical description of the relationships between the spatiotemporal variables of the studied system. The interests of modelling are to be able to evaluate the future spatiotemporal evolution of the system's functions in the face of one or more hitherto unobserved disturbances or simply to overcome a lack of historical data.

I.2.1 Resilience concept in the scientific literature

Today, in the scientific literature, the concept of resilience is used in many disciplines and applied to many systems. It was first used in materials physics at the end of the 19th century and later in psychology and computer science, before being used in agronomy, among other fields (Martin, 2015). The common idea of resilience is the capacity of the system to maintain or recover its properties despite disturbances over which it has no control. This capacity is often divided into components to facilitate its measurement (Meuwissen et al., 2019; Tendall et al., 2015). For example, Tendall et al. (2015) identify 4 components (Figure I.7): (i) the capacity to withstand disturbances, (ii) the capacity to absorb disturbances, (iii) the capacity to recover essential functions as quickly as possible (engineering resilience) and (iv) the capacity to adapt or transform. Finally, Carpenter et al. (2001) emphasised the importance of specifying which properties or functions of the system (resilience 'of what') and which disturbances (resilience 'to what') are being considered.

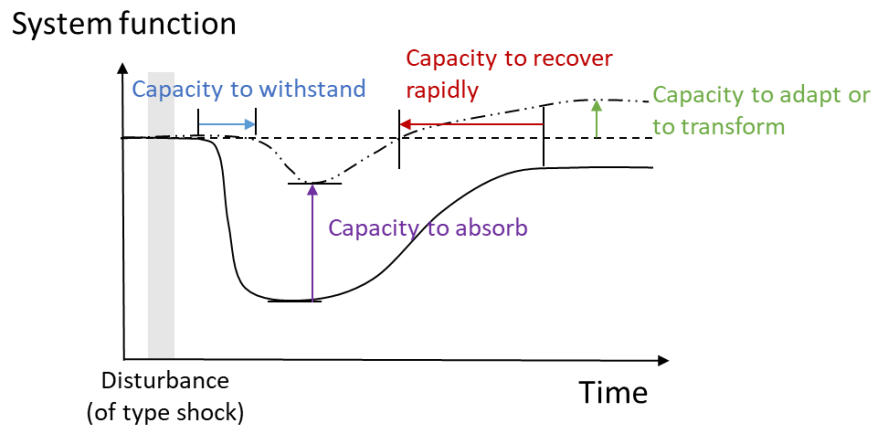


Figure I.7 Diagram of components of resilience of a system function to a shock-type disturbance, adapted from Tendall et al. (2015)

I.2.2 Assessment indices of resilience

Based on the components of resilience, depending on the quantitative approach adopted and the formalism used to describe the dynamics of the system in the context of modelling, *i.e.* its functions or properties, many measurement indices have been proposed. For example, in the case of dynamic macro-models with stable equilibria (or basins of attraction), it can be the amount of disturbance that a system can absorb without undergoing a jump in state into another basin of attraction (e.g. Beddington et al., 1976). The resilience measure can be the inverse of the time required after a shock to return to a state close to that before the disturbance in the case of agent based dynamic models (par exemple Ortiz and Wolff, 2002). In the case of controlled dynamic macro-models (in the form of differential equations), it can be the inverse of the cost of returning after a shock to a state from which the property can again be maintained (Martin, 2004). The latter two measures could also be used in the analysis of quantitative historical data. In the case of statistical data analysis, the resilience measure can be spatial and/or temporal statistical indices calculated from spatio-temporal data (Kahiluoto et al., 2019; Seekell et al., 2017) and be based not on resilience components but on resilience criteria (or attributes) (Cabell and Oelofse, 2012; Meuwissen et al., 2019; Resilience Alliance, 2010). For example, the Resilience Alliance (2010) proposed 4 generic resilience criteria: (1) diversity in responses to disturbances but also in functions; (2) modularity and connectivity, *i.e.* the internal division of the system into independent but connected modules; (3) cohesion of actors, which favours their collaboration and involvement; (4) autonomy of the territory in decision-making, food production, inputs etc.

I.2.3 Resilience concept in the farming system literature

The concept of resilience has also been increasingly applied in recent years to farming systems (or systems that encompass it²) in the scientific literature, resulting in numerous definitions (Douxchamps et al., 2017; Stone and Rahimifard, 2018). For example, Tendall et al. (2015) have defined the resilience of a food system as its capacity, and that of its components, to provide sufficient, appropriate and accessible food for all, over time in the face of various and unexpected disturbances, thus linking to the concept of food security (Comité de la sécurité alimentaire mondiale, 2012). Meuwissen et al. (2019), in their view, the resilience of a farming system is defined as its ability to perform its functions in the face of increasingly complex and cumulative economic, social, environmental and institutional shocks and constraints, through its capacity (*i.e.* components) for robustness, adaptability and transformation.

The scope of resilience assessments (both qualitative and quantitative) of farming systems is heterogeneous in the scientific literature, but some trends emerge. Resilience assessments of food systems focus mainly on the food security function, *i.e.* at the base on agricultural production ('what' resilience) (Dardonville et al., 2020; Stone and Rahimifard, 2018). Assessments of the resilience of farming systems mostly consider climate change as the only source of disturbance (resilience 'to what') (Dardonville et al., 2020). Another recent source of disruption considered is the COVID-19 pandemic. (Dixon et al., 2021; Meuwissen et al., 2021; Savary et al., 2020; Štreimikienė et al., 2021). Other assessments specify the potential consequences of disruptions for food security rather than a source of disruption, such as food import supply shocks (Fader et al., 2013; Fraser et al., 2015; Marchand et al., 2016) while some do not specify any particular disruption (Seekell et al., 2017). Finally, the spatial scale or scales of farming system resilience assessment also vary: it can be an administrative or geographical region (Das et al., 2020; Li et al., 2011; Zampieri et al., 2020), a country (Diserens et al., 2018; Jacobi et al., 2018; Keil et al., 2008), a continent (Dixon et al., 2021) etc. Few resilience assessments are multi-scale although Tendall et al. (2015) emphasise its importance, as disturbances and functions may differ or decline according to scale, and conclusions about changes to be made may be in trade-off according to scale.

² Indeed, the application of this concept can be applied to 'agriculture' as well as to (Das et al., 2020; Štreimikienė et al., 2021) as well as 'agri-food supply chains (Stone and Rahimifard, 2018; Umar et al., 2017; Voorn et al., 2020) or the wider 'food system'. (Dixon et al., 2021; Jacobi et al., 2018; Seekell et al., 2017).

I.2.4 Quantitative resilience assessment in the farming system literature

Among the quantitative assessments of farming system resilience, some have conducted statistical analysis of historical data of farming system variables (Das et al., 2020; Hannaford, 2018; Kahiluoto et al., 2019; Smith and Edwards, 2021; Suweis et al., 2015) while others have explored a mathematical model of a farming system (Accatino et al., 2014; Li et al., 2011; Martin, 2004). Quantitative assessments with a modelling approach are fewer in number than quantitative assessments based on historical data of variables (Douxchamps et al., 2017).

Regarding statistical analyses, Kahiluoto et al. (2019) assessed the resilience of wheat production to climate-change-related extreme weather events in several European countries over 2002-2009 period computing a response diversity index based on the wheat yield response to agroclimatic variables. Seekell et al. (2017) mapped the generic resilience of food systems at the global scale estimating three indicators (production diversity, food access and biophysical capacity) based on data from 1992 to 2011. Suweis et al. (2015) explored the resilience of food security at the global scale to shocks arising from environmental fluctuations, trade policies, and market volatility computing two indicators of stability and reactivity between population dynamics and food availability from 1985 to 2010. Concerning modelling approaches, Martin (2004) assessed the resilience of the oligotrophic property of a lake to an increase in phosphorus concentration after phosphorus input by farmers on cropland with a dynamic controlled model using viability theory and measuring resilience as the inverse of the cost function to come back to the initial state. Li et al. (2011) explored the resilience of food security and economic profitability of farming systems in North China Plain to climate change impact on the water cycle simulating and describing area of wheat and profit from crop production.

I.3 Research question, general method and aims of the thesis

The current state of European farming systems, and the global challenges, which are sources of vulnerabilities for European agriculture, call for contributions to assessments of the resilience of these farming systems. The research work carried out during this thesis focused on a quantitative assessment with a modelling approach of the food security resilience of European farming systems to input supply (or import) constraints that could be linked to the consequences of the global peak oil.

This work was part of the European Horizon 2020 project SURE-Farm³ and the resilience assessment framework developed in this project (Meuwissen et al., 2019). In particular, this work contributed to a work package that aimed to develop an integrated impact assessment tool to make long-term projections towards efficient provision of private and public goods. It was also part of the CLand project⁴ and contributed to research on the optimisation of farming systems in the face of environmental pressures.

In terms of functions, the resilience assessment has focused on food security, *i.e.* on food production, one of the essential functions of a farming system, but also on climate change mitigation. In terms of disruptions, it focused on constraints on input imports that could be linked to global peak oil, an issue that is little considered by farming system resilience assessments. The assessment consisted of a quantitative analysis with a modelling approach, an approach not often found in farming system resilience assessments. Furthermore, no quantitative analysis of the food security resilience of European farming systems in the face of declining fossil fuel and input supplies has been carried out so far. In this thesis, a farming system is understood as a population of farms located in a common and limited geographical area with similar biophysical, economic and social conditions (Giller, 2013). Resilience is understood as the ability of a farming system to ensure food security over time in the face of disturbances (definition inspired by Tendall et al. (2015)). The assessment was carried out at the farming system scale, at which the food security function begins to make sense (unlike at the farm level) and at which this function could be ensured in the face of constraints on the input import. The inputs considered are feed and synthetic nitrogen fertilisers, two inputs whose production and import require fossil fuels and which are directly involved in the growth of livestock or plants.

³ Towards Sustainable Resilient EU Farming systems - <https://www.surefarmproject.eu>

⁴ <https://cland.lsce.ipsl.fr/>

Thesis research question

How resilient are European farming systems to input supply constraints related to global peak oil?

To answer this research question, I developed a dynamic macro-model (annual time step) of nitrogen flows of a farming system consisting of three compartments (livestock, plant and soil) and two land uses (permanent grassland and cropland) with each plant and soil compartments. In this model, plant yield is a function of soil mineral nitrogen, livestock numbers are a function of feed availability and soil organic matter is a function of livestock manure and crop residues.

I explored two components of resilience in farming systems with two modes of model use tailored to the components: (1) robustness, *i.e.* their ability to maintain food production in the face of constraints on input imports related to global peak oil (Meuwissen et al., 2019), with or without changes in crop-livestock compositions, in simulation mode, and (2) adaptability potential, *i.e.* the changes in crop-livestock compositions that can be envisaged to increase robustness in the face of input import constraints (Meuwissen et al., 2019), in multi-objective optimisation mode. The time horizon of the simulations considered is 2050, assuming that the global peak oil will occur in the 2020s and a linear decline in world oil production to zero by 2050. The simulation mode is used to calculate the final states of a system after a forced trajectory of controls and disturbances (*What-if* scenario) (Ay et al., 2014; Deryng et al., 2011; Fernandez-Mena et al., 2020; Grundy et al., 2016; Mehdi et al., 2015). The multi-objective (or constrained) optimisation mode aims to explore a set of controls that optimise a set of objectives (*What-for* scenario) (Groot et al., 2016; Kropp et al., 2019; ten Berge et al., 2000; Todman et al., 2019; Verhagen et al., 2018).

Thus, I have divided the research question into three sub-objectives, which were: (i) to explore the robustness of European farming systems to a progressive decrease in input imports without changing practices or compositions, (ii) to explore compositional changes in European farming systems that improve their robustness, *i.e.* decrease their dependence on inputs, (iii) to explore the trade-off, in European farming systems, between two functions, the robustness of food production in the face of input constraints and the reduction of greenhouse gas emissions (climate change mitigation), according to changes in practices and compositions implemented. The climate change mitigation function was considered for the latter sub-objective in order to identify whether changes in practices and compositions that increase robustness also mitigate climate change.

These three sub-objectives were addressed in 4 chapters for different case studies adapted to the sub-objectives. I addressed the first sub-objective first in Chapter 1 for three French farming systems (field crops - Plateau Picard, intensive monogastric and dairy cattle - Central Brittany, and extensive ruminant - Bocage Bourbonnais) and then in Chapter 2 for all French farming systems, corresponding in both chapters to the administrative entity *Petite Région Agricole* characterised by agronomic and pedological homogeneity. I addressed the second sub-objective in Chapter 3 for the three French farming systems of Chapter 1. Finally, I addressed the third sub-objective in Chapter 4 for a Portuguese farming system (extensive beef cattle farms - Alentejo) corresponding to the administrative entity *NUTS-2* (which corresponds to the administrative region level in France) that I qualified as an agricultural region. The scopes of the analyses carried out in the four chapters are summarised in Table I.1.

Table I.1 Summary description of the scope of the analyses carried out in the 4 chapters of the thesis. The mode of analysis, the scale of analysis, the compositional changes simulated, the functions considered and the resilience component assessed are specified.

Chapter	Model analysis mode	Level-Scale	Change in practice or composition	Functions	Resilience component measured
1	Simulation - What-if scenario	3 small agricultural regions in France		Food production (quantity)	Robustness (ability to resist and ability to absorb)
2	Simulation - What-if scenario	Small agricultural regions in France		Food production (quantity)	Robustness (ability to resist and ability to absorb)
3	Multi-objective optimisation - What-for scenario	3 small agricultural regions in France	Crop composition, herd size	Food production (quantity)	Adaptability (potential)
4	Simulation - What-if scenario	Agricultural region of Alentejo in Portugal	Livestock diet, herd size, permanent grassland type	Food production (quantity); Climate change mitigation	Robustness (ability to resist and ability to absorb)

The thesis is structured around 6 chapters: a general methodology, 4 chapters that address the sub-objectives of the thesis and a general discussion. Below I briefly outline the aims of these chapters and the methodology employed where relevant.

General methodology

In this chapter, I explain the reasons for the choice of the type of model designed in this thesis and how the model is used. I also describe the Chapter 2 version of the model and detail the similarities or differences in the disturbance scenarios or model versions between the four chapters. And I present the case studies on which the analyses were focused.

Chapter 1

The aim of this chapter was to calculate and compare the robustness of food production of three types of French farming systems to constraints on input imports, and to identify links between robustness and crop-grass-livestock composition. To achieve this, we simulated the robustness without compositional changes of crop-sourced food production and animal-sourced food production (and their combination) to gradual decreases in the availability of imported feed and/or synthetic fertilisers over 30 years using the model.

Chapter 2

The aims of this chapter were firstly to assess with indicators the robustness of French farming systems to constraints on input imports, and secondly to explore the links between robustness and crop-grassland-livestock compositions, generalising the links between robustness and crop-grassland-livestock compositions identified in Chapter 1. To achieve this, we simulated a progressive decline in synthetic fertiliser and feed imports over 30 years with no change in composition using the model. We defined and calculated two robustness indicators: (1) the robustness window, *i.e.* the period during which the food production of farming systems does not fall below 95% of current food production; (2) the robustness intensity, *i.e.* the share of current total food production that remains at year 30. We grouped the French farming systems according to the robustness indicators and related these groups to the crop-grassland-livestock composition indicators. The indicators were mapped across France.

Chapter 3

The aims of this chapter were first to explore the trade-offs between the objectives related to increasing self-sufficiency: crop-sourced food production, animal-sourced food production (to be maximised), use of synthetic fertilisers and imports of feed (to be minimised). We investigated the trade-offs by considering changes in crop composition, and the composition and quantity of livestock as levers. The second aim was to explore the set of changes in crop-livestock composition that best alleviate these trade-offs, *i.e.* the potential for adaptability to constraints on input imports. To achieve this, we used multi-objective optimisation techniques applied to the model and for three types of French farming systems (those in Chapter 1) by formulating two scenarios: (i) maximising crop- and animal-sourced food production, and minimising the use of synthetic fertilisers and imported feed (ii) maximising crop and animal-sourced food production imposing zero input imports.

Chapter 4

The aim of this chapter was to explore the trade-off between minimising net greenhouse gas emissions and increasing the robustness of meat production to constraints on input imports depending on the changes in management practices and composition implemented, for the beef cattle farming system in Alentejo, Portugal. To achieve this, we added beef cattle herd dynamics and the carbon cycle to the model and simulated the impact of changes in practices and composition (increase in the area of sown biodiverse permanent grasslands rich in legumes, grass fattening of steers, reduction in herd size and increase in animal productivity) on the greenhouse gas balance and the robustness of meat production to a 30-year progressive decrease in the use of synthetic fertilisers and imported feed.

General discussion

In this chapter, I summarise the scientific contributions of the research carried out during this thesis, then I present methodological reflections concerning the approach followed, the simulated disturbance scenarios, the definition of the food production objective, and the uncertainties of the model, and finally I set out research and application perspectives.

II General methodology

II.1 Why this type of model?⁵

To my knowledge, no study has explored the resilience of farming systems to constraints on input supply using a model designed for this purpose (see General Introduction). I defined a suitable type of model to answer the research question and designed a model based on existing models in the literature rather than reusing them, as they did not share all the necessary features detailed below.

Firstly, the choice of the type of model is related to the research question. The research question implied the use of a time-dynamic, macro model with annual or monthly time steps. The time-dynamic feature of the model is linked to the concept of resilience, which is ideally assessed on the basis of time trajectories of system functions. The macro feature and the monthly or annual time step allow a low number of state dimensions and therefore a low number of calculations to solve the system of equations in simulation mode and thus to analyse the model with complex modes such as multi-objective optimisation which allows to assess the adaptability (potential) component of resilience. In addition, the model must describe the flows (and stocks) associated with the functioning of the farming system. These flows, depending on the resource considered (labour, money, biomass), *i.e.* the approach adopted (biophysical or socio-economic), can be accounted for in units of labour, money, energy, mass of matter (fresh or dry) or mass of nutrients. In addition to existing socio-economic assessments (Herrera et al., 2020), I chose a biophysical approach to propose a biophysical assessment of resilience in work package 5 of the SURE-Farm project. This approach was already part of my field of knowledge, unlike the socio-economic approach. I then chose to account for N biomass flows because it is an essential nutrient for living organisms and it is a well-documented and modelled cycle (Robertson and Vitousek, 2009). Table II. 1 summarises biophysical models of farming systems identified in the literature that served as inspiration for the design of the model in this PhD thesis or were similar to the one developed.

In this PhD thesis, I sought to assess the resilience of European farming systems to constraints on input supply. Inputs include, for example, irrigation water, fuels, plant protection products, mineral and synthetic fertilisers and feed. I have chosen to focus on feed and synthetic N fertilisers, two inputs that require fossil fuels to produce and import, and which are directly involved in the growth of animals or plants. Fuel, plant protection products (which also require fossil fuels for production and import) and water were not considered because I did not get to know any simple mathematical relationship (either statistical or mechanistic) at annual or monthly time steps between plant or animal growth and these inputs.

⁵ This section overlaps with the introduction of the Chapter 1.

Table II. 1 Characteristics of the model in this PhD thesis, models that served as inspiration or models similar to the one developed. “N.A.” stands for Non-Applicable.

Characteristic	Model					
	From the PhD	GOANIM	FAN	GRAFS	BioBaM	TYFAM
Source		(Barbieri et al., 2021)	(Fernandez-Mena et al., 2020)	(Billen et al., 2014)	(Morais et al., 2021)	(Poux and Aubert, 2018)
Micro or macro	Macro	Macro	Micro	Macro	Macro	Macro
Spatially explicit	No	Yes	Yes	No	No	No
Spatial resolution	Farming system	5 arcmin	Farm	Region , country or territory	Region	Region
Time dynamic	Yes	No	Yes	No	No	No
Time step	Annual	N.A.	Annual	N.A.	N.A.	N.A...
Type of approach	Biophysical	Biophysical	Biophysical	Biophysical	Biophysical	Biophysical
Accounting unit	Mass of N	Energy and Mass of N	Mass of matter or mass of N	Mass of N	Mass of C, mass of N and mass of matter	Mass of N, mass of matter and energy
Compartments	Cropland (soil & plant); Permanent grassland (soil & plant); Livestock	Cropland (soil & plant); Permanent grassland (plant); Livestock; Human diet	Cropland (soil & plant); Permanent grassland (plant); Livestock	Cropland (soil & plant); Permanent grassland (plant); Livestock; Fishery & aquaculture; Human diet	Soil; Cropland (plant); Permanent grassland (plant); Livestock; Human diet	Cropland (soil & plant); Permanent grassland (plant); Livestock; Human diet; Industry
Main input data	Livestock numbers, diet and production yield; Land uses and crop cover; Maximum plant yield; Stock of soil organic matter	Livestock numbers, diet and production yield; Land uses and crop cover; Maximum plant yield	(Per farm or farm type) Livestock numbers, diet and production yield; Plant yield; Land uses and crop cover	Livestock numbers and production; Land uses and crop cover; Plant yield; Synthetic N fertiliser application; Food production; Food trade	Livestock efficiency and feed composition; Land uses and crop cover; Maximum plant yield; Human diet	Livestock numbers, diet and production yield; Human diet & food export and import; Plant yield; Land use and crop cover

Table II. 1 (continued).

Characteristic	Model					
	From the PhD	GOANIM	FAN	GRAFS	BioBaM	TYFAM
Main outputs	Food production; Synthetic N fertiliser application (depending on the analysis mode)	Food production; Losses to the environment	Food and energy production; Exchanges number; Environmental performance (e.g. N balance, GHG balance)	Losses to the environment; Yield-fertilisation relationship	Environmental performance (e.g. N balance, GHG balance); Land-use	Food production ; Environmental performance (e.g. N balance, GHG balance); Feed production
Modelling objective(s)	Assessing food production robustness to input import constraints; Assessing potential adaptability in crop-livestock composition for maximising food production to input import constraints	Exploring if, how and where organic farming expansion would be limited by N availability; assessing if organic farming could feed the planet	Exploring and assessing opportunities for a circular economy in small farming regions and to unravel interactions between recycling, environmental performance and food production	Assessing the functioning of the global agro-food system in terms of N flows within and between agricultural entities	Assessing various strategies (in terms of area availability and demand, diets, yields in cropland and on grazing lands, and feed conversion ratios) for achieving a sustainable global food system in 2050, including organic farming.	Identifying if and under what conditions a European scale agroecological transition of the food system would be possible and able to tackle environmental as well as public health challenges
Main causal link/relation	Plant yield as a linear function of N supplied to soils up to a maximal yield; Livestock number as a function of feed availability; Dynamic soil organic matter	Crop yield as a linear function of N supplied to soils up to a maximal yield; Livestock number as a function of feed availability	Crop yield as a linear function of N supplied to soils up to a maximal yield	N.A.	N needs as a function of maximum crop yield; Land use is a function of human diet (food demand) and livestock feeding respectively its efficiency	N.A.
Analysis mode	Simulation, Multi-objective non-linear optimisation, viability theory	Bi-objective linear optimisation	Simulation	N.A.	Simulation (Land-use change; Human diet change; Efficiency measures)	Simulation (Livestock numbers; Land use and crop cover)

II.2 Modes of analysis used⁶

I have mobilised two modes of analysis to assess the different components of resilience (see General Introduction). In particular, I have used simulation to assess robustness and multi-objective optimisation to assess adaptability potential.

Simulation consists of the calculation over time of the state variables for one or a few trajectories of forced controls and disturbances. The advantage of this mode is that it is simple and requires few calculations. Its disadvantage is that only a few control and disturbance trajectories are explored. And the definition of these trajectories by experts, by the modellers themselves or by the actors in the farming system is a function of their subjectivity, *i.e.* they describe the future only as they anticipate it. This mode was used in chapters 1, 2 and 4 of this PhD thesis to assess robustness to constraints on input supply. In chapters 1 and 2, only the disturbances varied while in Chapter 4, disturbances and controls varied in the scenarios. I performed the model analyses in simulation mode in R language and used the “ode” solver from the “deSolve” package (Soetaert et al., 2021). The use of a solver facilitated the sensitivity analyses in chapters 1 and 4 using the “FME” package (Soetaert and Petzoldt, 2021).

Multi-objective optimisation consists of the systematic exploration of combinations of drivers and the calculation of objectives for each combination. When not all objectives can be achieved together, it allows for the calculation of a Pareto frontier (Accatino et al., 2019; de Groot et al., 2010; Shi et al., 2021) which is the set of combinations of objectives for which it is not possible to improve one objective without degrading another (Castelletti et al., 2010). The shape of this frontier then makes it possible to determine the relationships (trade-offs or synergies) between the objectives. The disadvantage of this mode compared to simulation is that it requires more calculations. The optimised model can be static or dynamic over time. In Chapter 3, I optimised the model in its dynamic version, *i.e.* the objective values corresponded to the values after 30 years of implementation of the combinations of the driving variables. I optimised food production (maximisation) and input import (minimisation) by varying the crop-livestock. This allowed me to assess the adaptability potential, *i.e.* the sets of changes in the crop-livestock compositions of farming systems that, by reducing input use, could improve resilience to supply constraints. I used the concept of adaptability potential rather than the one of adaptability because the identified compositional changes are potentials and not adaptive responses of the system to disturbances. I carried out the analyses of the model in optimization mode with Python language and used the NSGA II evolutionary genetic algorithm from the “inspyred” package (Garrett, 2022).

⁶ This section overlaps with the General introduction.

II.3 Model description - Version of Chapter 2 ⁷

The version of the model described is that of Chapter 2 (simulation mode).

II.3.1 General description

The model conceives a farming system as consisting of two land uses (cropland and permanent grassland) and a livestock compartment (Figure II.1). Each land use has a plant and a soil compartment and livestock graze permanent grasslands (ruminants in this case) or are kept in housing facilities according to allocation coefficients. Effluents are allocated to permanent grasslands or housing facilities proportionally to the time spent and the fraction excreted in housing facilities is applied on cropland soils. The soil compartment in each land use consists of an organic N stock and a mineral N balance (the model does not consider mineral N residues). The plant compartment is conceptualized as a single plot per land use but which is composed of several surfaces allocated to different plant species. Plant production is proportional to the availability of soil mineral N (assuming N as the only limiting factor), animal-sourced food production is a function of the available feed (counted as N), local or imported.

The model has an annual time step. At each step the soil organic N stock and the livestock numbers are updated and the food productions (plant- and animal-sourced) are calculated. The soil organic N stock is increased with organic N inputs (plant residues or livestock effluents) and decreased with outputs (soil organic matter mineralization). Synthetic fertilizer, atmospheric deposition, biological N fixation by legumes, mineralized soil N and the mineral parts of organic amendments contribute to the plant N mineral fertilization. Plant production is allocated to humans and/or livestock, depending on the species diet. I assumed that livestock do not eat crop residues and graze only permanent grassland. N losses occur during effluent management and soil management to air or water. The livestock number decreases when feed availability is lower than their needs. No exchange of residues between the two land uses was considered. Imported feed and synthetic fertilisers represent external human-imported N inputs to the farming system. Organic amendments are applied or decompose homogeneously on both land uses, even on permanent crops, the year after being excreted, collected (effluents) or harvested (residues).

⁷ This section overlaps with the descriptions of the model in chapters 1 and 4. The model version is close to the one in Chapter 1 and the notation system is similar to that in Chapter 4.

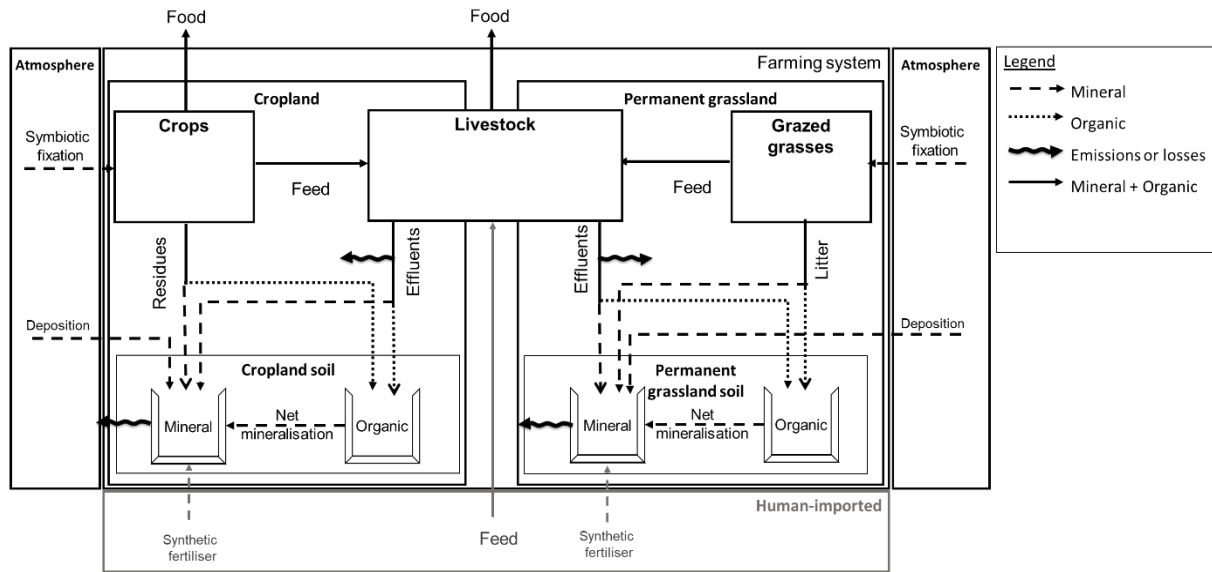


Figure II.1 Conceptual scheme of the model. Boxes are the compartments and arrows are the nitrogen flows. Nitrogen flows are of different types: mineral (dashed lines), organic (dot lines), or mixed (full lines). The external flows that enter the farming system come either from the atmosphere or are imported by humans (in grey). The wavy arrows represent gaseous or liquid losses of nitrogen.

II.3.2 Description per compartment

I describe hereby the main model equations. A list of all the variables are in the Table II. 2 and a list of all the parameters are in the Table II. 3.

Variables can refer to nitrogen (letter n). They can refer to flows (dot-topped, e.g., $\dot{n}_{i,t+1}^{Fert}$) or stocks (not topped, e.g., $n_{i,t+1}^{Soil}$), can be an unitary (lower-case) or a total value (upper-case), and can refer to organic (hat-topped, e.g., $\hat{n}_{i,t}^{R,A}$) or mineral flows (check-topped, e.g., $\check{n}_{i,t}^{R,A}$). Index i corresponds to plants, j to species, k to feed categories, l to land use and p to animal products.

II.3.2.1 Soil

The variables characterizing the soil compartment for each land use are the active organic N stock $n_{i,t}^{Soil}$ [kgN/ha], and the flow of mineral N $\dot{n}_{i,t}^{Fert}$ [kgN/ha/year] per plant.

Organic nitrogen stocks dynamics

The dynamics of active soil organic N is a mass balance equation and corresponds to the dynamics of soil organic C (following Clivot et al., (2019)) transposed to N by multiplying by C:N ratios [-] and accounting for the immobilisation phenomenon (described below) (equation (1) - for cropland).

$$n_{i,t+1}^{Soil} = n_{i,t}^{Soil} + (\dot{n}^H + \dot{n}_{i,t}^{Eff} + \dot{n}_{i,t}^{R,A} * (1 - (\xi_{EXP} * \xi_{FSS,t})) + \dot{n}_{i,t}^{R,R}) - (\mu_l * n_{i,t}^{Soil} - \dot{n}_{i,t+1}^{Immo}) \quad (1)$$

Input terms are the humified parts of organic amendments (*i.e.*, aerial residues $\dot{n}_{i,t}^{R,A}$ [kgN/ha/year], root residues $\dot{n}_{i,t}^{R,R}$ [kgN/ha/year], livestock effluents $\dot{n}_{i,t}^{Eff}$ [kgN/ha/year] and human sewage sludge for cropland only \dot{n}^H [kgN/ha/year]). The output term is the net mineralisation of soil organic N, which is equal to the mineralised flow ($\mu_l * n_{i,t}^{Soil}$) minus the immobilisation flow $\dot{n}_{i,t+1}^{Immo}$ [kgN/ha/year], being μ_l [-] a constant mineralisation rate per land use.

The humified part of an organic amendment is known using its humification coefficient Φ [-] and multiplying by the ratio of its C:N ratio over the soil C:N ratio. It corresponds to the quantity of N necessary to humify the C of the organic amendment, *i.e.* to help the decomposition of the organic C in the amendment. If the quantity of N in the organic amendments is not enough to humify the C of the organic amendment, part of the mineralised soil organic N is immobilised to do so ($\dot{n}_{i,t+1}^{Immo}$). This occurs when the humification coefficient Φ multiplied by the ratio of the organic amendment C:N ratio over the soil C:N ratio is higher than 1 (Trinsoutrot et al., 2000) which is typically the case for plant aerial residues (Fuchs et al., 2014). Concerning aerial residues $\dot{n}_{i,t}^{R,A}$ for cropland, a share ξ_{EXP} [-] is exported as livestock bedding, and a share $\xi_{FSS,t}$ [-] of the exported crop residues is reapplied the year after with the effluents. The human sewage sludge \dot{N}^H [kgN/year], the human population, and the share of recovered human excretion are assumed constant.

Mineral nitrogen flows and losses

In both land use, the mineral N fertilised to the soil $\dot{n}_{i,t+1}^{Fert}$ per plant is the sum of the mineral part of N flows applied to the soil and the net mineralisation of the soil organic N (equation (2) - for cropland). Mineral N fertilised to the soil $\dot{n}_{i,t+1}^{Fert}$ per plant is in each time step, either consumed by plants or lost. The N flows applied to the soil are the synthetic fertiliser $\dot{n}_{i,t+1}^{Syn,App}$ [kgN/ha/year], the atmospheric deposition \dot{n}^D , assumed constant over time, and the mineral parts of organic amendments: aerial residues $\dot{n}_{l,t}^{R,A}$, root residues $\dot{n}_{l,t}^{R,R}$, livestock effluents $\dot{n}_{l,t}^{Eff}$, and human sewage sludge for cropland only \dot{n}^H . The mineral part of an organic amendment corresponds to the part that do not humify. Synthetic fertiliser is applied to each plant according to their needs. Synthetic fertiliser only consists of mineral N and it is only applied to plants that are composed by less than 100% of legumes (except low-productive permanent grasslands).

$$\dot{n}_{i,t+1}^{Fert} = (\dot{n}^H + \dot{n}_{l,t}^{Eff} + \dot{n}_{l,t}^{R,A} * (1 - (\xi_{EXP} * \xi_{FSS,t}))) + \dot{n}_{l,t}^{R,R} + (\mu_1 * \dot{n}_{l,t}^{Soil} - \dot{n}_{l,t}^{Imm}) + \dot{n}_{i,t+1}^{Syn,App} + \dot{n}^D \quad (2)$$

Application of mineral N to the soil leads to losses, assessed using emission factors from IPCC (2006). Leaching $\epsilon^{L,APP}$ [-] and N_2O emissions during application $\epsilon^{N_2O,APP}$ [-] and soil management $\epsilon^{N_2O,SM}$ [-] occur for all the mineral N flows applied. Volatilisation happens at different level between organic amendments $\epsilon^{V,ORG}$ [-] and synthetic fertiliser $\epsilon^{V,SYN}$ [-] applications. The soil mineral N available after losses for plant uptake $\dot{n}_{i,t+1}^{Fert,Av}$ corresponds to the mineral N fertilised to the soil $\dot{n}_{i,t+1}^{Fert}$ reduced by the losses and enriched by the biological N fixed by legumes \dot{n}_i^{BF} if applicable (plants of the Fabaceae family) (equation (3)). The soil mineral N available after losses to the plants in cropland is equal to:

$$\dot{n}_{i,t+1}^{Fert,Av} = \dot{n}_{i,t+1}^{Fert} * \epsilon^{TOT} - [\dot{n}^H + \dot{n}_{l,t}^{Eff} + \dot{n}_{l,t}^{R,A} * (1 - (\xi_{EXP} * \xi_{FSS,t})) + \dot{n}_{l,t}^{R,R}] * \epsilon^{V,ORG} - \dot{n}_{i,t+1}^{Syn,App} * \epsilon^{V,SYN} + \dot{n}_i^{BF} \quad (3)$$

.where $\epsilon^{TOT} = (1 - \epsilon^{L,APP} - \epsilon^{N_2O,APP} - \epsilon^{N_2O,SM})$. For permanent grassland, the equation is similar except that no aerial residues $\dot{n}_{l,t}^{R,A}$ are exported as livestock bedding and that no human sewage sludge \dot{n}^H are applied.

II.3.2.2 Plant

Plant compartments are composed of surfaces cultivated with different crops or grazed grasses, *i.e.* plants. Plants can be permanent or annual. The areas of both land use (cropland and permanent grassland), *i.e.* plant compartments, are assumed constant, and their sum gives the utilised agricultural area (UAA) of the farming system.

I parametrised each crop and each grazed grass differently, *i.e.* each crop or grazed grass has a set of traits useful for calculating biomass production following Clivot et al. (2019): area A_i [ha], fresh matter yield of the harvested or grazed organ $\dot{y}_{i,t}$ [kg/ha/year], harvest index HI_i [-], shoot-to-root ratio SR_i [-], N contents of the different parts of the plant σ_i [kgN/kg fresh matter], humification coefficients for the residues Φ_i^R [-], and the biological N fixation by legumes \dot{n}_i^{BF} . All these parameters are assumed constant over time and independent from the yield. I also assumed biophysical conditions constant.

Plant yield

The harvested or grazed organ yield $\dot{y}_{i,t}$ per plant *i.e.*, the quantity of biomass harvested or grazed from the edible parts of the plants, is a piece-wise linear function of the available soil mineral N $\dot{n}_{i,t}^{Fert,Av}$. The yield $\dot{y}_{i,t}$ increases linearly from 0 to a constant maximum yield \dot{y}_i^{MAX} [kg/ha/year of fresh matter] with soil mineral N, consistently with previous studies (de Wit, 1992) (equation (4)). Below the maximum yield, the available soil mineral N is limiting. Above the maximum yield, the plant no longer assimilates the available soil mineral N, and the excess is considered lost to water or air (Garnier et al., 2016).

$$\dot{y}_{i,t} = \begin{cases} \delta_i * \dot{n}_{i,t}^{Fert,Av} & , \text{if } \dot{n}_{i,t}^{Fert,Av} < b_i^P \\ \dot{y}_i^{MAX} & , \text{otherwise} \end{cases}, \quad (4)$$

The slope of the yield response curve to soil mineral N before saturation δ_i is specific to each plant and depends on the N need \dot{n}_i^{Need} [kgN/ha/year] per plant at the maximum yield \dot{y}_i^{MAX} . The N need \dot{n}_i^{Need} per plant corresponds to the N content in the different parts of the plant for the maximum yield, if the plant is annual. For permanent plants, the N need \dot{n}_i^{Need} per plant corresponds to the N content in the harvested or grazed part of the plant for the maximum yield. I assumed that the maximum yield \dot{y}_i^{MAX} corresponds to the typical yield \dot{y}_i^{TYP} [kg/ha/year of fresh matter] of the plant in the farming system considered.

Plant and residues production

The biomass harvested or grazed $\dot{N}_{i,t}^{Harv}$ per plant is obtained through the N content of the harvested or grazed organ σ_i^H : $\dot{N}_{i,t}^{Harv} = \dot{y}_{i,t} * A_i * \sigma_i^H$. Plant residues are a function of the fresh matter harvested or grazed organ yield $\dot{y}_{i,t}$, the harvest index HI_i , the shoot-to-root ratio SR_i , and the residue N content σ_i^R : above-ground residues are equal to $\dot{N}_{i,t}^{R,A} = \dot{y}_{i,t} * A_i * \sigma_i^{R,A} * \frac{1-HI_i}{HI_i}$, and root residues are equal to $\dot{N}_{i,t}^{R,R} = \dot{y}_{i,t} * A_i * 1.65 * \sigma_i^{R,R} * \frac{1}{SR_i * HI_i}$. The coefficient 1.65 in the root residues equation accounts for extra root production. I assumed that livestock graze all the aerial biomass of permanent grasslands. Permanent plants do not have residues in the model (except permanent grassland).

Plant production allocation

For cropland, the N content of the harvested organ $\dot{N}_{i,t}^{Harv}$ is allocated, by means of allocation coefficients $v_{i,k}$ [-] per plant and per feed category, assumed constant over time, to different uses: food, feed, industrial (e.g., biofuels), seed stocks or processing (e.g., oil-protein crops). The processed crops are then partially conveyed for food or feed in the forms of co-products and meals. The feed categories are energy concentrates, proteins concentrates and forages. The feed subcategories are cereal and co-products (energy concentrates), oil-protein seeds and oilseed cakes (protein concentrates), fodder and grazed grass (forages). In the case of a feed surplus (feed need lower than the feed locally available) in a feed subcategory, if the feed is edible by humans (cereals, oil-protein crops), it is reallocated for food.

Plant fertilisation need

The need for fertilisation $\dot{n}_i^{Fert,Need}$ [kgN/ha/year] per plant corresponds to the N need \dot{n}_i^{Need} , considering losses related to the application of soil mineral N. The need for fertilisation is estimated from the equations (2) and (3), replacing $\dot{n}_{i,t}^{Fert,Av}$ by \dot{n}_i^{Need} , $\dot{n}_{i,t}^{Fert}$ by $\dot{n}_i^{Fert,Need}$, considering volatilisation emission factors equal ($\epsilon^{V,ORG} = \epsilon^{V,SYN}$) and considering atmospheric deposition and net mineralisation subject to volatilisation (equation (5)).

$$\dot{n}_i^{Fert,Need} = \frac{\dot{n}_i^{Need} - \dot{n}_i^{BF}}{(1 - \epsilon^{L,APP} - \epsilon^{N_2O,APP} - \epsilon^{N_2O,SM} - \epsilon^{V,SYN})} \quad (5)$$

The need for fertilisation $\dot{n}_i^{Fert,Need}$ is satisfied first by natural flows and then by amendments that are homogeneously applied to the soil. If the fertilisation need $\dot{n}_i^{Fert,Need}$ is not met by the natural flows and organic amendments, synthetic fertiliser $\dot{n}_{i,t}^{Syn,App}$ per plant is applied to meet the need for fertilisation and to achieve the maximum yield of the plant. The synthetic fertiliser need $\dot{n}_{i,t}^{Syn,Need}$ [kgN/ha/year] per plant is equal to the fertilisation need $\dot{n}_i^{Fert,Need}$ minus the natural flows of mineral N (net

mineralisation $\mu_l * n_{l,t}^{Soil} - \dot{n}_{l,t+1}^{Immo}$, biological fixation \dot{n}_i^{BF} and atmospheric deposition \dot{n}^D) and the mineral parts of organic amendments applied (equation (6)).

$$\dot{n}_{i,t+1}^{Syn,Need} = \max\left(\dot{n}_i^{Fert,Need} - (\mu_l * n_{l,t}^{Soil} - \dot{n}_{l,t+1}^{Immo} - \dot{n}_i^{BF} + \dot{n}_{l,t}^{Eff} + \dot{n}^H + \dot{n}_{l,t}^{R,A} + \dot{n}_{l,t}^{R,R} + \dot{n}^D), 0\right) \quad (6)$$

The minimum quantity between the synthetic fertiliser need $\dot{N}_t^{Syn,Need}$ [kgN/year] and the synthetic fertilizer available to import $\dot{N}_t^{Syn,Av}$ [kgN/year] is applied to the plant area fertilised with synthetic fertilizer. This quantity is then applied in proportion to the needs $\dot{N}_{i,t}^{Syn,Need}$ per plant over the synthetic fertiliser need $\dot{N}_t^{Syn,Need}$. The synthetic fertiliser applied $\dot{N}_{i,t}^{Syn,App}$ per plant is equal to: $\dot{N}_{i,t}^{Syn,App} = \frac{\dot{N}_{i,t+1}^{Syn,Need}}{\dot{N}_{t+1}^{Syn,Need}} * \min(\dot{N}_t^{Syn,Av}, \dot{N}_t^{Syn,Need})$.

II.3.2.3 Livestock

The livestock compartment is composed of different species: poultry, pigs, sheep & goats, and cattle. Each species is characterised by an average annual number $L_{j,t}$ [LU] *i.e.*, the average livestock number present daily in the farming system.

Feed

A species is characterised by its diet *i.e.*, the individual feed need $\beta_{j,k}$ [kgN/LU] per feed category and per species. The feed need $\dot{N}_{j,k,t}^{Feed,Need}$ [kgN/year] per feed category and per species is defined by:

$$\dot{N}_{j,k,t}^{Feed,Need} = L_{j,t} * \beta_{j,k}$$

The feed locally available $\dot{N}_{j,k,t}^{Feed,Loc}$ per feed category and per species is given by $\dot{N}_{j,k,t}^{Feed,Loc} = (\sum_i \dot{N}_{i,t}^{Harv} * v_{i,k}^L) * \alpha_{j,k,t}$ with $\alpha_{j,k,t}$ being the ratio between the feed need $\dot{N}_{j,k,t}^{Feed,Need}$ per species and per feed category, and the feed need $\dot{N}_{k,t}^{Feed,Need}$ of all the species per feed category. The total feed available $\dot{N}_{j,k,t}^{Feed,Tot}$ [kgN/year] per category and per species is equal to the sum of the feed locally available $\dot{N}_{j,k,t}^{Feed,Loc}$ and the feed imported (*i.e.*, what is available to import) $\dot{N}_{j,k,t}^{Feed,Imp}$ [kgN/year].

The feed shortage $S_{j,k,t}$ [-] per species and per feed category is equal to the difference between the feed need $\dot{N}_{j,k,t}^{Feed,Need}$ and the feed available $\dot{N}_{j,k,t}^{Feed,Tot}$ for the species and for the feed category considered. The difference is divided by the feed need per species: $S_{j,k,t} = \max(0, \frac{\dot{N}_{j,k,t}^{Feed,Need} - \dot{N}_{j,k,t}^{Feed,Tot}}{\dot{N}_{j,t}^{Feed,Need}})$. The feed shortage is null if the total feed available $\dot{N}_{j,k,t}^{Feed,Tot}$ exceeds the need.

Population dynamics

The livestock numbers follow a dynamic over time dependent on feed availability and herd management. The livestock number $L_{j,t}$ per species changes with the management rate $M_{j,t}$ [-] (equation (7)). A positive value of the management rate corresponds to the willingness of the farmer to increase the livestock number, whereas a negative value corresponds to the willingness of the farmer to decrease the livestock number.

$$L_{j,t+1} = (1 + M_{j,t+1}) * L_{j,t} \quad (7)$$

The management rate $M_{j,t+1}$ per species is a decreasing function of the feed shortage $S_{j,t+1}$ (equation (8)). If a feed shortage is equal to or higher than a threshold T [-], the management rate is negative and is a linear decreasing function of the feed shortage $S_{j,t+1}$ reflecting the decision of the farmer to decrease the livestock number. If a feed shortage is smaller than T , the management rate is equal to zero.

$$M_{j,t+1} = \begin{cases} 0, & \text{if } S_{j,t+1} < T \\ -S_{j,t+1}, & \text{if } S_{j,t+1} \geq T \end{cases} \quad (8)$$

Animal-sourced food production

Animal-sourced food production $\dot{N}_{j,t}^{Food,Liv}$ [kgN/year] per species is obtained by multiplying the livestock number $L_{j,t}$ per species, the individual animal-sourced food production coefficients $c_{j,p}$ [kgN/LU] per species and per livestock product, assumed constant over time, and the feed shortage $S_{j,t}$ per species (equation (9)).

$$\dot{N}_{j,t}^{Food,Liv} = \begin{cases} \sum_p c_{j,p} * L_{j,t} * (1 - S_{j,t}), & \text{if } S_{j,t} < T \\ \sum_p c_{j,p} * L_{j,t} * (1 - S_{j,t}) + c_{j,meat} * L_{j,t} * S_{j,t}, & \text{if } S_{j,t} \geq T \end{cases} \quad (9)$$

If a feed shortage $S_{j,t}$ is more than a threshold T the animal-sourced food production $\dot{N}_{j,t}^{Food,Liv}$ decrease proportionally and the slaughter of livestock also leads to a proportional increase in meat production.

Effluent

Effluents from livestock \dot{N}_t^{Eff} [kgN/year] are computed as the difference between the feed intake $\dot{N}_t^{Feed,Intake}$ [kgN/year] and the animal-sourced food production $\dot{N}_t^{Food,Liv}$ (INRA et al., 2018b). Some of these excretions occur in housing facilities $\dot{N}_{cropland,t}^{Eff}$ and others are deposited during grazing (by ruminants) $\dot{N}_{perm,gra,t}^{Eff}$. Part of these excretions are lost either to the air or to the water. The part of excretions in housing facilities, after losses, is available for application on cropland the following year.

The feed intake $\dot{N}_t^{Feed,Intake}$ corresponds to the feed need $\dot{N}_t^{Feed,Need}$ without feed shortage. Otherwise, if a feed shortage $S_{j,t}$ is less than a threshold T the feed intake $\dot{N}_t^{Feed,Intake}$ decrease proportionally. If a feed shortage $S_{j,t}$ is more than a threshold T , the feed intake $\dot{N}_t^{Feed,Intake}$ corresponds to the feed need $\dot{N}_t^{Feed,Need}$ of the livestock number L_t after slaughter.

The ratio between the grazed grass intake $\dot{N}_{j,grazed\ grass,t}^{Feed,Intake}$ per species and the feed intake $\dot{N}_{j,t}^{Feed,Intake}$ per species determines the effluents on permanent grassland per species.

Excretions from housing facilities are stored and mixed with exported aerial residues for livestock bedding before being applied to cropland soils. These phases of excretion in housing facilities and storage result in emissions of NH_3 by volatilisation ($\epsilon^{V,B}$ and $\epsilon^{V,S}$ [-]), N_2O by denitrification (ϵ^{N_2O} [-]) and leaching losses (ϵ^L [-]) (equation (10)).

$$\dot{N}_{cropland,t}^{Eff} = \dot{N}_t^{Eff} - \dot{N}_{perm,gra,t}^{Eff} = \left(\sum_j \left((\dot{N}_{j,t}^{Feed,Intake} - \dot{N}_{j,t}^{Food,Liv}) * \left(1 - \frac{\dot{N}_{j,grazed\ grass,t}^{Feed,Intake}}{\dot{N}_{j,t}^{Feed,Intake}} \right) \right) + (\xi_{EXP} * \xi_{FSS,t}) * \sum_{i \in \Gamma} \dot{N}_{i,t}^{R,A} \right) * \epsilon^{TOT} \quad (10)$$

,where $\epsilon^{TOT} = (1 - \epsilon^{V,B} - ((1 - \epsilon^{V,B}) * \epsilon^{V,S}) - \epsilon^{N_2O} - \epsilon^L)$ and Γ the plants that belong to cropland.

The share $\xi_{FSS,t}$ corresponds to the feed sufficiency of the farming system *i.e.*, the feed locally available $\dot{N}_t^{Feed,Loc}$ divided by the feed need $\dot{N}_t^{Feed,Need}$.

II.3.3 Parameter sources and variable initialization

The sources of the parameters are detailed in Table II. 3 and in the Supplementary Material of Chapter 1. Similarly, the initialisation of the state variables is detailed in the Supplementary Material of Chapter 1. I detail below the differences in the sources of the parameters and the initialisation of the state variables in Chapter 2 compared to Chapter 1.

The biological N fixation \dot{n}_i^{BF} per plant was estimated using the equation from Anglade et al. (2015) and is dependent on the fresh matter plant yield. I assumed this flow constant over time and function of the typical fresh matter plant yield \dot{y}_i^{TYP} . The livestock numbers come from EFSE and originate from the 2010 agricultural census values at the communal level (non-secreted data) (Therond et al., 2017). Humification coefficients ϕ and C:N ratios of organic amendments (effluents and residues) were taken from Le Noë et al. (2017). The C:N ratio of cropland soils comes from ESDAC data (Ballabio et al., 2019), and I assumed that the C:N ratio of permanent grassland soils is worth twice the value of the C:N ratio of cropland soils (*i.e.*, ~ 20) (Leifeld et al., 2008). The soil organic C stocks in cropland soils also come from ESDAC data (Lugato et al., 2014). I assumed the soil organic C stocks in permanent grassland soils worth 60,000 kgC in the 0-30cm depth. I kept the assumption that the active part of soil organic matter in the 0-30cm depth is in equilibrium (inflows are equal to outflows) initializing it using the spin-up method (Xia et al., 2012). In other words, I assumed that current practices have remained unchanged for 30 years.

Table II. 2 Model variables description with their notations and units.

Compartment	Variable	Rating	Unit
Soil	Soil organic N per land use	$n_{l,t}^{Soil}$	kgN/ha
	Mineral N fertilised to the soil per plant	$\dot{N}_{i,t}^{Fert}$	kgN/year
	Soil mineral N available to plants after losses per plant	$\dot{N}_{i,t}^{Fert,Av}$	kgN/year
Plant	Fresh matter plant yield per plant	$\dot{y}_{i,t}$	kg/ha/year of fresh matter
	Plant organ harvested or grazed per plant	$\dot{N}_{i,t}^{Harv}$	kgN/year
	Plant aerial residues per plant	$\dot{N}_{i,t}^{R,A}$	kgN/year
	Plant root residues per plant	$\dot{N}_{i,t}^{R,R}$	kgN/year
	Share of the aerial crop residues exported as livestock bedding applied the year after with effluent on cropland soil	$\xi_{FSS,t}$	-
	Soil mineral N immobilisation per land use	$\dot{N}_{l,t}^{Immo}$	kgN/year
	Synthetic fertiliser applied per plant	$\dot{N}_{i,t}^{Syn,App}$	kgN/year
	Synthetic fertiliser need per plant	$\dot{N}_{i,t}^{Syn,Need}$	kgN/year
	Synthetic fertiliser available to import per plant	$\dot{N}_{i,t}^{Syn,Av}$	kgN/year
	Livestock	Livestock number per species	$L_{j,t}$
Feed need per species and per feed category		$\dot{N}_{j,k,t}^{Feed,Need}$	kgN/year
Feed intake per species and per feed category		$\dot{N}_{j,k,t}^{Feed,Intake}$	kgN/year
Feed locally available per species and per feed category		$\dot{N}_{j,k,t}^{Feed,Loc}$	kgN/year
Feed imported per species and per feed category		$\dot{N}_{j,k,t}^{Feed,Imp}$	kgN/year
Total feed available per species and per feed category		$\dot{N}_{j,k,t}^{Feed,Tot}$	kgN/year
Feed shortage per species and per feed category		$S_{j,k,t}$	-
Animal-sourced food production per animal product and per species		$\dot{N}_{j,p,t}^{Food,Liv}$	kgN/year
Effluent per land use (from housing facilities or deposited during grazing)		$\dot{N}_{l,t}^{Eff}$	kgN/year
Management rate per species		$M_{j,t}$	-

Table II. 3 Model parameters description with data source and nominal value for non-multidimensional parameters.

Compartment	Parameter or variable name	Rating	Nominal value ¹	Unit	Source
All	Humification coefficient (Effluents or residues)	Φ	REP	%	(Le Noë et al., 2017)
	C:N ratio (Effluents or residues)	CN	REP	-	(Le Noë et al., 2017)
	Human effluents recovered and applied as sludge on field	\dot{N}^H	REP	kgN/year	INSEE, (Esculier, 2016)
Soil	Atmospheric deposition on soil of NO_x	\dot{n}^D	10	kgN/ha/year	(Norwegian Meteorological Institute, 2020)
	Emission factors - N ₂ O emissions due to soil management	$e^{N_{2O},SM}$	3	%	Based on (IPCC et al., 2006, p. 1) fixed value
	Emission factors - Soil mineral N leaching	$e^{L,APP}$	20	%	(Lin et al., 2001)
	Emission factors - N ₂ O emissions of synthetic fertilisers application	$e^{N_{2O},APP}$	1	%	(IPCC et al., 2006, p. 1)
	Emission factors - Volatilisation of organic fertilisers application	$e^{V^{ORG}}$	20	%	(IPCC et al., 2006, p. 1)
	Emission factors - Volatilisation of synthetic fertilisers application	$e^{V^{SYN}}$	10	%	(IPCC et al., 2006, p. 1)
	Mineralisation rate per land use	μ_l	REP	-	(Clivot et al., 2019)
C:N ratio of the soil per land use	CN_l^{Soil}	REP	-	(Ballabio et al., 2019)	
Plant	Harvested biomass to humans per plant	v_i^H	REP	-	(Therond et al., 2017)
	Harvested or grazed biomass allocated to livestock per plant and per feed category	$v_{i,k}^L$	REP	-	(Therond et al., 2017)
	Shoot-to-root ratio per plant	SR_i	REP	-	(Clivot et al., 2019), (Comifer - Groupe Azote-Soufre, 2013)
	Harvest index per plant	HI_i	REP	%	(Clivot et al., 2019), (Comifer - Groupe Azote-Soufre, 2013)
	Typical yield per plant	\dot{y}_i^{TYP}	REP	kg/ha/year of fresh matter	(Ministère de l'Agriculture et de l'Alimentation, 2022)
	Area cultivated per plant	A_i	REP	ha	(Ministère de l'Agriculture et de l'Alimentation, 2022)

Table II. 3 (continued).

Compartment	Parameter or variable name	Rating	Nominal value ¹	Unit	Source
Plant	Biological N fixation per plant	\dot{n}_i^{BF}	REP	kgN/ha/year	(Anglade et al., 2015)
	N content of the harvested organ per plant	σ_i^H	REP	kgN/100kg of fresh matter	(IPCC et al., 2006, p. 1), (Clivot et al., 2019), (ANSES, 2020)
	N content of the aerial residues per plant	σ_i^{RA}	REP	kgN/100kg of fresh matter	(IPCC et al., 2006, p. 1), (Clivot et al., 2019),
	N content of the root residues per plant	σ_i^{RR}	REP	kgN/100kg of fresh matter	(IPCC et al., 2006, p. 1), (Clivot et al., 2019),
	Share of aerial crop residues exported as livestock bedding	ξ_{EXP}	35	%	(Harchaoui and Chatzimpiros, 2019)
	Plant fertilisation need per plant	$\dot{n}_i^{Fert,Need}$	REP	kgN/ha/year	Computed
	Plant N need per plant	\dot{n}_i^{Need}	REP	kgN/ha/year	Computed
	Slope of the relationship between harvested biomass and soil mineral N available to the plant	δ_i	REP	-	Computed
Livestock	Individual feed need per species and per feed category	$\beta_{j,k,t}$	REP	kgN/LU/year	(Therond et al., 2017)
	Individual animal-sourced food production coefficient per species and per animal product (meat, egg and milk)	$c_{j,p}$	REP	kgN/LU/year	(Therond et al., 2017)
	Feed shortage threshold beyond which the livestock number is decreased	T	10	%	Set arbitrarily
	Emission factors - Volatilisation during storage of housing facilities effluents	ϵ^{VS}	5	%	(Service de l'observation et des statistiques, 2013)
	Emission factors - Volatilisation during excretion of effluents in housing facilities	ϵ^{VB}	30	%	(Service de l'observation et des statistiques, 2013)
	Emission factors - N_2O emissions of effluents in housing facilities and during storage	ϵ^{N_2O}	1	%	(Service de l'observation et des statistiques, 2013)
	Emission factors - Leaching of effluents during excretion and storage in housing facilities	ϵ^L	10	%	(IPCC, 2019)

¹ REP: see data tables on the repository

II.4 Scenarios simulated or optimised

In chapters 1, 2 and 4, I simulated constraints on input supply, which may be related to a global peak oil, such as a linear decrease in the availability of synthetic fertiliser and/or feed imports (see section II.1). I have set a time horizon of 30 years, assuming a linear decline in global oil production to zero by 2050. This decline in the import availability of the two inputs considered starts from an initial value depending on current needs and ends at 0. In all three chapters I simulated a joint decline of both inputs (*Synth-Feed-*). In Chapter 1, I also simulated two other scenarios, which corresponded to a decrease only in the availability of imported feed (*Feed-*) or a decrease only in the availability of imported synthetic fertiliser (*Synth-*). The initial values of the import availability of both inputs vary slightly between the three chapters. The characteristics of these scenarios in chapters 1, 2 and 4 are summarised in the Table II. 4.

Table II. 4 Initial and final values of the scenarios of linear decrease in the availability of synthetic fertilisers and feed imports in chapters 1, 2 and 4.

Chapter	Input	Value	Scenario Synth-	Scenario Feed-	Scenario Synth-Feed-
1	Synth	Initial	70% of the plant's mineral N fertilisation need	70% of the plant's mineral N fertilisation need	70% of the plant's mineral N fertilisation need
		Final	0	Initial value	0
	Feed	Initial	Maximum between 100% of the feed import need per feed category and 2,000 tonnes of N.	Maximum between 100% of the feed import need per feed category and 2,000 tonnes of N.	Maximum between 100% of the feed import need per feed category and 2,000 tonnes of N.
		Final	Initial value	0	0
2	Synth	Initial	N.A.	N.A.	70% of the mineral N fertilisation need of the plants on the fertilised areas
		Final	N.A.	N.A.	0
	Feed	Initial	N.A.	N.A.	100% of feed need by feed category
		Final	N.A.	N.A.	0
4	Synth	Initial	N.A.	N.A.	100% of the mineral N fertilisation need of crops
		Final	N.A.	N.A.	0
	Feed	Initial	N.A.	N.A.	100% of feed need by feed category
		Final	N.A.	N.A.	0

The simulations or optimisations carried out in this PhD thesis present differences or similarities in terms of modelling component (e.g. concerning the N flow allocation rules) or model input data. These differences or similarities are summarised in the Table II. 5.

Table II. 5 Differences or similarities between chapters in terms of modelling component or input data.

Modelling component or input data	Chapter			
	1	2	3	4
Crop residue management	35% of aerial crop residues exported for livestock bedding within or outside the farming system. The amount used in the farming system is obtained by dividing with the maximal coefficient of feed self-sufficiency among the feed subcategories.	35% of aerial crop residues exported for livestock bedding within or outside the farming system. The amount used in the farming system is obtained by dividing with the maximal coefficient of feed self-sufficiency among the feed subcategories.	No crop residues exported	No crop residues exported
Dynamics of active soil organic matter of permanent grasslands	Initial active soil carbon stock (0-10 cm) for spin-up method, C:N and mineralisation rate: Single values for both land uses (those for cropland soils).	Initial active soil carbon stock (0-10 cm) for spin-up method of 20,000 kgC C:N equal to the C:N of the cropland soil multiplied by 2 Single mineralisation rate for both land uses.	Initial active soil carbon stock (0-10 cm) for spin-up method of 20,000 kgC C:N equal to the C:N of the cropland soil multiplied by 2 Single mineralisation rate for both land uses.	Initial active soil carbon stock (0-10 cm) for spin-up method of 20,000 kgC C:N equal to the C:N of the cropland soil multiplied by 2 Single mineralisation rate for both land uses.
Permanent grassland residues	Considered as annual crops: aerial and root residues humify each year - mineral N need includes residue need. Ruminants consume all above-ground biomass.	Considered as annual crops: aerial and root residues humify each year - mineral N need includes residue need. Ruminants consume all above-ground biomass.	Considered as annual crops: aerial and root residues humify each year - mineral N need includes residue need. Ruminants consume all above-ground biomass.	Considered as annual crops: aerial and root residues humify each year - mineral N need includes residue need. Ruminants do not consume all the above-ground biomass (depending on their needs and numbers)
	$HI < 1$	$HI = 1$	$HI = 1$	$HI = 1$ (except for biodiverse sown grasslands)

Table II. 5 (continued).

Modelling component or input data	Chapter			
	1	2	3	4
Fertilisation of permanent grassland with synthetic fertilisers	Yes (productive grasslands)	Yes (productive grasslands)	Yes (productive grasslands)	No
Humification coefficients of crop residues	0.5	Values from Le Noë et al. (2017)	Values from Le Noë et al. (2017)	Values from Le Noë et al. (2017)
Livestock number	Values from the 2010 agricultural census at the small agricultural region level	Values from the EFESE project (2010 agricultural census at communal level, not secreted)	Values from the EFESE project (2010 agricultural census at communal level, not secreted)	N.A.
Feed categories for the calculation of feed shortages	Energy concentrates, protein concentrates and forages	Energy concentrates, protein concentrates and forages	Concentrates and forages	Concentrates and forages
Animal-sourced food production	Production coefficients per species and per product constant over time from the EFESE project.	Production coefficients per species and per product constant over time from the EFESE project.	Production coefficients per species and per product constant over time from the EFESE project.	From herd dynamics (meat production only)
Feed surplus reallocated to humans	Yes (cereal and oilseed)	Yes (cereal and oilseed)	Yes (cereal and oilseed)	No
Biological N fixation	$\dot{n}_{i,t}^{BF} = f(y_{i,t})$	$\dot{n}_i^{BF} = f(y_i^{TYP})$	$\dot{n}_i^{BF} = f(y_i^{TYP})$	$\dot{n}_i^{BF} = f(y_i^{TYP})$
Emissions of N_2O from biological N fixation	No	No	No	Yes

II.5 Case studies⁸

The analyses in chapters 1, 3 and 4 focused on four European farming systems (Figure II.2), while Chapter 2 concerns all French farming systems (Small Agricultural Region (SAR) entity - *Petite Région Agricole* in French) whose UAA represents more than 15% of the total area of the farming system.

Chapters 1 and 3 focused on three French farming systems (*Petite Région Agricole* entity): (i) Plateau Picard, a field crop farming system with few livestock, (ii) Bretagne Centrale, an intensive monogastric and dairy farming system, and (iii) Bocage Bourbonnais, an extensive beef farming system. Chapter 4 focused on a Portuguese farming system (*NUTS-2* entity): Alentejo, an extensive beef farming system in *Montado* ecosystems (agroforestry landscapes with low tree density).

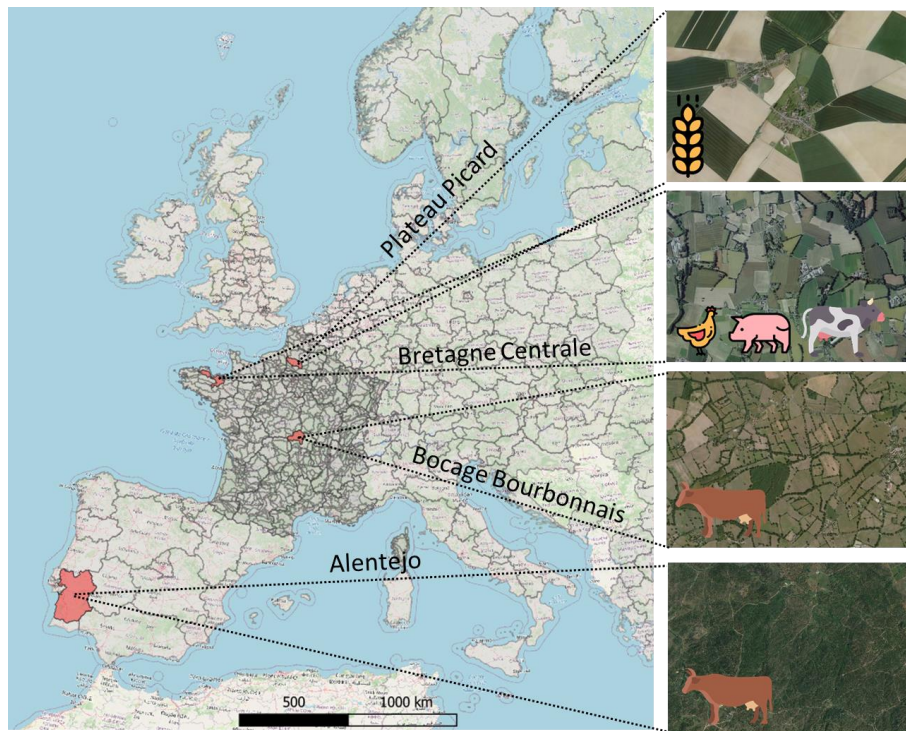


Figure II.2 Locations, landscapes and dominant techno-economic orientations of the four European farming systems selected as case studies for chapters 1, 3 and 4. The map on the left is from OpenStreetMap. The aerial photographs on the right are from geoportail.gouv or google maps at 1:17000 scale.

⁸ This section overlaps with the introductions and materials and methods in chapters 1, 3 and 4.

II.5.1 Three French farming systems ⁹

In Chapter 1, I wanted to calculate and compare the robustness of food production to input import constraints according to the crop-grassland-livestock composition, and in Chapter 3, I wanted to explore, among other things, the set of changes in crop-livestock compositions that maximise food production while minimising input imports. For that purposes, I chose French farming systems with distinct crop-grassland-livestock compositions. First, I considered the Bocage Bourbonnais which was a case study of the SURE-Farm project (which co-funded this PhD thesis) chosen to contribute to the integrated assessment of the future resilience of this farming system in work package 5. Then I chose Plateau Picard and Bretagne Centrale which have dominant technico-economic orientations quite distinct from the Bocage Bourbonnais. I assumed that the SAR level is an adequate level of representation of a farming system. Plateau Picard and Bretagne Centrale were validated using the classification of Jouven et al. (2018), which grouped SARs according to the adequacy between local crop production and feed needs.

Table II. 6 Agricultural areas of the three French farming systems in 2016 (IGN, 2016).

Variable	Small agricultural region		
	Bocage Bourbonnais	Bretagne Centrale	Plateau Picard
Livestock number (LU/ha UAA) ¹	1	3.8	0.3
UAA (ha)	185,182	176,823	153,425
Share of fodder area (except permanent grassland) (%)	30.5	42.2	5.3
of which artificial grassland area (%)	3.2	1.4	14.9
of which temporary grassland area (%)	86.9	49.7	14.9
of which annual fodder area (%)	10	48.9	70.3
Share of permanent grassland area (%)	48.7	6.7	6.2
of which low-productivity permanent grassland area (%)	0.2	0.9	0
Share of cereal area (%)	18.4	45.7	59.4
Share of oil and protein crop area (%)	3.4	4.5	15.9
Share of sugar crop area (%)	0	0	9.3
Share of 100% legume crop area (%)	1.5	1.2	4.8

¹ data from the EFESE project, which come from the communal data of the 2010 agricultural census, not secreted (Therond et al., 2017).

⁹ These descriptions below are based on datasets from different years: 2016 for crop areas, and 2010 for livestock numbers. I have assumed a similar livestock number in 2016.

Bocage Bourbonnais is a SAR in the Allier department in the Auvergne-Rhône-Alpes region with an area of 273,345 ha. The UAA covers 68% of its total area. The dominant technical and economic orientation of the farms in this farming system is the breeding of extensive beef cattle, mainly of the Charolais breed (Ministère de l'Agriculture et de l'Alimentation, 2010). These cattle graze for more than eight months of the year on permanent grasslands separated by hedges, in a bocage landscape (Figure II.2). Permanent grasslands represent almost 50% of the UAA, while temporary grasslands represent about 30% of the UAA (Table II. 6). Cattle numbers were over 250,000 in 2010, for an equivalent of 145,255 LU, bringing the stocking rate for cattle to 1 LU/ha of forage area (Table II. 6 and Table II. 7). In the classification of Jouven et al. (2018), this farming system belongs to the group "balanced livestock and plant production with surplus concentrates".

Plateau Picard is a SAR in the Oise department in the Hauts-de-France region with an area of 216,665 ha. The UAA covers 71% of its total area. The dominant technical and economic orientation of the farms in this farming system is field crops (Ministère de l'Agriculture et de l'Alimentation, 2010). Almost 10% of the UAA is used for sugar beet and more than 75% of the UAA is used for cereals or oilseeds (Table II. 6). The livestock number is low (0.3 LU/ha of UAA). Among the breeding farms present, dairy cattle farms are dominant, with 73,075 heads in 2010 for an equivalent of almost 40,000 LU, *i.e.* a stocking rate for cattle of 4.1 LU/ha of forage area, the latter representing about 10% of the UAA (Table II. 6 and Table II. 7). In other words, this farming system imports fodder and also substitutes fodder with concentrates in the cattle's diet during the five months of the year when the cattle are in stalls, in particular to boost milk production (INRA et al., 2018a). As a result, the proportion of concentrates in the cattle's diet is twice as high as in the Bocage Bourbonnais (Therond et al., 2017). Thus, cattle farming in this farming system is more intensive than in the Bocage Bourbonnais. This farming system does not appear in the classification of Jouven et al. (2018) due to the low livestock number.

Bretagne Centrale is a SAR in the Côtes d'Armor department in the Brittany region with an area of 274,771 ha. The UAA covers 64% of its total area. The dominant technical-economic orientations of the farms in this farming system are off-ground monogastric farming (pigs and poultry) and dairy cattle farming (Ministère de l'Agriculture et de l'Alimentation, 2010). In 2010, the pig number exceeded 1,500,000 head, the poultry number 5,000,000 head, while the cattle number was around 300,000 head, including 100,000 dairy cows (Table II. 7). The stocking rate is thus 3.8 LU/haUAA (Table II. 6). Dairy cattle farms are intensive in terms of diet, as in Plateau Picard, where the proportion of concentrates in the cattle's diet is also twice as high as in Bocage Bourbonnais (Therond et al., 2017). However, cattle farms are not as intensive as in Plateau Picard because the stocking rate for cattle is 1.7 LU/ha of forage area (mostly temporary grassland - 42% of the UAA) and they are in stalls only 2 or 3 months of the year (Table II. 6 and Table II. 7). In the classification of Jouven et al. (2018), this farming system is part of the "dependent livestock production" group with more than 30% of the dry matter consumed by livestock imported (concentrates).

Table II. 7 Livestock number by species and species category in heads (data from the 2010 agricultural census at canton or small agricultural region (SAR level) or in LUs (data from the EFESE project, which come from the data of the 2010 agricultural census at communal level, not secreted). "Sec" means that these data are under statistical secrecy. The data at SAR level from the 2010 agricultural census was used in Chapter 1, while the data from the EFESE project was used in chapters 2 and 3.

Species	Species class	Small agricultural region											
		Bocage Bourbonnais				Bretagne Centrale				Plateau Picard			
		Number of heads (SAR level data)	Number of heads (data at canton level)	Livestock number in LU	Number of months spent grazing	Number of heads (SAR level data)	Number of heads (data at canton level)	Livestock number in LU	Number of months spent grazing	Number of heads (SAR level data)	Number of heads (data at canton level)	Livestock number in LU	Number of months spent grazing
Cattle		206,594	266,045	145,255		99,424	283,646	150,672		26,162	73,075	39,642	
	Cattle younger than 1 year	58,462	79,902		9	58,056	81,304		9	17,996	28,362		7
	Cattle older than 1 year	64,752	85,242		8	41,368	83,274		6	8,166	18,571		6
	Suckler cows	61,736	86,092		8	Sec	15,068		10	Sec	7,576		7
	Dairy cows	6,210	6,581		8	Sec	103,124		10	Sec	17,944		7
Sheep		Sec	92,618	18,600	9	Sec	3,476	879	9	Sec	11,508	2,162	8
Goat		4,021	3,835		9	239	165		10	248	13		8
Poultry		803,508	328,944	9,635		6,497,121	5,457,716	155,086		279,822	3,493	3,822	
	Broilers	678,828				Sec				147,202			
Pigs		14,604	49,149	10,926		871,114	1,832,188	373,820		7,667	Sec	2,721	
	Sows		2,385				143,566				Sec		

II.5.2 Grass-based beef cattle farming system in Alentejo, Portugal

Alentejo is a rural and agricultural region in the south of Portugal with an area of 3,138,500 ha (Figure II.2). The UAA covers 68% of its total area (Table II. 8). The dominant technical-economic orientation is the breeding of beef cattle on grass (more than 65% of livestock in LU) (Table II. 9). This region is the main beef production area in Portugal; the meat produced is mainly exported to other regions in Portugal and also to the Middle East (Araújo et al., 2014). The vast majority of beef cattle graze permanent grasslands all year round, particularly in the *Montado* ecosystems (Table II. 8 and Table II. 9). *Montado* ecosystems are extensive agroforestry landscapes typical of the Iberian Peninsula, in which low-density forests coexist with permanent grasslands (Pereira et al., 2009). The area of permanent grassland represents more than 60% of the UAA and the area of permanent grassland in *Montado* ecosystems represents 53.9% of the area of permanent grassland (Table II. 8). The area of sown biodiverse permanent grassland rich in legumes represents almost 25% of the permanent grassland area (50% of which is in the *Montado* ecosystem) (Table II. 8). These sown biodiverse permanent grasslands are financially incentivised since 2009 by the Portuguese government to increase the carbon stocks of agricultural soils, as a climate change mitigation action (Teixeira et al., 2015). Field crops cover almost 24% of the UAA and half of them are annual forage crops (oats and maize) or temporary grasslands (Table II. 8). These fodder crops are used to feed the 10% of beef cattle that stall for more than 3 months per year on average (steers) (Instituto Nacional de Estatística, 2019) (Table II. 9). The stocking rate, all species combined, is 0.65 LU/haUAA (Table II. 8 and Table II. 9).

Table II. 8 Agricultural area in ha in Alentejo, Portugal, 2019 (Instituto Nacional de Estatística, 2020, 2019)

Surface	Share (%)	Area (ha)
UAA	100	2,144,066
Cropland	23.8	509,271
of which grain legumes (for feed or food)	2.5	12,556
of which fodder area (annual fodder or temporary grassland)	50.8	258,874
of which annual fodder crops	16	41,295
of which cereal area	20.3	103,512
of which wheat	19.2	19,919
of which barley	17.7	18,273
of which maize	11	11,361
Permanent crops	15.1	323,733
of which permanent grassland	10.2	33,000
of which olive tree	60.8	197,628
Permanent grassland	61.1	1,310,017
of which sown and spontaneous improved	24	315,000
of which under cover of woods and forests (<i>Montado</i> ecosystem)	53.9	705,800
of which sown and spontaneous improved	22.2	156,880

In Chapter 4, I wanted to explore the robustness of meat production in the face of input supply constraints as well as the reduction in net GHG emissions of scenarios of changes in practices and compositions that aim to adapt to and/or mitigate climate change. This Portuguese case study was suitable for this purpose for several reasons: (1) feed imports have increased due to the increase in cattle numbers by 60% since 1999 in Alentejo and the use of synthetic fertilisers also for the improvement of permanent grasslands (Instituto Nacional de Estatística, 2019; Rodrigues et al., 2020) (2) cattle farming is an important source of GHG emissions from the agricultural sector; (3) it faces increasingly frequent droughts, due to climate change, which reduce grassland yields and feed self-sufficiency (Huguenin et al., 2017; Jongen et al., 2013; Karimi et al., 2018; Nardone et al., 2010) and (4) partially implemented practices such as grass fattening of steers and set of sown biodiverse permanent grasslands rich in legumes contribute to climate change mitigation, forage self-sufficiency and synthetic N fertiliser self-sufficiency.

Table II. 9 Livestock number by species in head number and LU in Alentejo, Portugal, in 2019 (Instituto Nacional de Estatística, 2019). The coefficients for converting the head number into LU were taken from Eurostat.

Species and species class	Share (%)	Number (heads)	Livestock unit coefficient	Number (LU)
Cattle	100	664,620	N.A.	409,103
Dairy cows	3.9	25,827	1	25,827
Other cattle	96.1	638,793	0.6	383,276
of which grazing all over the year	90.4	577,748	0.6	346,649
Pigs	100	449,430	0.2	89,886
Sheep	100	1,139,565	0.1	113,957
Dairy ewes	3.3	37,872	0.1	3,787
Poultry	100	369,465	0.03	11,084

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

We have seen that European farming systems are dependent on fossil fuels and therefore vulnerable to the consequences of global peak oil, like constraints on input imports. Their food production resilience is therefore questioned. The use of a farming system biophysical model is one way to assess this resilience. Since this dependence on imported inputs varies according to the crop-grassland-livestock composition of the farming system, the aim of this chapter is to explore the robustness of food production without changes in the composition of the three types of French farming systems chosen in this thesis to a progressive decrease over 30 years to zero in the import of feed and synthetic nitrogen fertilisers, and to open up the discussion on the links between crop-grassland-livestock composition and robustness. For this purpose, the model is used in simulation mode.

In this chapter, the UAA of the three farming systems were overestimated compared to the UAA in 2016 due to an error during the intersection procedure of the land use data from Registre Parcellaire Graphique 2016 on the ArcGIS geographic information software (double counting of plots) (IGN, 2016). After correction (for the analyses of Chapter 2) and new simulations, we observed that the crop composition as well as the shapes of the food production trajectories and therefore the conclusions did not change. Only the food productivity values varied.

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

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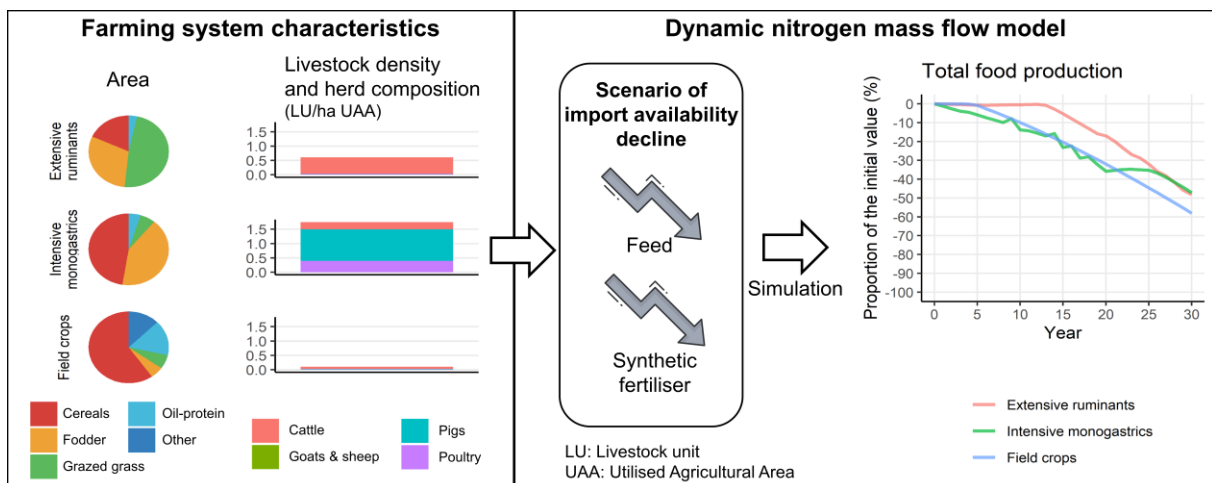
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Highlights

- Global peak oil production may lead to a decline in input availability.
- We designed a time-dynamic nitrogen flow model of a farming system on a territorial scale.
- We compared the food production robustness of three French farming systems to synthetic fertiliser and feed import declines.
- Crop-grassland-livestock balance determines the short-term robustness of food production.
- Configurational changes in farming systems are needed to cope with peak oil.

Graphical abstract



Abstract

Agriculture in Western Europe is predominantly input-intensive (fertilisers, water, fuel, pesticides) and relies on feed imports. As a result, it is dependent on oil, which may start to decline in production in the 2020s, thus exposing the agricultural sector to potential economic stress, including increased input prices and decreased farmer purchase capacities. Therefore, it is necessary to assess the capacity of European farming systems (FS) to maintain production levels despite a decline in oil production (*i.e.*, robustness). We aimed to model and compare the time variations in the animal- and crop-sourced production of three French FS under three scenarios of decreased availability of feed and synthetic fertiliser imports. We developed a FS-scale dynamic model that considers nitrogen flows between livestock, plant, and soil compartments. Plant production is a function of soil mineral nitrogen levels, and livestock numbers depend on feed availability. The three FS are characterised by different crop-grassland-livestock balances: (i) field crop (Plateau Picard), (ii) intensive monogastric (Bretagne Centrale), and (iii) extensive ruminant (Bocage Bourbonnais). The three scenarios consist of different combinations of synthetic nitrogen fertilisers and feed import availability declines until 2050: a decrease in synthetic fertilisers only (*Synth-*), a decrease in feed imports (*Feed-*), and a decrease in both external inputs (*Synth-Feed-*). The first two scenarios highlight the positive role of livestock effluents and permanent grasslands on the robustness of food production. In the *Synth-Feed-* scenario, the extensive ruminant FS exhibits robustness (no decline in food production) for 13 years, whereas the field crop FS exhibits robustness for 4 years. In contrast, the intensive monogastric FS shows decreased food production within the first year. The difference between the two crop-livestock FS can be explained by livestock density, herd composition but also plant cover composition. In the long term, all three FS show a decrease in food production between 45–60%. Our modelling work shed some light on the role of ruminants and permanent grasslands in making FS more robust to decreases in synthetic fertiliser and feed import availability, increasing the time with no production decline after the perturbation starts. For longer-time resilience, configurational changes are still necessary, however a greater robustness gives opportunity to implement them, therefore facilitating adaptation and transformation. Our model paves the way to the study of resilience of FS from the point of view of their crop-grassland-livestock configuration and their dependence on external inputs.

Keywords

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

1.1 Introduction

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

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

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

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

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

1.2 Material and Methods

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

1.2.1 General model description

The model conceives the FS as consisting of soil, plant, and livestock compartments. The plant and soil compartments are distributed in two land uses: permanent grasslands and cropland (which includes temporary grasslands) (Figure 1.1). The livestock compartment is composed by livestock species (with different dietary needs) which are either kept in housing facilities or grazing on permanent grasslands. The soil compartment is composed of a stock of active organic nitrogen and a pool of mineral nitrogen assimilated by crops or permanent grasses. Depending on the species and on the share of grazed grass in livestock diet, effluents from the livestock compartment are applied to cropland or permanent grasslands.

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

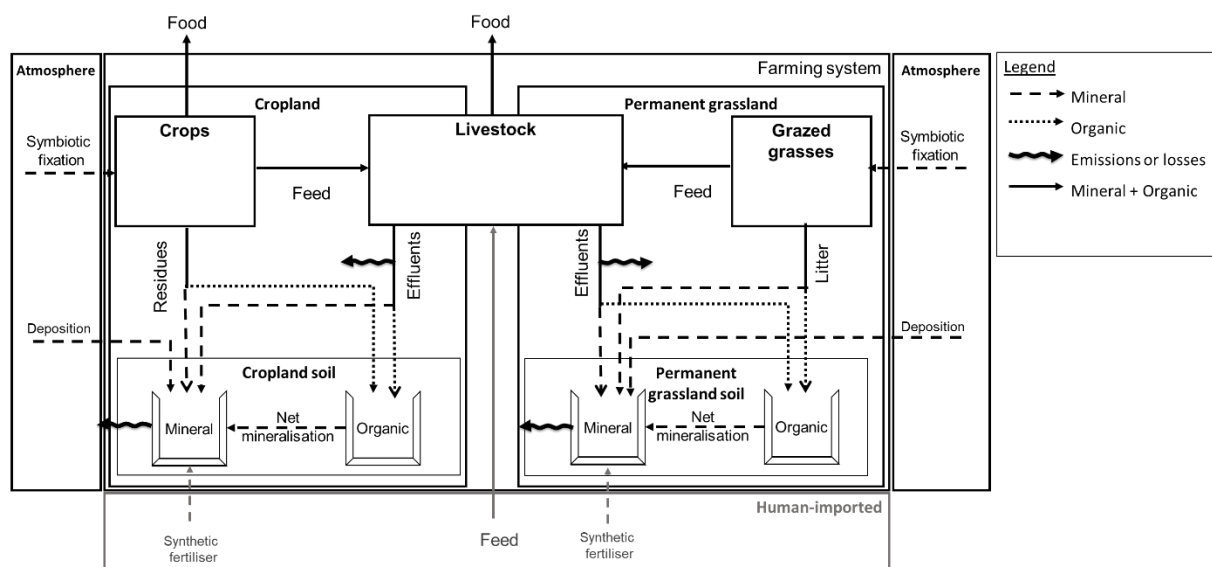


Figure 1.1 Conceptual scheme of our model formed by nitrogen compartments (boxes) and flows (arrows). Nitrogen flows are mineral (dashed lines), organic (dotted lines), or a mix (unbroken lines). The external flows that enter the FS come either from the atmosphere or are imported by humans (in grey)

1.2.2 Mathematical description by compartment

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

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

1.2.2.1 Soil compartments

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

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

Organic nitrogen dynamics

The dynamics of soil organic nitrogen correspond to the dynamics of soil carbon (see the AMG model (Clivot et al., 2019)) transposed to nitrogen and are described by a mass balance equation (Equations (1-1) and (1-2) below). We replaced the quantity of carbon by the quantity of nitrogen using C:N ratios. The mineralised soil organic nitrogen is immobilised to humify the carbon in the input biomass flow when there is not enough nitrogen in the flow to do so (*i.e.*, when the C:N ratio of the input flow is high

compared to that of the soil and when the humification coefficient is high) (Trinsoutrot et al., 2000). Plant residues have generally higher C:N ratios than livestock effluent (Fuchs et al., 2014).

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

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

Equations (1-1) and (1-2) represent a nitrogen balance in cropland and permanent grasslands, whose inputs are the organic parts of aerial residues ($\hat{r}_t^{A,C}$ and $\hat{r}_t^{A,G}$ [kg/ha]), root residues ($\hat{r}_t^{R,C}$ and $\hat{r}_t^{R,G}$ [kg/ha]), livestock effluents ($\hat{e}_t^{L^B}$ and $\hat{e}_t^{L^G}$ [kg/ha]), and human sewage sludge for cropland only (\hat{e}^H [kg/ha]). The model does not assume any nitrogen losses in the organic form to water. Output terms are the net mineralisation of organic nitrogen, which is equal to the mineralised flow ($\mu * n_t$) minus the immobilisation flow ($i_{t+1}^{M,C}$ and $i_{t+1}^{M,G}$ [kg/ha]), being μ^C and μ^G constant mineralisation rates.

Mineral nitrogen flows and losses

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

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

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

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

1.2.2.2 Plant compartments

Plant compartments are composed of surfaces cultivated with different crops or grazed grasses. The areas of these surfaces are assumed constant, and their sum gives the total utilised agricultural area

(UAA) of the FS. Each crop or grazed grass is parameterised differently. Each crop or grazed grass (i) is assigned a set of traits: area (A_i [ha]), fresh matter yield of the harvested or grazed organ ($y_{i,t}$ [kg/ha]), harvest index, shoot-to-root ratio and nitrogen contents. All these coefficients make it possible to calculate the nitrogen in plant production.

Plant yield

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

Plant and residues production

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

1.2.2.3 Livestock compartment

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

Feed

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

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

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

Livestock population dynamics

The time evolution of livestock populations is ruled by a dynamic model. The livestock number ($L_{j,t}$) for a species (j) changes with the management rate ($\tau_{j,t}^M$ [-]) (Equation (1-5) below). A positive value of the management rate corresponds to the willingness of the farmer to increase the herd size, whereas a negative value corresponds to the willingness of the farmer to decrease the herd size.

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

Animal-sourced food production

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

Livestock effluents

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

1.2.3 Simulated scenarios

We designed scenarios of progressive declines in the availability of synthetic fertiliser and feed imports over thirty years. This time horizon made it possible to observe the consequences of the perturbations on the food production with sufficient hindsight, and to simulate a decline in oil availability that could be possible in the event of a global oil peak in the 2020s. The first scenario (*Synth-*) corresponds to a linear decrease in the availability of imported synthetic fertilisers (S_t^A) with no feed imports decrease. The second scenario (*Feed-*) corresponds to a linear decrease in the availability of feed imports ($I_{k,t}^A$) for each feed category (k) with no synthetic fertiliser import decrease. The third scenario (*Synth-Feed-*) corresponds to a joint linear decrease in the availability of the two external human imported inputs (S_t^A and $I_{k,t}^A$). The trajectories of input decreases start from an initial value decrease linearly until zero at the time horizon. Regarding the availability of synthetic fertiliser imports, the initial value (S_0^A) corresponds to 70% of the total initial mineral nitrogen needs of the plants (see Supplementary Material) so that the simulation is started without a synthetic fertiliser shortage, as the synthetic fertilisation needs never exceeds 70% of the plant nitrogen needs. Regarding the availability of feed imports, the initial value for each feed category ($I_{k,0}^A$) corresponds to the initial import needs per feed category (k). If the initial import needs for a feed category are less than 1,000 tons of nitrogen, then a value of 1,000 tons is assigned to the import availability for that feed category.

In these scenarios, the considered livestock species are cattle, goats and sheep (ruminants), pigs and poultry (monogastrics). Diet is concentrate-only for the monogastrics and contains at least 70% fodder for ruminants (Hou et al., 2016; Therond et al., 2017). The nominal value of the management rate (T_j^M) is zero. The considered animal-sourced food products are eggs, milk, and meat. The plant categories considered are a subset of the categories used in the *Registre Parcellaire Graphique* (RPG) (IGN, 2016), inspired by the French agricultural census (Ministère de l’Agriculture et de l’Alimentation, 2022). The main categories of crops considered are cereals, oil and protein crops, sugar crops, industrial crops, tuber crops, fruit and vegetables, and fodder. Within the fodder category, we differentiate temporary grasslands (harvested or grazed grasslands less than 6 years old composed of 100% or partly of grasses), artificial grasslands (temporary grasslands composed of 100% legumes) and annual forage crops. Crops consisting of 100% legumes are not fertilised with synthetic fertiliser (Service de l’observation et des statistiques, 2013), as well as low-productive permanent grasslands. The feed categories for the different plants are cereals, oil-protein, fodder, grazed grass, co-products, and oilseed meal. We also considered a category labelled ‘other’ that includes fruits, vegetables, and tubers (classification based on the French National Ecosystem Assessment (Therond et al., 2017)). Only permanent grasslands are used for livestock grazing. Oilseed meals are derived from the processing of oilseeds into oil. Co-products come from the processing of cereals, fruit and vegetables for human consumption. More details about plant and feed classifications are available in the Supplementary Material. The nitrogen needs of a plant are

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

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

1.2.4 Case studies

We applied this model to three FS types characterised by distinct proportions of livestock numbers and plant areas. We chose three French small agricultural regions (SAR, *Petite Region Agricole* in French). The SAR (average area of 76,800 ha) is an ideal representation of a FS, as already used in other studies (Accatino et al., 2019; Mouysset et al., 2012; Teillard et al., 2017). Jouven et al. (2018) grouped SAR to reflect the adequacy between local plant production and livestock consumption. We picked three SAR (Table 1-1) from different groups of the classification by Jouven et al. (2018): (i) an *extensive ruminant* FS (Bocage Bourbonnais), taken from the group ‘*balanced livestock and plant production with surplus concentrates*’ consisting of mainly ruminant farms; (ii) an *intensive monogastric* FS (Bretagne Centrale), taken from the group ‘*dependent livestock production*’ consisting of mainly monogastric farms with more than a 30% dependence on dry matter imports; (iii) a *field crop* FS (Plateau Picard), characterised by the prominent presence of crops and a very low livestock stocking rate and therefore

not considered in the clustering by Jouven et al. (2018). In summary, the choice of the scenarios was aimed at exploring the roles of the stressors, and the choice of the SAR was aimed at exploring the roles of the FS configuration in terms of crops, grasses and livestock.

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

Variable	Extensive ruminants	Intensive monogastrics	Field crops
Number of inhabitants in 2017 [person]	103,150	210,844	188,749
Protein requirement of the local FS population in nitrogen* [kg/ha UAA]	2	4	4.1
Livestock density [LU/ha UAA]	0.62	1.75	0.11
Share of ruminants [-]	0.95	0.14	0.76
Total utilised agricultural area [ha]	234,941	237,592	207,642
Share of fodder area** [-]	0.30	0.41	0.05
of which artificial grassland area	0.03	0.01	0.14
of which temporary grassland area	0.10	0.50	0.71
of which annual fodder area	0.87	0.49	0.15
Share of permanent grassland area [-]	0.48	0.06	0.06
of which low-productivity permanent grassland area	0.02	0.08	0
Share of cereals area [-]	0.18	0.47	0.60
Share of oil and protein crop area [-]	0.03	0.05	0.16
Share of sugar crop area [-]	0	0	0.09
Share of 100% legume crop area*** [-]	0.02	0.01	0.05
Initial stock of soil organic nitrogen in the 30cm soil depth in agricultural land [kg/ha UAA]	8,010	6,206	7,464
Initial stock of cropland active soil organic nitrogen in the 30cm soil depth n_0^C [kg/ha]	2,707	2,554	2,260
Initial stock of permanent grassland active soil organic nitrogen in the 30cm soil depth n_0^G [kg/ha]	2,625	2,179	2,055
Mineralisation rate of the soil organic matter in agricultural land [-]	0.06	0.07	0.09

*daily protein requirement of 80g/person

**except permanent grasslands

***not fertilised by synthetic nitrogen in the model

1.2.5 Parameters

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

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

1.3 Results

Time evolution of food production (Figure 1.2), and mineral nitrogen fertilisation flows (Figure 1.3), per FS and per scenario are examined.

Food production decreases over time because of the decreased input availability (Figure 1.2). However, two things should be noted: (i) in some FS it starts to decline earlier than others; (ii) in some cases, the total food production is little or not affected, and in one case (the *Feed-* scenario for the intensive monogastric FS), it even increases. Local peaks in animal-sourced food production correspond to the destocking of livestock (and consequent meat production) during feed shortages. An initially positive feed surplus decreases in the event of a synthetic fertiliser shortage (in the extensive ruminant and field crop FS). However, an initially null feed surplus increases when livestock destocking takes place (in the intensive monogastric FS).

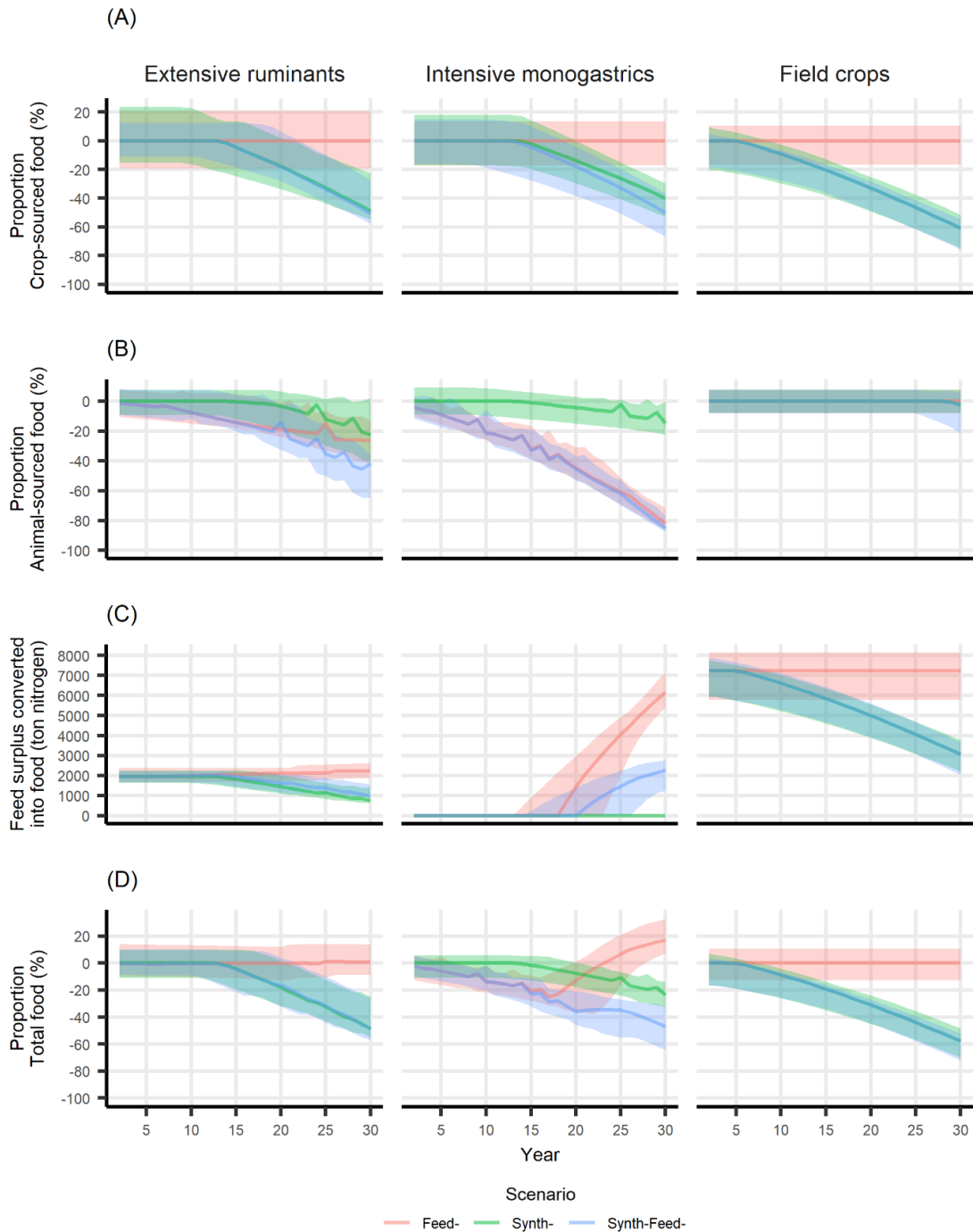


Figure 1.2 Simulated evolution of food production over time for the nominal parameter set as a percentage of the initial quantity or in tons of nitrogen for the three scenarios (colours) according to FS (columns). (A) Crop-sourced food production. (B) Animal-sourced food production (meat, milk, eggs). (C) Feed surplus converted into food in tons of nitrogen. (D) Total food production (aggregated crop- and animal-sourced food production and feed surplus converted into food). For the field crops FS, trajectories in the Synth- and Synth-Feed- scenarios overlap. The coloured ribbons correspond to the intervals of the minimum and maximum values from the global sensitivity analysis.

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

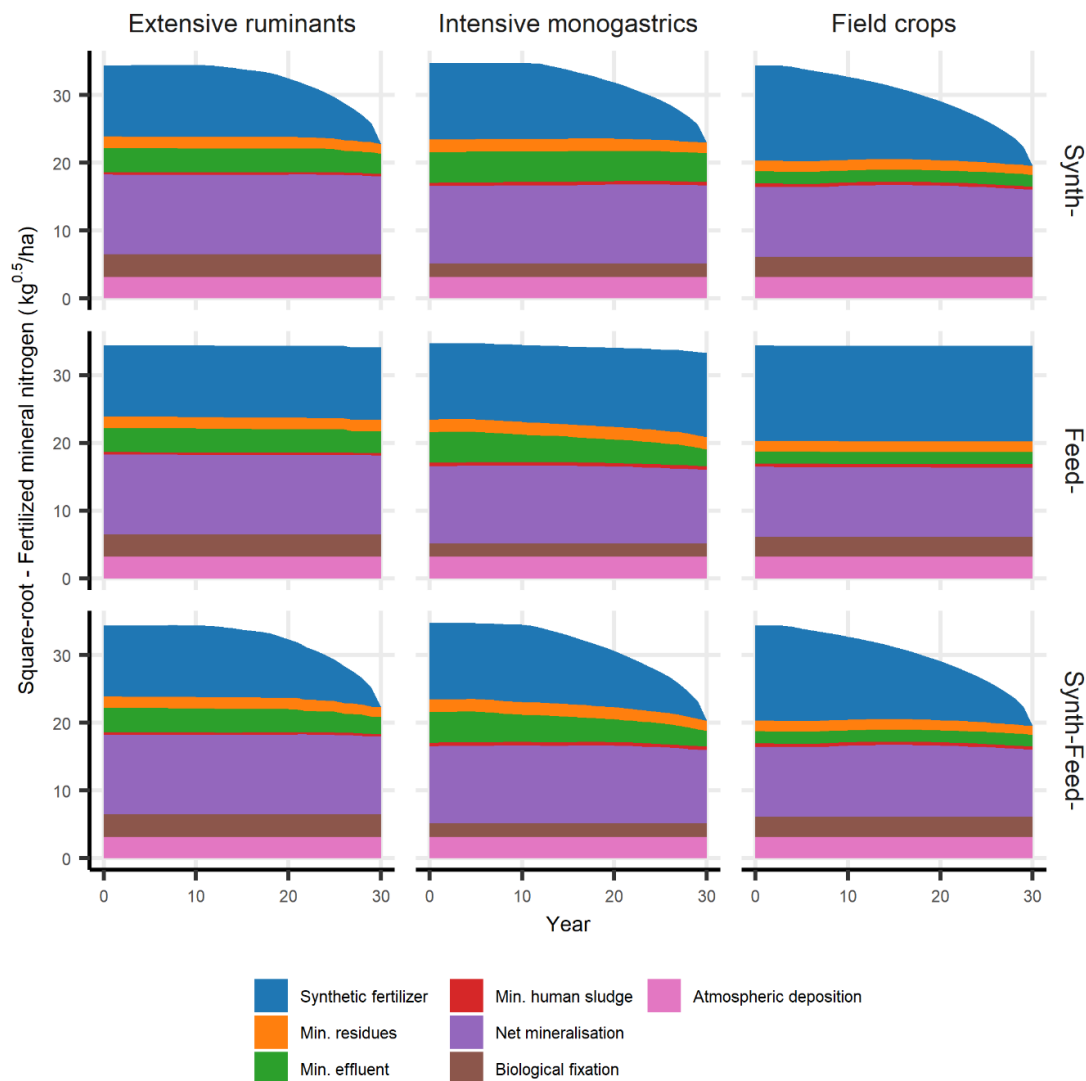


Figure 1.3 Area diagram of the averaged quantity of mineral nitrogen fertilised for both land uses per unit area of UAA ($\text{kg}^{0.5}/\text{ha}$) over time (in years) according to scenario (rows) and FS (columns) for the nominal parameter set. Y axis is put on a square root scale to facilitate the reading of the diagram.

The proportion of the different fertiliser sources changes over time in all the simulations (Figure 1.3). In the scenarios where the availability of synthetic fertilisers decreases (*Synth-* and *Synth-Feed-*), the FS eventually arrives at a fertiliser deficit at different times during the different simulations. This point is not reached in the *Feed-* scenario.

1.3.1 Extensive ruminant FS results

In the *Synth-* and *Feed-* scenarios for the extensive ruminant FS, the crop-sourced food production remains constant for the first 13 years and then it decreases linearly. However, when comparing by scenario, it is the most robust FS in the short term in all the scenarios, regarding total food production (Figure 1.2). Natural and organic nitrogen flows represent approximately 175 kg/ha (*i.e.*, ~60% of the total mineral nitrogen needs before losses) (Figure 1.3).

In the *Synth-* scenario, crop-sourced food production is constant until year 13. Then it decreases linearly (Figure 1.2A), reaching -50% of the initial production. The production of animal-sourced food remains almost constant until year 15 and then decreases reaching -20% of its initial production in year 30 (Figure 1.2B). Feed surplus decreases linearly from year 13 to year 30, reaching 1,000 tons (Figure 1.2C). A decrease in crop-sourced food production and the destocking of livestock cause a decrease in the quantity of crop residues and livestock effluents applied to the soil but have little impact on the net mineralisation of soil organic nitrogen in cropland or permanent grasslands (Figure 1.3). Total food production is constant for the first 13 years, before nearly declining linearly to -50% in year 30 (Figure 1.2D).

In the *Feed-* scenario, crop-sourced food production does not decrease throughout the entire simulation (Figure 1.2A). Animal-sourced food production declines from the first year to approximately -25% in year 30, and it experiences one local peak (Figure 1.2B). The averaged net mineralisation flow also decreases very little as in the previous scenario (Figure 1.3). The total food production slightly increases from year 13 on because of the feed surplus converted into food (Figure 1.2C and D).

The *Synth-Feed-* scenario exhibits curves similar to those of the *Synth-* scenario for crop-sourced food production and feed surplus converted into food. However, animal-sourced food production decreases, nearly reaching -33% in year 30 and experiencing three local production peaks (Figure 1.2B). The averaged net mineralisation flow shows trends similar to those of the *Synth-* scenario, despite a larger decline in animal-sourced food production, reaching -5% in year 30 (Figure 1.3). Total food production reaches -50% in year 30, after remaining almost constant for the first 13 years (Figure 1.2D).

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

1.3.2 Intensive monogastric FS results

In the intensive monogastric FS, the total food production is the least affected among FS in the *Synth*-scenario in the long term (after year 15), but it is the most affected in the *Feed*- and *Synth-Feed*-scenarios in the short term (Figure 1.2). In this FS, natural and organic flows represent approximately 57% of total mineral nitrogen needs before losses (Figure 1.3). The quantity of mineral nitrogen from livestock effluents applied to cropland is the highest among the three FS (~20 kg/ha).

In the *Synth*- scenario, crop-sourced food production is not affected until year 13. It then decreases linearly until year 30, reaching -40% (Figure 1.2A). For animal-sourced food production, it is almost constant until year 13, before declining to -13% in year 30 (Figure 1.2B). It experiences two local meat production peaks linked to livestock destocking during feed shortages. The averaged net mineralisation flow varies little (Figure 1.3). The feed surplus value remains at 0 (Figure 1.2C). Total food production is constant for the first 13 years, before declining linearly to approximately -25% in year 30 (Figure 1.2D).

In the *Feed*- scenario, crop-sourced food production does not decrease throughout the entire simulation (Figure 1.2A). Animal-sourced food production nearly declines linearly from the first year, reaching -80% in year 30 and experiencing five local production peaks (Figure 1.2B). The averaged net mineralisation flow decreases to -9% from the initial value in year 30 (Figure 1.3). The feed surplus increases from year 18, reaching approximately 6,000 tons in year 30 (Figure 1.2C). Finally, total food production decreases linearly until year 17, reaching -25% (Figure 1.2D). It then increases linearly until year 30, reaching +20%.

The *Synth-Feed*- scenario exhibits curves similar to those of the *Feed*- scenario until year 13. However, from that year on, crop-sourced food production decreases linearly, reaching approximately -50% (Figure 1.2A), and animal-sourced food production is slightly lower in the long term compared with the *Feed*- scenario (-85%) (Figure 1.2B). It experiences five local production peaks. The averaged net mineralisation flow decreases from year 15 on reaching -10% in year 30 (Figure 1.3). The feed surplus increases from year 20 on, reaching approximately 2,200 tons in year 30 (Figure 1.2C). Total food production decreases, reaching more than -45% in year 30 (Figure 1.2D).

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

1.3.3 Field crops FS results

When a fertiliser shortage is simulated (*Synth-* and *Synth-Feed-* scenarios), total food production decreases linearly in the field crops FS due to a lower presence of livestock. The impact of these two scenarios are identical, the trajectories overlap (Figure 1.2). Natural and organic flows represent approximately 40% of the total mineral nitrogen needs before losses, the lowest share among the FS (Figure 1.3).

In the *Synth-* scenario, crop-sourced food production is constant until year 4. It then decreases linearly until year 30 (Figure 1.2A), decreasing by 62% of its initial value. This decline occurs as soon as there is a synthetic fertiliser shortage (Figure 1.3). This implies a decrease in the quantity of crop residues applied to the soil. The averaged net mineralisation flow first slightly increases and then decreases to approximately -8% in year 30 (Figure 1.3). The feed surplus decreases linearly to approximately 3,000 tons in year 30 (Figure 1.2C). The trajectory for total food production also has the same shape as the crop-sourced food production curve (Figure 1.2D). In year 30, total food production decreases by approximately 55% of its initial value.

In the *Feed-* scenario, crop- and animal-sourced food production as well as the feed surplus remain constant throughout the entire simulation, showing that a progressive decline in feed imports does not impair food production in this FS, contrary to what happens in the other FS. Therefore, total food production is also constant over time (Figure 1.2D).

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

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

1.4 Discussion

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

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

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

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

1.4.1 Interaction of crop-grassland-livestock composition affecting robustness

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

1.4.1.1 Cropland mineral fertilisation using livestock effluents

Livestock effluents have a similar humification coefficient but lower C:N ratios than crop residues in this model. Consequently, they contributed both to fill soil organic nitrogen stocks and to fertilise crops with mineral nitrogen. Livestock effluents complemented crop residues in organic amendments. They directly increased the net mineralisation flow of the cropland soil organic nitrogen stock because they did not influence the immobilisation flow. Indirectly, they increased the share of natural and organic flows among mineral nitrogen flows. The two FS with high stocking rates showed higher share of natural and organic flows in the mineral fertilisation balance than the field crop FS. Consequently, in the presence of a progressive synthetic fertiliser shortage, the time at which the FS experiences the effects was delayed. The *Synth*- scenario showed a higher total food production robustness of the crop-livestock FS compared with the field crop FS. As a mineral fertiliser, livestock effluents also attenuated a decline in crop production. In the *Synth-Feed*- scenario, the intensive monogastric FS exhibited a more prominent decline in crop-sourced food production compared with the *Synth*- scenario. This was due to the decline in animal-sourced food production in the first year. This difference is less pronounced for the extensive ruminant FS. The reason is that part of the ruminant effluents occur on permanent grasslands, which do not contribute to crop production. The use of livestock effluents as a substitute for synthetic fertilisers has already been largely implemented in crop-livestock farms, thus promoting synergy between livestock and crop compartments and enhancing nutrient self-sufficiency (see Li et al., (2021)). Nevertheless, at the FS level this synergy is not systematically promoted today in France (Loyon, 2017).

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

The net mineralisation flow of cropland soil organic nitrogen provided an important contribution to the mineral nitrogen fertilisation of crops. They are higher for extensive ruminant and intensive monogastric FS due to higher livestock effluent input quantities than in the field crop FS (see section 1.4.1.1). In addition, in the *Synth-Feed* scenario, the decrease in soil organic nitrogen stock in cropland is less important for those FS with high organic matter input from livestock.

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

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

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

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

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

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

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

1.4.2 Interaction between productivity and robustness

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

1.4.3 Decisive capacity of robustness for adaptability and transformability

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

1.4.4 Study and model limits

Certain assumptions made for this analysis have limitations. We assumed the parameters of these FS to be constant: plant yield was considered a function of mineral nitrogen fertilisation and was saturated at a fixed value; loss and emission coefficients were assumed to be constant and no improvements in practices that could reduce losses were considered; agricultural area and plant composition were also assumed to be constant. These assumptions seemed appropriate to answer the research question posed. However, in reality, some of these parameters have experienced minor changes since 1960. For example, since the end of the 20th century in France and Greece, crop nitrogen yields have stagnated at a decreasing nitrogen fertilisation rate. Yet in the Netherlands, they have increased at a constant nitrogen fertilisation rate (Lassaletta et al., 2014a). The efficiency of crop nitrogen use is increasing in these three countries, and it is clear that there is still room for improvement in the crop nitrogen use efficiency in Europe (Dobermann, 2005). Moreover, we assumed that nitrogen was the only limiting factor to crop yield, but other factors can be limiting, depending on climatic and soil conditions, for instance, water or other nutrients such as phosphorus (Csathó and Radimsky, 2009; Webber et al., 2015). Finally, we did not consider atmospheric deposition as a function of reactive nitrogen emissions (Liu et al., 2013), and did not take into account the phenomenon of dilution in the plant of the mineral nitrogen taken from the soil (Lemaire et al., 2008). Improvements to the model could include the addition of other nutrient cycles and the refinement of the relationship between yield and soil available mineral nitrogen.

1.5 Conclusion

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

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

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

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

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

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Appendices

Cropland soil organic nitrogen balance

In all the scenarios and FS, cropland soil organic nitrogen inputs decrease over time (Figure 1.4). In the scenarios with a synthetic fertiliser decline, the quantity of crop residues applied decreases, and the quantity of livestock effluents applied also decreases, especially in scenarios with a decline in feed imports. A decrease in crop residues lead to a decrease in immobilisation flow, whereas a decrease in livestock effluents does not impact the immobilisation flow. Organic amendment decreases lead to decreases in the soil organic nitrogen stock and net mineralisation flow in different proportions, depending on the FS. However, decreases in crop residues and immobilisation flow contribute in the short term to containing or even slightly increasing the net mineralisation flow. They also lead to shifting the date when the net mineralisation flow decreases, with respect to the soil organic nitrogen stock.

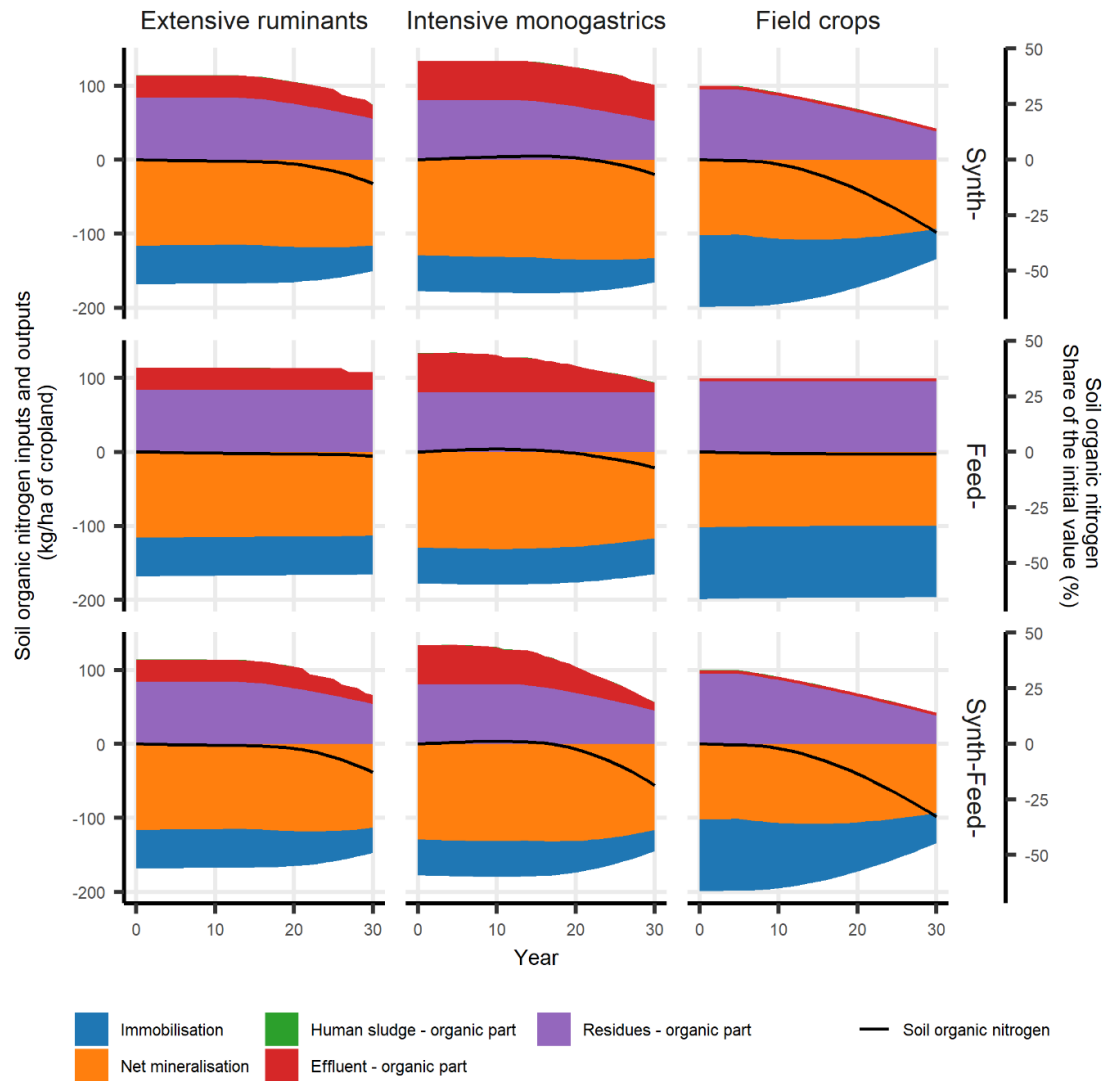


Figure 1.4 Area diagram of the quantity for cropland of soil organic nitrogen inputs and outputs per unit area (kg/ha) over time (in years) according to scenario (rows) and FS (columns) for the nominal parameter set. Cropland soil organic nitrogen stock variations are also shown as percentages (right y-axis).

Permanent grassland soil organic nitrogen balance

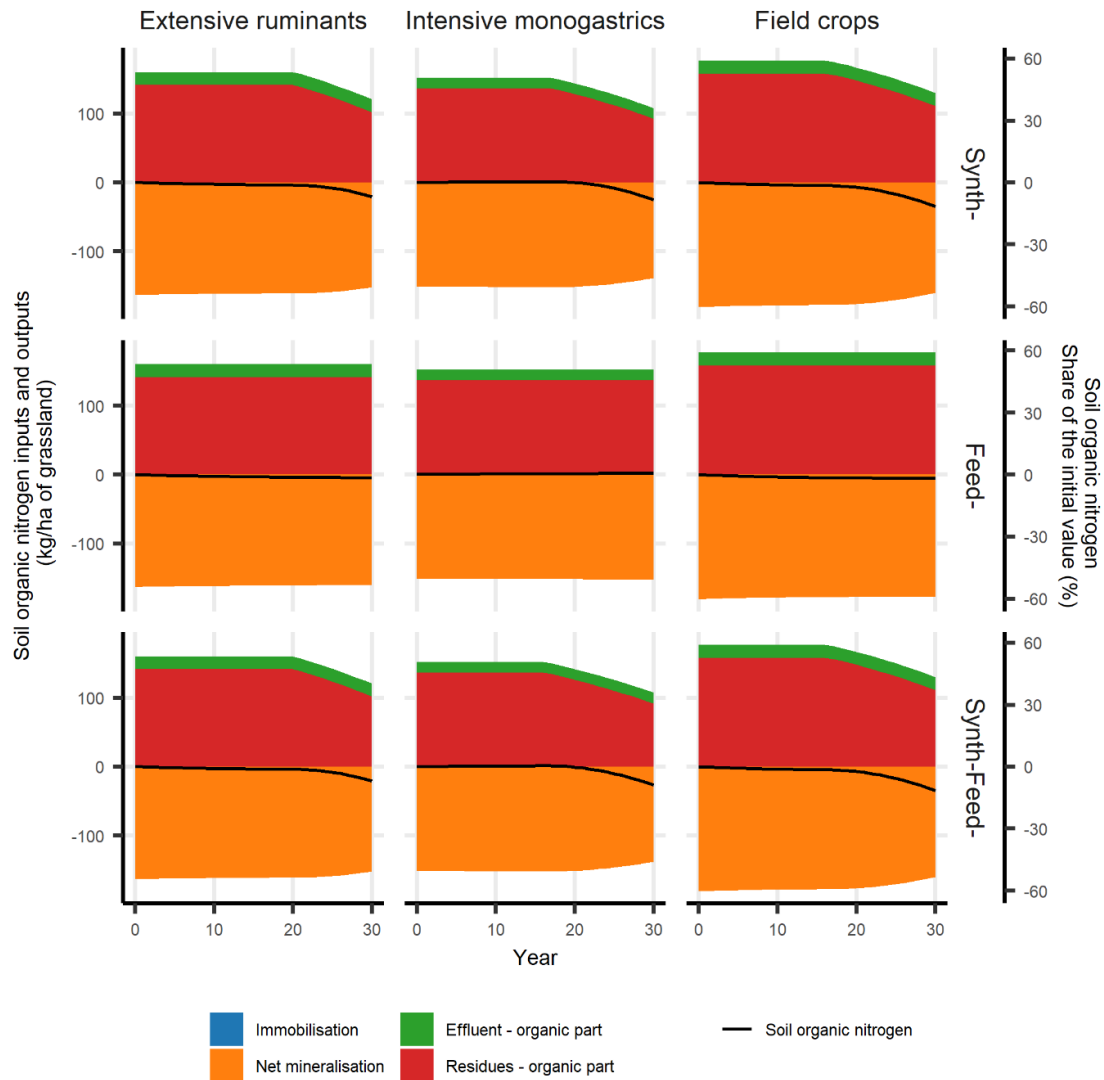


Figure 1.5 Area diagram of the quantity for permanent grassland of soil organic nitrogen inputs and outputs per unit area (kg/ha) over time (in years) according to scenario (rows) and FS (columns) for the nominal parameter set. Permanent grassland soil organic nitrogen stock variations are also shown as percentages (right y-axis).

In contrast to cropland, decreases in organic nitrogen input flows or soil organic nitrogen stock are smaller in all three FS and scenarios for permanent grassland, and there is not immobilisation of mineral nitrogen from soil organic nitrogen mineralisation (Figure 1.5). In the *Feed-* scenario, there is a slight decrease in soil organic nitrogen stock. And in scenarios with decreasing synthetic nitrogen imports, after 15 years, the residues input flows decrease and decreases in soil organic nitrogen stock accelerate. After 30 years, the soil organic nitrogen stock in permanent grasslands has decreased by 10-15%.

Livestock number

Depending on the species, the time evolution of the livestock number varies due to species-specific diets (Figure 1.6). Species in the monogastric group, fed only on concentrates, are less robust, especially in the *Feed-* scenarios, in which their numbers decrease in the short term (less than 15 years). In the long term, their decline can reach 100%. Ruminant numbers only decrease in the long term and to a lesser extent. However, in the monogastric intensive FS during the *Synth-Feed-* scenario, livestock numbers decrease by 50% in the year 30.

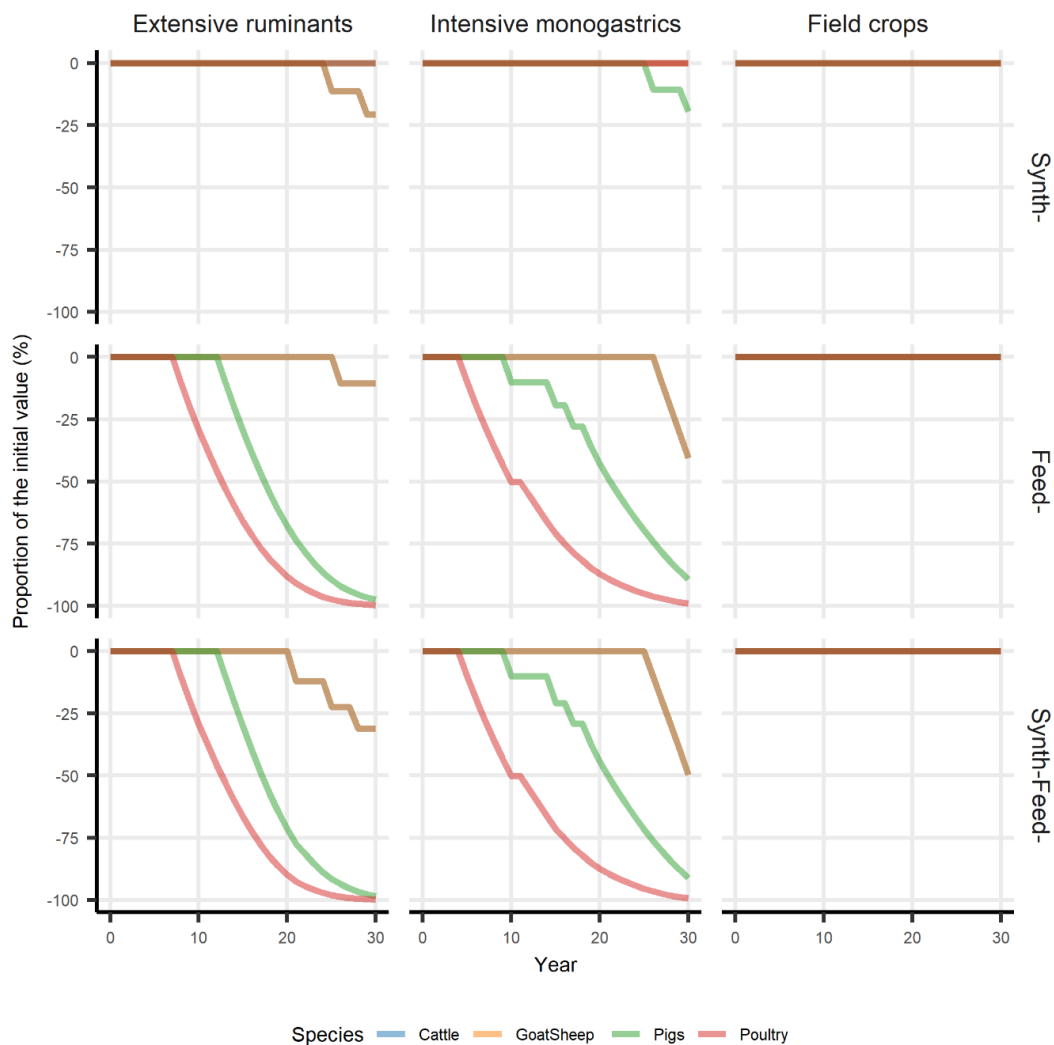


Figure 1.6 Time evolution of livestock numbers (%) for the three scenarios (rows) and FS (columns) per species for the nominal parameter set: cattle, goats and sheep, pigs, poultry. The curves for cattle and sheep/goats overlap because their diets are identical per FS. Among the monogastrics, poultry numbers tend to decline first. The decrease in ruminant numbers occurs during year 15, at the soonest, in the *Feed-* and *Synth-Feed-* scenarios.

Chapter 2 European agriculture's robustness to input import declines: a French case study

In Chapter 1, we have seen that the robustness of food production depends on the crop-grassland-livestock composition of the farming system, and that the extensive ruminant farming system was the most robust in the short and long term, having the greatest crop-livestock integration. In this chapter, the aim is to further explore the links between the robustness of food production (without compositional changes) and the crop-grassland-livestock composition at the French scale in simulation mode, in order to detail these links based on a greater diversity of farming systems. On this occasion, we built two robustness indicators that describe the trajectory of food production to input import constraints.

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European agriculture's robustness to input import declines: a French case study

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Abstract

European farming systems (FS) is currently dependent on oil, among other things for the transport of feed and the synthesis of mineral fertilisers. Disturbances, such as the global peak oil that could be reached by 2030, could result in supply shortages. It is necessary to investigate on the robustness of European FSs, *i.e.* their capacity to maintain food production with their current crop-grassland-livestock composition. The aims were (1) to assess the robustness of French FSs to a joint decline in the input imports and (2) to explore the links between levels of robustness and crop-grassland-livestock compositions. We simulated a progressive 30-years long decline of synthetic fertiliser and feed imports with a time dynamic FS nitrogen flow model. We then clustered French FSs according to their level of robustness and their level of dependency on input imports and put these clusters in relation to indicators of crop-grassland-livestock composition. Indicators were mapped over the whole France. French FSs maintained food production for a median of 8 years, before experiencing a 72% drop in food production after 30 years. The most specialised FSs (vineyards, intensive monogastrics or field crops) were the least robust on the short term (between 4 and 7 years), being the most dependent on inputs in relation to their needs, but on the contrary were the most robust on the long term (60% drop), except for field crops (about 75% drop), due to feed that could be allocated to food when livestock numbers decreased. On the contrary, mixed FSs were the most robust on the short term (from 8 to 19 years). However, the levels of robustness depended on the degree of crop-livestock integration. This study presents the first map of the robustness of French FSs to potential consequences of global peak oil. Changes in practices or compositions that decrease import dependency, such as an increase in legume areas and a decrease in feed-food competition, should be implemented as soon as possible to increase the resilience of these FSs.

Keywords

Robustness; Peak oil; Dynamic nitrogen mass flow balance; Farming system typology

2.1 Introduction

To keep high productivity levels, modern European agriculture depends on inputs, both synthetic fertilisers and imported feed (EEA, 2017; European Commission, 2019). Such dependency originated after the Second World War as part of the second agricultural revolution of modern times, which led to the specialisation, industrialisation and intensification of farming systems (FS) (Mazoyer and Roudart, 2002). As a result, the European agriculture is ultimately dependent on fossil fuels, for the transport of feed as well as for the synthesis of fertilizers (Barbier et al., 2019). This makes European agriculture vulnerable to price variability on the markets or even input supply shortages. The International Energy Agency estimated in 2018 that the world oil production peak could be reached within the next decade (IEA, 2018), implying increase and volatility of oil price and, consequently, of the price of fossil fuels and agricultural commodities (Irz et al., 2013; Naylor and Falcon, 2010; Vatsa and Miljkovic, n.d.). This variability in prices and production could lead to supply shortages and would, without rapid and effective interventionist public policies, threaten European food security.

In the face of such threat, how robust are European FSs, *i.e.* how strong is their capacity, *in their current composition*, to maintain their production? Following Giller (2013), we define a FS as population of farms located in a common and restricted geographical area, with similar biophysical, economic and social conditions. It is very likely that, in case of decreasing input availability, European FSs will adapt their compositions, especially in the long term. Nevertheless, studying and mapping the capacity of European FSs to resist *with their current composition* is a necessary step to identifying the most vulnerable compositions. The capacity to withstand disturbances without compositional changes was defined *robustness* by other studies (Accatino et al., 2014; Meuwissen et al., 2019; Mumby et al., 2014; Urruty et al., 2016), while other resilience components, adaptability and transformability, which imply compositional changes, are not addressed in this study. Studying and quantifying FS robustness is useful *e.g.*, for guiding public policies on agroecological transition.

To our knowledge, systematic quantitative assessments of the robustness, resilience or related properties (*e.g.*, vulnerability and sustainability) of European FSs consisted mostly of the analysis of historical or ad hoc data. Previous studies have mostly focused on climate-change-related extreme weather events (Dardonville et al., 2020; Das et al., 2020; Kahiluoto et al., 2019; Liang and Liu, 2021; Smith and Edwards, 2021; Suweis et al., 2015; Wiréhn et al., 2015); other studies did not specify a source of disturbance but specified the type of disturbance (food import supply shocks) (Fraser et al., 2015; Marchand et al., 2016), some others neither specified the source nor type of disturbance (Béné et al., 2019; Seekell et al., 2017). To give examples, Kahiluoto et al. (2019) explored the diversity of historical responses to climate-change-related extreme weather events of thousands of wheat cultivars in several European countries. Liang and Liu (2021) quantified the past variability of agricultural production in

northwest China related to climate change. Wiréhn et al. (2015) developed different composite indices for Sweden to quantify the climate-related vulnerability of agriculture. Fraser et al. (2015) reviewed the links between food storage and price volatility in the last 20 years and demonstrated that the size of grain reserves directly relates to price volatility. Marchand et al. (2016) identified, using a model and historical data, countries in the world where trade dependency may accentuate the risk of food shortages. Seekell et al. (2017) mapped the past generic resilience of food systems at the global scale using three indicators (production diversity, food access, biophysical capacity). Béné et al. (2019) mapped the sustainability of FSs for 20 indicators for 97 countries world-wide. To our knowledge, no systematic analysis of the future robustness of European FSs to consequences of peak oil (*i.e.* input import supply shock or decline) has been conducted.

In this study, the objectives were firstly to define and map robustness indicators at the scale of France, and secondly to describe the links between robustness levels and indicators of crop-grassland-livestock composition. France is a suitable case study, as it presents a wide diverse range of FSs (Jouven et al., 2018; Ministère de l'Agriculture et de l'Alimentation, 2010), corresponding to a diversity of dependencies in terms of synthetic fertilizers 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 model is time-dynamic and allows to explore robustness via simulations observing the trajectory of model outputs. Pinsard et al. (2021) showed that different crop-grassland-livestock compositions lead to different levels of robustness. Based on simulated trajectories, we defined robustness indicators, which, along with other indicators of import dependency, we used to divide FSs into clusters. We then explored how different clusters were linked to other indicators that characterize the crop-grass-livestock composition of FSs. This analysis made it possible to discuss French agriculture (also from an historical point of view) according to its vulnerability to import declines.

2.2 Material and Methods

The methodology (depicted in Figure 2.1) consisted of defining and calculating *robustness indicators* for all the French FSs using a dynamic N mass flow balance model (step 1). A FS was identified, as done in previous studies (see Accatino et al., 2019), with a *Small Agricultural Region* (hereafter SAR) a spatial unit of the French administrative system characterized by agronomic and soil homogeneity with an average surface of 76 800 ha. We considered the SARs in which the utilised agricultural area (UAA) represents more than 15% of the total area and the cropland area represents more than 1% of the UAA (652 SARs in total). For each SAR we calculated the robustness indicators based on the simulated temporal dynamics of food production under a 30-years scenario of linear decline in the availability of synthetic fertilizer and feed imports. Such a scenario can also be interpreted as a forced transition from conventional to 100% organic agriculture with no imported feed. As shown by Pinsard et al. (2021) for three SARs, faced with such a constraint, each SAR shows a decrease in food production, but some SARs are impacted more or less severely than others, according to their robustness. The robustness indicators serve to distinguish the forms of food production decline and to compare the SARs among themselves. The robustness indicators were then used as inputs for building a typology of SARs via cluster analysis (step 2), along with two other indicators that provide information on the level of input dependency. We then identified indicators that describe the crop-grass-livestock composition (hereafter *compositional indicators*) in a SAR and studied the relationships between these indicators and the clusters (step 3). The model is described here in a broad way, with details provided in Supplementary Material and in Pinsard et al. (2021); details are given for the indicator definition (Table 2-1) and cluster analysis. In the rest of the article, robustness, without specifying “of what to what”, refers to the total food production to input availability decline (synthetic fertilizer and imported feed).

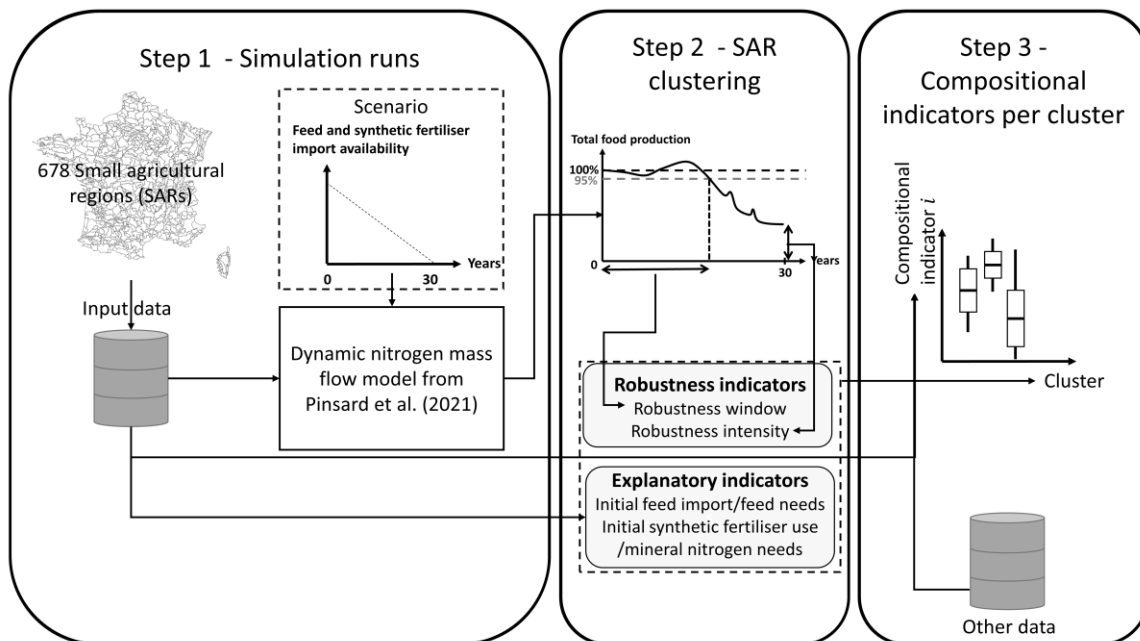


Figure 2.1 Scheme describing the methodology. Step 1 consists of running a dynamic N mass flow model (defined in Pinsard et al. 2021) for 652 small agricultural regions (SARs) of France under a simulated scenario of feed and synthetic fertilizer import availability decline over 30 years. Step 2 is a clustering (Hierarchical Agglomerative Classification) of two model outputs (the robustness indicators) with two other indicators: the percentage of imported feed out of the total feed needs and the percentage of synthetic fertilizer applied out of the total mineral N input. Step 3 consists of compositional indicators boxplot per SAR cluster.

2.2.1 General model description

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

At each annual time-step the active soil organic N stock and the livestock herd sizes are updated and the food productions (plant and livestock) are calculated. The active soil organic N stock is increased with organic N inputs (plant residues or livestock effluents) and decreased with outputs (organic matter mineralization). Synthetic fertilizer, atmospheric deposition, biological N fixation by legumes, mineralized soil N and the mineral parts of organic amendments contribute to the plant mineral fertilization. Plant production is allocated to humans and/or livestock, depending on the species. N losses occur during effluent management and soil management to air or water. The livestock number decreases when feed availability is lower than their needs. The need of the plants for mineral N is estimated from the typical yield in recent years in each SAR. The plant yield is a piecewise linear function of mineral N: the yield increases linearly with mineral N availability from 0 to a maximal yield, corresponding to the mineral N need of the plant. Above the mineral N need, the yield is considered constant as the maximal.

2.2.2 Scenario and simulations

The species considered are poultry, pigs, sheep, goats, and cattle. The feed categories are energy concentrates, proteins concentrates and forages. The feed subcategories are cereal and co-products (energy concentrates), oilseed and oilseed cakes (protein concentrates), 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 considered not fertilised with synthetic fertiliser. The quantity of effluents applied on cropland cannot exceed 170 kgN/ha, following the EU Nitrates Directives (European Commission, 2010). Livestock is assumed to only graze permanent grassland and not temporary grassland. The area of the surface allocated to each crop or grassland is constant over time. Livestock diets are also assumed to be constant.

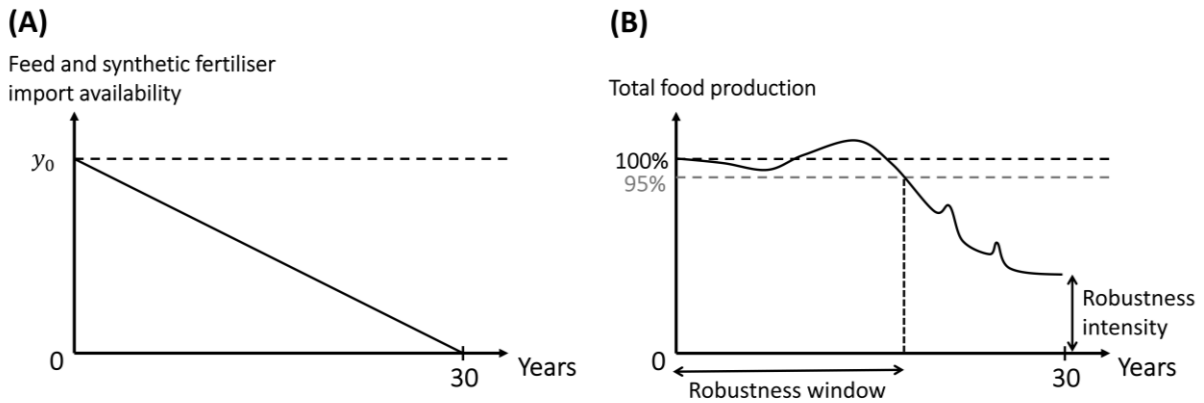


Figure 2.2 Trajectory of joint linear decline over 30 years in the import availability of synthetic fertilizer and feed (Panel A). y_0 is worth 70% of the total plant mineral N fertilization need of areas fertilized with synthetic fertilizer per SAR for synthetic fertilizer and, 100% the total need by livestock per feed subcategory per SAR for imported feed. Example of a total food production trajectory over time for a SAR from a model simulation of food production under input import availability decline (Panel B). The two robustness indicators are obtained from this trajectory. The robustness window is the consecutive number of years during which the food production of the FS does not fall below 95% of the initial food production. The robustness intensity is the share of the initial total food production at year 30.

We simulated, for each SAR, scenarios of decreasing input availability. Specifically, we imposed a trajectory of joint linear decline over 30 years in the import availability of synthetic fertilizer and feed. At time zero, the availability of synthetic fertilizer imports is imposed to be 70% of the total plant mineral N fertilization need of areas fertilized with synthetic fertilizer by SAR, while the availability of imported feed per feed subcategory corresponds to the total need by livestock for that feed subcategory per SAR. For both synthetic fertilizer and feed import, the trajectory is imposed to be 0 at 30 years, with linear decrease over time (Figure 2.2A).

2.2.3 Indicators of robustness to input import availability declines

The declining input availability always results in a gradual food production decline (Pinsard et al. 2021): the typical trajectory (depicted in Figure 2.2B) shows an initial maintenance of the food production (even after the input availability starts declining) and then a gradual decrease until the end of the simulation. However, some FSs start to decline later than others, and to a different extent. Based on the typical trajectory, we define two robustness indicators (Figure 2.2B): the *robustness window* and the *robustness intensity*. The robustness window is the length of the initial period in which the system is able to maintain its current level of food production even after the decline in input availability started.

We defined a threshold of 95% of the initial food production, below which we consider that the food production declines. The robustness intensity is the percentage of food production (calculated out of the initial quantity) at the end of the 30-years simulation. The robustness window sheds light on short-term robustness, while the robustness intensity sheds light on long-term robustness. These indicators characterize the various trajectories so to compare the SARs among them on the basis of their robustness to input availability decline. Note that the values of these indicators depend on the disturbance scenario. Undoubtedly, with a different trajectory of import availability decline, results would be different. However, in this study, SARs 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 for the subsequent clustering for all the SARs. A sensitivity analysis of the model was conducted in Pinsard et al. (2021), who showed a near-invariance for total food production over the 30 years of simulation in the same scenario as this study.

2.2.4 Clustering indicators

The purpose of the cluster analysis was to create a typology of SARs according to their robustness and dependency on external input. We selected four indicators, hereafter named *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 fertilizer applied* out of the total mineral N input [%]. Indicator (3) is calculated as the ratio of imported feed to feed need considering all the feed categories together expressed in mass of N. Indicator (4) corresponds to the percentage of mineral N from synthetic fertilizer over the total mineral N input (including organic amendments, deposition and biological N fixation). The choice of the clustering indicators originates from the conclusions drawn by Pinsard et al. (2021) after simulating input availability decline for three SARs. It is possible that for two distinct SARs with different uses of imported feed and synthetic fertilizer, the robustness indicators are similar. Indeed, in Pinsard et al. (2021), the robustness intensity is similar for an extensive ruminant and an intensive monogastric FSs. This is why, to allow a finer distinction, we added indicators (3) and (4) in addition to the robustness indicators.

We implemented a hierarchical agglomerative classification, which maximizes the variance between groups and minimizes the variance within groups (Murtagh and Legendre 2013). Before classifying, we manually clustered SARs with vineyard area representing more than 50% of the UAA to distinguish them from field crop SARs with similar robustness levels. Clustering was performed with the "hclust" function of the "stats" package on R, using Ward's method (option "ward.D2") (R Core Team, 2020). The optimal number of clusters was estimated graphically with the Hubert and D indicators of the "NbClust" package on R (Charrad et al., 2014).

Table 2-1 Indicators descriptions per type. UAA stands for utilised agricultural area and LU for livestock unit.

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

2.2.5 Compositional indicators

We considered a set of indicators (hereafter *compositional indicators*) describing the crop-grassland-livestock composition of the SARs. Three indicators regard the livestock numbers: (i) *number of monogastrics* [LU/haUAA], (ii) *number of ruminants* [LU/haUAA] and (iii) *total livestock number* [LU/haUAA]. The total livestock number is the numbers of monogastrics and ruminants added together. Three indicators regard agricultural areas: (iv) the *percentage of permanent grassland areas* in the UAA [%], (v) the *percentage of temporary grassland areas* in the UAA [%] and (vi) the *percentage of cereal and oilseed areas* (*i.e.*, field crops) in the UAA [%]. Indirectly, these three indicators also inform about the percentage of vineyards, industrial crops (beets and tubers), and fruit and vegetable crops (the remaining crops in the UAA). Three indicators regard self-sufficiency (lack or surplus) in feed by category: *self-sufficiency* [%] (vii) in *energy concentrates*, (viii) in *protein concentrates* and (ix) in *forages*. Feed self-sufficiency for a feed category is the ratio of livestock needs to local availability for this feed category, which is allocated to livestock. This indicator makes it possible to specify the source of dependency on feed imports, which may concern only 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 need or soil N stock of the FS: (x) *legume biological N fixation* [kgN/haUAA], (xi) the *cropland mineral N fertilization need* [kgN/ha] and (xii) the *active soil organic N stock in cropland* [kgN/ha]. Biological N fixation by legumes provides information on the natural flow of N to crops, whose intensity depends on cropping practices (in contrast to the deposition of N oxides from the air on the soil). The cropland mineral N fertilization need corresponds to the N need of the crops plus the losses to water and air from fertilization. Finally, the amount of active soil organic N in the cropland corresponds to the amount of soil organic N from which the mineralised N is derived (calculated with the model). The higher this amount, the higher the natural N fertility of the soil (modulated by the mineralization rate, which depends on the latitude).

2.2.6 Correlation matrix

We calculated the correlation matrix of the robustness and compositional indicators, using the Spearman correlation index ρ . This index ranges from -1 (perfect negative correlation) to +1 (perfect positive correlation); in this study, correlations were considered strong if higher than 0.7 in absolute value. A correlation matrix with all the compositional indicators calculated for this study is available in Appendices. Indeed, during this study, we also considered other indicators, however, we put aside them because they had similar correlations as a selected compositional indicator to the set of compositional and robustness indicators.

2.2.7 Input data

The data on cultivated and grazed land come from the *Registre Parcellaire Graphique* for the year 2016 (IGN, 2016). The livestock number, the livestock diet, as well as their productivity per livestock product originate from the 2010 agricultural census (Therond et al., 2017). The input data for all the SARs in France as well as details on the metadata and the R code are available in Zenodo repository (<https://doi.org/10.5281/zenodo.6350666>). For some SARs (about 50, including Corse), some data were missing, so we proceeded to interpolations for these missing values detailed hereafter. For biophysical data, such as soil C:N ratio, or organic matter mineralization rate, we used values from neighbouring SARs with similar environmental conditions. We also considered the values of individual N feed need per species and individual N productivity per product and per species too extreme from their national average (close to 0 or several hundred kgN/Livestock unit (LU)/year) equal to their national average. As in Pinsard et al. (2021), the active soil organic N stock is initialized with the spin-up method, assuming constant organic amendments for 30 years. However, in contrast to Pinsard et al. (2021), we assumed the initial active soil organic C stocks in permanent grassland soils is worth 20,000 kgC. We used 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 worth twice the value of the C:N ratio of cropland soils (*i.e.*, ~20) (Leifeld et al., 2008). Finally, we assumed the biological N fixation per plant constant over time and function of the typical fresh matter plant yield.

2.3 Results

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

2.3.1 Robustness indicators

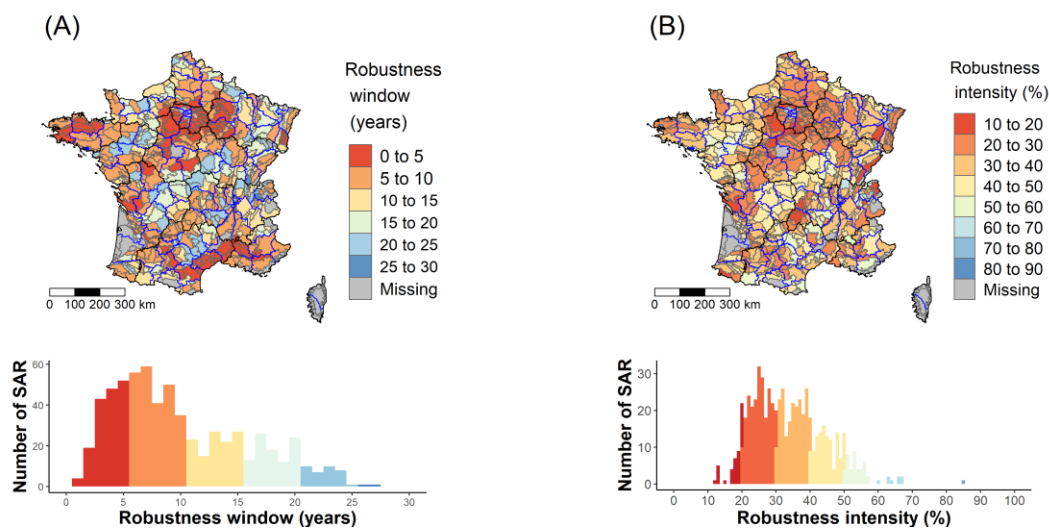


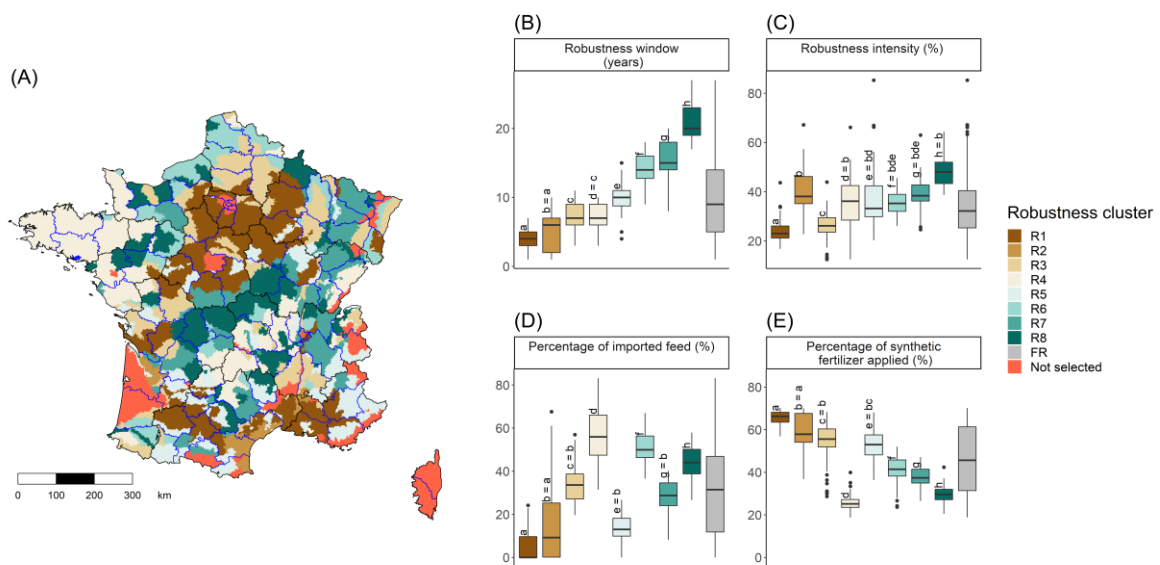
Figure 2.3 Maps of the robustness indicators (elaborated from the model output trajectories), with their frequency distribution histograms, at the SAR resolution in France. Simulations are run for a scenario of linear decrease in synthetic fertilizer and feed import availability. Panels represent (A) the robustness window (in years), i.e. time period during which food production does not fall below 95% of the initial total food production; (B) the robustness intensity (%), i.e. the percentage of the initial total food production after 30 years.

The levels of the two robustness indicators varied across France (Figure 2.3). The median robustness window of all the selected SARs was 9 years, with values ranging from 1 to 27 years (Figure 2.3A). The median robustness intensity of the SARs was 32%, with values ranging from 12% to 85% (Figure 2.3B).

SARs with similar values of the robustness windows appeared aggregated in space (Figure 2.3A). The 114 SARs with a robustness window lower than 5 years were mostly located in the Centre-North around the Paris region, in the South in Languedoc-Roussillon and in the West in Brittany. 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 for the robustness windows (Figure 2.3B). The 9 SARs with the highest robustness intensity (between 60% and 85%) were located in the centre (Auvergne-Rhône-Alpes) and in the South (Occitanie). Lowest levels of robustness intensity (between 10% and 20%) were found mainly in Ile-de-France, the Centre-South-East and the Centre (Auvergne-Rhône-Alpes in mountain climates and Centre-Val de Loire in oceanic climates).

2.3.2 Relationship between robustness clusters and compositional indicators



*Figure 2.4 Typology of robustness for French SARs. Panel (A) depicts the spatial representation of the clusters. Panels (B) to (E) represent boxplots of the 4 clustering indicators: (B) Robustness window (years); (C) Robustness intensity (%); (D) Percentage of imported feed out of the total feed needs (%); (E) Percentage of synthetic fertilizer applied out of the total mineral N input (%). In the boxplots, the line corresponds to the median value. Statistical difference (*t*-test) is described with a letter code. The first letter identifies the cluster (from a to h for clusters from R1 to R8); the letters after the equal sign refer to clusters with a median which is not statistically different.*

We found that the optimal number of clusters was 8, whose spatial distribution appeared quite aggregated (Figure 2.4A). The clusters were ordered (named from R1 to R8) by (significantly different) increasing median of the robustness window and then of the robustness intensity (Figure 2.4B and Figure 2.4C). For benchmarking, the France-wide distribution (*i.e.*, all the considered SARs) was also drawn for each indicator (grey in Figure 2.4). R2 was composed of 20 SARs, R1 of almost 150 SARs, while the others had less than 100 SARs. All of the considered French SARs had a median percentage of imported feed of less than 32% of livestock needs, ranging from 12% to 83% (Figure 2.4D). The percentage of synthetic fertilizer applied was 46% on median and varied between 19% and 70% (Figure 2.4E).

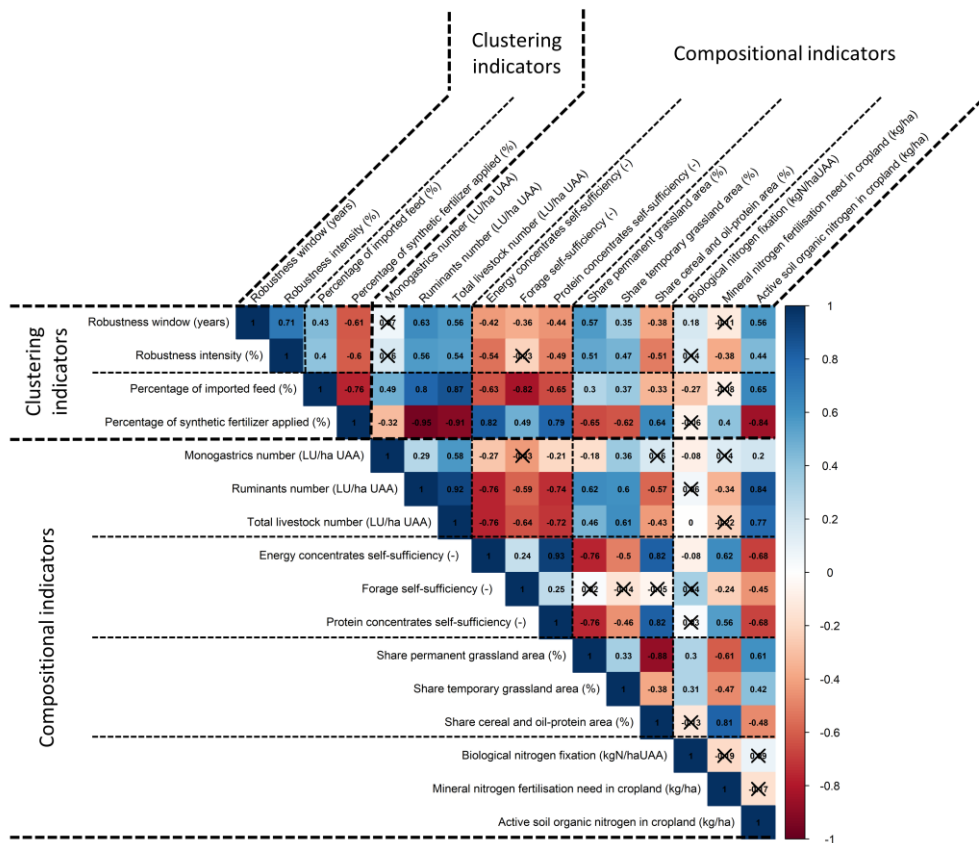


Figure 2.5 Correlation matrix of robustness indicators and compositional indicators in France at the SAR resolution, obtained with the R package «stats», with method «Spearman». Robustness indicators (Robustness window and intensity) are defined in Figure 2.2. We tested the significance of the correlations. A cross means that the correlation is not significant (p -value greater than 0.01).

The correlation matrix revealed that biological N fixation with forage self-sufficiency were the two indicators least correlated with other indicators (Figure 2.5). The strongest negative correlation ($\rho = -0.95$) was between the number of ruminants and the percentage of synthetic fertilizer applied. The negative correlation between the share of permanent grassland areas and the share of cereal and oil-protein areas was also strong ($\rho = -0.88$) as well as the negative correlation between the synthetic fertilizer 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 number, and between self-sufficiency in energy concentrates and self-sufficiency in protein concentrates ($\rho > 0.9$ for both correlations). The positive correlation between the percentage of imported feed and the total livestock number was also strong ($\rho = 0.87$) (Figure 2.5). In addition, the percentage of synthetic fertilizer applied appeared to be moderately negatively correlated with the percentage of permanent grassland area ($\rho = -0.65$). The biological N fixation by leguminous plants appeared only very weakly positively correlated with the robustness window ($\rho = 0.18$) (the correlation was not significant for the robustness intensity).

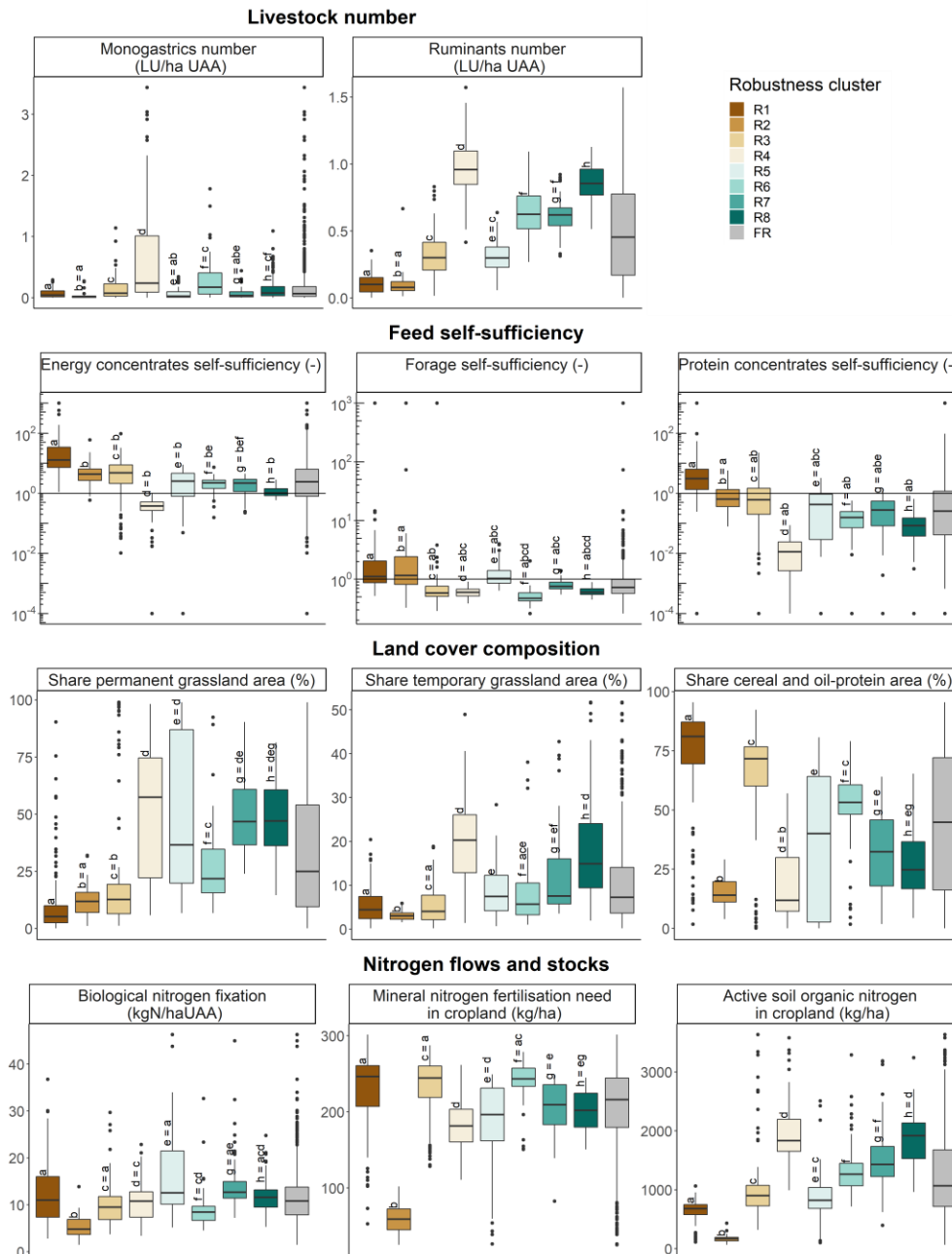


Figure 2.6 Boxplots showing the distribution of eleven compositional indicators within each robustness cluster and for all France (in grey): number of monogastrics (LU/haUAA); number of ruminants (LU/haUAA); self-sufficiency in energy concentrates (-); self-sufficiency in forages (-); self-sufficiency 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 air by legumes (kgN/haUAA); mineral N fertilisation need of cropland (kgN/ha); active soil organic N of cropland (kgN/ha). The total livestock number is not plotted showing similar correlations to the number of ruminants with the other indicators. The letters above the boxplots are from a statistical t-test between clusters and by indicator. In the boxplots, the line corresponds to the median value. Statistical difference (t-test) is described with a letter code. The first letter identifies the cluster (from a to h for clusters from R1 to R8); the letters after the equal sign refer to clusters with a median which is not statistically different.

Combination of compositional indicator distributions are significantly different among the 8 robustness clusters (Figure 2.6). We noted that the median number of ruminants is higher, for all SARs considered, than the median number of monogastrics (0.45 LU/haUAA vs. 0.07 LU/haUAA) (Figure 2.6). Furthermore, the median of self-sufficiency in protein concentrates did not exceed 30%. For all SARs considered, the median biological N fixation was 11 kgN/haUAA and the median active soil organic N in cropland was a bit more than 1000 kgN/ha.

2.3.3 Cluster description

Each robustness cluster was composed by specific values of clustering and compositional indicators: on this basis it was possible to label each of them. Table 2-2 presents a general overview of the characteristics of the robustness clusters, including the geographical indications. In the following descriptions, the indicator values reported are the median values (“M = ...”)

SARs in R1 presented the lowest values of the two robustness indicators (Figure 2.4B and Figure 2.4C). The percentage of imported feed was close to zero (Figure 2.4D) while the percentage of synthetic fertilizer applied was the highest (Figure 2.4E). The SARs in this cluster have among the lowest ruminant numbers, which made them the only ones with self-sufficiency in all three feed categories (Figure 2.6). The percentages of permanent and temporary grassland areas are among the lowest in France, while the percentage of cereal and oilseed areas of 80% and the high need for mineral N fertilisation of cropland (M~250kgN/ha) were the highest in France. Finally, the quantity of active soil organic N in cropland was the one of the lowest (M~690 kgN/ha). The SARs of R1 can be labelled as «*Intensive field crop regions with few livestock*».

The SARs of R2 had also the lowest robustness window values (M=6 years) (Figure 2.4B) but the ones of the highest robustness intensity values (M~40% for robustness intensity) (Figure 2.4C). The percentage of synthetic fertilizer applied was the highest (M~60%), while the need for mineral N fertilization of cropland was the lowest (M=60kgN/ha) (Figure 2.6). Finally, there was almost no import of feed and livestock. These SARs are “*wine-producing regions*” (see Figure 2.7 in Appendices). The amount of active soil organic N in cropland was the lowest (M~170 kgN/ha).

For SARs in R3 the values of robustness window were still low, but significantly higher than R1 (Figure 2.4B). The percentage of synthetic fertilizers applied was among the highest (M = 56%) for percentage of imported feed of 34% (Figure 2.4D and Figure 2.4E). These SARs have numbers of ruminants or monogastrics lower or close to the national median value (M=0.3 LU/haUAA and M= 0.07 LU/haUAA respectively) (Figure 2.6). The percentages of permanent and temporary grassland are among the lowest (M~13% and M ~4% respectively), and the percentage of cereals and oilseeds is the highest (M~72%) with the highest mineral N fertilisation need for cropland (M~245 kgN/ha). 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 showed the lowest robustness windows (M~7 years) (Figure 2.4B) and an average robustness intensity (M=36%) (Figure 2.4C). The percentage of imported feed was the highest (M~56%) (Figure 2.4D) for one of the lowest percentage of synthetic fertilizer applied (M=25%) (Figure 2.4E). They have a high number of monogastrics, contrary to the other clusters (M~0.24 LU/haUAA) (Figure 2.6). The number of ruminants is also among the highest (M=0.96 LU/haUAA). The SARs of R4 were the only ones without self-sufficiency in all the three feed categories at the same time. The percentage of temporary grassland area is 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*».

For the SARs in R5, the values of the two robustness indicators were slightly higher than the national median value (Figure 2.4B and Figure 2.4C). The percentage of imported feed was among the lowest (M~13%) (Figure 2.4D). These SARs have among the lowest monogastric numbers (M~0.02 LU/haUAA) and a median ruminant number of 0.3 LU/haUAA (Figure 2.6). They also had the highest self-sufficiency in forages and energy concentrates. The percentage of permanent grassland is one of the highest (M~37%), for one of the lowest need of mineral N fertilization of cropland (M~197kgN/ha). The SARs of R5 can thus be labelled «*Extensive or semi-extensive low density ruminant farming regions*».

For SARs in R6, the robustness intensity was slightly higher than the national median value (M~35%) (Figure 2.4C) while the robustness window was among the highest (M=14 years) (Figure 2.4B). The percentage of imported feed was the second highest (M~50%) (Figure 2.4D). These SARs have a number of ruminants higher than the national median and among the highest number of monogastrics (M~0.17 LU/haUAA) (Figure 2.6). These SARs had the lowest self-sufficiency in forages and protein concentrates. The percentage of cereal and oilseed areas is among the highest (M~53%). Finally, the need for mineral N fertilization of cropland was the highest (M~243 kgN/ha) while the percentage of synthetic fertilizer 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*».

SARs in R7 had among the longest robustness windows (M~15 years) (Figure 2.4B). They have the lowest percentage of cereal and oilseeds area and the lowest number of monogastrics (Figure 2.6). The percentage of permanent grassland area is one of the highest (M~47%). The number of ruminants is a bit higher than the national median value (M~0.62 LU/haUAA). Median values of 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 2.4B and Figure 2.4C) despite having among the highest values of the percentage of imported feed (Figure 2.4D). These SARs show the highest number of ruminants (M~0.9 LU/haUAA) with the highest percentages of permanent and temporary grassland areas (M=47% and 15% respectively) (Figure 2.6). The need for mineral N fertilization of cropland, the percentage of synthetic fertilizer applied and the self-sufficiency in protein concentrates and forages were lower than the national median. The amount of active soil organic N in cropland was the highest (M~1900 kgN/ha). The SARs of R8 can be labelled “*Semi-extensive high density ruminant farming regions*”.

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

Characteristic	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 Paris region (Centre-Val de Loire and Ile de France) in East-North-East (Grand-Est) and in South-South-West (Occitanie) in degraded oceanic climate of lowlands	Centre-South-West (Bordeaux vineyards - altered oceanic climate) and the South-South-West (Languedoc-Roussillon vineyards - clear Mediterranean climate)	In oceanic or mountain climates in Centre-South-West (Nouvelle-Aquitaine), in the North (Hauts-de-France) or in the Centre-South-East (Auvergne-Rhône-Alpes)	Western part (Bretagne) but also West (Pays de la Loire) and Centre-South-East (Auvergne-Rhône-Alpes), in regions with oceanic or mountain climates	Mainly in the South and South-East (Occitanie and Provence-Alpes-Côte d'Azur) in regions with a predominantly oceanic or mountain climate	North (Hauts-de-France), in the North-West (Normandy), and in the South-West (Nouvelle-Aquitaine), mostly in regions with an oceanic climate	Centre-East (Bourgogne-Franche-Comté), Centre South-West (Nouvelle-Aquitaine), Centre (Auvergne-Rhône-Alpes) and East-North-East (Grand-Est) in semi-continental, mountain or oceanic climates	East (Grand-Est), Centre (Auvergne-Rhône-Alpes) and South-South-West (Occitanie), mostly in regions with an oceanic or mountain climates

Table 2-2 (continued).

Characteristic	Robustness cluster							
	R1	R2	R3	R4	R5	R6	R7	R8
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 fertilizer applied (%)	H	M+	M+	L	M+	M-	M-	L
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)	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 need of cropland (kgN/ha)	M+	L	M+	M-	M-	M+	M-	M-

2.4 Discussion

Our first objective was to define robustness indicators, calculated out of the simulations of a dynamic N mass flow balance model, thereafter to map them for the majority of French SARs and identify SAR clusters according to robustness properties. Our second objective was to study the relationship between robustness clusters and indicators of crop-grassland-livestock composition. Results showed that, for the majority of SARs, without compositional changes, progressive input decline would lead to a decrease in food production. The clusters obtained showed statistically significant different values of compositional indicators, suggesting that crop-grassland-livestock compositions are key determinants for the robustness of FSs.

2.4.1 Crop-grassland-livestock compositions associated with robustness and input imports

2.4.1.1 *Crop-specialized SARs: a high dependency on synthetic fertilizers implies a low robustness window*

For the crop-specialized SARs (R1, R2 and R3) more than 75% of food production is crop-sourced. These SARs are poor in livestock and therefore also in manure and active soil organic N, causing the highest levels of synthetic fertilizer dependency, causing low robustness windows.

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. The low livestock density implies an almost-reached feed self-sufficiency and, consequently, a robustness of the animal-sourced food production. However, animal-sourced food production only accounts for a maximum of 20% of total food production (see Figure 2.7 in Appendices), therefore giving a poor contribution to the overall robustness. Moreover, the low livestock density implies low effluent input to crops ($M = 3$ and 9 kgN/ha respectively - see Figure 2.7 in Appendices) to contribute to active soil organic N and indirectly to soil organic N mineralization. For these SARs, we estimated active soil organic N stocks to be lower than the national median. This, in addition to the highest crop need for mineral N, further increases the dependency on synthetic fertilizers. Food production was therefore immediately impacted when the availability of imported synthetic fertilizers drops. These results generalize the one carried out by Pinsard et al. (2021) for the Plateau Picard, an intensive field crop SAR with some livestock production belonging to R3.

Wine-producing SARs

The SARs specialized in vineyards (R2) presented among the lowest robustness windows due to the higher percentages of synthetic fertilizers applied. Despite the relatively low need of mineral N fertilizer for vineyards, the dependency of synthetic fertilizer was still high in percentage because of the near-absence of livestock. Indeed, the amount of effluents applied on croplands (including vineyards) was the lowest ($M = 1\text{kgN/ha}$) and the active soil organic N stock was also the lowest, indicating low levels of soil organic N mineralization (coherently with soil sampling in these SARs (Martin, 2019)). However, these SARs presented a higher robustness intensity than R1 and R3, and even higher than the national median value. This result could be explained by the lower percentage of concentrates in the ruminant diets (see Figure 2.7 in Appendices), which would favour the animal-sourced food production robustness. This is the main difference with the R1 and R3 clusters, along with the livestock number.

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

For SARs with livestock (R4, R5, R6, R7 and R8), the analysis was more complex than for crop-specialized SARs. For clusters R5 to R8, the percentage of synthetic fertilizer applied explained the levels of robustness: the robustness levels were significantly increasing, or not significantly different, going from R5 to R8 and the percentage of synthetic fertilizer applied was significantly decreasing from R5 to R8. However, the percentage synthetic fertilizer did not only depend on the livestock number but also on the land cover composition.

On the contrary, the levels of robustness of R4, which were the lowest among livestock regions, were not explained by the percentage of synthetic fertilizer applied as it was the lowest among the SARs with livestock. The percentage of imported feed was the highest, but, in R6 and R8, percentages of imported feed were also higher than the national median value, while they were lower than the national median value in R5 and R7. This difference requires investigating the details of the integration between crops, grasslands and livestock, including other indicators such as the herd composition, and the levels of self-sufficiency by feed category.

Percentage of synthetic fertilizer applied were not only explained by the livestock number

Livestock effluents (strongly positively correlated to the livestock number) contribute to fertilise cropland with mineral N, and (unlike synthetic fertilizer) to fill the active soil organic N stocks in cropland. Effluents for monogastric farms, mainly off-ground, and part of the effluents from ruminants are available for crop fertilization (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 fertilizer (Le Noë et al., 2019; Li et al., 2021a). This corroborates our findings: the percentage of

synthetic fertilizer applied was strongly negatively correlated to the total livestock number as the active soil organic N in cropland was positively correlated to the total livestock number.

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

Intensive monogastric and ruminant farming regions with crops for livestock

SARs specialized in intensive monogastric and ruminant farming with crops for feed (R4) presented the lowest robustness levels among livestock regions as the high livestock number led to a high percentage of imported feed and thus to a low short-term robustness of the animal-sourced food production. As the crop-sourced food share is low, the total food production was quickly impacted. However, the SARs of R8 have also of a similar composition, but were the most robust. This difference (and also the low robustness for R4) can be explained by the herd composition, *i.e.*, mainly monogastric, unlike in R8. In the model, monogastric animals 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 in animal-sourced food production) came earlier.

Moreover, these SARs had a robustness intensity not significantly different than R5, R6 and R7 although the concentrates self-sufficiency was much lower in R4. This can be also be explained by herd composition. In these SARs, feed-food competition for biomass use is high ($M=75\%$ - see Figure 2.7 in Appendices) *i.e.*, the area of cereal and oilseed crops allocated for livestock consumption is significant. Consequently, the decrease in monogastrics increased the quantity of crops (cereals and oil seeds) allocated to human consumption (Pinsard et al. 2021). The results obtained for R4 generalized those obtained by Pinsard et al. (2021) for Bretagne Centrale, a SAR of intensive monogastric farms belonging to this cluster.

2.4.2 Biological N fixation and robustness levels

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

2.4.3 Specialization 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 FSs evolution (practices and composition) in the context of the second revolution of the modern times, which took place in the second half of the 20th century. The current specialization in France, based on the specificities of each territory, particularly those with the shortest robustness window (except wine-producing regions), took place as part of the industrialization of agriculture to increase food productivity (Mazoyer and Roudart, 2002). The increase in productivity was 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 specializing in intensive field crops (R1 and R3) took place during a process called "cerealization" from the 1970s, first through a decrease in the forage area and then from the 2000s onwards through a decrease in ruminants number (Perrot et al., 2015). This process was related to the assignation of crops to the best lands, while ruminant farming was used to valorise surfaces with low agronomic potential (Domingues et al., 2019a). In contrast, the emergence of intensive livestock farming SARs (R4) took place from the 1960s onwards and began with the dairy intensification of the dominant mixed crop farms with maize silage and temporary grasslands (Domingues et al. 2018). Indeed, R4 SARs have one of the highest percentages of temporary grassland area in the UAA. Off-farm poultry and pig farms were then developed to increase farmers' income and modernize farming practices. This development has largely benefited from the joint presence of slaughtering and feed manufacturing industries, but also from the nearby large seaports, which are a considerable asset for the agri-food industry. The density of monogastric livestock has thus been multiplied by 6 between 1938 and 2010 in the regions at the western part of France (Domingues et al. 2018).

2.4.4 Protein self-sufficiency under threat in 2050

We estimated for the 652 considered PRAs a food production, without compositional changes, of 12.6 kgN/haUAA after 30 years. In 30 years, the French population should be 74 million inhabitants (Blanpain and Buisson, 2016), and consequently the N need (80g of protein per capita per day) of the French population would be of 12.2 kgN/haUAA (constant UAA). Thus, with constant agricultural and food wastes (~30%), and exports, the protein needs of the French will not be met in 2050 in the case of a progressive decrease in input supply without changes in the compositions as well as 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 a context of input import constraints, *i.e.* to improve the robustness of French FSs.

2.4.5 Strategies for improving robustness: de-specializing agricultural regions?

We argue that French SARs could increase their robustness in the short and long term implementing an agroecological transition through adaptive or transformative actions (Caquet et al., 2020) aimed at increasing their food self-sufficiency. These actions would include increasing legume-cultivated areas (Billen et al., 2021b; Poux and Aubert, 2018; Solagro, 2017), adapting the livestock number to local crops and grasslands, reducing feed-food competition for biomass use by reducing ruminants' consumption of concentrates. The increase of legume area should be done in an agronomically relevant way, *i.e.* without 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 higher the opportunity to implement adaptations or transformations; the higher the robustness intensity, the less adaptations or transformations will be necessary because the structure of the system allows, to some extent, to cope with the decrease of inputs.

It was possible to identify actions to be carried out within each cluster to increase their robustness. SARs of R1, R2, R3 and R4 would benefit from a process of “despecialization”. For SARs specialised in intensive livestock farming (R4), a decrease in livestock number would reduce the feed import and the feed-food competition for biomass use. For example, the number of monogastric livestock could be reduced to be adapted 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 not competing with food (*i.e.*, co-products or fodder) (Poux and Aubert, 2018), and, at the same time, would increase the amount of livestock effluents applicable on cropland. In addition, a decrease in the need for mineral N fertilization would reduce the

need for synthetic fertilizers. For the wine-producing SARs (R2), the implementation of systematic inter-row plant cover would contribute to increasing the stock of active soil organic N and reduce the synthetic fertilizer need (Payen et al., 2021). Finally, for SARs with permanent grasslands and livestock (R5 to R8), the joint decrease in the crop yield, *i.e.* in the need for mineral N fertilization, and in the livestock number are necessary to reduce input imports. This action should be done together with an integration of the crops to 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 decrease the need for importing concentrates. However, possible trade-offs might occur: for example, a decrease in concentrate consumption by ruminants, would decrease milk yield (Solagro, 2017). For R6, an increase in the percentage of permanent and temporary grassland area would also contribute to the integration between crops, grasslands and livestock.

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

2.4.6 Study limitations

2.4.6.1 *Feed import perturbations considered independent of their geographical origin*

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

2.4.6.2 *A nutritional and mono-nutrient approach*

We assessed biomass fluxes in terms of N, but this could cause some distortions. For example, the relationship between livestock numbers and feed availability would imply different levels of feed self-sufficiency if estimated in dry matter. This difference can be seen by comparing the spatial distribution in France by SAR of feed self-sufficiency computed in mass of dry matter (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 risks of supply disruptions in the context of peak oil. In case of decreased availability to import of phosphate mineral fertilizers, the availability of soil mineral N could further decrease (Ågren et al., 2012; Ringeval et al., 2019).

2.4.6.3 *Robustness levels to be qualified in the face of climate change*

Extensive or semi-extensive ruminant FSs (which graze permanent grasslands most of the time - mainly R4, R5, R7 and R8) may be less robust to the consequences of climate change than intensive ruminant FSs (mainly in R3 and R6). Indeed, increasing drought frequency results in a more marked decrease in forage self-sufficiency for extensive or semi-extensive livestock systems than in intensive livestock systems based on crop systems (Dardonville et al., 2020). In other words, what is the most robust to input availability decline might not be robust from the point of view of climate change.

2.4.7 Quality of estimates

For some regions (Bretagne, Picardie and Eure-et-Loire), we compared our estimations (feed imports, synthetic fertilizer applied to cropland, livestock effluents applied to cropland, active soil organic N in cropland) with the estimates of Le Noë et al. (2018) and Le Noë et al. (2019). Estimates were comparable but some were a bit lower (active soil organic N in cropland) while some others were a bit higher (feed imports). For the total amount of synthetic fertilizer applied, we estimated almost 2.6 million tons N, *i.e.*, +15% compared to 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 fertilized with synthetic fertilizers, whereas only 50% of these areas are (Service de l'observation et des statistiques, 2013).

2.5 Conclusion

This study confirmed that a decrease in the availability of imported feed and synthetic fertilizers would have a significant negative impact on the food production of French FSs, if no changes in composition and practices are implemented. Our analysis also showed the heterogeneity of French FSs in terms of robustness. Specialized FSs (vineyards, field crops, or livestock) were the least robust in the short term. Mixed FSs were the most robust in the short term and the crop-livestock integration determined their levels of robustness.

Implementing changes in composition and practices, in a direction of "despecialization" and agroecological transition, would contribute to increasing robustness in the context of a global peak oil as well as to enhancing protein self-sufficiency. For some SARs, a decrease in the use of synthetic fertilizers would undoubtedly imply decreases in plant productivity and thus in total food production, while for other SARs, a decrease in feed-food competition for biomass use would contribute to an increase in total food production, even without inputs. Moreover, such changes would also contribute to climate change adaptation and mitigation. Future modelling could help to address possible trade-offs over time between climate change mitigation and food security objectives.

Acknowledgment

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Appendices

Definition of compositional indicators

Food productivity corresponds to crop-sourced food allocated to humans and animal-sourced food (meat, milk and eggs) [kgN/haUAA]. According to Pinsard et al (2021), the trade-off between food productivity and robustness indicators is not strict. A high productivity implies a higher dependency on imported inputs and thus a lower short- and long-term robustness, while a low productivity does not necessarily imply a higher short- and long-term robustness, depending on the degree of integration between livestock, grasslands and crops.

Feed-food competition for biomass use corresponds to the local consumption of cereals and oilseeds by livestock (seeds, oils and co-products - feed subcategories in competition with food) divided by the local cereal and oilseed production for humans and livestock [%]. Stronger feed-food competition for biomass use may imply relatively strong long-term robustness (intensity) (Pinsard et al. 2021).

The percentage of concentrates in the ruminant diet corresponds to the ruminant need for energy and protein concentrates in mass of N divided by the total ruminant need in mass of N [%]. The higher this percentage, the more intensive the ruminant farming can be described as. This is because the consumption of concentrates by ruminants accelerates the process of mass gain of the animals, and therefore meat production (Koch et al., 01:00; Morales Gómez et al., 2021).

The mineral amount of manure applied to cropland corresponds to the N in manure in housing facilities that is mineralized in the year it is applied to crops [kgN/ha]. The higher this amount, the less synthetic fertilizer is needed, depending on the need for mineral N fertilization of the cropland and the intensity of natural N flows.

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

Results

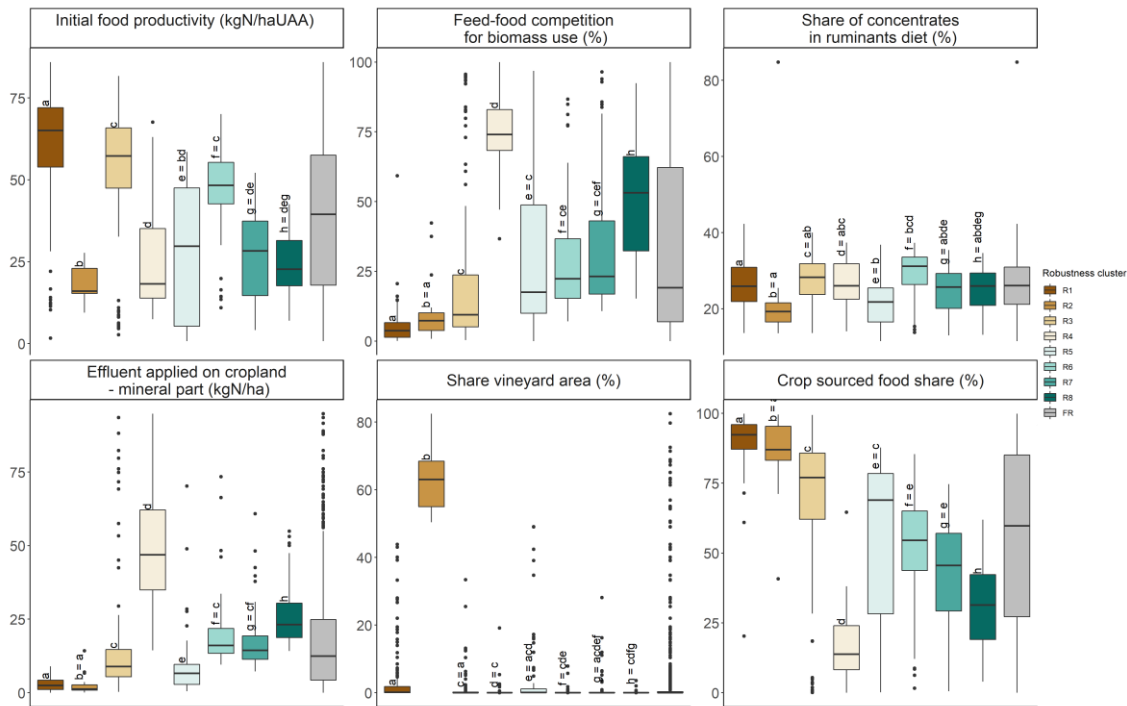


Figure 2.7 Boxplots of six compositional indicators by robustness cluster (in colour) and at the French scale (in grey): Initial feed productivity (kgN/haUAA); Feed-food competition for biomass use (%); Percentage of concentrates in ruminant diet in mass of N (%); Mineral amount of livestock manure applied to crops (kgN/ha); Percentage of vineyard area in UAA (%); Percentage of crop-sourced food (%). The letters above the boxplots are from a statistical *t*-test between clusters and by indicator.. The first letter corresponds to that of the cluster considered (from a to h for clusters from R1 to R8), then those after the equal sign to clusters for which the medians are not significantly different from that of the cluster in question. In the boxplots, the line corresponds to the median value..

Indicators without clear correlations with robustness levels

The results of this study show that the trade-off between productivity and robustness is not strict. Indeed, low-productivity SARs can be both low and high robustness. Nevertheless, high productivity is correlated with low levels of robustness. The results also show that the feed-food competition is not a proxy for the robustness window nor for the robustness intensity. Indeed, the most robust SARs (R8) have a median feed-food competition for biomass use of 50%, while SARs with low competition have intermediate or even low levels of robustness (R1, R2 or R3). This indicator is a function of the percentage of cereal and oilseed areas whose production is allocated to animals, then the livestock number and their diet. Depending on the livestock number, low feed-food competition can mean importing feed because of the lack of sufficient local production allocated to animals.

By cluster

For the R1, initial food productivity is the highest (M~65 kgN/haUAA). The feed-food competition for biomass use is on the contrary the lowest. For the SARs of R2, the initial feed productivity is the lowest, as is the feed-food competition. The percentage of concentrates in the ruminant diet is low, as is the amount of mineral N from livestock manure applied to crops. In these SARs, the percentage of vineyards is higher than 60%. For the SARs of R3, the initial food productivity is also the highest (M~57 kgN/haUAA). For the SARs in R4, the feed-food competition for biomass use is the highest (M~74%). The percentage of concentrates in ruminant feed is the highest (M~26%) with the highest amount of mineral N from livestock manure applied to crops. The share of crop-sourced food is less than 15%. For the SARs of R5, the initial feed productivity is among the lowest (M~30 kgN/haUAA). The percentage of concentrates in the ruminant diet is among the lowest as well as the amount of mineral N from livestock manure applied to crops. For the SARs of R6, the initial food productivity is among the highest with a percentage of concentrates in the ruminants' diet that is the highest (M~31%). For the SARs of R7, all the indicators have medians close to the national median value except for the initial food productivity which is lower. And for the SARs of R8, the initial food productivity as well as the percentage of crop-sourced food are in median lower than the national median. On the contrary, the feed-food competition and the amount of mineral N from livestock effluents applied to crops are have medians higher than the national median.

Chapter 3 Crop-livestock compositional changes maximising food while minimising synthetic fertilizer use and feed import for three French farming system types

In the previous two chapters, we have seen that French farming systems, without changes in their composition, would experience a significant decline in their levels of food production without inputs. Thus, the implementation of changes in practices or compositions that increase input autonomy and also food self-sufficiency would increase their robustness to input import constraints.

In this chapter, the aim is to assess the potential adaptability of the three types of French farming systems in Chapter 1, *i.e.* to identify and estimate the extent to which changes in crop-livestock compositions could maximise food production and minimise input imports compared to current levels, or maximise food production compared to levels without inputs. To do this, we used the model with another mode: multi-objective optimisation.

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Crop-livestock compositional changes maximising food while minimising synthetic fertilizer use and feed import for three French farming system types

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Abstract

European farming systems (FS) are currently dependent on synthetic fertilisers and feed imports, and thus, indirectly, on oil. In a context of global peak oil, their resilience, *i.e.* their capacity to maintain food production facing input availability constraints, is questioned. Input autonomy increases resilience but involves trade-offs: e.g., a decline in inputs could decrease decline in food production. The aims were to (1) explore the trade-offs between food production (crop- and animal-sourced) maximisation and input imports (synthetic fertilizer and feed) minimisation for three French FSs and (2) to explore crop-livestock compositional changes that, with respect to current composition, best alleviate this trade-off. We selected three FSs with different crop-livestock compositions: (i) field crops (Plateau Picard), (ii) intensive dairy cattle and monogastrics (Bretagne Centrale), (iii) extensive ruminants (Bocage Bourbonnais). We defined a dynamic FS nitrogen balance model and used multi-objective optimisation, formulating two scenarios: (1) maximisation of animal- and crop-sourced food productions, and minimisation of synthetic fertilizer and feed imports; (2) maximisation of food productions imposing zero input imports. In both scenarios, we found pairwise trade-offs between the objectives that differed in intensity according to the current shares of permanent grassland and crop for food areas. In scenario (1), the solutions that maximise total food production while minimising inputs were few in number, close to the current situation. In these solutions, the monogastric number increased at the expense of cattle due to their better nitrogen use efficiency, except in the extensive ruminant FS as permanent grassland could only be valorised by cattle. In scenario (2), solutions that maximise total food production showed more than 90% decrease in livestock number, and increasing areas of dry legumes and cereals for food. As a result, the feed-food competition for biomass use decreased significantly (below 5% in the three FSs in median). In both scenarios, the legume area did not systematically increase due, for instance, to the decrease in livestock numbers, *i.e.* in the feed demand. Our results showed that livestock composition redesign, coupled to crop productivity decrease, are essential levers to alleviate the trade-off between food productions and input use or imports. A shift in diets towards reduced animal protein intake as well as reduced losses in the food system would further increase resilience to input availability constraints when implementing the identified compositional changes

Keywords

Multi-objective optimisation; Potential adaptability; Dynamic nitrogen mass balance; Farming system; Pareto frontier

3.1 Introduction

During the 20th century, European agriculture boosted productivity via increased use of synthetic fertilisers (FAO, 2021) and intensive feedlot livestock production for the growing meat demand (FAO, 2021; Mazoyer and Roudart, 2002; Thornton, 2010). This caused a specialisation of farming systems (FS), where crops and livestock lack a mutual integration (Mazoyer and Roudart, 2002; Rega et al., 2020), with use of synthetic fertilizer and feed imported from other regions (Le Noë et al., 2018). For example, most of the oilseed cakes consumed by European livestock comes from Brazil (EEA, 2017). Thus, European agriculture indirectly depends on fossil fuels, both for the transport of inputs and for the synthesis of fertilisers (Harchaoui and Chatzimpiros, 2019). For this reason, external factors, such as the world oil production peak that could occur in the current decade (Auzanneau and Chauvin, 2021; IEA, 2018), as well as geopolitical crises in an input-producing countries, might cause variability and increase the price of agricultural commodities (Lagi et al., 2011; Naylor and Falcon, 2010; Vatsa and Miljkovic, n.d.), ultimately leading to supply shortages.

Faced with this threat to European food security, it is relevant to investigate the resilience of European FSs, *i.e.* their capacity to maintain production in adverse conditions (Meuwissen et al., 2019). Autonomy from input is acknowledged to strengthen such capacity, as it is identified as a resilience attribute (Cabell and Oelofse, 2012) and decreases environmental impact (Billen et al., 2021a; Garnier et al., 2016). Pinsard et al. (2022b)¹⁰ estimated the robustness of French FSs, *i.e.*, the capacity to maintain production without compositional change, in face of a linear decrease by 2050 of the availability of imported synthetic fertilisers and feed. They suggested the necessity for a majority of French FSs to implement changes in the crop-grassland-livestock composition (*i.e.*, adaptations or transformations). These changes would make the systems more autonomous so that they can produce enough with less or no inputs.

However, the compositional changes addressing the autonomy would likely cause trade-offs (Klapwijk et al., 2014; Muscat et al., 2020), as the objectives of a FS are multiple and potentially conflicting (Balbi et al., 2015; Deguines et al., 2014; Field et al., 2016). The FSs should be able to deliver at the same time crop- and animal-sourced food, while keeping a low level of synthetic fertilizer and imported feed (also for maintaining the quality of abiotic resources like air or water (Leip et al., 2015; Smith, 1998)). Li et al (2021) explored an optimal amount of livestock to have an effluent balance that meets the needs of local crops, avoiding excess manure. Reducing at the same time synthetic fertilizer and feed import might be challenging. While the presence of livestock might provide effluents and thereby reduce the

¹⁰ Oof this thesis

need of synthetic fertilizer, it might increase the need of imported feed. On the contrary, livestock reduction might decrease the need of imported feed, but also the availability of nitrogen (N) from effluents for fertilization, thereby requiring additional synthetic fertilizer. Increasing crop- and animal-sourced food productions at the same time is also challenging, due to competition between human and livestock uses (feed-food competition) of biomass and land (Muscat et al., 2020). The presence of livestock, although being a food source, reduces the amount of available crop-sourced food and has a lower productivity per hectare (Pinsard et al., 2022b).

To our knowledge, three sets of compositional changes in the FS reconcile food production with reduced inputs and consequently a reduced environmental impact. As mentioned in different studies (Billen et al., 2021a; Poux and Aubert, 2018; Solagro, 2017; Van Zanten et al., 2018), these are (i) an increase in legume areas, (ii) an integration of livestock with local crops (by playing on livestock diets, their numbers and the crop composition), and (iii) a decrease in plant productivity while decreasing local feed-food competition for biomass use (humans are fed first). Legumes fix atmospheric N, thus constituting a N inflow into the FS and reducing the use of synthetic fertilisers. The integration of livestock with local crops reduces feed imports. A decrease in plant productivity allows reducing synthetic fertilizer use, while a decrease in local feed-food competition for biomass use increases N use efficiency at the FS level.

Thus, trade-offs between input use minimization and food production maximization should be explored considering the degree of crop-livestock integration. In the same way, it is necessary to investigate optimised compositional changes that allow maximising food production while decreasing input use. We identify these possible compositional changes as the *adaptation potential* to input import constraints, because these changes corresponds to strategies according to which the current composition could be adapted to improve the robustness to the constraints. Multi-criteria optimisation makes it possible to systematically explore trade-offs among multiple objectives (Groot and Rossing, 2011; Klapwijk et al., 2014; Seppelt et al., 2013). Once the FS functioning is modelled with mathematical equations (driving variables are linked to objectives) and the parameters are set, it is possible to systematically explore combinations of the driving variables to compute the so-called *Pareto frontier* (Accatino et al., 2019; de Groot et al., 2010; Shi et al., 2021), which is the set of the possible combinations of objective performances for which it is not possible to improve one objective without worsening another (Castelletti et al., 2010). The shape of the Pareto front shows at which extent the satisfaction of an objective comes at expense of another (if the objectives are in trade-off) or leads to the satisfaction of another objective (if the objectives are in synergy). The exploration of the Pareto frontier not only makes it possible to analyse the relationship among objectives, but also to explore the compositions of the driving variables leading to certain objective combinations. Optimisation techniques have been largely used in exploring ecosystem service and biodiversity trade-offs at the large scale, where the relationships

among multiple objectives are studied (see Accatino et al., 2019; Butsic and Kuemmerle, 2015; Ruijs et al., 2013; Schroder et al., 2016; Shi et al., 2021; Teillard et al., 2017). At best of our knowledge, there are no studies of optimization of FSs objectives, specifically food production and input use.

In this study we set two aims. The first aim was to explore, for three distinct types of French FSs, the trade-offs between four objectives related to increasing autonomy: crop-sourced food production, animal-sourced production (to be maximised), synthetic fertiliser use and feed imports (to be minimised). We studied the trade-offs by considering as levers only changes in crop-livestock composition (in species) and quantity. Other possible levers are not considered in the study. For example, the N use efficiency at the plot or animal level was not considered, as the potential for reducing input use seems lower in France than in other parts of the world (Lassaletta et al., 2014a). The second aim was to explore the potential of adaptation to input availability constraints, *i.e.*, the set of compositional changes that maximise food production while minimising the use or import of inputs. This would make it possible to identify strategies for guaranteeing sufficient production while decreasing input dependency. To achieve these two aims, we adapted the model of Pinsard et al. (2021), which dynamically simulates N stocks and flows at the FS scale by considering the crop composition, the composition and size of the herd as well as the anthropogenic inputs (synthetic fertilisers and imported feed). We formulated two optimisation scenarios: (i) maximisation of crop- and animal-sourced food productions, and minimisation of synthetic fertiliser use and imported feed (ii) maximisation of crop- and animal-sourced food production in absence of synthetic fertiliser use and imported feed. The reduction or absence of inputs is envisaged in several prospective studies which aim, among other things, to reduce the environmental impact of European or French agriculture (Billen et al., 2021a; Poux and Aubert, 2018; Solagro, 2017).

3.2 Material and Methods

We used the model developed by Pinsard et al. (2021) applied to two multi-objective optimization scenarios (Figure 3.1). The model links driving variables (*i.e.*, compositional variables of the FS that represent the levers to improve input autonomy) to objectives. The driving variables were crops or grassland areas and livestock numbers (per species). The objectives were crop- and animal-sourced food productions (to be maximized), feed import and synthetic fertilizer use (to be minimized or kept null). In order to explore a diversity of situations, we ran the model for three types of French FSs with different crop-grassland-livestock composition.

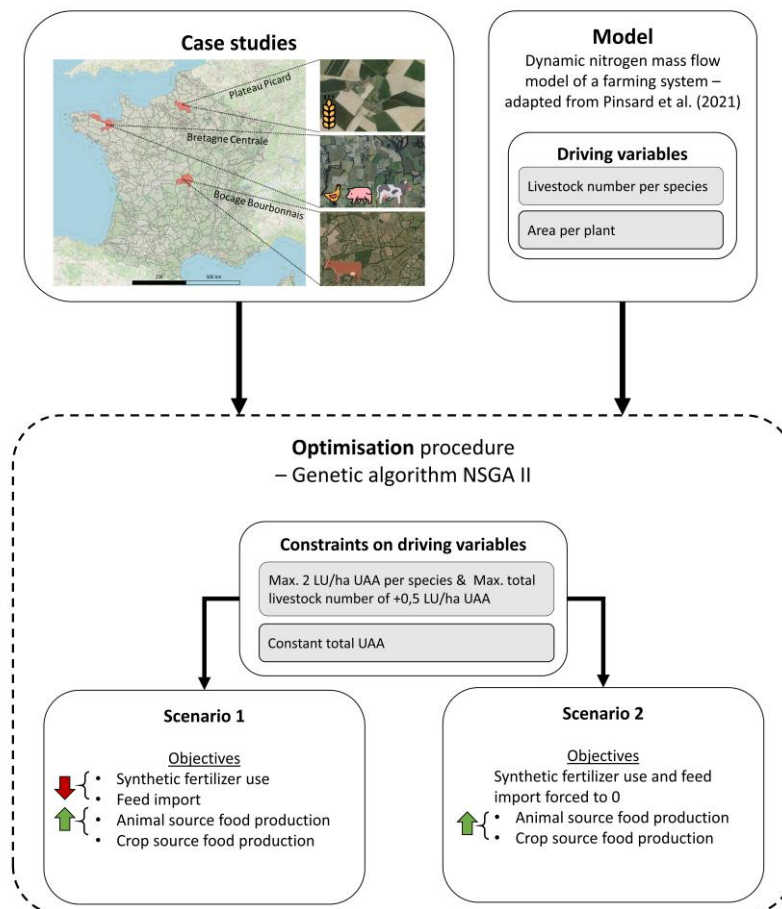


Figure 3.1 Method scheme. We used three different French farming system types as input data of the model from Pinsard et al. (2021). We adapted this dynamic N mass flow model to the optimisation scenario. The optimisation scenario consisted in maximising animal- and crop-sourced food productions, and in minimising synthetic fertilizer use and feed import. Driving variables were the livestock number per species and the cultivated area per plant. Constraints were a constant total utilised agricultural area (UAA), a maximal livestock density of 2 LU/haUAA per species and a maximal total livestock density of +0,5LU/haUAA from the current value for all the species. We used an evolutionary genetic algorithm (NSGA II) to solve this optimisation problem.

3.2.1 General model description

A summary of the model used is given here, while details are given in Pinsard et al. (2021) and in Pinsard et al. (2022b). The model depicts N flows and stocks in a FS, and is time-dynamic, with an annual time step. It considers the exchange of biomass between the soil, the plant (divided into two land uses: cropland and permanent grassland), and the livestock compartments. The stocks of organic matter in soil compartments (one per land use) are functions of the flows of organic matter from plants (residues) and livestock (effluents). The plant compartment is composed of areas allocated to different crop or grass species. Yields depend on the soil mineral N, which is filled with the flows of mineral N of natural, organic or anthropogenic origin. Plant production is allocated to humans and/or livestock, depending on the species. Anthropogenic mineral N needs (synthetic fertilizers) are calculated per plant species, to reach a target yield (the yield that the farmers want to achieve). The livestock number depends on the feed availability (locally produced and imported). N losses occur during effluent and soil management. The version of the model used corresponds to that of Pinsard et al. (2022b), with the difference that no crop residues are exported.

3.2.2 Optimization scenarios, driving variables and constraints

The species considered were poultry, pigs, sheep/goats (considered together), and cattle. The feed categories were energy concentrates (cereals and their co-products), proteins concentrates (oil-protein seeds and cakes) and forages (fodder and grazed grass). Only pure legumes was assumed as not receiving synthetic fertiliser. Plant areas were distinguished according to whether they receive synthetic fertilizer or not, according to feed category, and according to whether the crop is mostly allocated to livestock or to humans (see Figure 3.2 and Appendices).

The implementation of the two optimization scenarios consisted in systematically changing the driving variables, starting from the current composition of the FSs, for getting to the optimal composition for the objectives considered. In a multi-objective context, the optimal solutions form the Pareto frontier, *i.e.*, the set of compositions for which it is not possible to improve one objective without worsening another. In the optimisation process, the values of the objectives are derived from the 30-year implementation of compositional changes. In other words, we have not considered a progressive implementation of compositional changes from the current composition

Furthermore, we adapted the number of iterations to calculate the livestock number according to the feed availability and the plant yield according to the soil mineral N available, depending on the constraints of the optimization scenario and to shorten the calculation time. In scenario 1, we maximized the animal- and crop-sourced food productions and minimized the feed import and the synthetic fertilizer use. For this scenario, the plant as well as the livestock numbers were considered constant (plant yields

were posed equal to the target yields), *i.e.* synthetic fertilizer supplement the needs not met by the soil mineral N available naturally or from organic amendments, and feed imports the needs not met by local feed production. In scenario 2, we sought to maximize the animal- and crop-sourced food productions, imposing the absence of imported feed and use of synthetic fertilizers. Therefore, the target plant yields may not be obtained for plants with high mineral N needs and the feed need was adapted to local production. For this scenario, as plant yields and livestock numbers are indirectly dependent on each other, we iterated over 3 time steps to estimate the plant yields and the livestock number without input use.

The exploration of the Pareto frontiers allowed answering the first research question. Then, in the Pareto frontier, we selected, for scenario 1, all the solutions that maximize the total food production while minimizing the synthetic fertilizer use and the feed import in comparison to current objective values, hereafter referred to as “*MaxFoodMinImp*”. For scenario 2 we selected the solutions above the 90-th percentile of the total food production without input use, labelled “*MaxFoodNoImp*” hereafter. For these solutions, we explored the corresponding crop-livestock compositions, which correspond to strategies for improved input autonomy. We also looked at the feed-food competition for biomass use, which we defined as the local consumption of cereals and oil-protein seeds by livestock (feed categories in competition with food) divided by the local cereal and oil-protein seeds production for humans and livestock, and at the biological N fixation from the air by legumes.

The driving variables were crop area and livestock number per species. In the optimisation process, the driving variables corresponded to the current value (see Figure 3.2) multiplied by a random number that follows a uniform distribution between 0 and 20 so that the optimised compositions are not too far from the current situation, but also that plant or livestock species that are currently barely present are more present. In both scenarios, the utilised agricultural area (UAA) was set constant, and we posed a threshold of 2 LU/haUAA not to be exceeded per species and a threshold of 0.5 LU/haUAA in addition to the current total livestock number per FS. Other variables such as crop and grassland yields, allocation coefficients of the produced biomass or N loss rates during effluent or crop management were assumed constant in order to reduce computational time and to keep results easier to interpret. Nevertheless, we adapted the feed need by category according to local availability in scenario 2. This is equivalent to varying livestock diet. If there is a lack of local production to satisfy protein concentrate needs, these are moved to energy concentrate needs. For ruminants, if there is a lack of local production to meet their concentrate needs, the difference between their needs and local availability is shifted to their forage needs.

3.2.3 Case studies and input data

We implemented the two optimization scenarios for the same three FSs investigated by Pinsard et al. (2021): Bocage Bourbonnais, Bretagne Centrale and Plateau Picard (Figure 3.1). These three FSs are *small agricultural regions*, a spatial unit of the French administrative system characterised by a certain agronomic homogeneity and with an average UAA of 38,100 ha. These FSs have different crop-grassland-livestock compositions and distinct levels of robustness to input declines (Pinsard et al. 2021 and Figure 3.2). Bocage Bourbonnais is an extensive beef FS, Bretagne Centrale is an intensive monogastric and dairy cattle FS, and Plateau Picard is a field crop FS with few livestock. The input data for the model are the same as in Pinsard et al. (2022b).

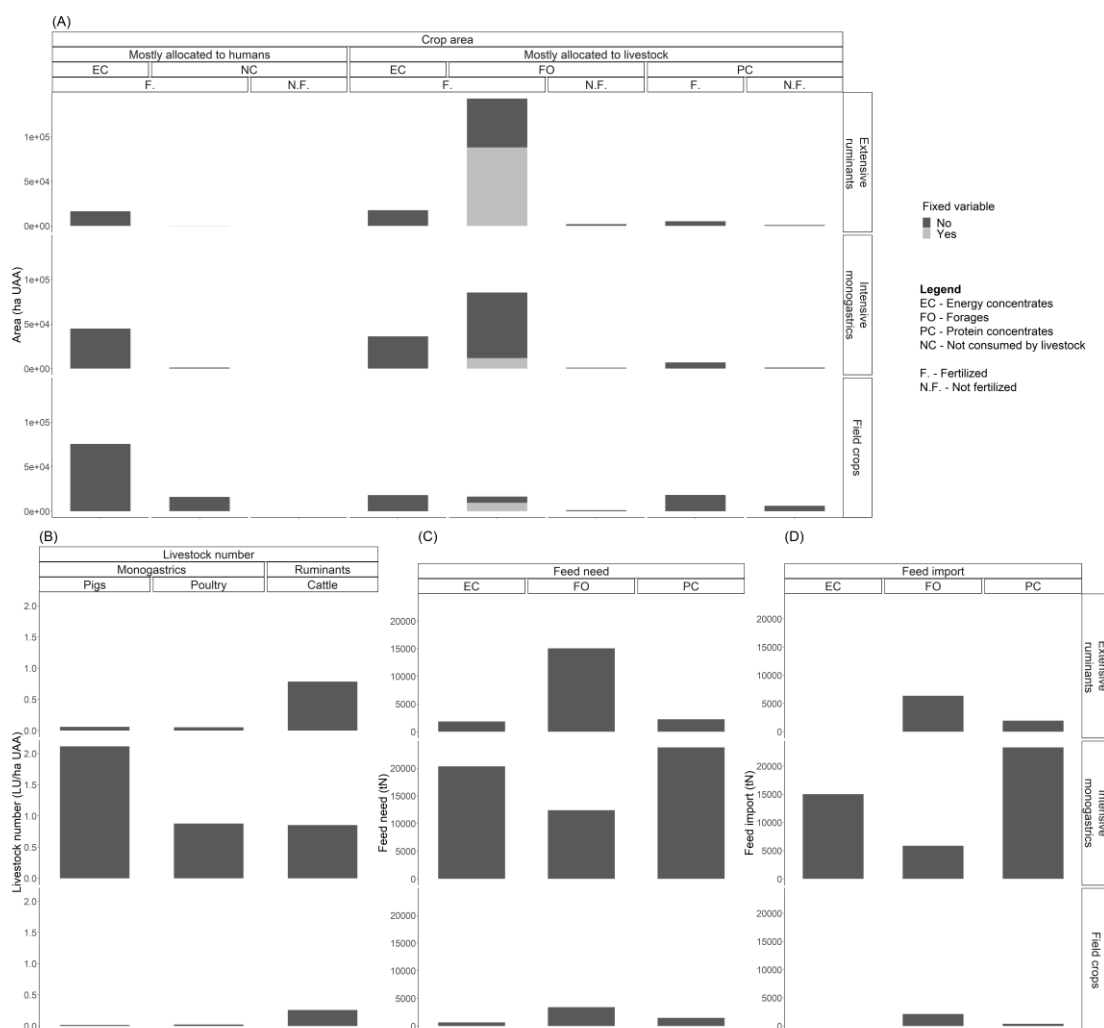


Figure 3.2 Current crop-livestock composition and feed flows by farming system (in line). (A) Plant areas in ha by whether the crop is predominantly allocated to livestock or humans, by feed category, and by whether they receive synthetic fertilizer; (B) Livestock number by species in LU/ha of utilised agricultural area (UAA). If the variable is fixed, its value does not change during the optimisation procedure. (A) Feed needs by category in tons of N; (B) Imported feed by category in tons of N.

3.2.4 Optimisation procedure

This optimization problem belongs to the class of non-linear programming problems. There were 34 driving variables to optimize and under constraints (4 livestock species and 30 plants). The genetic evolutionary algorithm is adapted to this type of problem. We coded in Python using the NSGA II genetic evolutionary algorithm from the "inspyred" package (Garrett, 2022). We set the mutation and crossover probabilities at 70% and implemented with a population of 100 individuals and for 1,000 generations. In scenarios, we kept constant the areas of fruits and vegetables (except legumes vegetables) and industrial crops (see Appendices) to reduce the number of driving variables, *i.e.* to facilitated the implementation, and because they are intended for human consumption to satisfy the need for nutrients other than protein or for other uses. We also kept constant the number of goats and sheep as they are currently low in the three selected FSs (they therefore do not appear on the figures), and the area of permanent grassland as we only wanted to explore variations in crop composition. The input data for the three French small agricultural regions with their metadata and the Python code are available in Zenodo repository (<https://doi.org/10.5281/zenodo.6348065>).

3.3 Results

3.3.1 Pareto frontiers

3.3.1.1 Scenario 1

The Pareto frontier of scenario 1 has four dimensions (one per objective). Therefore we showed its projection on plans referred to couples of objectives (Figure 3.3), which appears as a cloud of points visualizing the relationship (trade-off or synergy) among objectives. Each of the four projections of the Pareto frontier showed trade-offs with different intensities in the three FSs.

Crop-sourced food production is 3 times higher in the field crop FS than in the livestock FSs (Figure 3.3). Consequently, the use of synthetic fertilizers is also 3 times higher. In contrast, animal-sourced food production is 3 to 6 times higher in the extensive ruminant FS and the intensive monogastric FS respectively than in the field crop FS. Finally, feed import is more than 5 times higher in the intensive monogastric FS than in the other two FSs.

We also showed the *MaxFoodMinImp* solutions (points in blue - Figure 3.3). We found that these solutions presented values of the objectives close to the current values (maximum +/-15%), especially in the extensive ruminant FS. The *MaxFoodMinImp* solutions represented 6.89% of the Pareto frontier points in the field crop FS, 0.86% in the intensive monogastric FS, and 0.03% in the extensive ruminant FS.

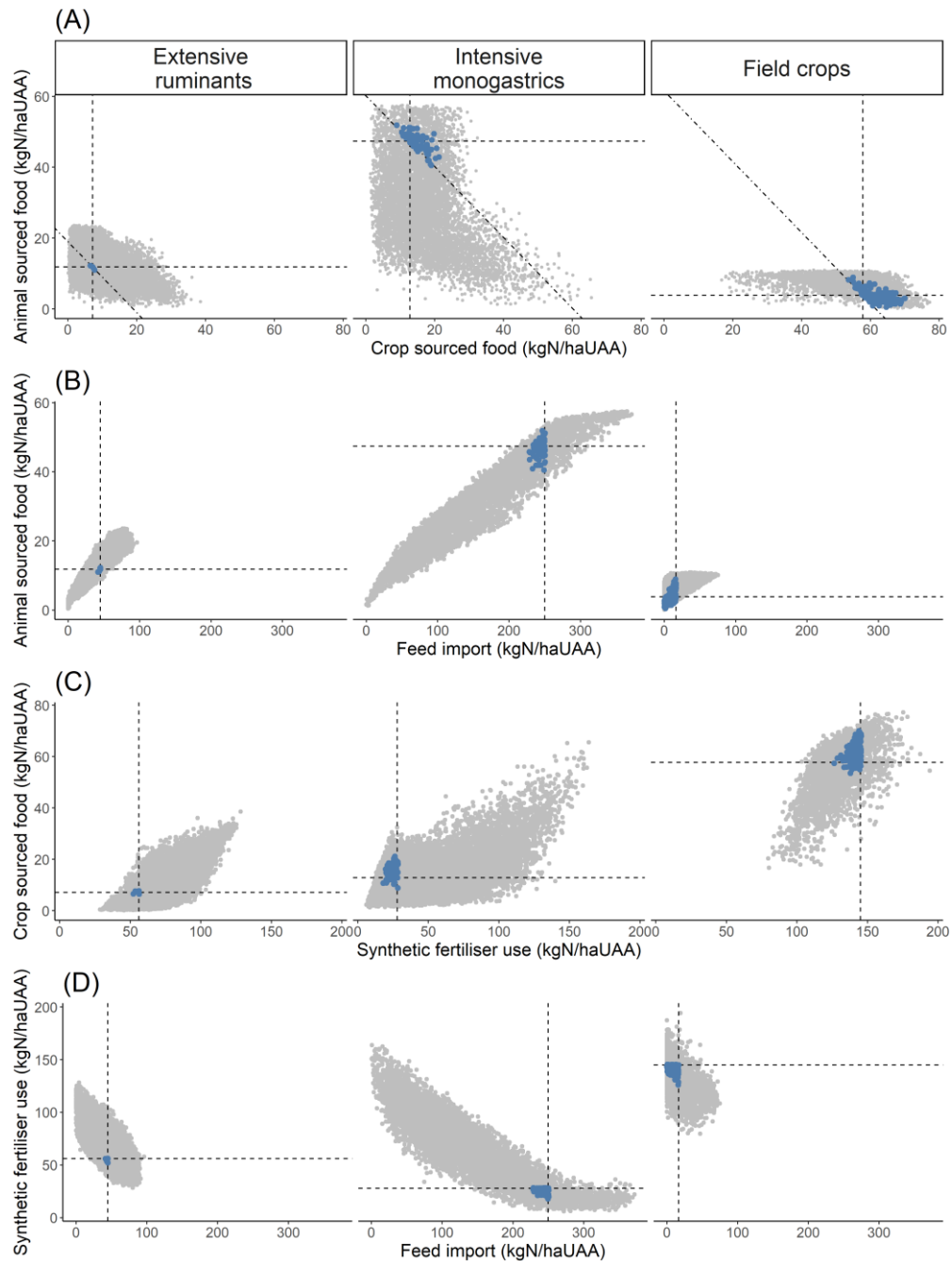


Figure 3.3 Pareto frontier (gray points) for the three farming systems (columns) of the optimization scenario 1. (A) Animal-sourced food production (kgN/haUAA) versus crop-sourced food production (kgN/haUAA); (B) Animal-sourced food production (kgN/haUAA) versus feed imports (kgN/haUAA); (C) Crop-sourced food production (kgN/haUAA) versus synthetic fertilizer use (kgN/haUAA); (D) Synthetic fertilizer use (kgN/haUAA) versus feed imports (kgN/haUAA). The blue points correspond to the crop-livestock compositions that minimize feed imports and synthetic fertilizer use and maximize the total food production relative to current values. The dotted black lines correspond to current values. The dot-dashed black lines on panel A correspond to the isoline of the current total food production. The objectives of scenario were the maximization of animal-sourced food production and crop-sourced food production, and the minimization of synthetic fertilizer use and feed imports. We considered the plant yields as well as the livestock numbers constant.

The relationship between animal- and crop-sourced food productions had two behaviours depending on the level of crop-sourced production. Above a threshold of few tens kgN/haUAA of crop-sourced food production, the two objectives showed a trade-off (increasing one would correspond to decrease the other one) (Figure 3.3A). Below this threshold there was no trade-off, and it was possible to increase to animal-sourced food production without decreasing crop-sourced food. This was more marked for livestock FSs (especially for the intensive monogastric FS), where the Pareto frontier formed a rectangle. The height of the rectangle is determined by the maximum possible livestock number posed as constraint in the optimisation.

Maximising animal-sourced food production and minimizing feed import appeared to be in trade-off, as the projections of the Pareto frontiers showed that increasing animal-sourced food production corresponded to increasing feed import (Figure 3.3B). However, the cloud of points was also thick, meaning that for the same value of feed import, it was possible to deliver different levels of animal-sourced food production. In other words, there were also solutions that envisage an increase in animal-sourced food production with a decrease in feed import (win-win) and, *vice versa*, a decrease in animal production with an increase in feed import (lose-lose). Finally, the frontiers were limited at a maximum level of animal-sourced food production values due to the constraints on the maximum livestock number imposed.

Maximising crop-sourced food production and minimizing synthetic fertilizer use were in trade-off, as the projections of the Pareto frontiers showed that an increase in crop production also implied an increase in synthetic fertilizer (Figure 3.3C). However the trade-off was not strict, as for given values of synthetic fertilizer use, there were different possible values of crop-sourced food production. In terms of synthetic fertiliser use the frontier as twice as wide (>100 kgN/haUAA) in the intensive monogastric FS as in the other two.

Minimizing feed import and minimizing synthetic fertilizer use were in trade-off (Figure 3.3D). Nevertheless, the cloud of points was thick (several tens of kgN/haUAA), meaning that for the same value of feed import, it was possible to have different levels of synthetic fertilizer use. Therefore, it was possible in the three FSs to have at least a synthetic fertilizer use of about 100 kgN/haUAA (or a little bit less for the extensive ruminant FS) without importing feed.

3.3.1.2 Scenario 2

In scenario 2, the Pareto frontier has two dimensions: animal-sourced food production and crop-sourced food production (Figure 3.4). Imported inputs were constrained to zero in this scenario. The Pareto frontier was a linear trade-off for the three FSs (the R^2 coefficients ranged between 0.96 and 0.99), but with different slopes. For the extensive ruminant FS, a 0.36 kgN/haUAA decrease in animal-sourced food production, a 0.22 kgN/haUAA decrease for the intensive monogastric FS, and a 0.33 kgN/haUAA decrease for the field crop FS made room for 1 kgN/haUAA of crop-sourced food production. These Pareto frontiers revealed win-win solutions in all three FSs that maximise both sources of food production. The minimum crop-sourced food production of the frontier is determined by the maximum possible livestock number in the optimisation process (> 5 kgN/haUAA in the field crop FS).

Without input imports, animal-sourced food production was ~ 3 kgN/haUAA for the extensive ruminant FS, compared to 4 kgN/haUAA for the intensive monogastric FS and ~ 1 kgN/haUAA for the field crop FS. For the extensive ruminant FS, crop-sourced food production was ~ 2 kgN/haUAA, for the intensive monogastric FS 5 kgN/haUAA and for the field crop FS more than 20 kgN/haUAA. The gap between the levels of animal-sourced food production of the three FSs was reduced, compared to scenario 1. However, this was not necessarily the case regarding crop-sourced food production.

We showed the *MaxFoodNoImp* solutions (points in purple - Figure 3.4). These solutions were those with the highest crop-sourced food production. They ranged from about 10 kgN/haUAA for the extensive ruminant FS to just below 30 kgN/haUAA for the field crop FS. For the field crop FS only, some of the *MaxFoodNoImp* solutions belonged to the win-win solutions, in the sense that animal- and crop-sourced food production increased together.

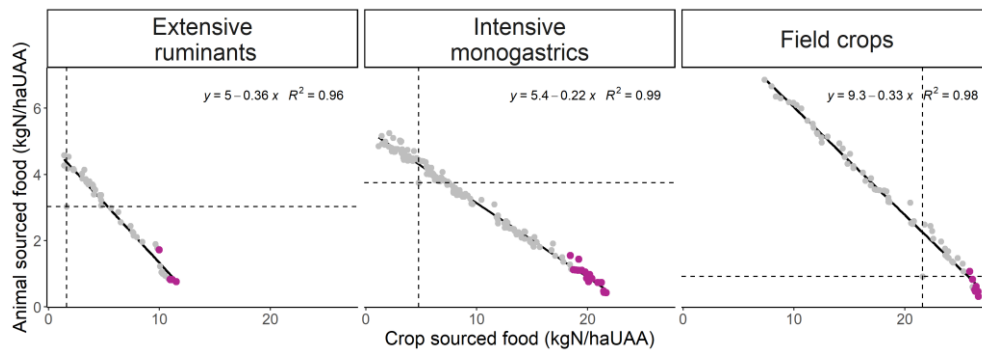


Figure 3.4 Pareto frontier (gray points) for the three farming systems (columns) of the optimization scenario 2: Animal-sourced food production (kgN/haUAA) versus crop-sourced food production (kgN/haUAA). The purple points correspond to the crop-livestock compositions that maximize the total food production (above the 90th percentile). The dashed black lines correspond to the current values. The linear regressions show the strictness of the trade-off between animal-sourced and crop-sourced food productions in the three farming systems. The objectives of scenario were the maximisation of animal-sourced food production and crop-sourced food production. Inputs are constrained to zero. The livestock numbers are adapted to the local feed production, and the plant yields to the available soil mineral N.

3.3.2 Selected solutions

In scenario 1, we selected the Pareto frontier solutions that maximise total food production while minimising the use of synthetic fertilisers and the feed import relative to current values (called *MaxFoodMinImp* - points in blue - Figure 3.3). In scenario 2, we selected the Pareto frontier solutions above the 90th percentile of the total food production, as inputs are forced to zero (called *MaxFoodNoImp* - points in purple - Figure 3.4). In these solutions, we explored the corresponding values of crop-livestock compositions, feed need and import, biological N fixation and feed-food competition for biomass use. In the following description of the results, without precision, any variation described concerns the median value.

3.3.2.1 Crop-livestock compositions, feed needs and imports

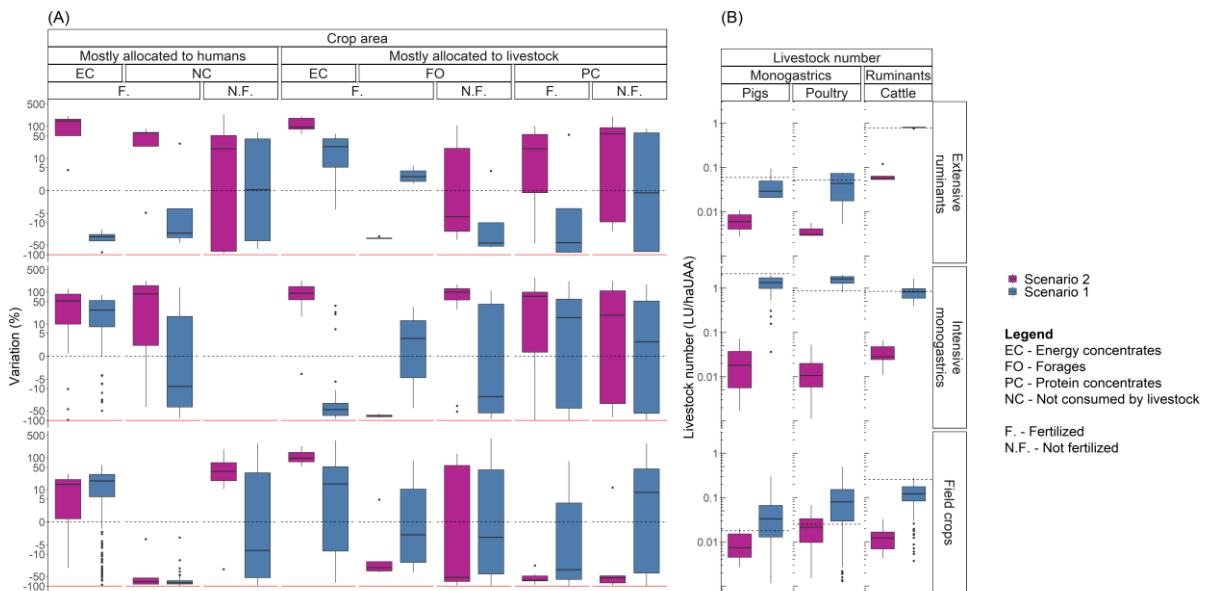


Figure 3.5 Variations in percentages from current values of crop-livestock composition by farming system (in line) of the selected compositions of the two optimization scenarios: (A) Plant areas by whether the crop is predominantly allocated to animals or humans, by feed category for animals, and by whether they receive synthetic fertilizer; (B) Livestock number by species. We selected, for scenario 1, the solutions that maximize the total food production while minimizing the synthetic fertilizer use and the feed import in comparison to current objective values, while for scenario 2, we selected the solutions above the 90th percentile of the total food production. Black dashed lines correspond to current values. The red lines correspond to -100% of the current value, i.e. zero in absolute terms. In scenario 1, we aimed at maximizing the animal- and crop-sourced food productions and minimizing the import of feed and the use of synthetic fertilizer. We considered the plant yields as well as the livestock numbers constant. In scenario 2, we sought to maximize the animal- and crop-sourced food productions, without importing feed and using synthetic fertilizers. The livestock numbers are adapted to the local feed production, and the plant yields to the available soil mineral N.

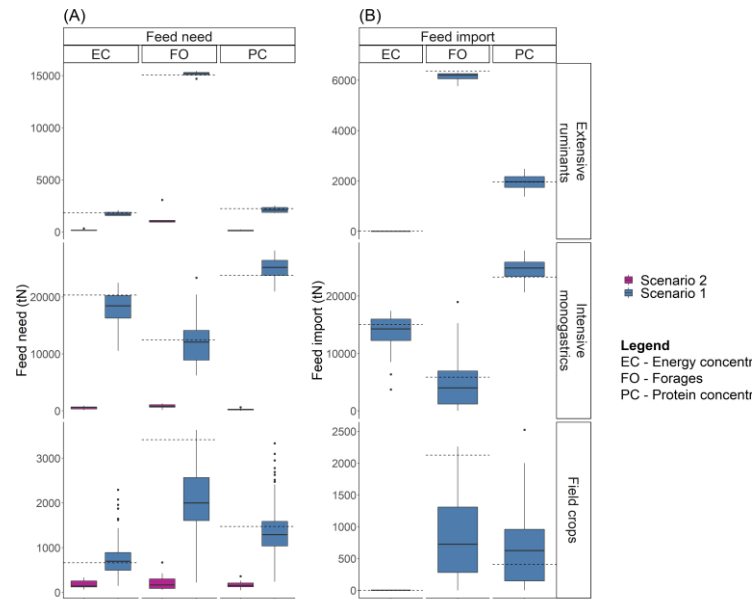


Figure 3.6 Feed flows by farming system (in line) by category (columns) in tons of N of the selected compositions of the two optimization scenarios: (A) feed needs; (B) imported feed. We selected, for scenario 1, the solutions that maximize the total food production while minimizing the synthetic fertilizer use and the feed import in comparison to current objective values, while for scenario 2, we selected the solutions above the 90th percentile of the total food production. The dashed black lines correspond to current values. In scenario 1, we aimed at maximizing the animal- and crop-sourced food productions and minimizing the import of feed and the use of synthetic fertilizer. We considered the plant yields as well as the livestock numbers constant. In scenario 2, we sought to maximize the animal- and crop-sourced food productions, without importing feed and using synthetic fertilizers. The livestock numbers are adapted to the local feed production, and the plant yields to the available soil mineral N. Feed imports are constrained to zero in scenario 2.

The changes in crop-livestock composition differed according to the FS type and scenario, but with common trends among FSs. The areas of artificial grassland ('FO' and 'N.F.' in Figure 3.5A) decreased in scenario 1. The areas of cereals and tubers for food or feed ('EC') as well as dry legumes ('NC' and 'N.F.') increased in the three FSs in scenario 2. The cattle number remained unchanged or decreased in both scenarios (Figure 3.5B).

For the extensive ruminant FS, all the food crops increased in scenario 2 while they decreased or remained unchanged in scenario 1. Regarding plants for feed, in scenario 1, cereals for feed ('EC') and annual fodder fertilised ('FO' and 'F.>') increased while the other decreased or remained unchanged (especially the non-fertilised plants). In scenario 2, fodder areas decreased while concentrates areas increased. Regarding livestock, in both scenarios, the monogastric number decreased but in more marked way than in scenario 2 (Figure 3.5B). The cattle number increased slightly in scenario 1 but decreased significantly in scenario 2. Cattle remained the main species in scenario 2 (>0.05 LU/haUAA). In scenario 1, the fodder need increased a bit (Figure 3.6A) but the fodder import decreased (Figure 3.6B).

For the intensive monogastric FS, in scenario 2, all the plants, except annual fodder fertilised ('FO' and 'F.)'), increased. In scenario 1, areas of legumes vegetables ('NC' and 'F.)'), of cereals for feed ('EC') and of annual fodder fertilised ('FO' and 'F.>') decreased while the other areas increased (Figure 3.5A). Regarding livestock, in scenario 1, cattle number remained unchanged, while the poultry number increased at the expense of the pig number (Figure 3.5B). In scenario 2, the livestock numbers decreased significantly for the three species. Like in the extensive ruminant FS, the cattle number (~ 0.04 LU/haUAA) was higher than the monogastric number in scenario 2. In scenario 1, the need for fodder decreased in favour of the protein concentrates need (Figure 3.6A). The import of fodder also decreased in favour of the import of protein concentrates (Figure 3.6B).

For the field crop FS, in scenario 1, area of cereals for feed or food ('EC') as well as protein seeds ('PC' and 'N.F.>') increased while other areas decrease. In scenario 2, areas of dry legumes ('NC' and 'N.F.>') and cereals for feed or food ('EC') increased while the other areas decreased (Figure 3.5A). Regarding livestock, in scenario 1, the monogastric number (almost 0.1 LU/haUAA) increased to the expense of cattle. In scenario 2, the livestock number of the three species decreased, and the monogastrics were dominant (Figure 3.5B). In scenario 1, the fodder and protein concentrates needs decreased (Figure 3.6A), whereas the fodder import decreased and the protein concentrates import increased (Figure 3.6B).

3.3.2.2 Biological N fixation and feed-food competition for biomass use

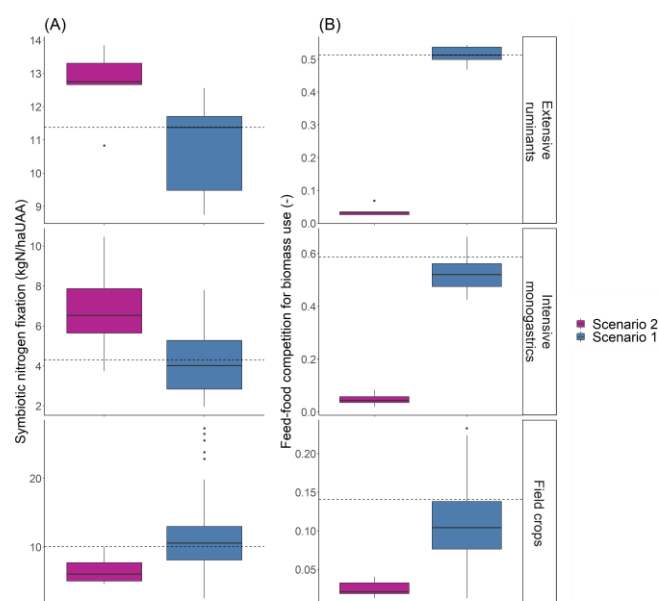


Figure 3.7 Biological N fixation from the air (A) and feed-food competition for biomass use (B) of the selected compositions of the two optimization scenarios for the three farming systems (in line). We selected, for scenario 1, the solutions that maximize the total food production while minimizing the synthetic fertilizer use and the feed import in comparison to current objective values, while for scenario 2, we selected the solutions above the 90th percentile of the total food production. In scenario 1, we aimed at maximizing the animal- and crop-sourced food productions and minimizing the import of feed and the use of synthetic fertilizer. We considered the plant yields as well as the livestock numbers constant. In scenario 2, we sought to maximize the animal- and crop-sourced food productions, without importing feed and using synthetic fertilizers. The livestock numbers are adapted to the local feed production, and the plant yields to the available soil mineral N. Feed imports are constrained to zero in scenario 2. Black dashed lines correspond to current values.

In their current compositions, all three FSs have a biological N fixation of less than 12 kgN/haUAA (Figure 3.7A). In scenario 1, *MaxFoodMinImp* solutions in the three FSs showed a biological N fixation close to the current values. Whereas in scenario 2, *MaxFoodNoImp* solutions were higher than current value in the two livestock FSs and lower in the field crop FS. In this scenario, the biological N fixation did not exceed 15kgN/haUAA.

The feed-food competition indicator for biomass use is currently about 50% in the extensive ruminant FS, compared to 60% for intensive monogastric FS, and less than 15% for field crops FS (Figure 3.7B). In *MaxFoodMinImp* solutions, the feed-food competition for biomass use decreased little in the three FSs in comparison to current values. In contrast, it decreased significantly in *MaxFoodNoImp* solutions. It was less than 5% in all three FSs.

3.4 Discussion

In this study, the first aim was to explore, for three distinct types of French FSs, the trade-offs between FS objectives linked to input autonomy: maximising the production of animal-sourced and crop-sourced food, and minimising the feed import and the use of synthetic fertiliser. The levers considered were changes in crop-livestock composition. The second aim was to explore the set of changes in crop-livestock composition that would maximise the total food production while minimising inputs use. We used the dynamic N flow model of a FS of Pinsard et al. (2021) and formulated two optimization scenarios: (i) maximisation of crop-sourced and animal-sourced food production, and minimisation of synthetic fertiliser use and feed imports (ii) maximisation of crop- and animal-sourced food productions without synthetic fertiliser use and feed imports.

Our results showed trade-offs between objectives (considered pairwise) of scenario 1, but Pareto frontiers were showing different intensities according to the FS type. In scenario 2, the trade-off between animal- and crop-sourced food productions was linear in absence of input availability, and with different slopes according to the FS type. In scenario 1, we selected the solutions that maximise total food production while minimising the use of synthetic fertilisers and the feed import relative to current values (labelled *MaxFoodMinImp*). In scenario 2, we selected the solutions above the 90th percentile of the total food production, as inputs are forced to zero (labelled *MaxFoodNoImp*). *MaxFoodMinImp* solutions were few in number and close to the current ones, while *MaxFoodNoImp* solutions corresponded to the maximum values of crop-sourced food production. In these selected solutions, for the three FS, areas of artificial grassland increased in scenario 1 and areas of cereals for food or feed and dry legumes increased in scenario 2. The number of monogastrics decreased in scenario 1 in the field crop and intensive monogastric FSs. In scenario 2, livestock numbers decreased for all the three species, feed-food competition for biomass use decreased significantly while the biological N fixation increased (except in the field crop FS).

3.4.1 Trade-off intensities explained by crop composition

In both scenarios, all the explored relationships between objectives were trade-offs. However, for the same trade-off, the intensity varied according to the FS type, *i.e.*, to the crop-livestock composition. Crop- and animal-sourced food productions showed a threshold behaviour (Figure 3.3A), specially marked for the monogastric FS. Below a threshold of crop-sourced food production, multiple values of animal-sourced food production were possible for given levels of crop-sourced food production. In particular, situations maximizing these two objectives were possible thanks to high feed imports. Feed import contributes to animal-sourced food production without using local plant production, and indirectly to the presence of manure, which allows greater crop-sourced food production while

decreasing the need of synthetic fertilizer. However, they are not without consequences: for this FS, located in Brittany, the imports are mainly soya meals from South America (Barbier et al., 2019) and are responsible for deforestation of tropical forests (Pendrill et al., 2019). Above the threshold, feed import is minimized, so the increase in crop-sourced food production, is only possible with a reduced livestock number. A low livestock number frees up cereals and oil-protein seeds for food, *i.e.* the feed-food competition for biomass use is reduced.

In the extensive ruminant FS the threshold (in terms of crop-sourced food production) was lower than the intensive monogastric FS. This difference can be explained by the share of permanent grassland area in the UAA which is much higher in the extensive ruminants FS (~50%) (Figure 3.2). Permanent grassland area was kept constant in the optimisation scenarios, and thus reduced the area that food crops can occupy in the optimisation process. The high share of permanent grassland area in the extensive ruminant FS also explains why the maximum crop-sourced food production was 50% lower in this FS than in the intensive monogastric FS. Furthermore, despite similar shares of permanent grassland area in the UAA, maximum crop-sourced food production is higher in field crop FS than in intensive monogastric FS. This difference can be explained by the current shares of crop area for food (cereals for food and tubers, fruit and vegetables, and dry legumes) and of cereals and oil-protein seeds area for feed (that are in competition with food), which are higher in the field crop FS.

Crop- and animal-sourced food productions formed a straight line in scenario 2 (Figure 3.4), with different slopes in different FSs. As they were straight line, the intensity (or slope) depends on the maximum crop-sourced food and the maximum animal-sourced food. Like in scenario 1, the maximum obtained crop-sourced food production was the highest in the field crop FS, and then in the intensive monogastric FS (the x-intercept in Figure 3.4). These differences can also be explained by the share of permanent grassland area, as well as the food crop area. Regarding the maximum animal-sourced food production, it was the highest in the field crop FS and the lowest in the extensive ruminant FS (the y-intercept in Figure 3.4). This difference can also be explained by the share of permanent grassland area in the UAA (the highest in the extensive ruminant FS) (Figure 3.2). These grasslands can only be eaten by ruminants. However, ruminants have a lower N use efficiency than monogastrics (Oenema, 2006), *i.e.* for a same number of livestock unit, ruminants give a lower animal-sourced food production. Despite this, animal-sourced food maximisation is still achieved through the presence of ruminants, and the valorisation of permanent grassland.

3.4.2 *MaxFoodMinImp* solutions: increasing the monogastric number can optimise all the objectives

3.4.2.1 A joint decrease in inputs requires a decrease in crop yields

Relationships between the considered couples of objectives were all trade-offs. Consequently, in scenario 1, the *MaxFoodMinImp* solutions were few in number and close to current objectives values. Indeed, a high livestock number leads to a high animal-sourced food production and to a low synthetic fertiliser use (because of higher effluents applied to cropland), but to a low crop-sourced food production (as they consumed local crop production) and to a high feed import. This result confirmed that lowering crop yields is necessary in addition to lower livestock numbers to jointly reduce the use of synthetic fertilizers and the feed import, as shown by Billen et al. (2021) and Poux and Aubert (2018). However, reduced crop yields also implies a reduced total food production, as observed in scenario 2.

3.4.2.2 An increase in monogastric number if the crop composition allows it

The *MaxFoodMinImp* solutions also showed that some crop-livestock composition changes in the three FS types could improve all the objectives. The main change identified is an optimisation of the crop-livestock integration, with an increase in the proportion of monogastrics in the herd. The ability to implement this increase depended on the FS type. Some of the *MaxFoodMinImp* solutions in the field crop FS and in the intensive monogastric FS showed an increase in the number of monogastrics (only poultry for the intensive monogastric FS) at the expense of the cattle number. This result can be explained the higher N use efficiency of monogastrics (Oenema, 2006). Their effluents also contribute more to mineral N fertilisation, and consequently substitute more synthetic fertilizer than those of ruminants (slurry vs. manure) (Fuchs et al., 2014). Thus, the increase in monogastric numbers at the expense of cattle made it possible to increase the production of animal-sourced food production without increasing the input flows (synthetic fertiliser use and feed import).

This increase in monogastrics was made possible by the proportion of crop areas that are sources of concentrates, which currently exceeds 20% of the UAA in both FSs, and is the result of a FS-specific optimisation of the integration between crops and livestock. The area of protein crops increased in the intensive monogastric FS to meet the increased demand (from poultry, as they have a diet richer in protein concentrates than in energy concentrates, unlike pigs - see input data in the Zenodo repository) and not to increase its import too much, while the opposite is true in the field crop FS despite the increase in the monogastric number. Indeed, the decrease in the cattle number was bigger in this FS, and led to a decrease in the demand for protein concentrates (partly freed up for monogastrics). Regarding energy concentrates, the variation in the area of cereals for feed followed the variation in the need for energy concentrates in these two FSs. As for fodder, imports decreased with the decrease in ruminants need (field crop FS) or with the increase in local production (intensive monogastric FS).

On the contrary, in the extensive ruminant FS, most of the *MaxFoodMinImp* solutions implied a decrease in the monogastric number, while cattle number slightly increased. This difference can once again be explained by the current high shares of permanent grasslands area in the UAA. Only ruminants can eat grass from permanent grasslands. Thus, the number of ruminants fed without increasing feed import is significantly higher than the number of monogastrics. And the animal-sourced food production is higher with that number of ruminants, despite their lower N use efficiency. Moreover, this low N use efficiency of ruminants also explains why the number of solutions in the Pareto frontiers that could satisfy all the objectives is particularly low compared to other FSs. The possibility of reducing the area of permanent grassland in the optimisation process would thus increase the number of solutions that maximise total food production while reducing input imports.

3.4.3 *MaxFoodNoImp* solutions: Without inputs, lower feed-food competition maximises food production

In scenario 2, in absence of inputs, the *MaxFoodNoImp* solutions were also those with the highest values of crop-sourced food production (and the lowest animal-sourced food production). This is explained by the higher N use efficiency of crops compared to livestock, *i.e.* for one unit of N input (mineral fertiliser or feed), food productivity is higher (Bouwman et al., 2013). Livestock numbers decreased more than 90% from current values (even in the field crop FS which has currently a low livestock number), and cereals and oil-protein seeds could be allocated to human consumption, thereby reducing feed-food competition for biomass use. This latter was indeed lower than 5% in the three FSs (Figure 3.7). Other perspective studies calculated (at the European or French scale) the livestock decrease needed in scenarios of input reduction for 2050 while satisfying human demand (Billen et al., 2021a; Poux and Aubert, 2018). Those study estimated the need of reducing livestock by ~50%, which is less than our result. This difference is explained by the way we selected solutions. In scenario 2 we selected solutions that maximised the total food production (above the 90th percentile), which turned out to be those with the highest crop-sourced food production. The maximisation of the crop-sourced food production brought to an increase in the crop area for food to the expense of the area for feed (the biomass allocation coefficients of being fixed in the optimisation process). Indeed, all crop area for food increased in the three FSs in scenario 2, except the legume vegetables in the field crop FS. The *MaxFoodNoImp* solutions are in line with the principle "plant biomass should be used by humans first" when looking for circularity in agricultural production (De Boer and Ittersum, 2018).

These *MaxFoodNoImp* solutions had the lowest values of animal-sourced food production on the Pareto frontier, but these values were not zero, and were worth a little less than 1 kgN/ha UAA in median. In other words, the maximum total food production is not reached when the livestock number is zero, although their N use efficiency is lower than crops. Indeed, they can valorise co-products and forages, more specifically permanent grasslands which were fixed in the optimisation scenarios, *i.e.* biomass that humans cannot eat. This is in line with the analysis by Van Zanten et al. (2018), and with the principle "livestock should be used for what they are good at", *i.e.* converting by-products from the food system and grass resources into valuable food and manure (Van Zanten et al., 2019).

Finally, the *MaxFoodNoImp* solutions, due to the absence of inputs, presented lower levels of total food production than the current situation. This decrease was more marked in the intensive FSs (intensive monogastric and field crop) because for the field crop FS the use of synthetic fertiliser is high (~140 kgN/haUAA) and for the intensive monogastric FS the feed import is high (~250 kgN/haUAA). Nevertheless, these levels of total food production (>10 kgN/haUAA) would be sufficient to meet the protein needs of the local human population in all three FSs alone (<10 kgN/haUAA) (even considering 30% losses within the food system) (Pinsard et al., 2021). They were already sufficient to satisfy the local population without inputs and compositional changes (Pinsard et al., 2021).

3.4.4 Legumes: marginal impact due to the current limited area

Legumes fix atmospheric N and thus do not require to be fertilised (Schneider and Huyghe, 2015). Consequently, they contribute to reducing the dependence on synthetic fertiliser of FS and play a key role in agriculture projections that aimed at reducing inputs and environmental losses (Barbieri et al., 2021; Billen et al., 2021a; Morais et al., 2021; Poux and Aubert, 2018; Solagro, 2017). However, in some of our solutions that minimise the use of synthetic fertiliser in both scenarios, the area of legumes decreased. One reason is that their current area is small in the three FS: dry legumes cover currently less than 50 ha in the extensive ruminant and field crop FSs, artificial grassland between 1,000 and 2,000 ha in the three FSs and protein crops 1,000 ha in the livestock FSs and 6,000 ha in the field crop FS (IGN, 2016). Because of the constraints posed, small area do not play a major role in our optimization scenarios, having a poor impact on crop productivity at the FS scale. A second reason is that the feed need of the feed category to which they contribute decreased. For instance, forage need decreased in most of the selected solutions in both scenarios, justifying the decrease of artificial grassland areas. However, although the protein concentrates need decreased in most of the selected solutions and in both scenarios (except in scenario 2 and in the field crop FS), the current high import need for that feed category (in comparison to the need) in the three FSs made relevant the increase of the protein crops area.

Concerning biological N fixation, in *MaxFoodMinImp* solutions for the three FSs, the increase in protein crop areas compensated the decrease in artificial grassland areas, as the median biological N fixation is equal to the current one. In *MaxFoodNoImp* solutions, in the livestock FSs, the increase in artificial grassland and protein crop areas is associated to an increase in biological N fixation (between 20% and 25% on average). However, in absolute values, the biological N fixation is much lower than the projections of prospective studies that aimed to reduce the environmental impact of European agriculture (~50kgN/ha of cropland) (Billen et al., 2021a; Poux and Aubert, 2018). In *MaxFoodNoImp* solutions, in the field crop FS, the increase in dry legume area, was too small (less than 20 ha) to compensate the loss of biological N fixation originated from the decrease in artificial grassland and protein crop.

3.4.5 Resilience considerations regarding the implementation of compositional changes

Implementing the changes in crop-livestock compositions identified in scenario 2 would be beneficial for the robustness of food production in the face of input constraints, however it would imply a decrease in food productivity at the FS scale. Although this productivity would be sufficient to meet the needs of the local population of the FSs, it could constrain food exports (the agri-food N balance in France, especially for cereals, is in surplus: these exports represented 100,000 tN in 2006 (Le Noë et al., 2016)) and increase food imports if the demand for animal-sourced protein does not change. To maintain food exports, and to avoid increasing food imports, two changes in the food system are needed: (1) an adaptation of diets and (2) a reduction of food losses. Between 2009 and 2013, the average European person consumed 6 kgN per person per year, 55% of which was of animal-sourced (Billen et al., 2021a). The adoption of a diet richer in plant protein than animal (demitarian diet) would avoid or minimize food imports (Billen et al., 2018; Solagro, 2017), in the case of an increase in the share of crop-sourced food. Similarly, the decrease in the over-consumption of proteins would also contribute to it, given that an average protein need of 5 kgN per person per year is sufficient for good health (Billen et al., 2021a). Secondly, food losses from primary production to consumption represented, on a European scale, ~20% of the biomass produced in fresh matter (Stenmarck et al., 2016). Thus, reducing food losses at different stages of the agri-food chain would also contribute to increasing the flow available for export.

The compositional changes identified to reduce input use constitute the potential for adaptability to constraints (progressive decline or disruption) on input imports. However, in the face of these constraints, it may not be possible to implement all of these compositional changes as fast as the incidence of constraints because they require structural changes in the food system, such as the development of the legume processing sector, or changes in food habits.

3.4.6 Study limits and research perspectives

3.4.6.1 *Limited crop-grassland compositional changes*

Possible crop-grassland compositional changes in the optimisation scenarios were limited by the assumptions we made. First, we have only assumed variations in the areas of existing crops. Therefore, if a crop is not currently grown in a FS, it cannot appear in the optimisation process. This is the case, for example, with dry legumes in the intensive monogastric FS. The absence of these crops in some small agricultural regions in France is not surprising as they currently represent no more than 0.05% of the UAA nationwide (15,000 ha) (Schneider and Huyghe, 2015). Second, we considered permanent grassland area to be fixed. However, currently in some FSs in France, permanent grasslands are ploughed up to be cultivated when the land is considered arable (Ballet, 2021; Peyraud and Peeters, n.d.; Souchère et al., 2003), *i.e.* the share of permanent grassland area in the UAA has a decreasing trend. Based on this, Poux and Aubert (2018) and Solagro (2017) projected a decrease, albeit slight (between 5% and 15%), in the area of permanent grassland in European or French agriculture respectively in 2050.

3.4.6.2 *A restricted food production objective*

Both food production objectives in scenarios were in mass of N (protein) and total, *i.e.* they were not detailed by food item (plate approach) as in Billen et al. (2021), Poux and Aubert (2018) and Solagro (2017). That is another reason why we set as constant the fruit and vegetable areas to avoid their potential decrease with this total nitrogen target. However, in Europe, between 2009 and 2013, the consumption of fruit and vegetables was below the nutritional recommendations (Billen et al., 2021a), so their production and consumption should be increased. To consider this recommendation, the food production objectives could be detailed per food item in future optimisation scenarios.

3.4.6.3 *Non-modelled agroecological practices*

The N balance of the plant-soil compartments in the Pinsard et al. (2021) model has an annual time step and considers only one crop per year per plot. In other words, the model only considers monocultures or crop rotations. However, sequential or simultaneous polyculture practices, such as intercropping or cover crops, which can be identified as agroecological solutions (Chemineau, 2013; Malézieux et al., 2009), can reduce the use of synthetic fertilisers while maintaining crop productivity. For example, the combination of cereals and legumes on a plot scale can increase the production of both crops (for the same total area of both crops grown as monospecifics), contribute to the feed or food, and do so with reduced or no synthetic fertiliser use (Rodriguez et al., 2020). This crop association currently represents no more than 50,000 ha in France (Schneider and Huyghe, 2015). Thus, modelling such practices would undoubtedly highlight their role in both maximising food production and reducing N inputs (synthetic fertilisers and feed). However, modelling such practices would increase the complexity of the plant-soil

compartments as it would require coupling the model of Pinsard et al. (2021) to more precise soil-plant models than the one used in the model (AMG – see Clivot et al. (2019)) with monthly time steps such as CENTURY (Parton, 1996) or daily time steps such as STICS (Brisson et al., 2003). This complexity would considerably increase the number of iterations in the optimisation process.

3.4.6.4 *Non-estimated environmental impacts*

We have not estimated the environmental impacts (e.g., greenhouse gas emissions) of the compositional changes nor included an objective for representing a reduction of such impact. Including this would allow investigating compositional changes that maximise food production while minimising the use or import of inputs as well as greenhouse gas emissions. Indeed, nitrous oxide emissions could be higher for compositional changes that maximise animal-sourced food production at the expense of crop-sourced food production than for compositional changes that maximise the opposite (Peyraud et al., 2014). Moreover, the positive climate impact of lower methane emissions would be less important for such changes in composition (Lynch et al., 2020).

3.5 Conclusion

In this study, we explored the trade-offs between food production maximisation and input use or import minimisation for three distinct types of French FSs. We used optimisation techniques applied to a dynamic N balance model considering changes in crop-livestock composition. We found trade-offs between the four objectives considered: animal-sourced and crop-sourced food productions, synthetic fertiliser use and feed import. The share of permanent grassland area mainly explained the slope of the trade-offs between objectives. We also found that compositional changes that maximise total food production while minimising input use or import, *i.e.* the potential of adaptability to input import constraints, consisted in decreasing feed-food competition for biomass use. The legume area did not systematically increase due to for instance the decrease in livestock numbers, *i.e.* in the feed demand. The modelling carried out in this study thus represents a complementary tool for building transitions towards more resilient FSs. Taking into account environmental impact reduction objectives as well as the modelling of agroecological practices would refine the desirable changes in crop-livestock compositions.

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Appendices

Table 3-1 Classification of plants according to whether the plant is predominantly allocated to livestock or humans, their feed category, and whether they receive synthetic fertiliser. The shares allocated to humans or livestock are used to determine their main allocation. In the implementation, certain areas of plants have been fixed.

Plant name	Mostly allocated to ...	Feed category	Fertilized with synthetic fertilizer	Share allocated as food	Share allocated as feed	Fixed variable
Barley	Livestock	Energy concentrates	Fertilized	0,05	0,9	No
Berries	Humans	Not consumed	Fertilized	1	0	Yes
Bulbs	Humans	Not consumed	Fertilized	1	0	Yes
Citrus fruits	Humans	Not consumed	Fertilized	1	0	Yes
Annual crop fodder	Livestock	Forages	Fertilized	0	1	No
Dry legumes	Humans	Not consumed	Not fertilized	0,9	0	No
Durum wheat	Humans	Energy concentrates	Fertilized	0,85	0,1	No
Fruit vegetables	Humans	Not consumed	Fertilized	1	0	Yes
Grain maize	Livestock	Energy concentrates	Fertilized	0,05	0,7	No
Grapes	Humans	Not consumed	Fertilized	0,5	0	Yes
Grass meadows	Livestock	Forages	Fertilized	0	1	No
High productivity natural permanent grassland	Livestock	Forages	Fertilized	0	1	Yes
Leafy stem vegetables	Humans	Not consumed	Fertilized	1	0	Yes
Legume meadows (or artificial grasslands)	Livestock	Forages	Not fertilized	0	1	No
Legumes vegetables (garden pea or beans)	Humans	Not consumed	Fertilized	1	0	No
Low productivity natural permanent grassland	Livestock	Forages	Not fertilized	0	1	Yes
Maize silage	Livestock	Forages	Fertilized	0	1	No

Table 3-1 (continued).

Plant name	Mostly allocated to ...	Feed category	Fertilized with synthetic fertilizer	Share allocated as food	Share allocated as feed	Fixed variable
Mixed meadows (grass and legumes)	Livestock	Forages	Fertilized	0	1	No
Mushrooms	Humans	Not consumed	Fertilized	1	0	Yes
Nuts	Humans	Not consumed	Fertilized	1	0	Yes
Oilseeds	Livestock	Protein concentrates	Fertilized	0,2	0,6	No
Other cereals	Livestock	Energy concentrates	Fertilized	0	0,95	No
Other tubers	Humans	Energy concentrates	Fertilized	0,85	0,1	Yes
Pome fruits	Humans	Not consumed	Fertilized	1	0	Yes
Potato for consumption	Humans	Energy concentrates	Fertilized	0,9	0,1	No
Potato starch	Humans	Energy concentrates	Fertilized	0,8	0,2	No
Protein crops	Livestock	Protein concentrates	Not fertilized	0,1	0,8	No
Rice	Humans	Energy concentrates	Fertilized	0,85	0,1	Yes
Root fodder	Livestock	Forages	Fertilized	0	1	No
Root vegetables	Humans	Not consumed	Fertilized	1	0	Yes
Rye	Livestock	Energy concentrates	Fertilized	0,15	0,8	No
Soft wheat	Humans	Energy concentrates	Fertilized	0,4	0,4	No
Soybean	Livestock	Protein concentrates	Not fertilized	0,1	0,8	No
Stone fruits	Humans	Not consumed	Fertilized	1	0	Yes
Sugar crop	Humans	Energy concentrates	Fertilized	0,7	0,1	Yes
Tropical fruits	Humans	Not consumed	Fertilized	1	0	Yes

Chapter 4 Robust strategies for future meat production and climate change mitigation under imported input constraints in Alentejo, Portugal

In Chapter 3, we have seen that changes in livestock composition, associated with a decrease in crop productivity, are key levers to alleviating the trade-off between input imports and food production in a farming system. However, the set of possible compositional changes may be large. Thus, adding an environmental impact reduction objective would help to refine the compositional changes that alleviate the trade-off between food production and environmental impact. In this chapter, the aim is to explore how changes in crop-livestock practices and compositions could alleviate the trade-off between food production robustness to input import constraints and climate change mitigation in the Portuguese extensive beef farming system.

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Robust strategies for future meat production and climate change mitigation under imported input constraints in Alentejo, Portugal

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Abstract

The Alentejo region in Portugal is critical to the country's beef industry but has been experiencing increased droughts and decreased crop yields. Farmers increasingly rely on imported synthetic fertiliser and feed. The uncertainty of global oil supply and prices threatens the robustness of Alentejo's beef cattle farming systems. Their capacity to sustain meat production facing constraints is jeopardized by uncertain supply and prices of imported inputs. Adding to this challenge is the need for reducing greenhouse gas emissions to meet decarbonisation goals. At present, these challenges are being addressed through management practices such as increasing highly productive sown biodiverse pastures and fattening steers on grass rather than concentrates, both practices that reduce net greenhouse gas emissions. However, the effect of these practices on the robustness of beef production when inputs are scarce is unknown. Here we study whether it is possible to mitigate climate change and satisfy the demand for meat under input constraints for future Alentejo cattle farming systems. We adapted a dynamic nitrogen mass flow model to assess herd dynamics and calculate a greenhouse gas emissions balance. We applied the model for seven scenarios corresponding to different combinations of management practices over fifty years with increasing input constraints. We found a strong trade-off between robustness of meat production and climate change mitigation. The only option that minimised the reduction of meat production (up to 35%) and reduced greenhouse gas emissions over fifty years (up to 120%) was a combination of high-yield legume-rich pastures, maximisation of grass intake, herd size reduction, and increased animal productivity. These measures would have economic consequences for stakeholders and could face resistance from consumers. Their success would likely require financial incentives and enhanced communication of the advantages.

Keywords

Beef cattle farming systems; Dynamic model; Nitrogen mass flow balance; Sown biodiverse pastures rich in legumes; Global peak oil

4.1 Introduction

In southern European Mediterranean regions, grassland-based beef cattle farming systems (BCFS) are an important part of the rural economy (Araújo et al., 2014). However, as droughts become longer and more frequent, crop yields have decreased, threatening feed self-sufficiency (Huguenin et al., 2017; Jongen et al., 2013; Karimi et al., 2018; Nardone et al., 2010; Scasta et al., 2015), and farmers have relied more on imported forages and feed concentrates, as well as synthetic fertilisers for pasture improvement (Rodrigues et al., 2020). If, as suggested, global peak oil is near (Delannoy et al., 2021; IEA, 2018), increased oil prices could threaten the supply of imported agricultural inputs that support BCFS. The resultant economic instability and social disruption might also jeopardise the robustness of meat markets (Anderson, 2009; Weis, 2013), specifically, the ability of BCFS to maintain their meat supply (adapted from Meuwissen et al. 2019).

In the Portuguese region of Alentejo, grass-based BCFS are part of *Montado* ecosystems. These ecosystems are extensive agro-forestry landscapes, in which low-density forests co-exist with grassland understory, the latter often grazed by sheep and cattle (Figure 4.1) (Pereira et al., 2009). The agricultural sector, including beef production, is economically important in Alentejo, representing more than 11% of the total gross value added (Instituto Nacional de Estatística, 2020). Alentejo is the main beef production region in Portugal, exporting within Portugal and to other European and Middle Eastern countries (Araújo et al., 2014). However, it is also among the most desertified regions in Europe and vulnerable to any decline in imported agricultural inputs arising from oil price increases. Additionally, BCFS in Alentejo contributes approximately 30% of the greenhouse gas (GHG) emissions of the Portuguese agricultural sector, mainly from enteric fermentation (APA, 2018). The Portuguese government has set, for instance, the reduction of CH₄ emissions from enteric fermentation as a policy goal, aiming to decrease the beef cattle population by 25% by 2050, while increasing the productivity of beef cattle to compensate (Republica Portuguesa, 2019). Therefore, BCFS in Alentejo face the double challenge of increasing robustness of their meat supply to mitigate the effects of increased energy costs while reducing GHG emissions.



Figure 4.1. “[Alentejana beef cattle grazing in a Montado ecosystem in Alentejo, Portugal](#)” by João H.N. Palma. No changes were made to the picture. CC BY-NC-ND 2.0

Two promising management practices have been partially adopted by Alentejo farmers seeking to reduce GHG emissions. They also can contribute to climate change adaptation and to improving BCFS economic viability. These practices are: (a) shifting low-yield semi-natural pastures to sown biodiverse pastures rich in legumes (Morais et al., 2018; R. F. M. Teixeira et al., 2018), and (b) finishing steers on grass rather than on energy and protein concentrates (Costa et al., 2012). Sown biodiverse pastures, mixes of up to 20 different high-yield grasses and legume seeds (Teixeira et al., 2011) are more productive than natural pastures. Finishing animals on grass reduces the cost of feeding and improves animal health and welfare (Hocquette et al., 2014) but can also increase CH₄ emissions from enteric fermentation due to the lower digestibility of grass (IPCC, 2019). The two practices are sometimes implemented jointly, but trade-offs may occur. The effect of combining these practices on the robustness of meat production to the availability of imported agricultural inputs and the effectiveness of reducing GHG emissions in grass-based BCFS in Alentejo is unknown.

If a study of GHG emissions and BCFS' robustness to declines in imported agricultural inputs is to be conducted in parallel, a modelling approach that simulates the dynamics of a farming system is required. Robustness is a dynamic property (Pinsard et al., 2021). Dynamics of biophysical variables in agroecosystems include the nitrogen and carbon levels in soil organic matter as well as GHG emissions. In addition, time-dynamic modelling enables the simulation of new challenges, such as declines in feed and synthetic fertiliser supply. A population-based model, unlike an agent-based model, can overcome the lack of biophysical data, whether at the level of the farm or region. In previous studies, either the GHG emissions or the robustness of farming systems to declines in imported agricultural inputs has been addressed, and the GHG balances of BCFS at the farm level has been well characterised (de Vries et al., 2015; Poore and Nemecek, 2018), especially for Alentejo (R. Teixeira et al., 2018). These GHG balances are rarely time-dynamic, which is required for an accurate estimate of the effect of methane emissions on the climate (Lynch et al., 2020). Pinsard et al. (2021) estimated the robustness to declines in imported agricultural supplies for animal production in the French region of Bocage Bourbonnais, a BCFS similar to Alentejo, but did not assess GHG balance. Puillet et al. (2014) estimated meat and milk production and direct GHG emissions from cattle at the scale of the French country based on herd management practices, but reductions in imported inputs were not considered in their simulations (indirect GHG emissions), nor were interactions between crops and livestock (soil carbon stocks and indirect GHG emissions) necessary for assessing GHG balance. Other studies estimate both GHG emissions and livestock production according to changes in practices and configurations and have considered crops, but these parameters were static over time (Garnier et al., 2019; Herrero et al., 2013; R. Teixeira et al., 2018). To our knowledge, no study has employed a dynamic model to quantify and explore the trade-off between GHG reduction and the robustness of meat production to declines in imported inputs.

Here, we modelled the impact of management practices and combinations thereof on robustness of beef production and GHG emissions of the BCFS in Alentejo facing constraints on imported inputs. At the farming system level, we analysed the trade-off between minimising GHG emissions and increasing the robustness to declines in imported input availability. We adapted the time-dynamic biophysical model of Pinsard et al. (2021) by adding a sub-model of herd dynamics and meat production and incorporated the carbon cycle to estimate GHG emissions. First, we describe the model and the scenarios considered. Then, we compare and identify combinations of management practices that enhance robustness of meat production. Finally, we simulate the GHG balance of the different combinations of management practices, asking whether scenarios that enhance robustness also meet GHG reduction targets of the Portuguese government.

4.2 Materials and methods

4.2.1 Model overview

We adapted the N-flow time-dynamic model by Pinsard et al. (2021), which integrates plants and livestock compartments in the farming system, describes plant growth as a function of soil mineral nitrogen availability, and describes herd dynamics as a function of feed shortage. We included the following: (i) the carbon cycle, (ii) beef cattle herd dynamics, and (iii) a GHG balance sub-model. The model has a discrete one-year time step. It divides the BCFS into two land uses: permanent pastures and cropland (Figure 4.2). State variables were the nitrogen and carbon organic stocks in the soils of cropland and permanent pastures, number of heads, and plant residue quantities. Each land use is composed of a soil and a plant compartment. The two soil compartments are composed of an active organic matter stock and a mineral nitrogen flow. The two plant compartments are composed of surfaces occupied by different crops or permanent pasture types. The BCFS is also composed of a beef cattle herd compartment composed of age and sex classes with different dietary needs (dynamics adapted from Puillet et al. (2014)). Cattle share their time between the housing facility and permanent pastures. Effluents deposited in housing are applied over cropland, effluents deposited during grazing remain on pastures. Body weight gain is a linear function of feed intake.

Nitrogen flows through compartments in mineral and organic form, whereas carbon flows, based on nitrogen through C:N ratios (except the soil organic carbon dynamics), only in organic form. Imported feed and synthetic fertiliser were external inputs to the BCFS. Plant yields were functions of the soil mineral nitrogen available after losses, which for legumes is also affected by biological nitrogen fixation. Variation in head number and meat production was a function of feed shortage, calculated according to the needs and to the imported and locally produced feed. Severe shortages may lead to decreased weight gain or slaughter. Nitrogen losses occurred during soil and effluent management. No exchange of residues between the two land uses was considered.

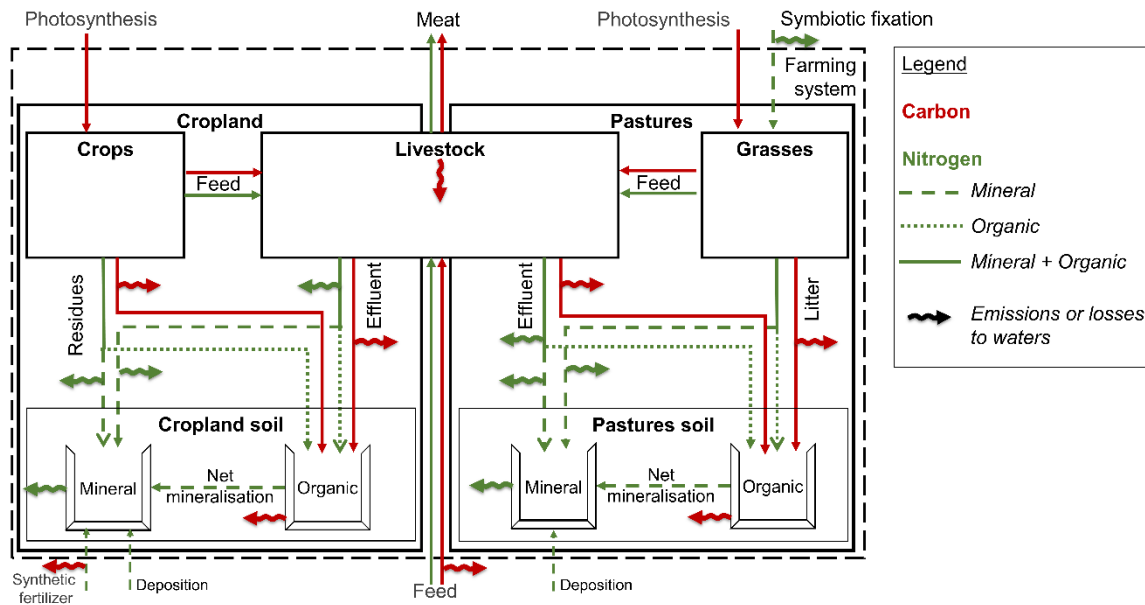


Figure 4.2. Conceptual scheme of the model. Boxes are the compartments and arrows are the nitrogen flows (in green) or carbon flows (in red). Nitrogen flows are of different types: mineral (dashed lines), organic (point lines), or mixed (full lines). The wavy arrows represent gaseous or liquid losses of nitrogen or carbon.

4.2.2 Description of model and adaptations

We describe the main model equations, while a complete description is in the Supplementary Material. Variables can refer to nitrogen (letter n) or carbon (letter c). They can refer to flows (dot-topped, e.g., $\dot{n}_{l,t+1}^{Fert}$) or stocks (not topped, e.g., $n_{l,t+1}^{Soil}$), can be per unit of area/livestock unit (lower-case) or in absolute value (upper-case), and can refer to organic (hat-topped, e.g., $\hat{n}_{l,t}^{OA}$) or mineral flows (check-topped, e.g., $\check{n}_{l,t}^{OA}$).

4.2.2.1 Plant

We parametrised each crop and each pasture type differently, *i.e.* each crop or pasture type has a set of traits useful for calculating biomass production following Clivot et al. (2019): area A [ha], typical yield of the harvested or grazed organ (in fresh matter) y^{TYP} [kg.ha⁻¹], harvest index HI [-], consumption index (the part effectively grazed by cattle) for pastures CI [-], shoot-to-root ratio SR [-], nitrogen and carbon contents of the different parts of the plant σ^N [kgN.kg⁻¹] and σ^C [kgC.kg⁻¹], humification coefficients for the residues Φ^R [-], the nitrogen quantity fixed by legumes per hectare \dot{n}^{BF} and the share of digestible energy for beef of the edible part α^{DE} [%]. All these parameters are assumed constant over time and independent from the yield. We assumed that yield $y_{i,t}$ [kg.ha⁻¹] increases linearly from 0 to the

maximum yield (assumed to be the typical yield) and then it saturates: $y_{i,t} = \max\left(y_i^{TYP}, \dot{n}_{i,l,t}^{Fert,Av} * \frac{y_i^{TYP}}{\dot{n}_{i,l}^{TYP}}\right)$, where $\dot{n}_{i,l,t}^{Fert,Av}$ is the soil mineral nitrogen available by a plant per hectare and $\dot{n}_{i,l}^{TYP}$ the soil mineral nitrogen need by a plant per hectare to reach the typical yield. Above that, the nitrogen surplus is lost to the environment.

4.2.2.2 Soil

The variables characterizing the soil compartment for each land use l are the active organic nitrogen stock $n_{l,t}^{Soil}$ per hectare, the active organic carbon stock $c_{l,t}^{Soil}$ per hectare and the flow of mineral nitrogen $\dot{n}_{l,t}^{Fert}$ per hectare. Organic amendments (residues and effluents) are applied homogeneously the year after being harvested or collected. Mineral nitrogen is in each time step, either consumed by plants or lost. A part of organic amendments humifies with a humification coefficient Φ [-]. For carbon, the non-humified part goes to the atmosphere as CO₂. For nitrogen, if the share of the organic amendment that humifies is higher than its nitrogen content, the difference is subtracted from the soil organic nitrogen mineralisation, *i.e.* is immobilised. On the contrary, the mineral share of the organic amendment is available to plants.

Soil organic carbon and nitrogen dynamics

The dynamics of soil organic carbon, following Clivot et al. (2019) is a mass balance equation:

$$c_{l,t+1}^{Soil} = c_{l,t}^{Soil} * (1 - \mu_l) + \dot{c}_{l,t}^{rA} + \dot{c}_{l,t}^{rR} + \dot{c}_{l,t}^E. \quad (4-1)$$

Input terms are the humified carbon quantities of amendments per hectare (*i.e.*, the aerial residues $\dot{c}_{l,t}^{rA}$, root residues $\dot{c}_{l,t}^{rR}$ and cattle effluents $\dot{c}_{l,t}^E$). The output term is the mineralisation of soil organic carbon (being μ_l [-] the mineralization rate).

We derived the dynamics of soil organic nitrogen from equation (4-1) by multiplying by C:N ratios and accounting for the immobilisation phenomenon (see Supplementary Material).

Mineral nitrogen flows and losses

In both land use, the soil mineral nitrogen available for plants $\dot{n}_{i,l,t}^{Fert,Av}$ per hectare is the sum of the mineral part of nitrogen flows applied to the soil and the net mineralisation of the soil organic nitrogen. The input mineral nitrogen flows are the atmospheric deposition \dot{n}^D and the mineral part of organic amendments $\dot{n}_{i,t}^{OA}$. For cropland, synthetic mineral fertiliser $\dot{n}_{i,t}^{Synth}$, is applied to each crop, according to their needs. Legumes crops or pastures partially get nitrogen from the air during the biological nitrogen fixation \dot{n}^{BF} .

Application of mineral nitrogen to the soil leads to losses, assessed using emission factors from IPCC (2006). Leaching ($\epsilon^{L,APP}$ [-]) and N₂O emissions during application ($\epsilon^{N_2O,APP}$ [-]) and soil management ($\epsilon^{N_2O,SM}$ [-]) occur for all the mineral nitrogen flows applied. Volatilisation happens at different level between organic amendments ($\epsilon^{V,ORG}$ [-]) and synthetic fertiliser ($\epsilon^{V,SYN}$ [-]) applications. Finally, N₂O emissions occur because of biological nitrogen fixation for legumes ($\epsilon^{N_2O,LEG}$ [kgN₂O.kgN⁻¹]). The soil mineral nitrogen available after losses to the plants in cropland is equal to:

$$\begin{aligned} \dot{n}_{i,l,t+1}^{Fert,Av} = & [\dot{n}_{l,t}^{OA} + (\mu_l * n_{l,t}^{Soil} - \dot{n}_{l,t+1}^I) + \dot{n}^D + \dot{n}_{l,t+1}^{Synth}] * (1 - \epsilon^{TOT}) - \dot{n}_{l,t}^{OA} * \epsilon^{V,ORG} \\ & + \dot{n}_i^{BF} * (1 - \epsilon^{N_2O,LEG}) - \dot{n}_{l,t+1}^{Synth} * \epsilon^{V,SYN} \end{aligned} \quad (4-2)$$

, where $\epsilon^{TOT} = \epsilon^{L,APP} - \epsilon^{N_2O,APP} - \epsilon^{N_2O,SM}$ and $\dot{n}_{l,t}^{OA} = \dot{n}_{l,t}^{rA} + \dot{n}_{l,t}^{rR} + \dot{n}_{l,t}^E$. For pastures, the equation is similar except that the quantity of synthetic mineral fertiliser applied $\dot{n}_{i,t}^{Synth}$ is null as permanent pastures are typically not fertilized in Alentejo.

4.2.2.3 Beef cattle herd

The herd was divided into five classes based on age ($a = 1$, < 1 year old; $a = 2$, 1 – 2 years old; $a = 3$, > 2 years old) and sex ($s = M$ for males, $s = F$ for females): young steers (1, M), old steers (2, M), young heifers (1, F), old heifers (2, F), suckler cows (3, F). Each class was characterised by an annual average number $L_{(a,s),t}$ [head], annual average weight $\bar{W}_{(a,s)}$ [kg live weight], beginning $W_{(a,s)}^I$ and final $W_{(a,s)}^E$ weights [kg live weight], and an annual feed need $\dot{n}_{(a,s)}^{Feed,Need}$ per head. Old steers were the main class that was fattened and finished for meat production. Suckler cows give birth to calves with a certain fertility rate β (male:female ratio is 1:1). Ratios of calves, before becoming steers or heifers, and young heifers, can be slaughtered in case of feed shortage $S_{(a,s),t}$ to reduce herd size, and fractions $\gamma_{(a,s),t}$ of the old heifers, young steers, and young heifers are slaughtered to produce meat. For slaughtered old steers, the feed impacts the final live weight at the end of the year $W_{(2,M)}^E$, not the number of animals slaughtered. Finally, a share of suckler cows ($\gamma_{(3,F)}$) is slaughtered at the renewal of this cattle class with the heifers that calve for the first time or in case of feed shortage ($S_{(3,F),t}$). Herd dynamics are detailed in Figure 4.3 . The equations of the annual average number per cattle class $L_{(a,s),t}$ are available as supplementary material.

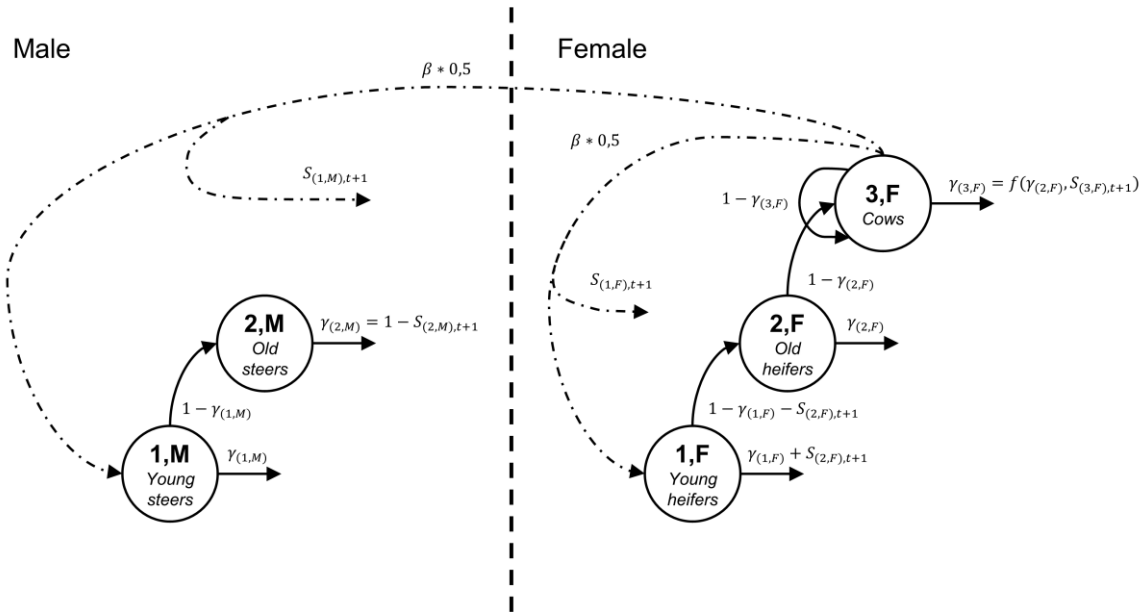


Figure 4.3 Description of beef cattle herd dynamics by age and sex class. Male are composed of two age classes, while females are composed of three age classes. Cows (3,F) give birth to young steers (1,M) and young heifers (1,F). Continuous arrows leaving the circles correspond to fractions of animals slaughtered (γ) or going to the next age class ($1 - \gamma$). These shares are either fixed or a function of feed shortage coefficients $S_{(a,s),t}$. Point-dot arrows leaving cows (3,F) correspond to the birth of offspring. A share β of the cows (3,F) give birth, with a ratio of female to male calves of 50%. Feed shortage can lead to the premature slaughter of offspring, young heifers (1,F), and cows (3,F), and to final weight decrease for old steers (2,M).

The quantity of meat produced P_t [kg carcass] is a function of the number of heads slaughtered, and their live weight at the beginning of the year $W_{(a,s)}^I$ or at the end of the year $W_{(a,s)}^E$ for old steers (the carcass weight of the Alentejo cattle breeds is approximately 60% of the live weight). The quantity of meat produced P_t is equal to:

$$\begin{aligned}
 P_{t+1} = & \beta * 0.5 * L_{(3,F),t} * (S_{(1,M),t+1} * W_{(1,M)}^I + S_{(1,F),t+1} * W_{(1,F)}^I) + L_{(2,M),t} \\
 & * (1 - S_{(2,M),t+1}) * W_{(2,M)}^E \\
 & + L_{(1,M),t} * \gamma_{(1,M)} * W_{(2,M)}^I + L_{(1,F),t} * (\gamma_{(1,F)} + S_{(2,F),t+1}) * W_{(2,F)}^I \\
 & + L_{(2,F),t} * \gamma_{(2,F)} * W_{(3,F)}^I + L_{(3,F),t} * \gamma_{(3,F)} * W_{(3,F)}^I
 \end{aligned} \tag{4-3}$$

Each cattle class is fed with a diet m for a share of the year $\tau_{(a,s),m}$. Each diet m has different proportions $\alpha_{k,m}$ in feed categories k . The feed needs $\dot{N}_{(a,s),k,t}^{Feed,Need}$ per category and per class are defined by: $\dot{N}_{(a,s),k,t}^{Feed,Need} = L_{(a,s),t} * \dot{n}_{(a,s)}^{Feed,Need} * \sum_m \alpha_{k,m} * \tau_{(a,s),m}$. The feed locally available $\dot{N}_{k,t}^{Feed,Loc}$ per category is equal to the quantity of harvested or grazed organ biomass $\dot{N}_{i,t}^H$ multiplied by the share allocated to cattle consumption $v_{i,k}$ [-]: $\dot{N}_{k,t}^{Feed,Loc} = \sum_i \dot{N}_{i,t}^H * v_{i,k}$.

The total available feed $\dot{N}_{k,t}^{Feed,Tot}$ per category is the sum of the locally available feed $\dot{N}_{k,t}^{Feed,Loc}$ and the imported feed $\dot{N}_{k,t}^{Feed,I}$: $\dot{N}_{k,t}^{Feed,Tot} = \dot{N}_{k,t}^{Feed,Loc} + \dot{N}_{k,t}^{Feed,I}$. The available feed per category and per cattle class $\dot{N}_{(a,s),k,t}^{Feed,Av}$ is equal to the difference between the total available feed per category and the sum of the feed need of the cattle classes for the category considered that are fed in priority to the cattle class considered: $\dot{N}_{(a,s),k,t}^{Feed,Av} = \max\left(\dot{N}_{k,t}^{Feed,Tot} - \sum_{(a,s) \in Y_{(a,s)}} \dot{N}_{(a,s),k,t}^{Feed,Need}, 0\right)$.

The shortage coefficient $S_{(a,s),k,t}$ per cattle class and per feed category is equal to the difference between the feed need $\dot{N}_{(a,s),k,t}^{Feed,Need}$ and the feed available $\dot{N}_{(a,s),k,t}^{Feed,Av}$ for the cattle class and the feed category considered. The difference is divided by the feed need: $S_{(a,s),k,t} = \max\left(\frac{\dot{N}_{(a,s),k,t}^{Feed,Need} - \dot{N}_{(a,s),k,t}^{Feed,Av}}{\dot{N}_{(a,s),k,t}^{Feed,Need}}, 0\right)$. The shortage coefficient is null if the available feed exceeds the need.

Empirical evidence from Alentejo suggests that, in the event of a shortage, cows are fed first to maintain the level of Common Agricultural Policy subsidies, which depend on the number of cows (“suckler cow premium”) (Viegas et al., 2012). However, incorporating this practice in the model would lead to inter-annual variations in herd size and consequently in meat production during feed shortages. We have chosen to avoid this variability.

The quantity of cattle effluent per class $\dot{N}_{(a,s),t}^E$ is computed as the difference between the feed intake $\dot{N}_{(a,s),t}^{Feed,Need}$ and the nitrogen accumulation in the animals $N_{(a,s),t}^L$, and (for cows) the nitrogen in offspring $\dot{N}_{(a,s),t}^{Offs}$, and milk $\dot{N}_{(a,s),t}^{Milk}$, and is function of the time spent grazing $\tau_{(a,s)}^G$. Nitrogen in suckler cow milk $\dot{N}_{(3,F),t}^{Milk}$ corresponds to the nitrogen feed need of offspring during the 6 first months. Accumulation of feed intake as body weight gain per cattle class $N_{(a,s),t}^L$ corresponds to the number of heads $L_{(a,s),t}$ multiplied by the variation in live weight $\Delta W_{(a,s)}$, the nitrogen content of body tissues $\sigma^{N,C}$ [kgN.kg live weight⁻¹] and considering 65% content of water in animal bodies. Nitrogen in offspring $\dot{N}_{(3,F),t}^{Offs}$ is computed from the previous equation, considering an initial live weight W_{Offs}^I equal to 0.

Excreta generated in housing facilities are stored before being applied to crops the following year as we assumed that effluent excreted on permanent pastures do not enter the nitrogen stocks until one year later. The excretions in housing facilities and the storage of effluent result in emissions of ammonia by volatilisation ($\epsilon^{V,B}$ and $\epsilon^{V,S}$ [-]), while excretion over permanent pastures also implies volatilisation ($\epsilon^{V,G}$ [-]). Both situations also lead to emissions of N₂O by denitrification (ϵ^{N_2O} [-]) and leaching losses (ϵ^L [-]).

4.2.2.4 GHG balance

Adding the carbon cycle to the Pinsard et al. (2021) model enabled estimating (following Teixeira et al. (2018)) the emissions of the three main greenhouse gases (CO₂, CH₄, and N₂O; Ritchie and Roser 2020) and thus develop GHG balance at the BCFS level. Photosynthetic carbon capture during plant growth were obtained following Clivot et al. (2019). We multiplied the carbon content of the different parts of the plant by the crop yield $y_{i,t}$, the harvest index HI_i , and the shoot-to-root ratio for residues SR_i^R . We did not consider carbon content of imported feed or the GHG emissions from the cropping practices for this imported feed.

CO₂ emission flows

CO₂ emissions from soil organic carbon mineralisation were obtained by multiplying the active soil organic carbon stock $c_{l,t}^{Soil}$ by the mineralisation rate μ_l (see equation (4-1)). CO₂ emissions from the mineralisation of organic amendments ($\dot{C}_t^{CO_2,RES} + \dot{C}_t^{CO_2,EFF}$) correspond to the total carbon quantity of the amendment deducted from the carbon quantity humified. We considered CO₂ emissions embedded in the imported synthetic fertiliser and feed, due to transportation and production. For synthetic fertiliser, we used an emission factor for Western Europe considering production and transport $\epsilon_{SF}^{CO_2}$ [kgCO₂.kgN⁻¹] (FAO, 2017). For feed import, we considered CO₂ emissions linked to the biomass transportation by truck: we multiplied the biomass weight by an emission factor $\epsilon_{FI}^{CO_2}$ [kgCO₂.(T.km)⁻¹] (ADEME, 2012) accounting for an average distance of 1000 km (roundtrip distance between the north of Portugal, source of most imported feed and the Alentejo region), and a carbon content of 50% of the biomass imported (TNO Biobased and Circular Technologies, 2021).

We assessed CO₂ emissions of cattle respiration $\dot{C}_t^{CO_2,Resp}$ as the difference between the carbon intakes (feed) $\dot{C}_t^{Feed,Need}$, and the quantity accumulated in body tissues ΔC_t^L , and out-takes (enteric fermentation \dot{C}_t^{EF} , excretion \dot{C}_t^E , offspring \dot{C}_t^{Offs} , and milk \dot{C}_t^{Milk}). The carbon quantities of feed intake and excretion were obtained by multiplying their nitrogen quantities by their respective C:N ratios. The carbon quantity in milk $\dot{C}_{(3,F),t}^{Milk}$ corresponds to the offspring nitrogen feed need for the first six months $\dot{N}_{(3,F),t}^{Milk}$ multiplied by C:N ratio of the mil. Accumulation of feed intake as body weight gain per cattle class $C_{(a,s),t}^L$ corresponds to the number of heads $L_{(a,s),t}$ multiplied by the variation in live weight $\Delta W_{(a,s)}$ and the carbon content of body tissues $\sigma^{C,C}$ [kgC.kg live weight⁻¹] (considering 65% body water content). The carbon in offspring $\dot{C}_{(3,F),t}^{Offs}$ was obtained in the same way, considering the initial live weight W_{Offs}^I as 0.

Non-CO₂ emission flows

Methane emissions from cattle effluents $\dot{C}_t^{CH_4, EFF}$ were calculated using an emission factor for the total quantity of carbon ($\epsilon_{eff}^{CH_4}$ [-]) and deducted from the effluent carbon to estimate mineralisation-related CO₂. Methane emissions from enteric fermentation $\dot{C}_t^{CH_4, EF}$ were computed using the Tier 2 IPCC (2019) equation for non-dairy cattle with the CH₄ yield, linearly interpolated along feed digestibility. Feed digestibility is the sum of the digestible energy per crop consumed α_i^{DE} by beef cattle herd per feed category, divided by the total gross energy for the feed category considered. We used feed nutritional values tables for ruminants of INRA et al. (2018) for the digestibility per crop.

Total GHG balance

The annual total GHG balance is the sum of all the GHG flows for one year from both land use and from the cattle herd, converted into CO₂-e using the global warming potential for 100 years (GWP₁₀₀) or the global warming potential star (GWP*) for CH₄. The CO₂ flows captured by plants during photosynthesis are negative values. The use of GWP* for short-lived gases in the atmosphere (approximately 20 years for CH₄) is recommended as it is particularly relevant when assessing their impact on global average temperature over time, or in the case of a net zero-GHG-emissions target (IPCC 2021 - Box 7.3). Indeed, the GWP* allows approximation of the impact of short-lived gases emissions on the climate more accurately than GWP₁₀₀, while the use of GWP₁₀₀ underestimates the impact on the climate when emissions increase exponentially and overestimates it when they are constant or decreasing (Lynch et al., 2020; Thompson and Rowntree, 2020). When it comes to comparing the evolution of GHG emissions over time under different scenarios of changes in agricultural management practices, as in this study, the use of the GWP* coefficient is not essential. However, we decided to calculate the GHG balance with both coefficients, to compare the carbon intensity of meat production with other studies, which use the GWP₁₀₀ coefficient. This also allowed highlighting the differences in the estimated impact of CH₄ emissions on the climate depending on the metric used. We considered the global warming potentials from the fifth assessment report of the IPCC without carbon feedbacks (Myhre et al., 2013).

4.2.2.5 Parameters and state variables

We collected data for 2018. For cropland, permanent pastures, and cattle herd parameters, we used the values from Hou et al. (2016), Teixeira et al. (2018a) and Pinsard et al. (2021). Details regarding the parameter nominal values, and sources are available as supplementary material. The model was coded in R language using the package “deSolve” for solving the dynamic equation system.

Head numbers of suckler cows comes from the statistical database INE (Instituto Nacional de Estatística, 2020). Head numbers for other cattle classes were computed with the cattle population dynamics equations, considering no feed shortage. The total quantities of aerial and root residues are initialised

using typical values of plant yield in Alentejo. Soil organic nitrogen and carbon stocks in the 10 cm soil depth in permanent pastures and in cropland are set equal to the average measured organic carbon content multiplied by a bulk density (respectively 11 700 and 12 000 kg.ha⁻¹) and using a C:N ratio equal to 15 and 10 respectively (Ballabio et al., 2016). For cropland, we initialised the active soil organic matter stock in the 10-cm soil depth using the spin-up method (Xia et al., 2012), and considering the immobilisation phenomenon for the nitrogen cycle, and without fixing the soil C:N ratio. We found about 30% of active stock. We estimated the mineralisation rate equal to 13% using the equation of the version 2 of the AMG model (Clivot et al., 2019). For permanent pastures, we estimated the mineralisation rate of 5.5% considering that 100% of the initial stock in the 10cm soil depth is active.

4.2.3 Simulations

4.2.3.1 Management practices

We considered three management practices: (i) increasing sown biodiverse pastures in a given area (pasture productivity, “*PP*”), (ii) shifting from a concentrate-based diet to a forage-based diet for old steers (fattening on forage, “*FF*”), and (iii) increasing animal productivity and decreasing herd size to reach the GHG target fixed by the Portuguese government (livestock decrease, “*LD*”) (Republica Portuguesa, 2019). Other practices, such as the use of enteric fermentation inhibitors (algae) as feed (Lean et al., 2021), were not considered as not widely used in Alentejo.

The management practice “*PP*”, is intended to increase the productivity of permanent pastures. This should make the farms more self-sufficient with respect to fodder needs while reducing net GHG emissions, as increased biomass production increases carbon sequestration, but also depending on the stocking rate and since when have these pastures been sown (Morais et al., 2018). In 2014, there were 140,000 hectares of sown biodiverse pastures in Portugal (4% of its agricultural land (Teixeira et al., 2015)), and we assumed that this has not changed much. The management practice “*FF*” involves fattening old steers on permanent pastures to reduce input cost and increase self-sufficiency of the farm. We considered that old steers are full-time kept in housing facilities while other classes graze year-round. The management practice “*LD*” is intended to decrease GHG to meet the goals set by the Portuguese government of reducing for instance CH₄ emissions from enteric fermentation by 25% from 2020 to 2050 (Republica Portuguesa, 2019). The directive suggests “changes in the numbers of the various species” and “productivity improvements through genetics”, which we consider will involve reducing head number, genetically improving animal productivity, and shifting to more productive breeds to maintain the meat production levels.

4.2.3.2 Simulated scenarios

Scenarios were combinations of a challenge and three management practices, simulated on a time horizon of 50 years (by 2070). The challenge consisted of reduced external inputs (synthetic fertilisers and feed imports). In the simulation, a trajectory was imposed that started from an initial value and decreased linearly to 0 after 30 years (by 2050). The remaining 20 years of simulation display the inertia effects. The initial value of the availability of imported synthetic fertiliser corresponds to the total initial nitrogen needs of crops. The initial value for the availability of imported feed in each feed category corresponds to the initial feed need per feed category.

We assumed that management practice changes were put in place linearly over time. Practice “*PP*” was modelled by doubling of the initial sown biodiverse pastures area share over the semi-natural pasture area share by 2050. Practice “*FF*” corresponded to a shift to a diet composed of 70% of forages. Practice “*LD*” was modelled as a 25% decrease in head number of suckler cows and a 10% increase in animal productivity. Although these management practice changes would be made at the farm level, we modelled their cumulative effect at the farming system scale.

We simulated seven scenarios (see Table 4-1). The first scenario is the *status quo* with no challenge (*SQ-NC*) or changes in management practices, serving as a baseline against which to assess the effect of the other scenarios on the robustness of meat production and net GHG emissions. There were six other scenarios: without management practices, so that we could assess the effect of the challenge by itself (*EC*); with increased pastures productivity (*PP*); with diet shift of old steers to a forage-based diet (*FF*); with head number decrease and animal productivity increase (*LD*); with combinations of “*PP*” and “*FF*” (*PP-FF*); and with the three practices together (*PP-FF-LD*).

Table 4-1 Challenge and management practices (columns) combination per scenario (rows). The "V" indicates that the challenge or management practice change for the column in question is present in the scenario for the line in question

Scenario	Challenge	Management practice		
	Feed and synthetic fertiliser: Import availability decrease	Permanent pastures: Increase in sown biodiverse pasture area share ("PP")	Fattened old steers: Shift from a concentrate-based diet to a forage-based diet ("FF")	Animal productivity increase and herd size decrease ("LD")
Baseline („SQ-NC“)				
Effect of the challenge („EC“)	V			
Increase of permanent pasture productivity ("PP")	V	V		
Steers finished on permanent pastures ("FF")	V		V	
GHG Roadmap 2050 („LD“)	V			V
Increase of permanent pasture productivity and steers finished on permanent pastures ("PP-FF")	V	V	V	
GHG Roadmap 2050 with increase in feed self-sufficiency ("PP-FF-LD")	V	V	V	V

4.3 Results and Discussion

4.3.1 Initial feed self-sufficiency

From the input data, we estimated the initial feed self-sufficiency. At time 0, old steers only ate concentrates and were the only class fed on concentrates. The concentrate needs of steers older than one year was about 3,500 tons of nitrogen per year (Figure 4.4). Local concentrate ingredients were mostly barley and wheat and satisfied more than 80% of the concentrate needs. The forage needs of the other beef cattle classes was about 30,000 tons of nitrogen per year, mostly consumed by cows and heifers older than one year. Young heifers and steers are weaning suckler cows half of the year. Local forage production came primarily from permanent pastures and fulfilled more than 90% of forage needs.

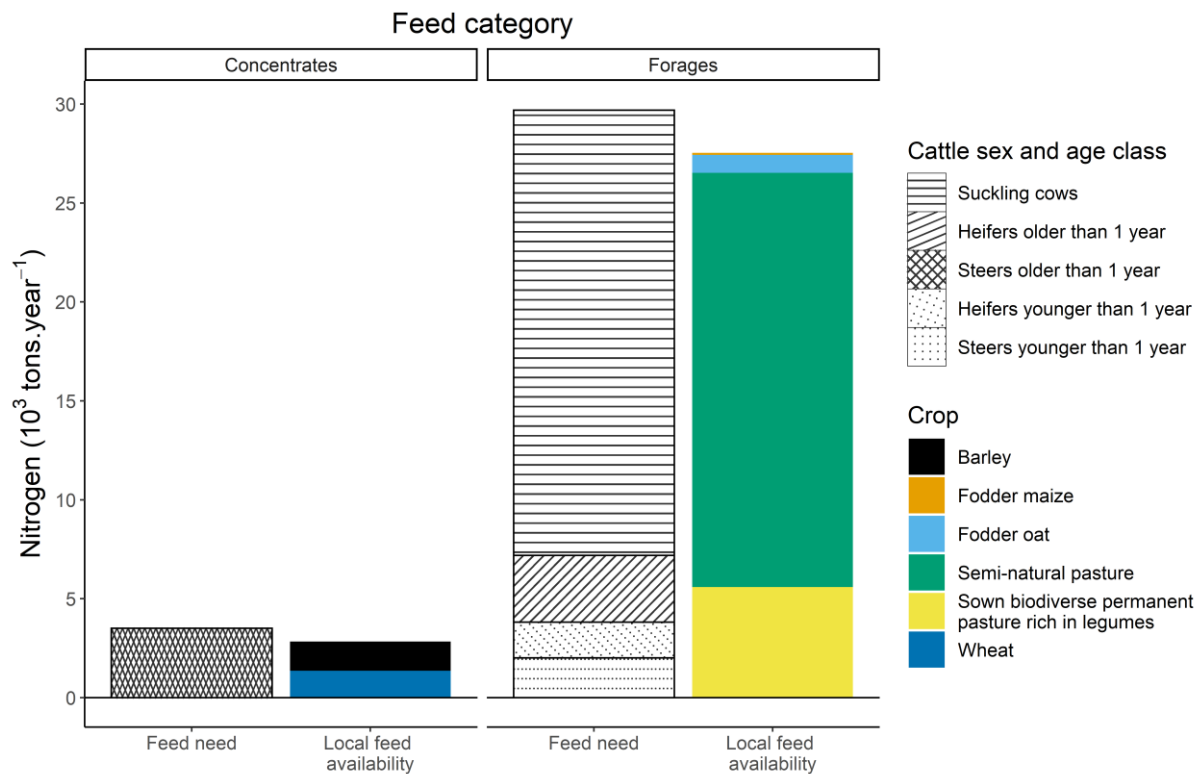


Figure 4.4. Feed needs versus local feed availability of the beef cattle farming systems in Alentejo per feed category (horizontal facets) in tons of nitrogen per year. On the x-axis, the stacked bars on the left represent the feed needs per cattle class, and the stacked bars on the right represent the local feed availability per crop. For a feed category, the local feed availability divided by feed needs corresponds to the local feed self-sufficiency of that feed category. Feed self-sufficiency for both feed categories ranged from 80% to almost 90%. Beef cattle largely graze semi-natural or sown biodiverse pasture in Alentejo. Local feed availability from sunflower and soybean were not represented because it was negligible.

Local feed production and the diet of the different cattle classes suggested that the BCFS were almost self-sufficient with respect to concentrates and fodder. In reality, self-sufficiency with respect to concentrates is lower, since most protein and energy concentrates have been imported in recent years (IACA, 2020). This is probably because the amount of land planted to wheat and barley, (used in concentrates) allocated to animals in Alentejo is actually lower than used in the model. Otherwise, forage self-sufficiency predicted by the model agrees with the survey conducted by Santos et al. (2019), in which 30% of beef farmers in Alentejo reported not being self-sufficient in fodder. Indeed, 70% forage self-sufficiency of the non-self-sufficient beef farms would imply 91% forage self-sufficiency of all beef farms in Alentejo.

4.3.2 Temporal dynamics of meat production

The time trajectories of meat production varied across the different scenarios (Figure 4.5). Without a voluntary decrease in the number of heads (all scenarios except *LD* and *PP-FF-LD*), the trajectories of meat production overlapped for the first 20 years and were constant over time at more than 60,000 tons carcass. Regardless of the combination of practices considered, meat production decreased over the 50 years when imports decreased. However, some trajectories were more robust than others. Either meat production began to decline later in the simulation (short-term robustness), or the decline was less at the end of the simulation (long-term robustness).

Both short- and long-term, the *PP-FF* trajectory was the most robust and the *LD* trajectory was the least robust. In the *PP-FF* scenario, meat production only decreased from year 30 onwards, to approximately 50 000 tons after 50 years. As Alentejo is home to more than 60% of Portuguese beef cattle (IFAP, 2020), we assume that more than 60% of its beef production is also. With this assumption, the level of production would decline to levels of the early 1970s in the *PP-FF* scenario (Instituto Nacional de Estatística, 2020). In the *LD* scenario, the meat production decreased from the beginning of the simulation and overlapped with *PP-FF-LD* scenario until year 23. At the end of the simulation, 25 000 tons of carcass had been produced. In the *PP-FF-LD* scenario, meat production was 40 000 tons in year 50. This was the third most robust scenario in the long term, just a bit less robust than the *FF* scenario. In the *EC* and *PP* scenarios, production started to decline in year 22, while in *PP-FF* scenario, it started in year 31, after a production peak. The production declines in the *FF* scenario in year 29, before the decline in *PP-FF* scenario, with a production peak of 65 000 tons of carcass in year 26. We observed a decline in production with increased forage self-sufficiency (scenarios *PP*, *PP-FF*, *PP-FF-LD*), and suggest that the productivity of local crops is high and import of synthetic fertilisers is necessary to maintain crop yields and, indirectly, meat production.

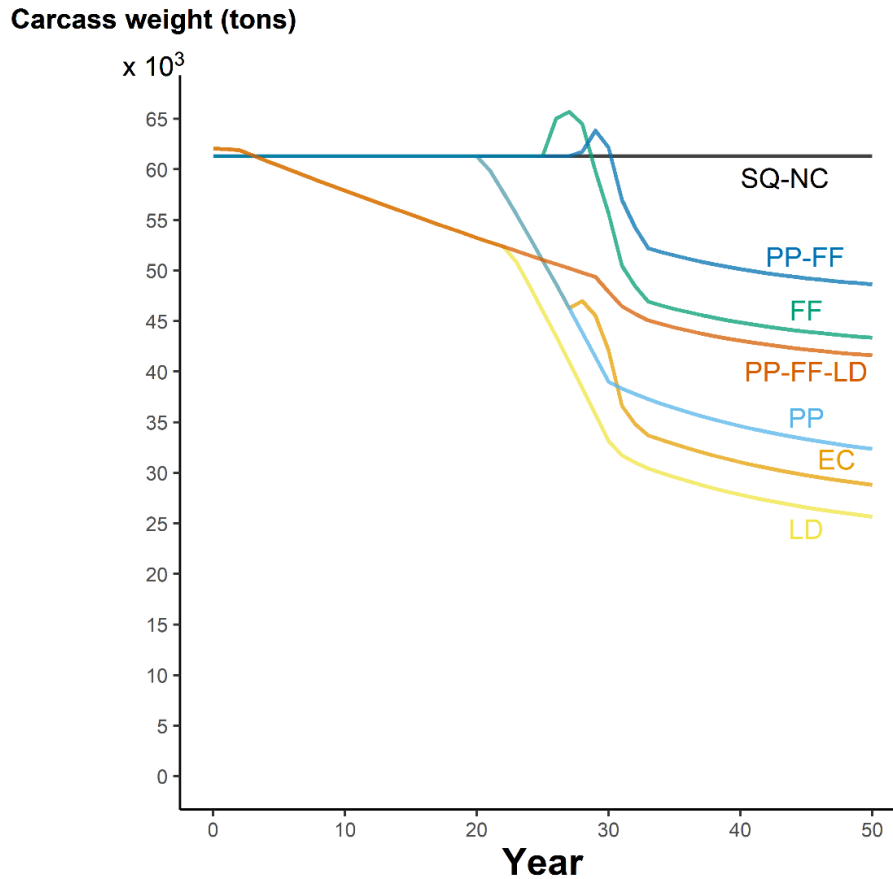


Figure 4.5. Meat production in the different scenarios over 50 years as predicted by the model. The *SQ-NC* scenario is the baseline scenario; the status quo with no challenge or change in management practices. In the *EC* scenario, the challenge is implemented with no management practice. In the *PP* scenario permanent pastures productivity was increased. In the *FF* scenario, the diet of old steers was shifted from a concentrate-based diet to a forage-based diet. In the *LD* scenario, animal productivity was increased, and head number decreased as part of the roadmap of the Portuguese government to reduce greenhouse gas emissions. In the *PP-FF* and *PP-FF-LD* scenarios, both management practices were implemented.

The *PP* scenario resulted in greater self-sufficiency with respect to forage, but less self-sufficiency with respect to concentrates. The latter was due to decreased local crop production resulting from a shortage of synthetic fertiliser. We observed the opposite in the *FF* scenario: there was less need for concentrates and greater need for forage. The *PP* trajectory was less robust, in the short and long term, than the *FF* trajectory, and we concluded that shortage of concentrates was more detrimental to production than shortage of forage, perhaps because only the old steers consumed concentrates. Also, since old steers are intended for meat production, a decrease in their feed will result in reduced live weight at slaughter.

4.3.3 GHG emissions

4.3.3.1 Per emission flow

Nitrous oxide emissions from soil management and legumes was the largest N_2O flow over the 50 years ($\sim 450 \text{ ktCO}_2\text{-e. year}^{-1}$) (Figure 4.6a). The N_2O emission flow from effluent management accounted for about $140 \text{ ktCO}_2\text{-e. year}^{-1}$ (Figure 4.6b). Emissions from enteric fermentation was the largest CH_4 flow ($\sim 600 \text{ ktCO}_2\text{-e. year}^{-1}$ with the GWP^* and $\sim 2\,500 \text{ ktCO}_2\text{-e. year}^{-1}$ with the GWP_{100}) (Figure 4.6c). The CH_4 emission flow from effluent on permanent pastures accounted for about $50 \text{ ktCO}_2\text{-e. year}^{-1}$ with the GWP^* , and about $210 \text{ ktCO}_2\text{-e. year}^{-1}$ with the GWP_{100} (Figure 4.6d).

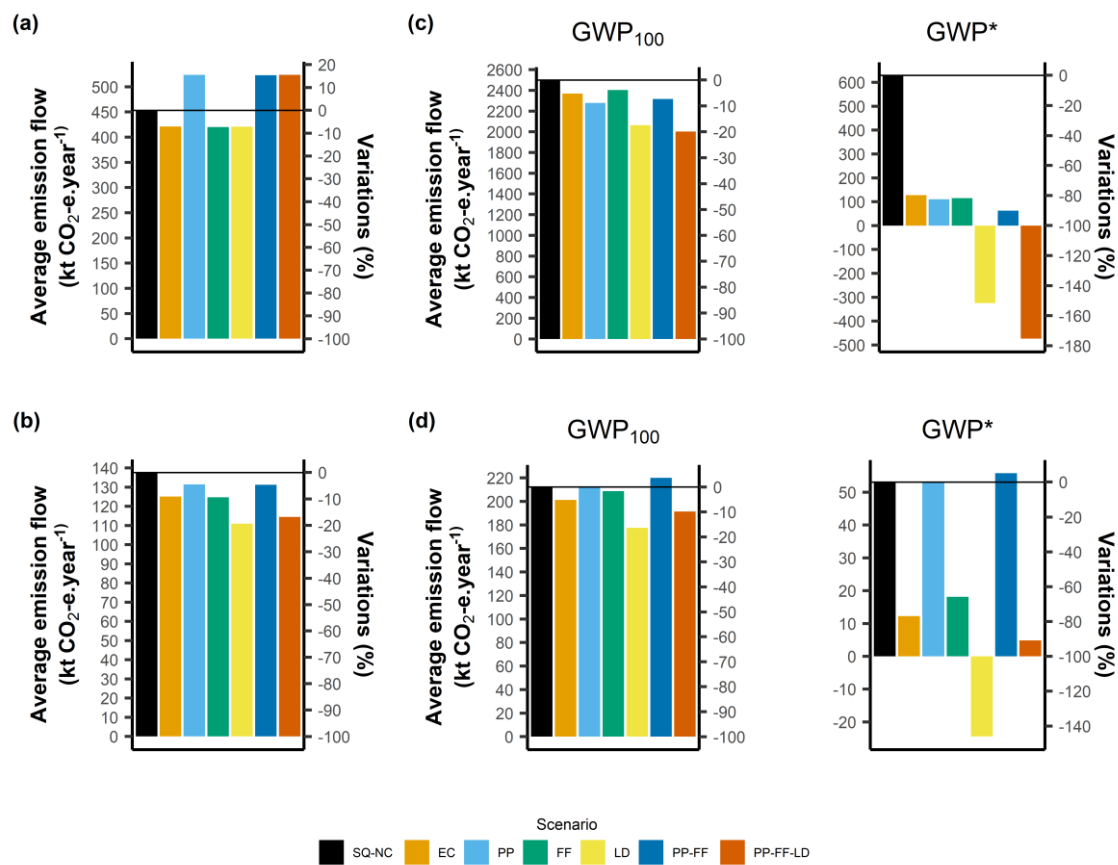


Figure 4.6. Annual average greenhouse gas (GHG) emission flows for the different scenarios for the 50-year simulation time. The CH_4 emission flow from the application of effluent on cropland was not shown as it is lower than $50 \text{ ktCO}_2\text{-e. year}^{-1}$. (a) N_2O emissions from soil management and legumes (b) N_2O emission flow from effluent management (c) CH_4 emission flow from enteric fermentation (d) CH_4 emission flow from effluent on permanent pastures. The right axis shows emission variations in % from the baseline scenario (SQ-NC). (SQ-NC, status quo with no challenge; EC, effect of the challenge by itself (no management practices); PP, pasture productivity; FF, fattening on forages; LD, livestock decrease; GWP_{100} , global warming potential over 100 years; GWP^* , short-term global warming potential)

In case of increased pasture productivity (*PP*, *PP-FF* and *PP-FF-LD* scenarios), the 50-year annual average N₂O emission flows from legumes and soil management was higher than in the baseline scenario (*SQ-NC*) (by 15%) (Figure 4.6a). The increase in N₂O emissions from soil and legume management was related to the shift to sown biodiverse pastures, which led to an increase in mineral nitrogen flow in the permanent pastures soil (R. Teixeira et al., 2018). In all the scenarios with the challenge, the 50-year annual average N₂O emissions from effluent management were between 0% and 20% less than in the baseline scenario (*SQ-NC*) (Figure 4.6b). This decrease is a proxy for the decrease in the number of livestock or the decrease in feed consumption by old steers due to the lack of available feed and being the last class to be fed (see Supplementary Material – section SM3.2).

In all the scenarios with the challenge, the 50-year annual average CH₄ emissions from enteric fermentation were lower than in the baseline scenario (*SQ-NC*) (Figure 4.6c). Methane emission flow from enteric fermentation was the highest in the *FF* and *EC* scenarios among all the scenarios with the challenge, whether GWP₁₀₀ or GWP* were considered. This is due to a robust number of grazing livestock (see Supplementary Material – section SM3.2) or to a diet with more fibre, which would have lower digestibility than concentrates (Beauchemin et al., 2008; INRA et al., 2018a). The CH₄ emission flow from enteric fermentation was the lowest in scenarios *LD* and *PP-FF-LD* and was even negative when GWP* was considered (between -300 and -500 ktCO₂-e.year⁻¹, respectively). The CH₄ emission flow from enteric fermentation was lower in the *PP-FF-LD* scenario compared to the *LD* scenario due to a slightly higher digestibility of sown biodiverse pastures compared to semi-natural permanent pastures. The annual average CH₄ emissions over the 50-year simulation from effluent on permanent pastures were almost always lower than those in the baseline scenario (*SQ-NC*), except in the *PP* and *PP-FF* scenarios (Figure 4.6d). Emissions were even negative in the *LD* scenario when GWP* was considered, as the head number was highly reduced (see Supplementary Material – section SM3.2). Emissions increased in the *PP-FF* scenario as old steers were finished on grass and the livestock number did not decrease, that is, the number of animals on permanent pastures increased.

4.3.3.2 Total balance

In the baseline scenario in total, the 50-year annual average CO₂ balance, considering only CO₂ flows, was approximately 200 ktCO₂-e.year⁻¹ (Figure 4.7a). The 50-year annual average total non-CO₂ GHG balance was approximately 1 300 ktCO₂-e.year⁻¹ with the GWP* and 3 300 ktCO₂-e.year⁻¹ with the GWP₁₀₀ (Figure 4.7b).

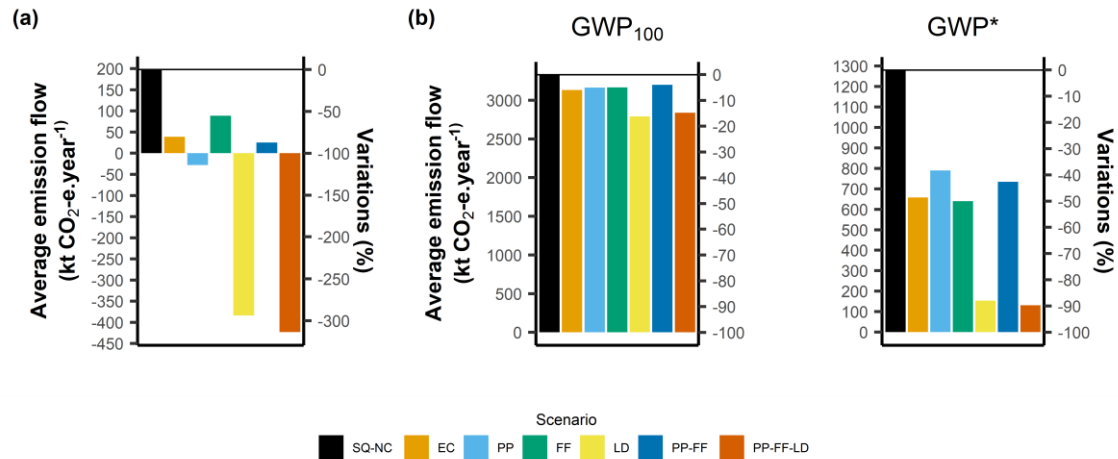


Figure 4.7. Annual average greenhouse gas (GHG) balances for the different scenarios for the 50-year simulation time. (a) Total CO₂ balance. (b) Total non-CO₂ GHG balance using both global warming potential (GWP) coefficients. Total CO₂ balance is the sum of CO₂ emission flows. The total non-CO₂ GHG balance is the sum of N₂O and CH₄ emission flows. The right axis shows emission variations in % from the baseline scenario (SQ-NC). (SQ-NC, status quo with no challenge; EC, effect of the challenge by itself (no management practices); PP, pasture productivity; FF, fattening on forages; LD, livestock decrease; GWP₁₀₀, global warming potential over 100 years; GWP*, short-term global warming potential)

Total CO₂ balance in all scenarios was lower than in the baseline scenario and negative in scenarios with reduced head number (LD and PP-FF-LD scenarios) (Figure 4.7a). In scenario PP, in which pasture productivity increased, the total CO₂ balance decreased by about 110%, despite a constant number of grazing livestock (see Supplementary Material – section SM3.2), confirming that sown biodiverse pastures contributes to increase soil organic carbon stocks (R. Teixeira et al., 2018). The balance was slightly higher in FF and PP-FF scenarios than in the PP scenario, and it may be that the sown biodiverse pastures were overgrazed when old steers were finished on grass; specifically, fewer of the residues in the total biomass produced were returned to the soil.

Total non-CO₂ GHG balance was lower in all scenarios than in the baseline scenario, with both GWP coefficients (Figure 4.7b). The decrease of head number coupled to animal productivity increase (*LD* and *PP-FF-LD* scenarios) reduced total non-CO₂ GHG balance the most, more than 90% from the baseline scenario with GWP*. This result is explained because a decrease in herd size coupled with an increase in individual productivity will inevitably reduce CH₄ from enteric fermentation without increasing N₂O emissions (Herrero et al., 2013; Ripple et al., 2014).

4.3.4 Total GHG balance versus meat production robustness

There was a strong trade-off between total GHG balance and robustness of meat production that varied with simulation time. Some efficiency gains were possible, depending on the combination of management practices changes put in place. However, maintaining meat production prevented strong reductions of GHG emissions, and GHG emission reductions established in policy objectives were only possible with reductions of meat production.

In scenarios without reduction in head number (*EC*, *PP*, *FF*, and *PP-FF* scenarios), with the GWP₁₀₀, the annual average total GHG balance was higher than or equal to the baseline scenario (up to 16%), while with the GWP* it was lower than the baseline scenario (between -35% and -45%). In *LD* and *PP-FF-LD* scenarios, with the GWP₁₀₀, the annual average total GHG balance was lower than the baseline scenario, from -4% to -17%, while with the GWP*, the decrease reached more than -120%. The local sensitivity analysis revealed that the total GHG balance was very sensitive to values of the soil and plant compartments parameters, notably humification rate, shoot-to-root ratio, and stocking rate (see Supplementary Material – paragraph SM3.2.5).

The annual average total GHG balance per unit of meat produced was more than 56 kg CO₂-e/kg carcass with the GWP₁₀₀ in the baseline scenario, in line with the median value of GHG balances of beef production collected by Poore and Nemecek (2018), assuming 25% protein in beef meat and a carcass to fat and bone-free-meat yield of 70% (52.5 kg CO₂-e/kg carcass). However, this value was 37% higher than that estimated for a similar BCFS (35 kg CO₂-e/kg carcass, acquired when converting to IPCC GWP AR5 factors and considering a live-weight to carcass yield of 60%) (Eldesouky et al., 2018; Morais et al., 2018). This difference can be explained by taking into account the mineralisation of crop residues during the humification process, despite a lower estimate of the climate impact of CH₄ emissions from enteric fermentation.

The annual average total GHG balance per unit of meat produced was less than 25 kg CO₂-e/kg carcass with the GWP* in the baseline scenario. The 2-fold difference between GWP₁₀₀ and GWP* observed while CH₄ emissions are not changing in the baseline scenario, shows how much GWP₁₀₀ leads to an overestimation of the impact of CH₄ emissions on the climate at constant or decreasing rate of emissions.

The annual average total GHG balance in absolute or per unit of meat produced was lower than in the baseline scenario in all the scenarios when GWP* was considered, but not when GWP₁₀₀ was considered (Figure 4.8). In the scenarios without reduced animal numbers (*EC*, *PP*, *FF*, and *PP-FF* scenarios), the total GHG balance per unit of meat produced when GWP₁₀₀ was used was higher than in the baseline scenario. In other words, the metric used determined whether we estimated an increase or decrease in net GHG emissions per unit of meat produced compared to the baseline.

Finally, both with GWP₁₀₀ and GWP*, the total GHG balance per unit of meat produced was the lowest in the *LD* and *PP-FF-LD* scenarios, and even negative when GWP* was used. This decrease in CH₄ emissions from enteric fermentation had a positive effect on the climate in these scenarios (“negative emissions” in CO₂-e), as the global warming capacity of the CH₄ emitted was lower than the global warming capacity of the CH₄ emitted 20 years ago, which would have been converted into CO₂. This phenomenon was captured with the GWP* metric but not with the GWP₁₀₀ metric (see Supplementary Material – section SM3.2). After a 30-year decrease, CH₄ emissions from enteric fermentation stabilised and the earlier positive effect on the climate decreased in the following 20 years to a new equilibrium with again a negative effect on climate. Thus, when considering the long term, the total GHG balance with GWP* would increase relative to the value with the 50-year time horizon, while the total GHG balance with GWP₁₀₀ would remain unchanged.

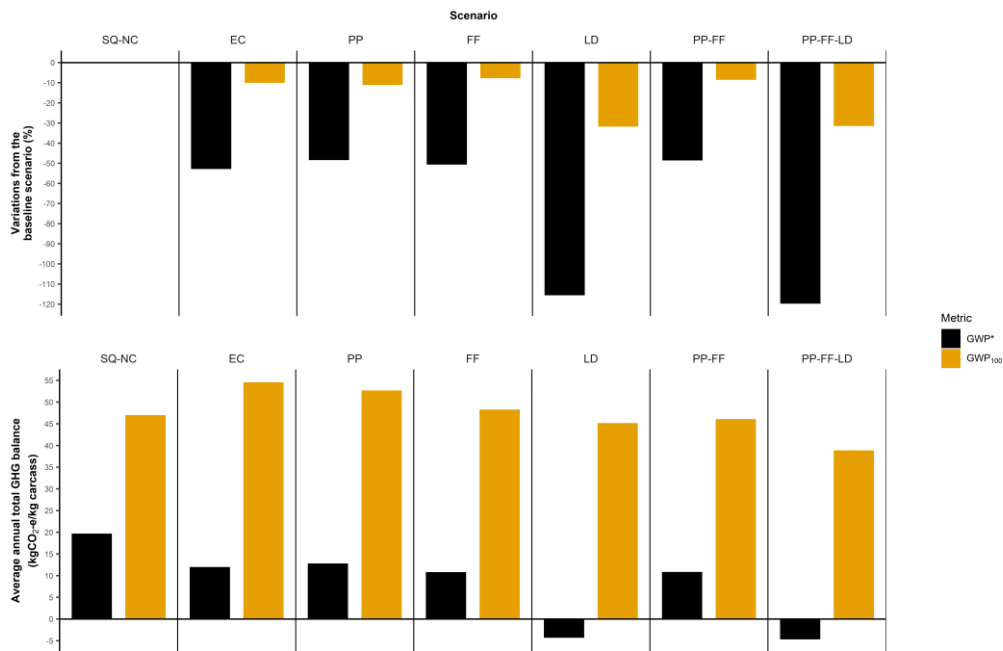


Figure 4.8. The annual average of the total greenhouse gas (GHG) emissions balance for the 50-year simulation, using GWP_{100} and the GWP^* . Upper panel, variations from the baseline scenario (SQ-NC) in %; Lower panel, in kg CO₂-e/kg carcass. (SQ-NC, status quo with no challenge; EC, effect of the challenge by itself (no management practices); PP, pasture productivity; FF, fattening on forages; LD, livestock decrease; GWP_{100} , global warming potential over 100 years; GWP^* , short-term global warming potential)

Combining all the practices (PP-FF-LD scenario), was the best compromise between meat production robustness and climate change mitigation over the next 50 years (Figure 4.5 and Figure 4.8). However, animal productivity gains targeted by the Portuguese government's roadmap were insufficient to maintain meat production (LD and PP-FF-LD scenarios) (Republica Portuguesa, 2019). Increasing the productivity of permanent pastures (for example, with sown biodiverse pastures) combined with a diet with more forages supported meat production the most and decreased net GHG emissions (Morais et al. 2018), as observed in the PP-FF scenario. However, this was not sufficient for the decarbonisation of the sector (considering the GWP^* coefficient). Indeed, the Portuguese government's roadmap projects a 50% reduction in emissions from agriculture, by decreasing loss of carbon in cropland soils and by increasing carbon sequestration in permanent pastures soils by 2050 compared to 2020 (Republica Portuguesa, 2019). A 50% reduction in net GHG emissions in this agricultural sub-sector was largely achieved in the LD and PP-FF-LD scenarios, scenarios with a decrease in head number (Figure 4.8), and just achieved in the EC and FF scenarios.

4.3.5 Implications of and limitations for the implementation of practice changes

We could not consider the possible effects of implementation of the three management practices at the level of the farm or farming system, for example on the work organisation, the economy of the BCFS, and new imported flows in the BCFS. These may impose limits to the implementation of these practices, for example, changing management practices may affect the resilience of the farm and BCFS.

Installation of sown biodiverse pastures requires machinery for tillage to prepare the field for sowing and fertilising (Teixeira et al., 2011). During the process, phosphorus, borax, and zinc sulphate are applied as cover fertilisation, lime is applied to increase the soil pH, and 30 kg·ha⁻¹ of seeds are used. The pastures should last for at least 10 years but may require frequent application of phosphorus fertiliser and limestone during this time. Considering that energy supply and input prices may be uncertain in the future, the feasibility of installing and maintaining new sown biodiverse pastures is also uncertain.

Fattening old steers on grass takes at least 18 months, longer than it does on concentrates (Keane et al., 2006; Morales Gómez et al., 2021), due to lower nutritional value of grass compared to concentrates (Brosh et al., 2004; IPCC, 2019), and the increased energy expenditure of grazing animals (Brosh et al., 2004; IPCC, 2019). We assumed in our model that grass-fattening did not take longer than 24 months. In reality, this practice is limited in recent years, especially in Alentejo, by the increased frequency of droughts due to climate change and resultant decreased forage production (Huguenin et al., 2017; Jongen et al., 2013; Nardone et al., 2010; Scasta et al., 2015). Therefore, without increasing the resilience of permanent pastures to drought, specifically, without increasing sown biodiverse pastures, the implementation of this practice could harm the robustness of the BCFS. Nevertheless, from an economic perspective, grass-fattening increases self-reliance of the farm and reduces costs (Escribano et al., 2016). The added value at sale may also be greater as it coincides with the preferences of Portuguese consumers (Marta-Pedroso 2008, Banovic 2009).

We assumed a 10% increase in animal productivity over 30 years, probably accomplished by transitioning the cattle population in Alentejo towards the most productive breeds and away from the current indigenous Portuguese suckler breeds or the Angus breed (Santos-Silva et al., 2020; Schenkel et al., 2004). In 2020, however, only 16.3% of the Alentejo cattle population were indigenous Portuguese suckler breeds (pure or crossbreeds) or the Angus breed (IFAP, 2020), and 67% were unspecified beef crossbreeds with unknown productivity. If the productivity of these crossbreeds is close to that of the pure indigenous breeds in Portugal, then an increase in individual productivity should be possible. Such a change in the composition of the cattle herd would run counter to the approach of preserving the genetic heritage of the indigenous suckler breeds (Araújo et al., 2014), and, even if less productive, native suckler breeds are adapted to the Mediterranean climate and recommended for extensive systems

affected by harsh soil and climatic conditions. The productivity of ostensibly highly productive breeds, such as Charolais or Limousin, is not apparent in such a climate and these breeds are more susceptible to diseases when changing diets in extensive BCFS (Pereira et al., 2008). Increasing animal productivity facing increasing drought not only requires consideration of herd composition, but also genetic selection of individuals within a pure breed or in the herd and may require decreasing cow size while increasing herd size (Nardone et al., 2010; Scasta et al., 2016).

Reduction in head number is unavoidable if we are to meet GHG reduction targets. This is not explicitly mentioned in the Portuguese roadmap for carbon neutrality, which ideally requires measures to encourage and accept a reduction in the beef demand and financial incentives to help professional conversion of some economic stakeholders of the Alentejo BCFS. Moreover, the drop in beef demand would contribute to Portugal's self-sufficiency. In 2020, in Portugal, beef consumption amounted to an average of 20.8 kg/inhabitant, *i.e.* approximately 400 g per week (Instituto Nacional de Estatística, 2020). The beef production in Alentejo estimated with this model in 2020, with an assumption of 70% carcass/marketable meat yield, is then sufficient for 20% of this national consumption. In case of a meat consumption halving by 2070, in the worst case scenario (LD scenario) beef production in Alentejo would be sufficient for 20% of Portuguese meat consumption, while in the best case scenario (PP-FF scenario) it would be sufficient for 35%, a number similar to the 70s-80s decades (Instituto Nacional de Estatística, 2020). Finally, the trade-off between reducing GHG emissions and maintaining the quantity of meat consumed raises ethical and moral questions that must be debated democratically.

Despite the limitations, there are levers that could support the successful implementation of these management practices. Portuguese consumers are willing to pay more for meat if it is of better quality, thus making it possible to increase the selling price if the production cost increases (Banovic, 2009). Meat from a grass-finished animal is darker, has a stronger taste, and healthier fatty acids; it is indeed preferred by well-informed consumers (Marta-Pedroso 2008). The area of sown biodiverse pastures in 2009-2014 was greatly expanded as a result of the financial and technical support of the Portuguese Carbon Fund (Teixeira et al., 2015). Similar schemes could be devised to encourage a decrease in herd size coupled with an increase in individual animal productivity, as well as to encourage farmers to finish steers on grass.

4.3.6 Study and model limitations

The main limitations of our work were the scope of the GHG balance, the resolution of the soil organic matter modelling, and the exclusion of other challenges facing an extensive BCFS.

For the GHG balance we considered both emissions from transportation of imported feeds and those associated with synthesis of nitrogen fertilisers. However, we excluded the emissions associated with import of seeds and production of phosphorus fertilisers for sown biodiverse pastures, and the carbon capture or emissions related to the cultivation of imported feed. We did not consider them for three main reasons: (i) they only concern the installation of the pasture, (ii) we lacked data, (iii) we considered the amount negligible compared to the other emission flows (Teixeira et al. 2018).

In our adapted model, land use (cropland or permanent pastures) consists of only one soil type with a single organic matter pool, on which the application of organic amendments is homogeneous. This implies an overestimation or underestimation of the stock of organic matter in the soil and of the net mineralisation flow available to plants at the plot level, which leads also to a mis-estimation of biomass production. This choice was due to lack of data on soil amendments and cropping practices for the plots in the region, but it would be appropriate to compare the soil organic matter values for these two levels of model complexity.

The challenges that the extensive BCFS in Alentejo may face include droughts, policy reforms, and global peak oil. All of these, for different reasons, could decrease local feed production and could result in decreased agricultural imports, either the availability or price. For climate change, the region is increasingly facing droughts that decrease the biomass production of permanent pastures (Huguenin et al., 2017; Jongen et al., 2013), and farmers must buy or import fodder and concentrates to secure their feeding system, making them dependent on external feed production and markets, and increasing the cost of production. The Common Agricultural Policy could continue to favour the intensification of extensive beef cattle farms (for instance intensification of forage production), making them more dependent on imported feed or synthetic fertilisers and on subsidies (Jones et al., 2014) but perhaps more robust to climate change.

4.3.7 Future research perspectives

Climate change will undoubtedly have a major effect on the extensive BCFS in Alentejo. Simulating the farming sensitivity to possible future climate scenarios, by considering the impact of droughts on plant yield, is a logical next step, and explicit modelling of farmers' economic responses to increasing prices of inputs prices and droughts should help identify policy mechanisms and incentives that would enhance robustness of meat production. Finally, phosphorus is a critical element for sown biodiverse pastures fertilisation (Teixeira et al., 2011) and comes mainly from non-renewable rock reserves. The production peak of these fertilisers could occur at the same time as peak oil (Cordell and White, 2011). Therefore, the phosphorus cycle should be added to the model to assess the impact of global peak oil and global peak phosphorus on meat production, pinpointing the management practices changes that enhance both meat production robustness and GHG emission reduction.

The unique aspect of our study is the time-dynamic exploration of changes in an extensive BCFS. We assessed the trade-off between robustness of meat production to input import constraints (due to a global peak oil) and net GHG emissions. We showed a strong trade-off between total GHG balance and meat production robustness, but with some room for efficiency gains depending on the combination of management practices changes put in place. In other words, enhancing only meat production robustness may compromise GHG emission reduction targets or vice-versa, unless there is a major change in the way farmers manage their land.

4.4 Conclusion

Two critical policy goals in agriculture are to enhance the robustness of meat production to unpredictable supply and prices of inputs and to reduce GHG emissions. Those two goals were poorly investigated jointly in previous studies. Here, we showed that they are likely to conflict. We arrived at this conclusion through the exploration, via modelling, of practices that have been shown to work in the present, alone and in combination, to address this double challenge. Indeed, those management practices mitigated climate change even when the farms faced decreased supplies of synthetic fertiliser and imported feed. However, meat production cannot be maintained at the current levels. The only option for ensuring the robustness of meat production and maximising the reduction of net GHG emissions is a combination of all management practices considered here. Individual practices or combinations thereof are insufficient. For example, finishing old steers on grass while increasing the productivity of permanent pasture promoted robust meat production but failed to reduce net GHG emissions. Implementing those two management practices plus decreasing the head number and increasing individual animal productivity is the only option for reducing net GHG emissions over the next 50 years to levels compatible with the GHG reduction roadmap of the Portuguese government.

Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data, material and code

The formatted data used as input to the model as well as output data are available in Zenodo repository, <https://doi.org/10.5281/zenodo.5727504>. The raw input data is freely available from the sources mentioned in the Supplementary Material.

The R code done to make the simulations of the current study is available in Zenodo repository, <https://doi.org/10.5281/zenodo.5727504>.

Authors' contributions

All authors contributed to the study conception and design. C. Pinsard designed the model. The study was supervised by R. Teixeira and T. Domingos. Data collection was performed by T. Morais and C. Pinsard. Coding, simulating, and output visualization were done by C. Pinsard. All the authors validated model outputs. The first draft of the manuscript was written by C. Pinsard and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

III General discussion

III.1 Contributions

The research carried out in this PhD thesis makes a significant contribution in terms of knowledge as well as methodology. The results obtained provided a first overview of the robustness of European farming systems in the face of input import constraints. They also shed light on the changes in practices and in the crop-livestock composition that are appropriate in these farming systems to increase their resilience, *i.e.* their potential for adaptability. This research has also contributed to answering two related research questions at the level of a small agricultural region in France: the state of play of the dependence on synthetic fertilisers and imported feed, and the projection of a 100% organic agricultural transition scenario.

III.1.1 Major findings of the thesis

European farming systems are vulnerable to global challenges, such as global peak oil. I thus sought to answer the following research question: *What is the resilience of European farming systems to constraints on input supply related to global peak oil?* To answer this question, I adopted a quantitative approach and developed a dynamic model of nitrogen flows of a farming system. I explored this model for three French farming systems (field crops - Plateau Picard, intensive monogastric and dairy cattle – Bretagne Centrale, and extensive ruminants - Bocage Bourbonnais) (chapters 1 and 3); for the majority of French farming systems (Chapter 2); and for a Portuguese extensive beef farming system (Alentejo) (Chapter 4). The components of resilience that I explored were robustness (chapters 1, 2 and 4) and adaptability potential (Chapter 3). I explored robustness in simulation mode with scenarios of a progressive decrease in input supply (synthetic fertiliser and imported feed) over 30 years because with this decrease in inputs, the current level of food production cannot be maintained, even with changes in crop-livestock compositions. I divided robustness into two sub-components: (1) the ability to withstand disturbances without a decline in food production, which I called the 'robustness window' (in number of years) and (2) the ability to absorb disturbances in the long term, which I called 'robustness intensity' (in %) (Chapter 2). I explored the adaptability potential in multi-objective optimisation mode with two scenarios in which, by systematically varying the crop-livestock composition, I maximised food production and minimised input imports. This is a question of adaptability potential rather than adaptability because the changes in composition explored are potentialities and not adaptive responses of the system to disturbances.

I thus answered the research question of this thesis through three sub-questions within these 4 chapters: (1) *What is the robustness of French farming systems to a progressive decrease in input imports in their current state, i.e. without any change in practices or compositions? (chapters 1 and 2);* (2) *What changes in the composition of three French farming systems reduce their dependence on inputs? What is their adaptability potential? (Chapter 3);* (3) *What is the relationship in a Portuguese extensive beef farming system between the robustness of meat production and the reduction of net greenhouse gas (GHG) emissions according to changes in practices and compositions? (Chapter 4).* Below I detail the answers to these 3 research sub-questions based on the results, interpretations and implications drawn from the chapters of this thesis.

How robust are French farming systems to a progressive decrease in input imports in their current state, i.e. without any change in practices or composition?

In Chapter 1, I defined the robustness window as the consecutive number of years during which the food production of the farming system does not fall below 95% of the current food production, and the robustness intensity as the share of the current food production at year 30. Then, I have showed that the extensive ruminant farming system had the longest robustness window (13 years) while the field crop farming system had a robustness window of 4 years. The intensive monogastric and dairy farming system had the smallest robustness window (1 year) being highly dependent on feed imports, especially protein concentrates. The robustness intensity was between 40% and 55% for the three farming systems. In Chapter 2, I have found that the majority of French farming systems had a median robustness window of 8 years and a robustness intensity of 28% (*i.e.* a 72% decline in food production at 30 years). They also revealed strong heterogeneity according to the specialisation of the farming system. The most specialised farming systems (intensive monogastric livestock or field crops) had the shortest robustness windows (between 4 and 7 years in median), being the most dependent on inputs in relation to their needs, but on the contrary they had the highest robustness intensity (40% in median), except for field crops (between 23% and 26% in median), due to the feed that could be allocated to food when the livestock number decreases. Mixed farming systems tended to have the longest robustness window (median of 8 to 19 years), but the levels of robustness were a function of the degree of integration between crops and livestock. In these two chapters, I have noted that livestock, through its effluents, reduced dependence on synthetic fertilisers by contributing to soil organic matter stocks and plant mineral fertilisation (strong correlations between these three variables in Chapter 2). The crop's active soil organic nitrogen stock (through its mineralisation) did indeed contribute significantly to the robustness of food production (this is discussed in Chapter 1), but in Chapter 2 its correlations to the robustness window and robustness intensity were only moderately positive due to the small share this flow represents in plant mineral fertilisation. I have made the same observation for another natural nitrogen flow: biological nitrogen fixation by legumes. Its correlation with the robustness window was

only weakly positive and that with the robustness intensity was not significant, due to the low intensity of this nitrogen flow today. I noted that livestock farming also causes feed-food competition for biomass use and decreases the nitrogen use efficiency at the farming system scale (*i.e.* its productivity) but that this competition represents a "potential stock" of (plant) food for humans if the livestock number decreases, as in intensive livestock farming systems. The release of this potential stock when livestock numbers decline explained the high robustness intensity of these farming systems and the moderately positive correlation between feed-food competition for biomass use and robustness levels. Finally, I showed that without changes in composition and practices and in the absence of inputs, *i.e.* with 100% organic agriculture, the future protein needs of the French population (in 2050) would not be met.

From these results and interpretations, I noted that the robustness window is a period during which adaptive or transformative actions, such as changes in practices or compositions, could be implemented to increase the resilience of European farming systems. Furthermore, it is very likely, in view of the past, and even more so in the face of a progressive decline in input supply, that European farming systems will change their practices and compositions. These changes will necessarily lead to a decrease in the dependence of the farming system on inputs to increase its resilience, as food production is in trade-off with the use or import of inputs (results of Chapter 3). Changes in practices and compositions could involve, for example, an increase in legume areas, greater crop-livestock integration, and a decrease in the need for mineral nitrogen in crops (analyses in Chapter 3). These changes would thus constitute a de-specialisation of European farming systems and an agroecological transition. These changes could also contribute to climate change mitigation and adaptation (analyses in Chapter 4).

*What changes in the composition of three French farming systems reduce their dependence on inputs?
What is their potential for adaptability?*

In Chapter 3, I found only trade-offs between the four optimisation objectives: maximising crop-sourced food production, maximising animal-sourced food production, minimising the use of synthetic fertilisers and minimising feed imports. However, the intensity of these trade-offs varied according to the current shares of permanent grasslands and food crops in the farming system. Solutions that maximised total food production and minimised input use were few in number and close to current values in the scenario in which there was no decline in crop yields. In this scenario, to reconcile the four objectives, the algorithm increased the number of poultry at the expense of cattle due to their better nitrogen use efficiency, except in the extensive ruminant farming system since the high share of permanent grassland in the utilised agricultural area (UAA) can only be eaten by ruminants (according to the assumptions model). In the scenario in which there was no use of synthetic fertilisers and no feed import, the solutions that maximised total food production corresponded to those with the highest crop-sourced food production values, as the livestock number of all species decreased drastically (~90% in median), except for monogastrics in the field crop farming system which hardly varied, their number being very low at present. As a result, feed-food competition for biomass use decreased significantly (less than 5% in all three farming systems in median). In both scenarios, the area of legumes did not systematically increase due to, for example, the decrease in the livestock number, *i.e.* the feed demand.

From these results and interpretations, I noted that livestock re-design associated to a decrease in crop productivity are key levers to mitigate the trade-off between food production and input imports. Shifting human diets towards less animal protein and reducing losses in the food system would increase resilience to input import constraints when implementing the identified compositional changes. In addition, adding an environmental impact reduction objective for a farming system would allow for the refinement of practice and compositional changes that alleviate the trade-offs between food production and environmental impact (discussed in Chapter 4).

What is the relationship in a Portuguese extensive beef farming system between the robustness of meat production and the reduction of net GHG emissions according to changes in practices and compositions?

In Chapter 4, I have found for the Alentejo region in Portugal a robustness window of 20 years and a robustness intensity of more than 50% (scenario with no change in practices and compositions). Decreasing the cattle herd size led to the lowest levels of robustness in meat production, while increasing the area of sown biodiverse pastures rich in legumes and grass-fattening of steers led to the highest levels of robustness. I have found that meat production was more affected by concentrate shortages than by forage shortages. I calculated total annual average net GHG emissions at 23.5 kg CO₂-e/kg meat carcass produced (with the metric global warming potential star (GWP*)), a 45% decrease (with GWP*) in these emissions in the scenarios with no reduction in herd size and a decrease of more than 120% (with GWP*) in the other scenarios. I thus identified a strong trade-off between the robustness of meat production and climate change mitigation. Nevertheless, efficiency gains were possible by playing on the combination of practices implemented. The largest gains were achieved by combining all practices: increasing the area of sown biodiverse pastures rich in legumes, grass-fattening of steers, reducing herd size and increasing animal productivity. This combination minimises the reduction in meat production (up to 35%) and reduces GHG emissions over 50 years (up to 120%). The use of the GWP* metric, in contrast to the GWP₁₀₀ (global warming potential 100 years) metric, has highlighted the positive effect on the climate that a reduction in the ruminant population could have by 2050.

From the results and interpretations, I highlighted that the decrease in herd size is inevitable to achieve the GHG reduction targets set by the Portuguese government. This reduction and the changes in practices and compositions will probably need to be accompanied by financial incentives and communication of the benefits to ensure their successful implementation.

III.1.2 Collateral contributions

I identified two further research questions that chapters 2 and 3 helped to answer. Firstly, in the Chapter 2 I mapped the levels of synthetic nitrogen fertiliser and feed dependency by feed category at the small agricultural region level and at the French scale. For synthetic nitrogen fertilisers, the finest level of such mapping available in the literature is that of the agricultural territory, of which there are 33 in France (Le Noë et al., 2018). In 2013, the NOPOLU expertise of the French Ministry of Ecology mapped the dependence on synthetic nitrogen fertilisers at the regional level (old classification) (Service de l'observation et des statistiques, 2013). The data on supply of synthetic nitrogen fertilisers (and mineral fertilisers in general) collected by UNIFA (UNion des Industries de la FertilisAtion) for the French Ministry of Agriculture, although they do not coincide 100% with use, could be used to carry out such a mapping and compare with the estimates. However, these data are not freely available, *i.e.* not published by the Ministry of Agriculture in raw format. Concerning imported feed, Jouven et al. (2018) have mapped the feed self-sufficiency in mass of dry matter at the level of a small agricultural region and at the scale of France. In addition, the SitraM database, which is freely available and lists exports and imports to and from other countries and between departments, specifying the places of origin and destination, could be disaggregated to the level of a small agricultural region in order to produce such a map. This database has already been used to estimate the distances and quantities exchanged in 2006 between 33 French agricultural territories using the AmstraM software developed to operate this database (Le Noë et al., 2016). Secondly, in the Chapter 3 I also explored at the scale of three small agricultural regions the changes in crop and livestock compositions that maximise the food production without inputs. These results represent regional translation of the projections of low –input or no-input agriculture at the European or French scale that reduce environmental impact while satisfying the food needs of the population (Billen et al., 2021; Poux and Aubert, 2018; Solagro, 2017). The changes in composition identified only partly converge with those of these prospective studies, given the current distinct crop-grass-livestock compositions of the three farming systems considered (this point is discussed in Chapter 3). Chapter 3 thus confirmed the interest in seeking to develop projections of low-input or no-input farming at the farming system scale, given the high degree of specialisation of farming systems in Europe, more specifically in Western Europe (Rega et al., 2020).

III.1.3 Methodological contributions

This thesis has also made two methodological contributions. The first is the model designed, which is innovative, simple and has a malleable perimeter. This type of model is innovative because it had not yet been designed in the scientific literature to my knowledge. However, this model is close to the biomass flow balance models of a farming system such as GRAFS (Generalized Representation of Agro-Food Systems) (Billen et al., 2014) or GOANIM (Global Organic Agriculture Nutrient Model) (Barbieri et al., 2021) with the major difference that it is dynamic over time. The model is simple, as it consists of few state variables, making it adaptable to complex modes of analysis such as the viability theory (Martin et al., 2011). The small number of state dimensions also allows the number of iterations to be kept to a reasonable level when solving numerically the system of equations. The model has a malleable scope since in its current versions a diversity of objectives (e.g. food production, net GHG emissions, mineral nitrogen surplus), a diversity of forms and combinations of constraints on inputs, and a diversity of driving variables (e.g. crop and livestock compositions, livestock diet) can be considered. The levels of analysis of the model could range from the farm to the country, but with of course very different levels of simplification of reality. The second contribution is to have mobilised several complementary modes of analysis to answer the research questions of this thesis. Indeed, I mobilised two modes of analysis to evaluate different components of resilience: simulation and multi-objective optimisation. Finally, the codes of the different versions of the model used in this thesis and the formats of the input data tables of the model are freely available on the Zenodo repository platform¹¹, thus allowing easy reuse by others.

¹¹ Chapter 2 - <https://doi.org/10.5281/zenodo.6350666>
Chapter 3 - <https://doi.org/10.5281/zenodo.6348065>
Chapter 4 - <https://doi.org/10.5281/zenodo.5727504>

III.2 Methodological reflections

III.2.1 Reflections on the potential for conflicting conclusions

In this thesis, I designed a model to assess the resilience of European farming systems to constraints on input supply related to global peak oil and evaluated different components of this resilience with different modalities of model use (optimization, simulation) and at different scales. The advantages of modelling are to explore the effect of previously unobserved disturbances or to fill a gap in historical data (see General Introduction). In this thesis, the unobserved disturbances or missing data are the constraints on the input supply (synthetic fertilisers and feed) for European farming systems. Nevertheless, modelling has the disadvantage of not being able to consider the complexity of the essential functions of a farming system and the disturbances, as it is a simplification of reality. However, the conclusions of a resilience assessment and the changes to be made to improve the resilience of a farming system could be in conflict depending on the sets of functions and disturbances considered, given that the functions and challenges a farming system is facing are multiple and spatially and temporally heterogeneous. In other words, failure to consider a function or issue could render changes in the farming system to improve its resilience inadequate (Les Greniers d'Abondance, 2020). Conflicting conclusions could lead to difficulties in deciding between changes in farming systems, as is typically the case in life cycle assessments (Bengtsson and Steen, 2000; Grubert, 2017).

In the work of this thesis, I have already identified possible conflicting conclusions depending on the disturbances considered. In Chapter 2, I highlighted that farming systems specialised in extensive ruminant livestock, mostly grass-fed, and therefore not very dependent on synthetic fertilisers and imported feed, were very robust in the short term to a decrease in input supply, in contrast to field crop farming systems. However, Dardonville et al. (2020) showed through a literature review that grassland yields in temperate climates are more impacted by the effects of climate change (especially in the face of increased drought frequency and intensity) than crop yields, suggesting that extensive ruminant farming systems would be less resilient to climate change than field crop farming systems. However, they also showed that this depended on location, *i.e.* biophysical conditions, but also on farming practices (e.g. irrigation, or cultivar selection) and on the climate phenomenon. Thus, making local climate projections seems to be an essential step in estimating the resilience of farming systems to climate change (SIDAM, 2019). In terms of the functions considered, however, I have not identified any conflicting conclusions. In Chapter 4, I showed that changes in practices such as reducing the size of the cattle herd and increasing the share of leguminous areas made it possible to improve food production and the reduction of net GHG emissions, *i.e.* two functions of the farming system, in the face of constraints on the import of inputs.

III.2.2 Reflections on the simulated disturbance scenario

In chapters 1, 2 and 4, I simulated constraints on input supply as a linear decline to zero over 30 years in imported feed and synthetic fertiliser use. This scenario reflects a linear decline in oil production to zero by 2050. If the other fossil fuels (natural gas and coal) follow the same trend, the decrease in net GHG emissions would be $-1.3 \text{ GtCO}_2\text{-e/year}$ and the objective of keeping the increase in the global average temperature below 1.5°C , set following the Paris climate agreement, would be respected (Evans, 2021; Keyßer and Lenzen, 2021). I thus simulated an optimistic climate scenario compared to the scenarios present in the literature, from the family of zero net emissions scenarios in 2050, because national climate action plans currently only envisage a 25% reduction in fossil fuel consumption by 2050, whereas a 75% reduction in fossil fuel consumption is at least necessary by 2050 in order to respect the 1.5°C target (IEA, 2021; Roelfsema et al., 2020).

Moreover, the simulated scenario also did not consider the use of carbon capture and storage (CCS) technologies, unlike the majority of climate scenarios (Bennett et al., 2017; IEA, 2021). These technologies make it possible to compensate for the CO_2 emissions linked to the combustion of fossil fuels and therefore to maintain partially fossil fuel consumption. For example, the International Energy Agency projects CCS use of around $7.5 \text{ GtCO}_2\text{-e/year}$ in 2050 in the zero net emissions scenario (IEA, 2021). These CCS technologies would therefore allow for the maintenance of oil consumption in agriculture for producing synthetic fertilisers, and by growing energy crops to feed the CCS plants (BECCS). However, concerns remain about operational safety, the long-term integrity of carbon storage, and the technical and economic feasibility of deploying these technologies on a large scale in time (IPCC and Edenhofer, 2014). Furthermore, the sustainability and precautionary threshold for the use of BECCS would be lower than projected in the Paris climate agreement (between 0.5 and $5 \text{ GtCO}_2\text{-e/year}$ or less than 100 Mha of energy crops) due to collateral effects on biodiversity, livelihoods and inter-temporal carbon balances (Creutzig et al., 2021). Moreover, the future use of fossil fuels in agriculture is questionable since energy neutrality of agriculture is possible, with surplus production for export or other uses than food (Harchaoui and Chatzimpiros, 2018) and agriculture was energy neutral before the modernisation of practices (Harchaoui and Chatzimpiros, 2019). Crop residues (and crops) can be used to feed draught animals or to produce biofuels for tractors and transport and input production, while crop residues and livestock manure introduced into a digester can produce methane which can be used as fuel (for a compressed gas engine) or as a raw material for synthetic nitrogen fertiliser.

The perturbation scenario simulated was a linear decrease over 30 years (until 2050) to zero in feed imports and synthetic fertiliser use. I have shown that this perturbation scenario, with or without changes in practices and compositions, would lead to a decrease in food productivity in the studied farming systems but that the protein needs of their local populations, considered constant, would be met. With a nitrogen approach, Billen et al. (2021), Morais et al. (2021) and Poux and Aubert (2018) have shown that it is possible to feed the European or world population with almost no input supply with changes in practices and compositions, while Barbieri et al. (2021), with an energy approach (*i.e.* in calories), showed that it is not possible to feed the world population with no feed import and synthetic fertiliser use with changes in practices and compositions. These studies took into account the impact of reduced mineral nitrogen fertilisation in the absence of synthetic fertilisers on biomass yields (as in this thesis) (Barbieri et al., 2021; Billen et al., 2021a) or calculate the mineral nitrogen balance (Morais et al., 2021; Poux and Aubert, 2018). This difference in conclusion in terms of food self-sufficiency without inputs can be explained both by the approach followed (energy versus nitrogen mass), but is probably mainly due to the increase in legume area considered and the associated biological nitrogen fixation flow, which is much lower in Barbieri et al. (2021) compared to Billen et al. (2021), Morais et al. (2021) and Poux and Aubert (2018).

III.2.3 Reflections on the food production objective

In chapters 1, 2 and 4, I described the robustness of food production trajectories based on objective food production levels that were current levels. However, current levels of food production in European farming systems are boosted by mineral fertilisers and imported feed, and therefore cannot be sustained in the face of input constraints. In other words, food production levels would be lower without these inputs, given the trade-off between food production and input import (results of Chapter 3). I have further shown that the margins for increasing current food production levels without increasing input use or import are small (results of Chapter 3 - Scenario 1). However, lowering food production levels is in fact collectively desirable both to reduce environmental impact (Billen et al., 2018) and to improve robustness (results of chapters 1, 2 and 4), and as long as it meets the food needs of the population it is intended to feed and respects the collective choices of imports and exports, *i.e.* the degree of food self-sufficiency being sought. Thus, the target level of food production could be estimated as the minimum food production needed to feed a defined population and satisfy the export and import choices.

The methodological challenge is then to determine the target population and its food needs. The target population is determined by the chosen spatial extent, *i.e.* the spatial extent to which food self-sufficiency is desired. And the food needs of the population depend on the size of the population and the approach chosen, *i.e.* per food item (“plate”) or total, and energy, dry or fresh mass, nutrient mass (e.g. protein, carbohydrate) or even surface area. The approach in this thesis was total and mass of nitrogen. Among the studies that project changes in agricultural practices and compositions, on a French, European or global scale, that allow for a reduction in environmental impact while satisfying the food needs of the population, Billen et al. (2021), Poux and Aubert (2018) et Solagro (2017) have adopted a plate approach, unlike Barbieri et al. (2021). Billen et al. (2021) et Poux and Aubert (2018) have accounted for in nitrogen mass, Barbieri et al. (2021) in energy and Solagro (2017) in mass of fresh matter. Faced with the methodological challenge of defining the spatial extent to which food self-sufficiency is desired, the CRATer tool (Calculateur de résilience alimentaire des territoires) developed by the association Les Greniers d'Abondance explores the adequacy between food production and food needs using a plate approach and a surface approach, and presents the results at different administrative levels: from the municipality to the region via the group of municipalities and the department. This tool thus makes it possible to navigate between the levels to identify production deficits in relation to needs according to the food item. Moreover, the methodological challenge of determining the target population and its food needs may be even more important when considering the spatial and temporal dynamics of populations. Constraints on the input supply related to global peak oil would have implications for the viability of urban living and consequently for the population density in urban areas, and would thus impact on the target level of food production in an administrative territory.

In the context of this thesis, a target level of food production that allows for a decrease in input use or import and satisfies the protein needs (total and nitrogen mass approach) of a defined population, and therefore lower than the current level of food production, could change the conclusions on the robustness of food production. As discussed in Chapter 1, without inputs (*i.e.* after 30 years of simulation in this chapter), the three farming systems would largely satisfy the protein needs of the local population (considering 30% losses at the food system level and a constant population), *i.e.* in the case of a territorial protein autonomy hypothesis, but at the cost of lower food exports. Therefore, with respect to this target, the three farming systems are robust in both the short and long term. Nevertheless, the extensive ruminant farming system would barely satisfy the average annual protein requirement of the French population in 2050 per surface unit, which is equal to about 17.4 kgN/haUAA without inputs (considering 30% losses at the food system level and a constant UAA), *i.e.* in the case of a national protein autonomy hypothesis, and this in the absence of international food exports and imports (this point is discussed in Chapter 2). The lower protein productivity of this farming system is explained by the high share of grassland in the UAA and the presence of ruminant livestock (results of Chapter 1). Livestock has a lower nitrogen use efficiency than crops, and ruminant farms also have a lower nitrogen

use efficiency than monogastric farms (this point is discussed in Chapter 3). The two autonomy hypotheses used to determine the targeted level of food production would also not identify the same level of food shortage at the territorial level. The hypothesis of territorial protein autonomy would identify the most important food shortages for the metropolises. It should be noted that these two hypotheses of autonomy were real at the beginning of the last century, before the modernisation of agriculture (Le Noë et al., 2018; Mazoyer and Roudart, 2002). The modernisation of agriculture was in fact accompanied by an increase in the international exchange of foodstuffs, and thus in the average distance travelled by a foodstuff, but also by a specialisation of farming systems (Mazoyer and Roudart, 2002). It has also been accompanied by an increase in the consumption of proteins, particularly of animal origin (Lassaletta et al., 2014b).

III.2.4 Reflections on model uncertainties

In the designed model, I set most parameter values and initial values of state variables from collected or measured data present in the literature. The literature data used may have been aggregated by the producers from the level of a small agricultural region to the country or may have been for a set of farms in a farming system. I estimated the other part of the parameter values and the initial values of the state variables. More precisely, I calibrated the stocks of active soil organic matter (nitrogen, carbon) of arable land and permanent grassland using the spin-up method, a method that is widely practiced in the soil modelling community (Xia et al., 2012) and which considers these stocks at equilibrium and constant fertilisation and cropping practices in the past. As the model variables are aggregated variables for many farms and therefore over thousands of hectares, the calibration of the parameter values and initial values of the state variables could not be carried out using measured data as this would have required a very large number of measurements.

Both methods of estimating parameter values and initial values of state variables are inherently uncertain. I carried out sensitivity analyses for both fixed and calibrated parameters to assess the impact of these uncertainties on the results of chapters 1 and 4. I did not perform sensitivity analysis in Chapter 2 (simulation mode) due to a large number of iterations given the number of farming systems in France, which is more than 600, nor in Chapter 3 (optimisation mode) due to an equally large number of iterations for each farming system. The results of the sensitivity analyses have shown in chapters 1 and 4 that the uncertainty interval on food production was almost invariant over time.

Using data collected or measured at the farming system scale to set parameters is a first step to reduce uncertainties. In this sense, synthetic nitrogen supply data collected by UNIFA could be used to estimate synthetic fertilizer use rather than inferring this use through typical crop yields that are not available at the small agricultural region scale. In terms of calibration, I could have calibrated the management rate of monogastric and ruminant herds in the first two chapters based on the historical evolution of herds.

To reduce uncertainties, I also modified the version of the model of Chapter 1 in chapters 2 and 3. I mobilised the humification coefficients of the organic soil amendments used by Le Noë et al. (2017), following the prevalence of the immobilisation phenomenon identified in Chapter 1. I used the EFESE livestock data, coming from the Ministry of Agriculture and Food's 2010 communal agricultural census and which was not secreted¹², and replaced the extreme values of the EFESE production coefficients and diet compositions with the national average values. The estimates of the parameter values and initial values of the state variables achieved seem reasonable to me, especially as they led to values of the model's output variables that were consistent with those in the literature (this point was discussed in Chapter 2).

¹² Personal communication from Laurence Puillet, author of this database in the framework of the EFESE project (Therond et al., 2017).

III.3 Research and applications perspectives

The research work carried out during this thesis opens up research perspectives, with or without conceptual development, to complete the answers to the research question of this thesis, to answer other research questions related to that of the thesis, and to shed light on the possible conflicting conclusions mentioned above. The model of this thesis could also be used to assist in the decision making of public policies for farming system transition.

III.3.1 Research perspectives without conceptual development

Without conceptual development, two research perspectives could be pursued to answer the research question of this thesis. Firstly, the sub-objectives of this thesis could be achieved for other European farming systems, e.g. for the other 10 European farming systems¹³ of the SURE-Farm project, which is co-funding the thesis. Nevertheless, I already simulated for the 11 farming systems of the project scenarios of changes in practices and compositions based on the Agri-SSP scenarios (Mitter et al., 2020) in the face of a progressive decline in the availability of imported inputs over 30 years, as part of deliverable 5.5 of the project, which aimed to assess the resilience of farming systems in the future (Accatino et al., 2020, p. 5). These simulations could be published in a journal and then discussed with the other analyses carried out for these European farming systems in the project (including the Bocage Bourbonnais) as part of the integrated resilience assessment. The latter involved, in addition to the simulations with the model of this thesis, in terms of qualitative analyses, workshops and interviews with stakeholders of the farming systems and analysis of grey literature on different topics: risk management, farm demographics, labour force, public policies, and past and future performance, critical thresholds, states and strategies of the farming systems. In terms of quantitative analyses, it consisted only of a modelling approach with different models: a land use optimisation model for the provision of ecosystem services, an agent based model focused on the evolution of farm structures, and based on the economic development of farms (AgriPoliS), the system dynamics focused on the mechanisms of feedback loops. This discussion would help to highlight conflicting conclusions about resilience and the changes needed to increase it.

¹³ The 11th case study of the project is the Bocage Bourbonnais, for which simulations and optimisation were already conducted in this thesis.

Secondly, another way of using the model could be mobilised to measure another component of resilience. For example, one could use the viability theory adapted to controlled dynamic systems. This mode is suitable for models with a state dimension of less than 7 and a control dimension of less than ~10 to have a feasible number of calculations. The viability theory allows to compute the set of initial states (called "viability kernel") of which at least one control trajectory allows to satisfy a set of objectives at each time step and at infinity, possibly facing perturbations (Accatino et al., 2014; Angeon and Bates, 2020; Martin, 2004). It also makes it possible to calculate control trajectories (e.g. changes in the crop-livestock composition) that are viable for states of the viability kernel, *i.e.* that satisfy objectives (e.g. food production) at each time step. Thus, this mode could allow, for example, in the case of so-called 'heavy' control trajectories, to calculate the adaptability of European farming systems when the food production objective is at risk of not being met in the face of input import constraints, *i.e.* the number of viable control sets (of changes in livestock and crop composition) at each time step where the viability of the system is threatened. A 'heavy' control trajectory is one where controls are kept constant as long as viability is not threatened (Aubin et al., 2011).

III.3.2 Research perspectives with conceptual development

With conceptual development, I identified 10 further research questions related to the main research question of the thesis, which to my knowledge have not been answered so far. These research perspectives and their research questions are listed in Table III. 1 and are located in a scheme of the model (Figure III. 1). Below I only detail those perspectives that have not been mentioned in the chapters of this thesis. Those mentioned in the chapters are: (a) Expansion of possible practice changes such as improving nutrient recycling rates in human and animal excreta or improving the efficiency of animal and crop nitrogen use (discussed in Chapter 2); (b) Consideration of land cover changes such as urbanisation of agricultural areas, expansion of agricultural areas onto forest areas, or expansion of crop areas onto permanent grassland areas (discussed in Chapter 3); (c) The addition of the biogeochemical cycle of phosphorus to the model (discussed in Chapter 2); (d) The inclusion of changes in agroecological practices (e.g. cover crops, intercropping, agroforestry, absence of protein concentrates in monogastric diet) (discussed in Chapter 3).

Furthermore, the research work of this thesis, namely the model developed, is already being used as a basis for two PhD theses that use optimisation techniques: Julia Hebbrecht's thesis started in 2020 and Ruizhen Wang's thesis started in 2021. Julia's thesis seeks to optimise biomass allocation as well as feed, manure and crop residue flows between small agricultural regions at the French scale to minimise environmental impacts and to maximise food production. Ruizhen's thesis seeks to optimize livestock diet composition and the livestock composition in terms of species groups to minimize methane emissions and feed-food competition and to maximize animal-sourced food production at the farming system scale.

Table III. 1 Research perspectives with conceptual development for assessing the resilience of European farming systems to constraints on input supply based on the model developed in this thesis.

Research Perspective No.	Conceptual development of the research perspective	Example of a research question (without specifying the robustness of input supply constraints)
Mentioned in the chapters	Consider other changes in practices or compositions such as improvements in nutrient recycling rates in excreta management and in the efficiency of nitrogen use for crops and livestock	What changes contribute most to the robustness of food production and to climate change mitigation?
	Consider structural changes as land cover changes	What impact does urbanisation on agricultural land, expansion of agricultural land at the expense of forests, or expansion of crop land on permanent grassland have on the robustness of food production?
	Add the biogeochemical cycle of phosphorus	How robust is food production to constraints on mineral fertiliser supply?
	Modeling agroecological practices (e.g. cover crops, intercropping, agroforestry, mixed breed herds)	To what extent do changes in agroecological practices contribute to increasing the robustness of food production without changes in composition and structure?
1	Consider other forms and combinations of constraints on input supply	How robust is food production to input supply disruptions?
2	Simulate agricultural transitions (changes in practices and compositions) and vary the start date and speed of these agricultural transitions	What are the impacts of the initial timing and speed of agricultural transitions on the robustness of food production and climate change mitigation?
3	Considering different food production objectives with a plate and multi-nutrient approach and based on the food needs of populations for different spatial extents	What differences are there in terms of robustness of food production depending on the production objective and the nutrients considered?
4	Analyse the spatial covariance of robustness indicators from the model with social, environmental and economic indicators	Are robustness hotspots, hotspots of public ecosystem service supply?
5	Coupled with an economic model	What changes in macroeconomic and accounting rules reduce disruptions to inputs and promote robust food production?
6	Modelling the impact of climate change and fuel supply constraints on crop yields	Faced with constraints on input supply and the consequences of climate change, what agricultural transitions promote robust food production?

(1) We could explore, in simulation mode, the robustness of European farming systems to other forms and combinations of constraints on input supply (feed imports and synthetic fertiliser use). We could simulate supply disruptions rather than gradual decreases in input availability as the global oil peak could also favour disruptions in input supply chains (Kerschner et al., 2013). Moreover, the outbreak of the Russian-Ukrainian military conflict in February 2022 foreshadows this type of disruption, as Russia has decided, following economic sanctions, to stop exporting mineral fertilisers to Europe (~25% of European consumption) (AFP, 2022). European farmers could therefore run out of mineral fertilisers in 2023, which would lead to a significant drop in agricultural production.

(2) The impact of agricultural transition scenarios (changes in practices and compositions) in simulation mode on the robustness of food production and climate change mitigation could be further explored (analyses in Chapter 4). The compositional changes identified in Chapter 3 for the three French farming systems could be mobilised in the scenario that maximises food production while decreasing input use as an end state of an agricultural transition scenario. The exploration could consist in studying the links between transition speed (implementation duration), transition start date, robustness of food production, and climate change mitigation (reduction of net GHG emissions) and would thus make it possible to discuss the interests and disadvantages (in terms of environmental impact and resilience) of making an agricultural transition to input-independent farming systems (import of feed and use of synthetic fertilisers) as soon as possible. The speed of the transition and the starting date of the transition would notably impact the stock of soil organic matter and thus its future contribution to agricultural production.

(3) We could compare the robustness of food production to constraints on input supply under different food production objectives based on the food needs of populations for different spatial extents and with a plate and multi-nutrient approach (see paragraph III.2.3). Food production could be calculated in terms of fresh matter mass and coupled with a table of nutritional composition per food item. The CIQUAL database developed by the French National Agency for Food, Environmental and Occupational Health Safety (ANSES) could for example be used for this coupling (ANSES, 2020). The robustness indicators for food production in Chapter 2 could be explored for different administrative levels, corresponding to different spatial extents of food self-sufficiency (small agricultural region, department, region), for nutrients other than protein (e.g. carbohydrates, vitamins, fibre). The differences could be compared according to the nutrient or set of nutrients considered and according to the spatial extent. Using the CRATer tool of the Greniers d'Abondance association, which allows to explore the adequacy between food production and food needs at different administrative levels, I assume that the differences in terms of robustness of food production for a farming system according to spatial extent will be significant.

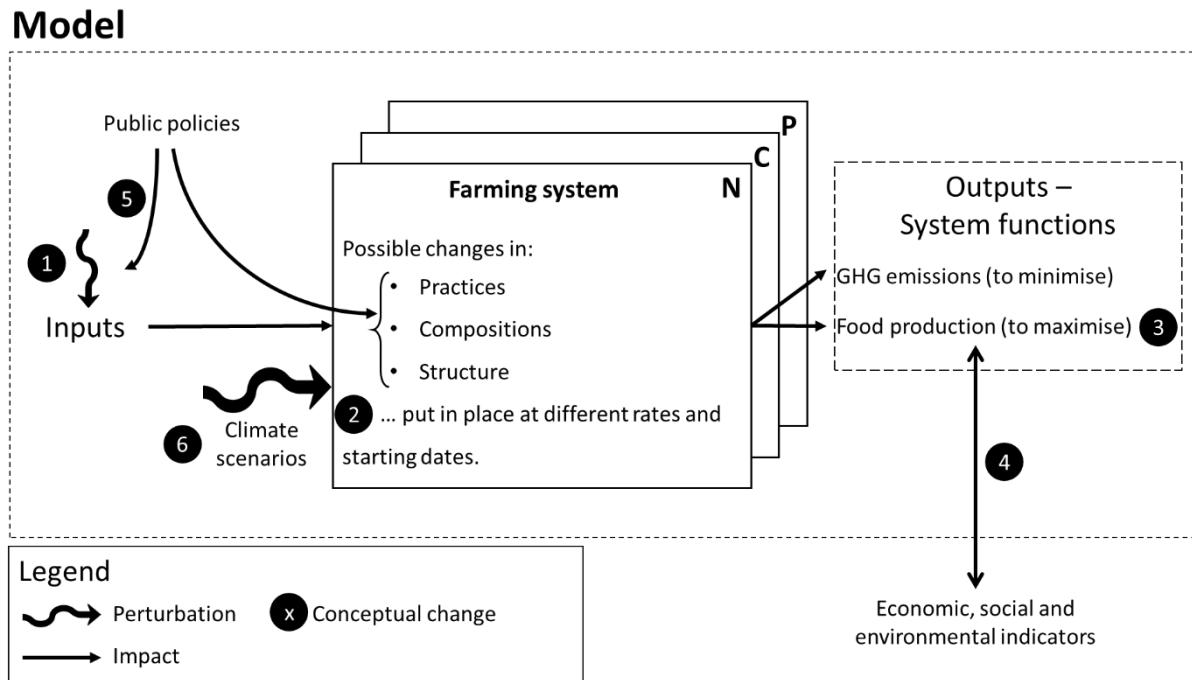


Figure III. 1 Scheme of some research perspectives for assessing the resilience of farming systems to input supply or climatic constraints based on the model designed in this thesis with conceptual development. The numbers correspond to the research perspectives listed in Table III. 1.

(4) The robustness indicators developed in this thesis (robustness window and robustness intensity) could be incorporated from modelling at large scales (national, regional) into statistical analyses of various dimensions of farming systems (social, economic, environmental). This perspective would fill in the absence in the versions of the model in this thesis of estimation of socio-economic indicators or, for example, modelling of the impact of agricultural practices on wild biodiversity. One could, for example, explore the spatial covariance at the French scale and at the level of a small agricultural region between the two indicators of robustness of food production from Chapter 2 and indicators of ecosystem services from the Joint Research Centre in order to identify hot spots or cold spots in terms of robustness and supply of public ecosystem services (Maes et al., 2016).

(5) The mechanisms that cause disruptions to input supplies could be explored to identify actions that reduce disruptions and thus increase the robustness of food production. To achieve this, coupling to a macro-economic and accounting model is necessary. Indeed, constraints on production and input supply can be linked only to decreases in the economic net return of actors in the input supply chain under current macroeconomic rules (energy and commodity price increases disconnected from reserves), while there is no shortage of energy and commodity resources to meet demand. Changes in macroeconomic rules are thus necessary to limit the increase in input prices and to allow farms economic access to inputs on a continuous basis, particularly in the face of shortages of energy and raw materials (supply deficit compared to demand). In the event of resource shortages, these rule changes must be rapid to prioritise

farming systems and allow them economic access. However, the economic and food crises of the last two decades showed the absence of rule changes, quickly or not, to avoid rising input and food prices (Naylor and Falcon, 2010). Thus, coupling the model of this thesis to an economic model would allow to detail the economic mechanisms of input pricing and input availability on markets and to explore public policies (macroeconomic and accounting rule changes) that decrease the disruption of input supply for European farming systems in the case of a global oil peak and thus promote the robustness of food production. This exploration could be combined with the exploration of changes in farming systems practices and compositions that promote the robustness of agricultural production to disturbances but also mitigate climate change.

(6) The robustness of food production to constraints on fuel supply and climate change could be explored in addition to constraints on the supply of synthetic fertilisers and feed as these constraints could occur simultaneously. To achieve this, the relationship between crop yields and fuel use will need to be modelled. The impact of different agricultural activities (e.g. sowing, ploughing, mowing, harvesting, application of plant protection products, application of organic amendments) on yield could be described mechanistically. This mechanistic relationship would require data on technical route per crop to calibrate the parameters. Constraints on fuel supply would impact on the performance of agricultural activities due to the lack of sufficient fuel for tractors and consequently on crop yields. To take into account the climatic scenarios, one could simulate with the help of an air-soil-plant model with daily time steps such as CERES (Kang et al., 2009) the evolution of crop yields with maximum mineral nitrogen input for different climate scenarios by 2050, and use these target yield trajectories per crop in the model of this thesis in simulation mode. This would allow us to explore the robustness of European farming systems according to changes in practices and composition for coupled climate and energy scenarios.

III.3.3 Applications perspectives

The model developed in this thesis and the prospective analyses of the robustness of food production carried out could be mobilised to raise the awareness of farming system stakeholders or even serve as a tool to help to develop public policies. To promote its appropriation in the context of these two objectives, the model or the model's results could be integrated into an application that would make it possible to simulate or optimise agricultural transitions, *i.e.* changes in practices, compositions or structure according to the disturbances considered and their forms, and to display the impact of these transitions on the functions of the system, and the resilience of the functions. First, this application could accompany participatory workshops with stakeholders of a farming system which aim would be to compare the changes envisaged and effects expected by these stakeholders with the modelled effects of these changes. For example, it could complement the SURE-Farm project's FoPIA 2 workshop (Framework Of Participatory Impact Assessment), which aims to assess the future resilience of farming systems based on the perceptions of stakeholders (Paas and Reidsma, 2020) or the workshop developed by Antier et al. (2018) which aims to create favourable conditions for an agroecological transition process by creating a shared framework that combines recognition of the diversity of production systems, ambitious long-term objectives and the integration of the vision of a majority of stakeholders. Second, the application could be a semi-qualitative basis for reflection to contribute to the development of public policies such as the territorial food projects (*Plans Alimentaires Territoriaux* in French - PAT) in France, which consist of the agricultural and food diagnosis of a territory and the development of a strategic and operational framework for partnership actions in a shared manner between the actors of the territory (Ministère de l'Agriculture et de l'Alimentation, 2018). The use of such awareness-raising or design tools is recommended by the national network of territorial food projects (RnPAT) (OnPAT, 2021). The RnPAT recommends, for example, using the CRATer tool from the Greniers d'Abondance association, which is accessible in the form of a web application, to raise the awareness of stakeholders of farming systems within the framework of a PAT (OnPAT, 2021).

IV General conclusion

European agriculture is currently dependent on fossil fuels, both for the transport of feed and for the synthesis of nitrogen fertilisers. However, peak oil could be reached by 2030 and lead to a rise in the price of oil and related commodities, especially as most fossil fuels are imported from abroad. This price increase would reduce farmers' ability to purchase agricultural inputs. Moreover, geopolitical crises could lead to disruptions in the supply of these inputs. Thus, the capacity of European farming systems to maintain food production in the face of this challenge, *i.e.* their resilience, is questioned. The objective of this thesis was to assess the resilience of European farming systems to constraints on the import of inputs (synthetic fertilisers and feed) linked to the global peak oil. To answer this question, I adopted a modelling approach, as this is rare in the literature on the resilience of farming systems and important constraints on input imports have not been observed until now, and developed a dynamic nitrogen flow macro model of a farming system. I explored this model for farming systems with distinct crop-livestock compositions in France and Portugal. I explored two components of the resilience of farming systems with two modalities of using the model: (1) robustness, *i.e.* their capacity to maintain food production in the face of a progressive decline in input imports over 30 years, in simulation mode, and (2) and adaptability potential, *i.e.* the changes in crop-livestock compositions that can be envisaged to increase robustness, in multi-objective optimisation mode.

I have estimated, in simulation mode, the dependence of these farming systems on synthetic nitrogen fertilizers and imported feed. Although heterogeneous, the dependence in France is high in median, and consequently a decrease in input imports to zero in 30 years led to a decrease of more than 70% of the food production in median without changes in the crop composition. Consequently, this decrease would not be sufficient to meet the future protein needs of the French population without increasing food imports. Changes in crop-livestock composition are therefore necessary without these inputs to meet future needs, *i.e.* to increase robustness or to maximise food production. I have then found, in optimisation mode, for three French farming systems that the decrease in livestock and the increase in food crop area, *i.e.* the decrease in feed-food competition for biomass use, contributed to this. However, I did not identify a significant and unequivocal increase in the legume area, which is the only natural source of new nitrogen molecules in a farming system, due to the constraints inherent in the optimisation process and the sharp decline in livestock numbers. Finally, these changes in composition or practices that improve robustness to constraints on input imports could compromise climate change mitigation. I confirmed this trade-off in a Portuguese farming system (extensive beef cattle farms) between robustness of animal-sourced food production and net greenhouse gas emissions. However, agro-ecological practices including the increase of biodiverse sown permanent pastures rich in legumes mitigated this trade-off.

Thus, the agroecological changes in composition and practices identified in this thesis should be implemented as soon as possible to increase the resilience of these European farming systems to constraints on input imports. However, it is clear that their implementation would involve technical and socio-economic changes within the food system, which are sources of lock-in, and therefore cannot be implemented overnight. These socio-technical lock-ins include, for example, the inertia of changes in eating and consumption habits, the inertia of genetic progress for legume seeds, the concentration of actors upstream or downstream of agricultural production, or the creation or disappearance of processing sectors (Atelier paysan, 2021; Meynard et al., 2018). Nevertheless, many levers exist to lift these lock-ins at different levels of farming systems. Changes in public policies (such as the Common Agricultural Policy) at scales higher than that of the farming system, such as the national or regional scale, is however necessary to remove many of them (Fouilleux, 2015). And specifically concerning changes in diets, changes in composition and practices would be all the more successful in satisfying the future protein needs of Europeans, *i.e.* avoiding an increase in food imports, as these needs will adapt (notably by decreasing the share of animal proteins) and decrease to follow the nutritional recommendations of national and international health organisations (Billen et al., 2021a; Morais et al., 2021).

Finally, this thesis has shown the interest in assessing, notably in a quantitative manner and a dynamic modelling approach, the robustness of European farming systems to the consequences of global peak oil, and moreover, complements environmental assessments that explore changes in the composition and practices of farming systems that aim to reduce their environmental impact (e.g. climate change, water quality). It paves the way for assessing resilience to the consequences of global peak oil and could, in its current state, be a tool for raising awareness among elected representatives and other stakeholders in farming systems about the threats of global peak oil and the solutions that exist. Nevertheless, the quantitative assessment of resilience carried out in this thesis and therefore the conclusions drawn are by nature incomplete, as it could not consider the multiple challenges and disturbances that European farming systems face but also their multiple functions. The conclusions drawn could therefore be contradictory for other perturbations and functions. I have suggested that this could be the case for extensive ruminant farming systems in the face of peak oil and climate change. Thus, the assessment carried out in this thesis should be pursued by considering the diversity of functions of a farming system but also of disturbances to highlight these possible contradictions. The completion of the resilience assessment of European farming systems to the challenges they face will, in my opinion, require the use of quantitative and qualitative assessments, as was the case in the European project SURE-Farm which co-funded this thesis. However, given the magnitude of the task, and the limited time horizon for carrying it out, the assessment should be carried out in concert by groups of experts and public and private stakeholders in each farming system, region and country (a multi-scale approach seems to me to be essential), rather than solely within research projects, in order to be as complete and as rapid as possible. Indeed, concerning disruptions related to dependence on fossil fuels and related commodities,

perturbations simulated in this thesis could occur earlier and faster, and constitute ad hoc supply disruptions, as the outbreak of the Russian-Ukrainian military conflict in February 2022 foreshadows. Indeed, this conflict has aggravated the increase in gas prices (linked until then to a deficit in Russian gas supply), pushing European fertiliser production plants to stop or slow down and contributing to the explosion in fertiliser prices (AFP, 2022). Moreover, Europe currently imports 25% of its mineral fertilisers from Russia, which decided to stop production following European economic sanctions after Russia's invasion of Ukraine. This context threatens, without significant alternative sources of gas and fertiliser, the possibility of satisfying the fertiliser needs of European farmers by 2023 and will most likely lead to a decrease in food production and to food riots in the countries importing the European overproduction. However, one positive collateral effect of this context is that it could make public and private actors in European farming systems aware of the risks of international energy and input dependency of European agriculture (Poinssot, 2022). Finally, the implementation of such resilience assessment programme in European farming systems could perhaps also contribute to avoiding the resilience concept, especially when the scope (resilience “from what to what”) is not clearly defined or made explicit, to be mobilised for political purposes to “justify the order of things”, *i.e.* that it falls into ideology to maintain the status quo and face the reality of the threats and degradations that faces European agriculture (Ribault, 2021).

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Appendix 1 Supplementary Material of Chapter 1

SM1.1 Material and methods

SM1.1.1 Soil compartments

SM1.1.1.1 Mineral nitrogen flows and loss

The mineral nitrogen effectively available for plant uptake ($f_{i,t+1}^{A,C}$ and $f_{i,t+1}^{A,G}$) corresponds to the quantity of soil mineral nitrogen ($f_{i,t+1}^C$ and $f_{i,t+1}^G$) reduced by the emissions and enriched by the atmospheric nitrogen fixed by legumes, if applicable (Equations (SM1-1) and (SM1-2)). Emission factors ($\epsilon^{L,APP}$, $\epsilon^{N_2O,APP}$ and $\epsilon^{N_2O,SM}$ [-]) are fixed coefficients representing leaching, and nitrous oxide emissions from applications and from effluent management, respectively. Emission factors ($\epsilon^{V,ORG}$ and $\epsilon^{V,SYN}$ [-]) correspond to the volatilisation of organic amendments and synthetic fertilisers, respectively. The term $\psi_{i,t}$ corresponds to biological nitrogen fixation, which is non-null only for the plants of the *Fabaceae* family.

$$f_{i,t+1}^{A,C} = f_{i,t+1}^C * (1 - \epsilon^{L,APP} - \epsilon^{N_2O,APP} - \epsilon^{N_2O,SM}) - [\check{\epsilon}^H + \check{\epsilon}^{L^B} + \check{\gamma}_t^{A,C} * (1 - (\xi_{EXP} * \xi_{FSS,t})) + \check{\gamma}_t^{R,C}] * \epsilon^{V,ORG} - s_{i,t+1} * \epsilon^{V,SYN} + \psi_{i,t+1} \quad (SM1-1)$$

$$f_{i,t+1}^{A,G} = f_{i,t+1}^G * (1 - \epsilon^{L,APP} - \epsilon^{N_2O,APP} - \epsilon^{N_2O,SM}) - [\check{\epsilon}_t^{L^G} + \check{\gamma}_t^{A,G} + \check{\gamma}_t^{R,G}] * \epsilon^{V,ORG} - s_{i,t+1} * \epsilon^{V,SYN} + \psi_{i,t+1} \quad (SM1-2)$$

SM1.1.1.2 Immobilisation flow

When organic amendments are applied to soil, the humification process of these amendments may immobilise nitrogen from the mineralisation flow of the soil organic matter. In other words, the immobilised nitrogen return to the soil organic matter during this process. The immobilisation flow ($i_{t+1}^{M,C}$ and $i_{t+1}^{M,G}$) is thus computed as the maximum between zero and the difference between the quantity of nitrogen needed to humify the organic amendments and the total quantity of organic nitrogen in the organic amendments. For example, for cropland aerial residues, the nitrogen needed to humify the applied aerial residues is equal to: $\hat{R}_t^{A,C,Hum} = \sum_i (R_{i,t}^{A,C} * (1 - (\xi_{EXP} * \xi_{FSS,t})) * \phi_i^{R,A,C} * \frac{CN_i^{R,A,C}}{CN_{soil}^C})$.

SM1.1.2 Plant compartments

Each crop or grazed grass (i) is assigned a set of traits: area (A_i [ha]), fresh matter yield of the harvested or grazed organ ($y_{i,t}$ [kg/ha]), harvest index (HI_i [-]), ratio of above-ground biomass to root biomass (SR_i [-]), nitrogen contents of the harvested or grazed organ (σ_i^H [kg/kg fresh matter]), the root residues (σ_i^{RR}), and the aerial residues (σ_i^{RA}). HI_i , SR_i and σ_i are constant over time and are independent from the yield. All these coefficients make it possible to calculate the nitrogen in plant production.

SM1.1.2.1 Plant yield

For each plant (i), the harvested or grazed organ yield ($y_{i,t}$ [kg/ha], the quantity of biomass harvested or grazed from the edible parts of the plants in fresh matter), is a piece-wise linear function of the available soil mineral nitrogen ($f_{i,t}^A$) that saturates at a constant maximum yield value (y_i^{MAX}) (Equation (SM1-3) below).

$$y_{i,t} = \begin{cases} \delta_i * f_{i,t}^A & , \text{if } f_{i,t}^A < b_i^P \\ y_i^{MAX} & , \text{otherwise} \end{cases} \quad (SM1-3)$$

The nitrogen need (b_i^P) of a crop or grazed grass (i) corresponds to the quantity of nitrogen in the different parts of a plant for the maximum yield of the harvested organ (y_i^{MAX}).

The slope of this relationship in Equation (SM1-3) before saturation (δ_i) is specific to each plant and depends on the nitrogen needs at the maximum yield.

SM1.1.2.2 Plant and residue production

Based on the AMG model (Clivot et al., 2019), the total quantity of nitrogen of the harvested or grazed organ ($H_{i,t}$) is obtained through the nitrogen content of the harvested or grazed organ (σ_i^H , $H_{i,t} = y_{i,t} * A_i * \sigma_i^H$). Plant residues nitrogen quantity is a function of the fresh matter harvested organ yield ($y_{i,t}$), the harvest index (HI_i), the aerial to root biomass ratio (SR_i), and the residue nitrogen content (σ_i^R): above-ground residues are equal to $R_{i,t}^A = y_{i,t} * A_i * \sigma_i^{RA} * \frac{1-HI_i}{HI_i}$, and root residues are equal to $R_{i,t}^R = y_{i,t} * A_i * 1.65 * \sigma_i^{RR} * \frac{1}{SR_i * HI_i}$. The coefficient 1.65 in the root residue equation accounts for extra root production.

SM1.1.2.3 *Repartition of harvested biomass*

For cropland, the nitrogen content of the harvested organ ($H_{i,t}$) is allocated, by means of repartition coefficients [-], to different destinations: direct human consumption (v^{HH}), feed (v^{HL}), industrial use (v^{HI} , e.g., biofuels), seed stocks (v^{HS}), or processing (v^{HT} , e.g., soybeans). The processed crops are then partially conveyed for human (v^{TH}) or livestock consumption (v^{TLO} and v^{TLM}) in the forms of co-products and meals.

SM1.1.3 **Livestock compartment**

SM1.1.3.1 *Feed*

The locally available quantity ($A_{j,k,t}^{FEED,LOC}$) of a feed category (k) to a livestock species (j) is given by $A_{j,k,t}^{FEED,LOC} = \left(\sum_{i \in \Gamma_k} H_{i,t} * v_i^{HL} + \sum_{i \in \Lambda_k} H_{i,t} * (v_i^{TLO} + v_i^{TLM}) \right) * \alpha_{j,k,t}$, with $\alpha_{j,k,t}$ being the ratio between the individual annual feed needs ($\beta_{j,k,t}$) and the total annual feed needs ($\beta_{k,t}$) of all the species for the feed category (k). Γ_k and Λ_k represent groups of plants with a harvested or grazed organ or a transformed crop that is allocated as feed category (k).

For a feed category (k) and all the species, if the total availability ($A_{k,t}^{FEED,TOT}$) is higher than the need ($B_{k,t}^L$), then there is no feed shortage and the FS has a surplus of the feed category.

The feed shortage ($M_{j,t}$) per species (j [kg]) corresponds to the feed shortage sum of all the feed categories ($M_{j,t} = \sum_k M_{j,k,t}$).

SM1.1.3.2 *Livestock population dynamics and animal-sourced food production*

The management rate ($\tau_{j,t+1}^M$) for a species (j) is a decreasing function of the feed shortage ($M_{j,t+1}$) (see Equation (SM1-4) below). If a feed shortage is equal to or higher than a threshold (T), the management rate is negative and is a linear decreasing function of the feed shortage ($M_{j,t+1}$), reflecting the decision of the farmer to decrease the herd size. If a feed shortage is smaller than T , the management rate is equal to a nominal value (T_j^M).

$$\tau_{j,t+1}^M = \begin{cases} T_j^M, & \text{if } M_{j,t+1} < T \\ -M_{j,t+1}, & \text{if } M_{j,t+1} \geq T \end{cases} \quad (SM1-4)$$

If a feed shortage ($M_{j,t}$) is less than a threshold (T), the animal-sourced food production coefficients decrease proportionally. If a feed shortage is more than a threshold (T), the slaughter of livestock leads to a proportional increase in meat production.

SM1.1.3.3 Livestock effluent

The ratio between the quantity of grazed grass ($B_{j,gg,t}$) and the total quantity of feed consumed ($B_{j,t}$) determines the quantity of effluents on permanent grassland per species (j).

Excretions from housing facilities are stored and mixed with exported aerial residues from livestock bedding before being applied to crops. These phases of excretion in housing facilities and storage result in emissions of ammonia by volatilisation ($\epsilon^{V,B}$ and $\epsilon^{V,S}$ [-]), nitrous oxide by denitrification (ϵ^{N_2O} [-]) and leaching losses (ϵ^L [-]) (see Equation (SM1-5) below).

$$E_t^{L^B} = E_t^L - E_t^{L^G} = \left(\sum_j \left(\sum_k \beta_{j,k,t} * L_{j,t} - \sum_t P_{j,t}^L \right) * \left(1 - \frac{B_{j,gg,t}}{\sum_k B_{j,k,t}} \right) + (\xi_{EXP} * \xi_{FSS,t}) * R_t^{A,C} \right) * (1 - \epsilon^{V,B} - ((1 - \epsilon^{V,B}) * \epsilon^{V,S}) - \epsilon^{N_2O} - \epsilon^L). \quad (SM1-5)$$

The share ($\xi_{FSS,t}$) corresponds to the total feed sufficiency of the FS (*i.e.*, the total needs B_t^L divided by the total availability of feed $A_t^{FEED,TOT}$).

Table SM1. 1 Description of model parameters and nominal values.

Parameter or variable name	Notation	Unit	Source	Nominal value ¹
Harvested biomass to humans	$v_i^{H^H}$	%	(Therond et al., 2017)	SM
Harvested biomass to livestock	$v_i^{H^A}$	%	(Therond et al., 2017)	SM
Harvested biomass to industry	$v_i^{H^I}$	%	(Therond et al., 2017)	SM
Harvested biomass used the year after for sowing	$v_i^{H^S}$	%	(Therond et al., 2017)	SM
Harvested biomass to transformation	$v_i^{H^T}$	%	(Therond et al., 2017)	SM
Harvested biomass transformed to humans	$v_i^{T^H}$	%	(Therond et al., 2017)	SM
Harvested biomass transformed to livestock as oil	$v_i^{T^{LO}}$	%	(Therond et al., 2017)	SM
Harvested biomass transformed to livestock as meal	$v_i^{T^{LM}}$	%	(Therond et al., 2017)	SM
Harvested biomass transformed to industry	$v_i^{T^I}$	%	(Therond et al., 2017)	SM
Humification factor – Human effluent	Φ^H	%	(Fuchs et al., 2014)	40
Humification factor – Livestock effluent	$\Phi_j^{L^B}$	%	(Fuchs et al., 2014)	SM
Humification factor – Aerial residues	$\Phi_i^{R^A}$	%	(Fuchs et al., 2014)	SM
Humification factor – Root residues	$\Phi_i^{R^R}$	%	(Fuchs et al., 2014)	SM
C:N ratio – Human effluent	CN^H	-	(Fuchs et al., 2014)	10
C:N ratio – Livestock effluent	$CN_j^{L^B}$	-	(Fuchs et al., 2014)	SM
C:N ratio – Aerial residues	$CN_i^{R^A}$	-	(Fuchs et al., 2014)	SM
C:N ratio – Root residues	$CN_i^{R^R}$	-	(Fuchs et al., 2014)	SM
Emission factors – Volatilisation during storage of housing facilities effluents	ϵ^{V^S}	%	(Service de l'observation et des statistiques, 2013)	5
Emission factors – Volatilisation during excretion of effluents in housing facilities	ϵ^{V^B}	%	(Service de l'observation et des statistiques, 2013)	30
Emission factors – N ₂ O emissions of effluents in housing facilities and during storage	$\epsilon^{N_{2o}}$	%	(Service de l'observation et des statistiques, 2013)	1
Emission factors – Leaching of effluents during excretion and storage in housing facilities	ϵ^L	%	(IPCC, 2019)	10
Emission factors – N ₂ O emissions due to soil management	$\epsilon^{N_{2o,SM}}$	%	Based on (IPCC et al., 2006, p. 1) fixed value	3
Emission factors – Soil mineral nitrogen lixiviation	$\epsilon^{L,APP}$	%	(Lin et al., 2001)	20
Emission factors – N ₂ O emissions of synthetic fertilisers application	$\epsilon^{N_{2o,APP}}$	%	(IPCC et al., 2006, p. 1)	1
Emission factors – Volatilisation of organic fertilisers application	$\epsilon^{V^{ORG}}$	%	(IPCC et al., 2006, p. 1)	20

Table SM1. 1 (continued).

Parameter or variable name	Notation	Unit	Source	Nominal value ¹
Emission factors – Volatilisation of synthetic fertilisers application	$\epsilon^{V^{SYN}}$	%	(IPCC et al., 2006, p. 1)	10
Mineralisation rate	μ^C, μ^G	%	Estimated based on (Clivot et al., 2019)	SM
C:N ratio of the soil	CN_{soil}^C, CN_{soil}^G	-	(Ballabio et al., 2019)	SM
Shoot-to-root ratio	SR_i	-	(Clivot et al., 2019), (Comifer - Groupe Azote-Soufre, 2013)	SM
Harvest index	HI_i	%	(Clivot et al., 2019), (Comifer - Groupe Azote-Soufre, 2013)	SM
Typical yield	y_i^{TYP}	100kg of fresh /ha	(Ministère de l'Agriculture et de l'Alimentation, 2022)	SM
Area cultivated	A_i	ha	(Ministère de l'Agriculture et de l'Alimentation, 2022)	SM
Biological nitrogen fixation	$\psi_{i,t}$	kg/ha	(Anglade et al., 2015)	SM
Nitrogen content of the harvested organ	σ_i^H	kg/100kg of fresh matter	(IPCC et al., 2006, p. 1), (Clivot et al., 2019), (ANSES, 2020)	SM
Nitrogen content of the aerial residues	σ_i^{RA}	kg/100kg of fresh matter	(IPCC et al., 2006, p. 1), (Clivot et al., 2019),	SM
Nitrogen content of the root residues	σ_i^{RR}	kg/100kg of fresh matter	(IPCC et al., 2006, p. 1), (Clivot et al., 2019),	SM
Share of aerial crop residues exported as livestock bedding	ξ_{EXP}	%	(Harchaoui and Chatzimpiros, 2019)	35
Quantity of human excretion recovered and applied as sludge on field	E^H	kg	INSEE, (Esculier, 2016)	SM
Slope of the relationship between harvested biomass and mineral nitrogen available to the plant	δ_i	-	Computed	SM
Quantity of the feed consumed per livestock unit and per species	$\beta_{j,k,t}$	kg/LU	(Therond et al., 2017)	SM
Meat production coefficient per species	c_j^{MEAT}	kg/LU	(Therond et al., 2017)	SM
Milk production coefficient per species	c_j^{MILK}	kg/LU	(Therond et al., 2017)	SM
Egg production coefficient per species	c_j^{EGG}	kg/LU	(Therond et al., 2017)	SM
Feed shortage threshold beyond which the livestock number is decreased	T	%		10
Atmospheric deposition on soil of NO_x	d	kg/ha	(Norwegian Meteorological Institute, 2020)	10

¹ SM: if a matrix, see supplementary material

SM1.1.4 Parameters

SM1.1.4.1 Soil compartments

The rates of nitrogen mineralisation (μ^C and μ^G) in the soil are estimated from the equations in version 2 of the AMG model (Clivot et al., 2019). This estimate requires biophysical and soil parameter values, which were collected from the Joint Research Centre database (Ballabio et al., 2019, 2016) (see Table SM1. 2 for the metadata). The C:N ratios of agricultural soils are obtained from ESDAC data (Ballabio et al., 2019). Atmospheric deposition (d) is assumed to be equal to 10 kg/ha nitrogen (Norwegian Meteorological Institute, 2020). Emission factors related to soil management are taken from the 2006 IPCC guidelines for soil management (IPCC et al., 2006). The value for $\epsilon^{N2O,SM}$ has been fixed to 0.03, $\epsilon^{L,APP}$ to 0.19, $\epsilon^{N2O,APP}$ to 0.01, $\epsilon^{V,ORG}$ to 0.2, and $\epsilon^{V,SYN}$ to 0.1.

SM1.1.4.2 Plant compartments

Nitrogen contents (σ_i) are taken from the 2006 IPCC guidelines for effluent management (IPCC, 2019), the AMG model for field crops (Clivot et al., 2019), or the CIQUAL ANSES database for fruits and vegetables (ANSES, 2020). The values for SR_i and HI_i come from the AMG model for field crops or have been calibrated manually for fruits and vegetables based on estimates of their nitrogen needs (b_i^{CROP}) and yields provided by the COMIFER association (with a 30% loss assumption) (Comifer - Groupe Azote-Soufre, 2013). Typical fresh matter yield values for the harvested or grazed organ come from the French Statistics and Forecasting Service of the Ministry of Agriculture, Agri-Food and Forestry (AGRESTE) database (Ministère de l'Agriculture et de l'Alimentation, 2022) and correspond to the average values for the years 2018, 2017, and 2016 by department. If there is no value for a plant in the department concerned, the national average value is used. The quantity of nitrogen fixed by nitrogen-fixing plants ($\psi_{i,t}$) is estimated using the coefficients and equation from Anglade et al. (2015) at each time step. We implemented an iterative loop algorithm, as yield is, in turn, a function of biological fixation. The slope of the relationship between the harvested or grazed organ yield and the available mineral nitrogen in the soil (δ_i) per plant (i) is obtained by dividing the maximum yield of the harvested organ (y_i^{MAX}) by the nitrogen needs (b_i^P) to achieve the maximum yield.

The cultivated area of each plant on agricultural land is known from the *Registre Parcellaire Graphique* (RPG) for the year 2016 (IGN, 2016). This composition is on the SAR (Small Agricultural Region – Petite Région Agricole in French) scale and is obtained by intersecting RPG spatial layer with the administrative boundaries of the SAR using QGIS software. The attribute table containing the cultivated areas (A_i) is then aggregated according to the plant classification adopted for this study.

SM1.1.4.3 Livestock compartment

Livestock effluent management emission factors come from the NOPOLU-Agri expertise (Service de l'observation et des statistiques, 2013). These factors vary according to the type of effluent (manure, slurry, or guano for poultry), the emission process, and the type of emission. Although the type of effluent depends on the type of livestock housing facility, only manure emission factors are considered (and not slurry), to remain consistent with our assumption of crop residue exportation. The animal-sourced food production coefficients ($C_{j,t}$) per species are taken from the EFESE expertise and are available by SAR (Therond et al., 2017). The values for the quantity and composition of the feed needs ($\beta_{j,k,t}$) per species and per feed category are also taken from the EFESE expertise and are available by SAR (Therond et al., 2017). The feed shortage threshold T at which the number of livestock is reduced is arbitrarily set at 10%.

SM1.1.4.4 Other

The repartition coefficients of the harvested biomass (v_i) correspond to the values of the EFESE expertise (Table 10-1-2, page 737) (Therond et al., 2017). The values of the humification coefficients (ϕ) according to the type of organic amendments are taken from Figure 3-1-6 of the MAFOR (Matières fertilisantes d'origine résiduaire) expertise (Fuchs et al., 2014). The values of the C:N ratios for organic amendments are also derived from this report. Because it is assumed that 35% of crop residues are exported from the field, the C:N ratios and humification coefficients for livestock effluents correspond to the values for manure.

Unlike livestock, it is assumed that human excretions (E^H) are not related to the quantity of food they ingest. The model assumes that humans excrete 5 kg nitrogen per person, of which only 10% is recycled in a waste-water treatment plant, and only 50% from this 10% is applied to the soil in FS (the rest is incinerated) (Esculier, 2016). The number of inhabitants per SAR is taken from the INSEE municipal data of the 2017 census.

Table SM1. 2 Metadata of the biophysical and soil parameters used to calculate the mineralisation rate of soil organic nitrogen and to obtain the initial soil organic nitrogen content.

Parameter name	Source	Year
Precipitation - sum of daily values [mm]	E-OBS gridded dataset. Available at https://c3surf.knmi.nl/dataaccess/access_eobs.php . Part of the Copernicus Programme by the European Commission.	2014
Temperature - daily average [°C]	E-OBS gridded dataset. Available at https://c3surf.knmi.nl/dataaccess/access_eobs.php . Part of the Copernicus Programme by the European Commission.	2014
Soil organic carbon [tC/ha]	Pan-European SOC stock of agricultural soils. Available at https://esdac.jrc.ec.europa.eu/content/pan-european-soc-stock-agricultural-soils	2010
C:N ratio of the soil [-]	Maps of Soil Chemical properties at European scale based on LUCAS 2009/2012 topsoil data. Available at https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data	2009
pH in soil water [-]	Maps of Soil Chemical properties at European scale based on LUCAS 2009/2012 topsoil data. Available at https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data	2009
CaCO ₃ concentration [g/kg soil]	Maps of Soil Chemical properties at European scale based on LUCAS 2009/2012 topsoil data. Available at https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data	2009
Irrigation [mm]	Annual water abstraction irrigation - Available at https://data.jrc.ec.europa.eu/dataset/02893547-8e38-47f5-b214-5fb8a37d9faa	2006
Potential evapotranspiration [mm]	Potential evapotranspiration (MAPPE model). Available at https://data.europa.eu/euodp/en/data/dataset/jrc-mappe-europe-setup-d-14-potential-evapotranspiration	2002-2006
Clay content [g/kg soil]	Topsoil physical properties for Europe (based on LUCAS topsoil data). Developed by the European Soil Data Center - Joint Research Center. Available at https://esdac.jrc.ec.europa.eu/content/topsoil-physical-properties-europe-based-lucas-topsoil-data	2009

SM1.1.5 Initialisation of model state variables

The total quantities of aerial and root residues (R_0^A and R_0^R) are initialised by setting the initial yield values ($y_{i,0}$) equal to the typical yield values. Head numbers according to species and species class are from the database of the AGRESTE and correspond to the 2010 Census of Agriculture values available for the respective SAR level (Ministère de l'Agriculture et de l'Alimentation, 2022). These head numbers are multiplied by the Eurostat standard livestock unit conversion coefficients to obtain LU values. The average annual LU numbers according to species class are then summed for each species. The quantity of soil organic nitrogen (n_0^C and n_0^G) is initialised using the spin-up method (Xia et al., 2012). This method, conceived for soil carbon dynamics, assumes that the soil stock of active carbon is at equilibrium and is a function of current vegetation and organic amendment practices. In other words, the share of active soil organic carbon is equal to the carbon of the organic flows entering the soil, initially divided by the mineralisation rate. This method has been applied to the equation transposed for nitrogen. The values of organic amendments applied to the soil and used for the spin-up method correspond to the quantity of livestock effluents using the initial number of livestock ($L_{j,0}$) with no feed shortage and crop residues (R_0^A and R_0^R) for maximum crop yield. The phenomenon of mineralised nitrogen immobilisation is considered for this initialisation.

SM1.1.6 Repartition rules implemented in the scenarios

Additional rules have been fixed for determining the nitrogen fertilisation needs per crop and the quantity of synthetic fertiliser applied, based on the needs of each plant and import availability. Variations in livestock diets and the reallocation of feed surplus to humans, if appropriate for human consumption, have also been allowed.

SM1.1.6.1 Nitrogen needs and fertilisation

The nitrogen need (b_i^P) of a plant (i) correspond to the quantity of nitrogen in the different parts of the plant for the maximum yield of the harvested or grazed organ (y_i^{MAX}). It is assumed that the maximum yield (y_i^{MAX}) corresponds to the typical yield (y_i^{TYP}) of the plant in the FS considered. It is also assumed that farmers are able to estimate the need for mineral nitrogen fertilisation (b_i^F [kg/ha]) per plant (i). The need for fertilisation (b_i^F) corresponds to the nitrogen need (b_i^P), considering losses related to the application of fertilisers to the soil. To simplify this estimate, it is considered that volatilisation losses concern all fertilisation flows and that they are worth $\epsilon^{V,SYN}$. The need for mineral nitrogen fertilisation per plant is equal to:

$$b_i^F = \frac{b_i^P - \psi_i}{(1 - \epsilon^{L,APP} - \epsilon^{N_{2O},APP} - \epsilon^{N_{2O},SM} - \epsilon^{V,SYN})}$$

This need for fertilisation is satisfied first by natural flows and then by amendments that are homogeneously applied to the soil. If the fertilisation needs (b_i^F) are not met by the natural flows and organic amendments, synthetic fertiliser ($s_{i,t}$ [kg/ha]) per plant (i) is applied to meet the need for mineral nitrogen fertilisation and to achieve the maximum yield of the plant.

SM1.1.6.2 Synthetic fertiliser application

The synthetic fertiliser need ($b_{i,t+1}^{SYN,C}$ and $b_{i,t+1}^{SYN,G}$ [kg/ha]) per plant (i) are equal to the fertilisation need (b_i^F) minus the natural flows of mineral nitrogen (net mineralisation, biological fixation, and atmospheric deposition) and the share of mineral nitrogen from the organic amendments. The synthetic fertiliser need per plant are equal to:

$$b_{i,t+1}^{SYN,C} = \max\left(b_i^F - \left(\mu^C * n_t^C - i_{t+1}^{M,C} + \check{e}_t^{L^B} + \check{e}_t^H + \check{r}_t^{A,C} * (1 - (\xi_{EXP} * \xi_{FSS,t})) + \check{r}_t^{R,C} + d\right), 0\right)$$

$$b_{i,t+1}^{SYN,G} = \max\left(b_i^F - \left(\mu^G * n_t^G - i_{t+1}^{M,G} + \check{e}_t^{L^G} + \check{r}_t^{A,G} + \check{r}_t^{R,G} + d\right), 0\right)$$

As synthetic fertilisers are imported, the minimum quantity based on the total synthetic fertiliser needs of the crops (B_{t+1}^{SYN} [kg]) and the quantity available for import (S_{t+1}^A [kg]) is applied to the crops

requiring synthetic fertilisation. The quantity of synthetic fertilisers available for import (S_{t+1}^A) is then applied in proportion to the needs ($B_{i,t+1}^{SYN}$) per plant (i) over the total needs of all the crops (B_{t+1}^{SYN}). This makes it possible to estimate the total quantity of synthetic fertilisers ($S_{i,t+1}$) applied to each crop (i):

$$S_{i,t+1} = \frac{B_{i,t+1}^{SYN}}{B_{t+1}^{SYN}} * S_{t+1}.$$

SM1.1.6.3 Feed

The feed need of a species (j) in a feed category (k) ($B_{j,k,t}^L$) is satisfied primarily by local plant production for the livestock ($A_{j,k,t}^{FEED,LOC}$) and then by the quantity of feed available for import ($I_{j,k,t}^A$ [kg]). The quantity of feed finally imported ($I_{j,k,t}$) corresponds to the minimum quantity based on the needs for imported feed and the quantity available for import ($I_{j,k,t}^A$).

Some feed categories can be substituted in pairs for a species (*i.e.*, there are constant individual feed needs ($\gamma_{j,l}^L$) per species (j) and feed pair (l) over time). Within a feed pair (l), the total quantity of feed available ($A_{j,k,t}^{FEED,TOT}$) of the first category (k) takes priority over the local plant production ($A_{j,k,t}^{FEED,LOC}$) of the other. Thus, locally produced and importable co-products, meals and grazing grass are consumed in priority to cereals, oil-protein crops and fodder respectively. Indeed, grazing grass cannot be imported.

SM1.1.6.4 Repartition of unconsumed feed to humans

The repartition coefficients of the harvested or grazed biomass are fixed and uncalibrated (except for the grazing grass-cultivated forage pair). As a result, this generates an over- or under-estimation of the actual local biomass allocated to livestock, and thus either a surplus or a shortage. In the case of a surplus, if the feed is edible by humans (cereals, oil-protein crops), it is reallocated for human consumption. This reallocation is carried out a posteriori after calculating the livestock feed needs based on the local and import availabilities. In the event of a shortage, this is supplemented by the feed import.

SM1.2 Results

SM1.2.1 Initial feed self-sufficiency and surplus

The livestock numbers and local feed production determine the feed self-sufficiency shares of the FS and provide information on possible sources (feed categories) and the extent of feed shortages. Feed self-sufficiency is calculated by dividing the local availability of feed for a feed category by the feed needs for that feed category. This calculation also reveals a feed surplus if the local production of livestock in a feed category exceeds the livestock needs for that category. The feed self-sufficiency and surplus values are consistent with the classification by Jouven et al. (2018). Only the intensive monogastric FS has a need for imported cereals and oil-protein crops for livestock (Table SM1. 3). However, the two crop-livestock FS depend on the import of meals (96% for the intensive monogastric FS and 78% for the extensive ruminant FS). The extensive ruminant FS is up to 67% self-sufficient on fodder. Finally, the field crops FS has a co-products self-sufficiency of 15%. The field crops FS provides a surplus of more than 20 times the need for cereals and meals and more than two times the need for oil-protein seeds. Likewise, the intensive monogastric FS provides a surplus of about two times the need for fodder, and the extensive ruminant system provides a surplus of three times the need for cereals.

Table SM1. 3 Initial feed self-sufficiency and surplus percentages from local plant production according to feed category and FS in the three scenarios for the nominal parameter set.

Farming system	Feed category					
	Cereals	Grass	Co-products	Fodder	Oil-protein	Meals
Extensive ruminants	320%	100%	No need	67%	105%	22%
Intensive monogastrics	61%	100%	No need	176%	23%	4%
Field crops	3027%	100%	15%	121%	2019%	218%

SM1.3 Correspondence tables

Table SM1. 4 Plants to feed categories

Plant name	Plant ID	Feed classification used to compute feed surplus converted into food		Feed classification used to compute feed shortage
		Feed category for harvested biomass	Feed category for transformed biomass	
SoftWheat	CER/11/a	cereals	co-products	concentrates
DurumWheat	CER/11/b	cereals	co-products	concentrates
Barley	CER/12	cereals	co-products	concentrates
Oat	CER/13	cereals	co-products	concentrates
Triticale	CER/14	cereals	co-products	concentrates
Rye	CER/15	cereals	co-products	concentrates
Maize	CER/16	cereals	co-products	concentrates
Sorghum	CER/17	cereals	co-products	concentrates
Rice	CER/18	cereals	co-products	concentrates
OtherCereals	CER/19	cereals	co-products	concentrates
MaizeFodder	FOUR/11	fodder	no	forages
OtherFodder	FOUR/19	fodder	no	forages
FodderRoots	FOUR/2	fodder	no	forages
ArtificialGrassland	FOUR/23	fodder	no	forages
TemporaryGrassland	FOUR/22	fodder	no	forages
PolyphytedGrassland	FOUR/21	fodder	no	forages
TemperateFruits	FRU	other	co-products	concentrates
Apricot	FRU/01/a	other	co-products	concentrates
Cherry	FRU/01/b	other	co-products	concentrates
Peach	FRU/01/c	other	co-products	concentrates
Plum	FRU/01/d	other	co-products	concentrates
Olive	FRU/01/e	other	co-products	concentrates
Apple	FRU/02/a	other	co-products	concentrates
CiderApple	FRU/02/b	other	co-products	concentrates
Pear	FRU/02/c	other	co-products	concentrates
Citrus	FRU/03	other	co-products	concentrates
OtherNuts	FRU/04	other	no	no
Walnut	FRU/04/a	other	no	no
Almond	FRU/04/b	other	no	no
Chestnut	FRU/04/c	other	no	no
Hazelnut	FRU/04/d	other	no	no
RedBerries	FRU/05	other	co-products	concentrates
TropicalFruits	FRU/06	other	co-products	concentrates
Vinegard	FRU/07/a	other	co-products	concentrates
Grapes	FRU/07/b	other	co-products	concentrates
SugarBeet	IND/11	other	co-products	concentrates
Linen	IND/21	other	no	no
Hemp	IND/22	other	no	no
Tobacco	IND/31	other	no	no

Table SM1. 4 (continued).

Plant name	Plant ID	Feed classification used to compute feed surplus converted into food		Feed classification used to compute feed shortage
		Feed category for harvested biomass	Feed category for transformed biomass	
Hop	IND/32	other	no	no
Chicory	IND/33	other	no	no
Aroma	IND/42	other	no	no
Lavanda	IND/49	other	no	no
Vegetables	LEG	other	co-products	concentrates
Artichoke	LEG/11	other	co-products	concentrates
Asparagus	LEG/12	other	co-products	concentrates
Celery	LEG/13	other	co-products	concentrates
Cabbage	LEG/14	other	co-products	concentrates
Endive	LEG/15	other	co-products	concentrates
Spinach	LEG/16	other	co-products	concentrates
Leek	LEG/17	other	co-products	concentrates
Lettuce	LEG/18	other	co-products	concentrates
	LEG/19	other	co-products	concentrates
Strawberry	LEG/21	other	co-products	concentrates
Eggplant	LEG/22	other	co-products	concentrates
Watermelon	LEG/23/a	other	co-products	concentrates
Melon	LEG/23/b	other	co-products	concentrates
Squash	LEG/23/c	other	co-products	concentrates
Cucumber	LEG/23/d	other	co-products	concentrates
IndustrialTomato	LEG/24/a	other	co-products	concentrates
Tomato	LEG/24/b	other	co-products	concentrates
Pepper	LEG/25	other	co-products	concentrates
Carrot	LEG/31	other	co-products	concentrates
Turnip	LEG/32	other	co-products	concentrates
Garlic	LEG/33	other	co-products	concentrates
Onion	LEG/34	other	co-products	concentrates
FodderBeet	LEG/35	other	co-products	concentrates
Radish	LEG/36	other	co-products	concentrates
Celeriac	LEG/37	other	co-products	concentrates
Salsify	LEG/38	other	co-products	concentrates
GardenPea	LEG/41	other	co-products	concentrates
GreenBean	LEG/42	other	co-products	concentrates
SweetCorn	LEG/5	other	co-products	concentrates
DryLegumes	LEG/6	oil-protein	no	proteinConcentrates
Mushrooms	LEG/7	other	co-products	concentrates
Rapeseed	OL/21	oil-protein	meals	proteinConcentrates
Sunflower	OL/22	oil-protein	meals	proteinConcentrates
Soya	OL/23	oil-protein	meals	proteinConcentrates
OtherOleaginous	OL/29	oil-protein	meals	proteinConcentrates
Pea	PR/31	oil-protein	no	proteinConcentrates
FabaBean	PR/32	oil-protein	no	proteinConcentrates

Table SM1. 4 (continued).

Plant name	Plant ID	Feed classification used to compute feed surplus converted into food		Feed classification used to compute feed shortage
		Feed category for harvested biomass	Feed category for transformed biomass	
Lupine	PR/33	oil-protein	no	proteinConcentrates
PermanentGrassland	STH/a	grass	no	forages
LowProductiveGrassland	STH/b	grass	no	forages
Potato	TUB/1	other	co-products	concentrates
PotatoSeed	TUB/11	other	co-products	concentrates
PotatoStarch	TUB/12	other	co-products	concentrates
PotatoConsumption	TUB/13	other	co-products	concentrates
OtherTubercules	TUB/2	other	co-products	concentrates

Table SM1. 5 Correspondence table from the AGRESTE livestock classification according to the study classification (species) and the livestock unit coefficient values.

RA_CHEPTEL_LIB	species	RA_CHEPTEL_M OD	Livestock unit coefficient (Eurostat)	Class in the species
Vaches laitières, y c. réforme	cattle	1.11.1	1	dairy cows
Vaches nourrices ou allaitantes, y c. réforme	cattle	1.11.2	0.8	other cattle
Bovins mâles castrés de 1 à 2 ans	cattle	1.12.1	0.7	young beef
Bovins mâles castrés de 2 ans et plus	cattle	1.12.2	1	beef
Bovins autres mâles de 1 à 2 ans	cattle	1.12.3	0.7	young bull
Bovins autres mâles de 2 ans et plus	cattle	1.12.4	1	bull
Bovins femelles de renouvellement de 1 à 2 ans	cattle	1.12.5	0.7	young heifer
Bovins femelles de renouvellement de 2 ans et plus	cattle	1.12.6	0.8	heifer
Bovins autres femelles de 1 à 2 ans	cattle	1.12.7	0.7	other young heifer
Bovins autres femelles de 2 ans et plus	cattle	1.12.8	0.8	other heifer
Veaux de 8 jours	cattle	1.13.1	0.4	young cattle
Veaux de boucherie	cattle	1.13.2	0.4	young cattle
Veaux abattus entre 8 et 12 mois	cattle	1.13.3	0.4	young cattle
Autres veaux mâles	cattle	1.13.4	0.4	young cattle
Autres veaux femelles	cattle	1.13.5	0.4	young cattle
Chèvres, y c. réforme	goatSheep	3.11	0.1	goats
Chevrettes pour la souche	goatSheep	3.12	0.1	goats
Autres caprins, y c. boucs	goatSheep	3.13	0.1	goats
Brebis mères laitières, y c. réforme	goatSheep	4.12	0.1	dairy ewes
Agnelles pour la souche	goatSheep	4.13	0.1	other ewes
	goatSheep		0.1	sheeps
Truies reproductrices de 50 kg ou plus, réforme exclue	pigs	5.11	0.5	sows
Porcelets, y c. post-sevrage	pigs	5.12	0.027	piglets
Jeunes porcs de 20 à 50 kg	pigs	5.13.1	0.3	pigs
Porcs de 50 kg ou plus, hors truies reproductrices	pigs	5.13.2	0.3	pigs
Lapines mères, race angora exclue	poultry	6	0.02	rabbits
Poules pondeuses d'oeufs de consommation	poultry	7.11.1	0.014	laying hens
Poules pondeuses d'oeufs à couver	poultry	7.11.2	0.014	laying hens
Poulettes	poultry	7.11.3	0.014	laying hens
Poulets de chair et coqs	poultry	7.12	0.007	broilers
Dindes et dindons	poultry	7.13	0.03	turkeys
Oies (à rôtir, à gaver)	poultry	7.14	0.03	geese
Canards à rôtir	poultry	7.15.1	0.03	ducks
Canards à gaver	poultry	7.15.2	0.03	ducks
Pintades	poultry	7.16	0.04	guinea fowl
Pigeons, cailles	poultry	7.19	0.03	pigeon

Table SM1. 6 Correspondence table from the RPG and AGRESTE plant classifications according to the study classification.

RPG plant ID	RPG plant name	AGRESTE plant ID	Study plant ID	Study plant name	Plant category used in the Table 1.1	Plant subcategory used in the Table 1.1 (if applicable)
BTH	Blé tendre d'hiver	1.11.1.11	CER/11/a	SoftWheat	Cereals	
BTP	Blé tendre de printemps	1.11.1.11	CER/11/a	SoftWheat	Cereals	
EPE	Épeautre	1.11.1.11	CER/11/a	Spelt	Cereals	
BDH	Blé dur d'hiver	1.11.1.12	CER/11/b	DurumWheat	Cereals	
BDP	Blé dur de printemps	1.11.1.12	CER/11/b	DurumWheat	Cereals	
BDT	Blé dur de printemps semé tardivement (après le 31/05)	1.11.1.12	CER/11/b	DurumWheat	Cereals	
ORH	Orge d'hiver	1.11.2	CER/12	Barley	Cereals	
ORP	Orge de printemps	1.11.2	CER/12	Barley	Cereals	
AVH	Avoine d'hiver	1.11.3	CER/13	Oat	Cereals	
AVP	Avoine de printemps	1.11.3	CER/13	Oat	Cereals	
TTH	Triticale d'hiver	1.11.4	CER/14	Triticale	Cereals	
TTP	Triticale de printemps	1.11.4	CER/14	Triticale	Cereals	
SGH	Seigle d'hiver	1.11.5	CER/15	Rye	Cereals	
SGP	Seigle de printemps	1.11.5	CER/15	Rye	Cereals	
MIS	Maïs	1.11.6	CER/16	Maize	Cereals	
SOG	Sorgho	1.11.7	CER/17	Sorghum	Cereals	
RIZ	Riz	1.11.8	CER/18	Rice	Cereals	
CAG	Autre céréale d'un autre genre	1.11.9	CER/19	OtherCereals	Cereals	
CGF	Autre céréale de genre Fagopyrum	1.11.9	CER/19	OtherCereals	Cereals	
CGH	Autre céréale de genre Phalaris	1.11.9	CER/19	OtherCereals	Cereals	
CGO	Autre céréale de genre Sorghum	1.11.9	CER/19	OtherCereals	Cereals	
CGP	Autre céréale de genre Panicum	1.11.9	CER/19	OtherCereals	Cereals	
CHA	Autre céréale d'hiver de genre Avena	1.11.9	CER/19	OtherCereals	Cereals	
CHH	Autre céréale d'hiver de genre Hordeum	1.11.9	CER/19	OtherCereals	Cereals	
CHS	Autre céréale d'hiver de genre Secale	1.11.9	CER/19	OtherCereals	Cereals	
CHT	Autre céréale d'hiver de genre Triticum	1.11.9	CER/19	OtherCereals	Cereals	
CPA	Autre céréale de printemps de genre Avena	1.11.9	CER/19	OtherCereals	Cereals	
CPH	Autre céréale de printemps de genre Hordeum	1.11.9	CER/19	OtherCereals	Cereals	
CPS	Autre céréale de printemps de genre Secale	1.11.9	CER/19	OtherCereals	Cereals	
CPT	Autre céréale de printemps de genre Triticum	1.11.9	CER/19	OtherCereals	Cereals	
CPZ	Autre céréale de printemps de genre Zea	1.11.9	CER/19	OtherCereals	Cereals	
MCR	Mélange de céréales	1.11.9	CER/19	CerealMix	Cereals	
MLT	Millet	1.11.9	CER/19	Millet	Cereals	
SRS	Sarrasin	1.11.9	CER/19	Buckwheat	Cereals	
MIE	Maïs ensilage	3.11.1	FOUR/11	MaizeFodder	Fodder	Annual fodder
FAG	Autre fourrage annuel d'un autre genre	3.11.9	FOUR/19	OtherFodder	Fodder	Annual fodder
BVF	Betterave fourragère	2	FOUR/2	FodderBeet	Fodder	Annual fodder
CAF	Carotte fourragère	2	FOUR/2	FodderCarrot	Fodder	Annual fodder
CHF	Chou fourrager	2	FOUR/2	FodderCabbage	Fodder	Annual fodder
FSG	Autre plante fourragère sarclée d'un autre genre	2	FOUR/2	FodderRoots	Fodder	Annual fodder
NVF	Navet fourrager	2	FOUR/2	FodderTurnip	Fodder	Annual fodder

Table SM1. 6 (continued).

RPG plant ID	RPG plant name	AGRESTE plant ID	Study plant ID	Study plant name	Plant category used in the Table 1.1	Plant subcategory used in the Table 1.1 (if applicable)
RDF	Radis fourrager	2	FOUR/2	FodderRadish	Fodder	Annual fodder
MC5	Mélange de légumineuses fourragères prépondérantes au semis implantées pour la récolte 2015 et de céréales	3.12.2	FOUR/21	PoliphytedGrassland	Fodder	Temporary grassland
MC6	Mélange de légumineuses fourragères prépondérantes au semis implantées pour la récolte 2016 et de céréales	3.12.2	FOUR/21	PoliphytedGrassland	Fodder	Temporary grassland
MC7	Mélange de légumineuses fourragères prépondérantes au semis implantées pour la récolte 2017 et de céréales	3.12.2	FOUR/21	PoliphytedGrassland	Fodder	Temporary grassland
MH5	Mélange de légumineuses fourragères prépondérantes au semis implantées pour la récolte 2015 et d'herbacées ou de graminées fourragères	3.12.2	FOUR/21	PoliphytedGrassland	Fodder	Temporary grassland
MH6	Mélange de légumineuses fourragères prépondérantes au semis implantées pour la récolte 2016 et d'herbacées ou de graminées fourragères	3.12.2	FOUR/21	PoliphytedGrassland	Fodder	Temporary grassland
MH7	Mélange de légumineuses fourragères prépondérantes au semis implantées pour la récolte 2017 et d'herbacées ou de graminées fourragères	3.12.2	FOUR/21	PoliphytedGrassland	Fodder	Temporary grassland
MLG	Mélange de légumineuses prépondérantes au semis et de graminées fourragères de 5 ans ou moins	3.12.2	FOUR/21	PoliphytedGrassland	Fodder	Temporary grassland
CPL	Fourrage composé de céréales et/ou de protéagineux (en proportion < 50%) et/ou de légumineuses fourragères (en proportion < 50%)	3.12.2	FOUR/22	PoliphytedGrassland	Fodder	Temporary grassland
DTY	Dactyle de 5 ans ou moins	3.12.2	FOUR/22	TemporaryGrassland	Fodder	Temporary grassland
FET	Fétuque de 5 ans ou moins	3.12.2	FOUR/22	TemporaryGrassland	Fodder	Temporary grassland
FLO	Fléole de 5 ans ou moins	3.12.2	FOUR/22	TemporaryGrassland	Fodder	Temporary grassland
GFP	Autre graminée fourragère pure de 5 ans ou moins	3.12.2	FOUR/22	TemporaryGrassland	Fodder	Temporary grassland
MOH	Moha	3.12.2	FOUR/22	TemporaryGrassland	Fodder	Temporary grassland
PAT	Pâturin commun de 5 ans ou moins	3.12.2	FOUR/22	TemporaryGrassland	Fodder	Temporary grassland
PTR	Autre prairie temporaire de 5 ans ou moins	3.12.2	FOUR/22	TemporaryGrassland	Fodder	Temporary grassland
RGA	Ray-grass de 5 ans ou moins	3.12.2	FOUR/22	Raygrass	Fodder	Temporary grassland
FF5	Féverole fourragère implantée pour la récolte 2015	3.12.1	FOUR/23	FodderFaba	Fodder	Artificial grassland
FF6	Féverole fourragère implantée pour la récolte 2016	3.12.1	FOUR/23	FodderFaba	Fodder	Artificial grassland
FF7	Féverole fourragère implantée pour la récolte 2017	3.12.1	FOUR/23	FodderFaba	Fodder	Artificial grassland
FFO	Autre féverole fourragère	3.12.1	FOUR/23	FodderFaba	Fodder	Artificial grassland
GES	Gesse	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
JO5	Jarosse implantée pour la récolte 2015	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
JO6	Jarosse implantée pour la récolte 2016	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
JO7	Jarosse implantée pour la récolte 2017	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
JOS	Autre jarosse	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
LEF	Lentille fourragère	3.12.1	FOUR/23	FodderLentil	Fodder	Artificial grassland
LFH	Autre lupin fourrager d'hiver	3.12.1	FOUR/23	FodderLupine	Fodder	Artificial grassland
LFP	Autre lupin fourrager de printemps	3.12.1	FOUR/23	FodderLupine	Fodder	Artificial grassland
LH5	Lupin fourrager d'hiver implanté pour la récolte 2015	3.12.1	FOUR/23	FodderLupine	Fodder	Artificial grassland
LH6	Lupin fourrager d'hiver implanté pour la récolte 2016	3.12.1	FOUR/23	FodderLupine	Fodder	Artificial grassland

Table SM1. 6 (continued).

RPG plant ID	RPG plant name	AGRES TE plant ID	Study plant ID	Study plant name	Plant category used in the Table 1.1	Plant subcategory used in the Table 1.1 (if applicable)
LH7	Lupin fourrager d'hiver implanté pour la récolte 2017	3.12.1	FOUR/23	FodderLupine	Fodder	Artificial grassland
LO7	Lotier implanté pour la récolte 2017	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
LOT	Lotier	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
LP5	Lupin fourrager de printemps implanté pour la récolte 2015	3.12.1	FOUR/23	FodderLupine	Fodder	Artificial grassland
LP6	Lupin fourrager de printemps implanté pour la récolte 2016	3.12.1	FOUR/23	FodderLupine	Fodder	Artificial grassland
LP7	Lupin fourrager de printemps implanté pour la récolte 2017	3.12.1	FOUR/23	FodderLupine	Fodder	Artificial grassland
LU5	Luzerne implantée pour la récolte 2015	3.12.1	FOUR/23	Alfalfa	Fodder	Artificial grassland
LU6	Luzerne implantée pour la récolte 2016	3.12.1	FOUR/23	Alfalfa	Fodder	Artificial grassland
LU7	Luzerne implantée pour la récolte 2017	3.12.1	FOUR/23	Alfalfa	Fodder	Artificial grassland
LUD	Luzerne déshydratée	3.12.1	FOUR/23	Alfalfa	Fodder	Artificial grassland
LUZ	Autre luzerne	3.12.1	FOUR/23	Alfalfa	Fodder	Artificial grassland
ME6	Mélicot implanté pour la récolte 2016	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
ME7	Mélicot implanté pour la récolte 2017	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
MED	Mélicot déshydraté	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
MEL	Autre mélicot	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
ML5	Mélange de légumineuses fourragères implantées pour la récolte 2015 (entre elles)	3.12.1	FOUR/23	FodderLegumes	Fodder	Artificial grassland
ML6	Mélange de légumineuses fourragères implantées pour la récolte 2016 (entre elles)	3.12.1	FOUR/23	FodderLegumes	Fodder	Artificial grassland
ML7	Mélange de légumineuses fourragères implantées pour la récolte 2017 (entre elles)	3.12.1	FOUR/23	FodderLegumes	Fodder	Artificial grassland
MLD	Mélange de légumineuses déshydratées (entre elles)	3.12.1	FOUR/23	FodderLegumes	Fodder	Artificial grassland
PFH	Autre pois fourrager d'hiver	3.12.1	FOUR/23	FodderPea	Fodder	Artificial grassland
PFP	Autre pois fourrager de printemps	3.12.1	FOUR/23	FodderPea	Fodder	Artificial grassland
PH6	Pois fourrager d'hiver implanté pour la récolte 2016	3.12.1	FOUR/23	FodderPea	Fodder	Artificial grassland
PH7	Pois fourrager d'hiver implanté pour la récolte 2017	3.12.1	FOUR/23	FodderPea	Fodder	Artificial grassland
PP5	Pois fourrager de printemps implanté pour la récolte 2015	3.12.1	FOUR/23	FodderPea	Fodder	Artificial grassland
PP6	Pois fourrager de printemps implanté pour la récolte 2016	3.12.1	FOUR/23	FodderPea	Fodder	Artificial grassland
PP7	Pois fourrager de printemps implanté pour la récolte 2017	3.12.1	FOUR/23	FodderPea	Fodder	Artificial grassland
SA5	Sainfoin implanté pour la récolte 2015	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
SA6	Sainfoin implanté pour la récolte 2016	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
SA7	Sainfoin implanté pour la récolte 2017	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
SAD	Sainfoin déshydraté	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
SAI	Autre sainfoin	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
SE5	Serradelle implantée pour la récolte 2015	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
SE6	Serradelle implantée pour la récolte 2016	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
SE7	Serradelle implantée pour la récolte 2017	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
TR5	Trèfle implanté pour la récolte 2015	3.12.1	FOUR/23	Clover	Fodder	Artificial grassland
TR6	Trèfle implanté pour la récolte 2016	3.12.1	FOUR/23	Clover	Fodder	Artificial grassland
TR7	Trèfle implanté pour la récolte 2017	3.12.1	FOUR/23	Clover	Fodder	Artificial grassland
TRD	Trèfle déshydraté	3.12.1	FOUR/23	Clover	Fodder	Artificial grassland

Table SM1. 6 (continued).

RPG plant ID	RPG plant name	AGRESTE plant ID	Study plant ID	Study plant name	Plant category used in the Table 1.1	Plant subcategory used in the Table 1.1 (if applicable)
TRE	Autre trèfle	3.12.1	FOUR/23	Clover	Fodder	Artificial grassland
VE5	Vesce implantée pour la récolte 2015	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
VE6	Vesce implantée pour la récolte 2016	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
VE7	Vesce implantée pour la récolte 2017	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
VES	Autre vesce	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
XFE	X-Felium de 5 ans ou moins	3.12.1	FOUR/23	ArtificialGrassland	Fodder	Artificial grassland
CBT	Cerise bigarreau pour transformation	0.1.12	FRU/01/b	Cherry	Fruits	
PVT	Pêche Pavie pour transformation	0.1.13	FRU/01/c	PeachTree	Fruits	
PRU	Prune d'Ente pour transformation	0.1.14	FRU/01/d	Plum	Fruits	
OLI	Oliveraie	0.1.15	FRU/01/e	OliveTree	Fruits	
VRG	Verger	0.2.11	FRU/02/a	TemperateFruits	Fruits	
PWT	Poire Williams pour transformation	0.2.13	FRU/02/c	Pear	Fruits	
AGR	Agrume	0.3	FRU/03	Citrus	Fruits	
CAB	Caroube	0.4	FRU/04	Carob	Fruits	
PIS	Pistache	0.4	FRU/04	Pistachio	Fruits	
NOX	Noix	0.4.11	FRU/04/a	Walnut	Fruits	
CTG	Châtaigne	0.4.13	FRU/04/c	Chestnut	Fruits	
NOS	Noisette	0.4.14	FRU/04/d	Hazelnut	Fruits	
PFR	Petit fruit rouge	0.5	FRU/05	RedBerry	Fruits	
AVO	Avocat	0.6	FRU/06	Avocado	Fruits	
VRC	Vigne : raisins de cuve	7.11	FRU/07/a	Vinegard	Fruits	
VRT	Vigne : raisins de table	7.12	FRU/07/b	Grapes	Fruits	
LIF	Lin fibres	4.12.1	IND/21	Linen	Industrial crops	
CHV	Chanvre	4.12.2	IND/22	Hemp	Industrial crops	
TAB	Tabac	4.13.1	IND/31	Tobacco	Industrial crops	
HBL	Houblon	4.13.2	IND/32	Hop	Industrial crops	
BAR	Bardane	4.14.9	IND/42	Aroma	Industrial crops	
BLT	Bleuet	4.14.9	IND/42	Aroma	Industrial crops	
BRH	Bourrache de 5 ans ou moins	4.14.9	IND/42	Aroma	Industrial crops	
CML	Cameline	4.14.9	IND/42	Aroma	Industrial crops	
CMM	Camomille	4.14.9	IND/42	Aroma	Industrial crops	
DOL	Dolique	4.14.9	IND/42	Aroma	Industrial crops	
MAV	Mauve	4.14.9	IND/42	Aroma	Industrial crops	
MLP	Millepertuis	4.14.9	IND/42	Aroma	Industrial crops	
MRG	Marguerite	4.14.9	IND/42	Aroma	Industrial crops	
PAQ	Pâquerette	4.14.9	IND/42	Aroma	Industrial crops	
PMV	Primevère	4.14.9	IND/42	Aroma	Industrial crops	
PPA	Autre plante à parfum, aromatique et médicinale annuelle	4.14.9	IND/42	Aroma	Industrial crops	
PPP	Autre plante à parfum, aromatique et médicinale pérenne	4.14.9	IND/42	Aroma	Industrial crops	
PSE	Pensée	4.14.9	IND/42	Aroma	Industrial crops	
PSN	Psyllium noir de Provence	4.14.9	IND/42	Aroma	Industrial crops	
PSY	Plantain psyllium	4.14.9	IND/42	Aroma	Industrial crops	
VAL	Valériane	4.14.9	IND/42	Aroma	Industrial crops	
VER	Véronique	4.14.9	IND/42	Aroma	Industrial crops	
LAV	Lavande / Lavandin	4.14.1	IND/49	Lavanda	Industrial crops	
MRJ	Marjolaine / Origan	4.14.1	IND/49	Aromatic	Industrial crops	

Table SM1. 6 (continued).

RPG plant ID	RPG plant name	AGRESTE plant ID	Study plant ID	Study plant name	Plant category used in the Table 1.1	Plant subcategory used in the Table 1.1 (if applicable)
SGE	Sauge	4.14.1	IND/49	Aromatic	Industrial crops	
SRI	Sarriette	4.14.1	IND/49	Aromatic	Industrial crops	
THY	Thym	4.14.1	IND/49	Aromatic	Industrial crops	
ART	Artichaut	6.11.1	LEG/11	Artichoke	Vegetables	
CEL	Céleri	6.11.3	LEG/13	Celery	Vegetables	
CHU	Chou	6.11.4	LEG/14	Cabbage	Vegetables	
CES	Chicorée / Endive / Scarole	6.11.5	LEG/15	Endive	Vegetables	
EPI	Épinard	6.11.6	LEG/16	Spinach	Vegetables	
OSE	Oseille	6.11.6	LEG/16	Sorrel	Vegetables	
POR	Poireau	6.11.7	LEG/17	Leek	Vegetables	
LBF	Laitue / Batavia / Feuille de chêne	6.11.8	LEG/18	Lettuce	Vegetables	
MAC	Mâche	6.11.8	LEG/18	LambLettuce	Vegetables	
ROQ	Roquette	6.11.8	LEG/18	Rocket	Vegetables	
ANE	Aneth	6.11.9	LEG/19	Condiment	Vegetables	
ANG	Angélique	6.11.9	LEG/19	Condiment	Vegetables	
ANI	Anis	6.11.9	LEG/19	Condiment	Vegetables	
BAS	Basilic	6.11.9	LEG/19	Condiment	Vegetables	
CAV	Carvi	6.11.9	LEG/19	Condiment	Vegetables	
CHR	Chardon Marie	6.11.9	LEG/19	Condiment	Vegetables	
CIB	Ciboulette	6.11.9	LEG/19	Condiment	Vegetables	
CRD	Coriandre	6.11.9	LEG/19	Condiment	Vegetables	
CRF	Cerfeuil	6.11.9	LEG/19	Condiment	Vegetables	
EST	Estragon	6.11.9	LEG/19	Condiment	Vegetables	
FNO	Fenouil	6.11.9	LEG/19	Fennel	Vegetables	
FNU	Fenugrec	6.11.9	LEG/19	Condiment	Vegetables	
MLI	Mélisse	6.11.9	LEG/19	Condiment	Vegetables	
MTH	Menthe	6.11.9	LEG/19	Mint	Vegetables	
ORT	Ortie	6.11.9	LEG/19	Condiment	Vegetables	
PSL	Persil	6.11.9	LEG/19	Condiment	Vegetables	
ROM	Romarin	6.11.9	LEG/19	Condiment	Vegetables	
FRA	Fraise	6.12.1	LEG/21	Strawberry	Vegetables	
AUB	Aubergine	6.12.2	LEG/22	Eggplant	Vegetables	
PAS	Pastèque	6.12.3.11	LEG/23/a	Watermelon	Vegetables	
MLO	Melon	6.12.3.12	LEG/23/b	Melon	Vegetables	
CCT	Courgette / Citrouille	6.12.3.14	LEG/23/c	Zucchini	Vegetables	
CMB	Courge musquée / Butternut	6.12.3.14	LEG/23/c	Butternut	Vegetables	
POT	Potiron / Potimarron	6.12.3.14	LEG/23/c	Pumpkin	Vegetables	
CCN	Concombre / Cornichon	6.12.3.15	LEG/23/d	Cucumber	Vegetables	
TOT	Tomate pour transformation	6.12.4.11	LEG/24/a	IndustrialTomato	Vegetables	
TOM	Tomate	6.12.4.12	LEG/24/b	Tomato	Vegetables	
PVP	Poivron / Piment	6.12.5	LEG/25	Pepper	Vegetables	
CAR	Carotte	6.13.1	LEG/31	Carrot	Vegetables	
PAN	Panais	6.13.1	LEG/31	Parsnip	Vegetables	
NVT	Navet	6.13.2	LEG/32	Turnip	Vegetables	
AIL	Ail	6.13.3	LEG/33	Garlic	Vegetables	
OIG	Oignon / Échalote	6.13.4	LEG/34	Onion	Vegetables	
BTN	Betterave non fourragère / Bette	6.13.5	LEG/35	SugarBeet	Sugar crops	

Table SM1. 6 (continued).

RPG plant ID	RPG plant name	AGRESTE plant ID	Study plant ID	Study plant name	Plant category used in the Table 1.1	Plant subcategory used in the Table 1.1 (if applicable)
RDI	Radis	6.13.6	LEG/36	Radish	Vegetables	
RUT	Rutabaga	6.13.8	LEG/38	Swede	Vegetables	
SFI	Salsifis	6.13.8	LEG/38	Salsify	Vegetables	
PPO	Petits pois	6.14.1	LEG/41	Pea	Vegetables	
HAR	Haricot / Flageolet	6.14.2	LEG/42	GreenBean	Vegetables	
MID	Maïs doux	6.15	LEG/5	SweetCorn	Vegetables	
LEC	Lentille cultivée (non fourragère)	6.16	LEG/6	Lentil	Dry legumes	
PCH	Pois chiche	6.16	LEG/6	ChickPea	Dry legumes	
TRU	Truffière (chênaie de plants mycorhizés)	6.17	LEG/7	Truffle	Vegetables	
CZH	Colza d'hiver	1.12.1	OL/21	Rapeseed	Oil and protein crops	
CZP	Colza de printemps	1.12.1	OL/21	Rapeseed	Oil and protein crops	
NVE	Navette d'été	1.12.1	OL/21	Rapeseed	Oil and protein crops	
NVH	Navette d'hiver	1.12.1	OL/21	Rapeseed	Oil and protein crops	
TRN	Tournesol	1.12.2	OL/22	Sunflower	Oil and protein crops	
SOJ	Soja	1.12.3	OL/23	Soja	Oil and protein crops	
ARA	Arachide	1.12.9	OL/29	Peanut	Oil and protein crops	
LIH	Lin non textile d'hiver	1.12.9	OL/29	Flax	Oil and protein crops	
LIP	Lin non textile de printemps	1.12.9	OL/29	Flax	Oil and protein crops	
MOL	Mélange d'oléagineux	1.12.9	OL/29	OleoMix	Oil and protein crops	
MOT	Moutarde	1.12.9	OL/29	Mustard	Oil and protein crops	
OAG	Autre oléagineux d'un autre genre	1.12.9	OL/29	OtherOleo	Oil and protein crops	
OEH	Autre oléagineux d'espèce Helianthus	1.12.9	OL/29	OtherOleo	Oil and protein crops	
OEI	Éillette	1.12.9	OL/29	OtherOleo	Oil and protein crops	
OHN	Autre oléagineux d'hiver d'espèce Brassica napus	1.12.9	OL/29	OtherOleo	Oil and protein crops	
OHR	Autre oléagineux d'hiver d'espèce Brassica rapa	1.12.9	OL/29	OtherOleo	Oil and protein crops	
OPR	Autre oléagineux de printemps d'espèce Brassica rapa	1.12.9	OL/29	OtherOleo	Oil and protein crops	
MPC	Mélange de protéagineux (pois et/ou lupin et/ou féverole) prépondérants semés avant le 31/05 et de céréales	1.13.1	PR/31	PeaMix	Oil and protein crops	
PAG	Autre protéagineux d'un autre genre	1.13.1	PR/31	OtherPea	Oil and protein crops	
PHI	Pois d'hiver	1.13.1	PR/31	Pea	Oil and protein crops	
PPR	Pois de printemps semé avant le 31/05	1.13.1	PR/31	Pea	Oil and protein crops	
FEV	Fève	1.13.2	PR/32	Faba	Oil and protein crops	
FVL	Féverole semée avant le 31/05	1.13.2	PR/32	Faba	Oil and protein crops	
LDH	Lupin doux d'hiver	1.13.3	PR/33	Lupine	Oil and protein crops	
LDP	Lupin doux de printemps semé avant le 31/05	1.13.3	PR/33	Lupine	Oil and protein crops	
PPH	Prairie permanente - herbe prédominante (ressources fourragères ligneuses absentes ou peu présentes)	3.12.3.11	STH/a	NaturalGrassland	Permanent grassland	
PRL	Prairie en rotation longue (6 ans ou plus)	3.12.3.11	STH/a	Grassland	Permanent grassland	
SPH	Surface pastorale - herbe prédominante et ressources fourragères ligneuses présentes	3.12.3.12	STH/b	OtherGrassland	Permanent grassland	
SPL	Surface pastorale - ressources fourragères ligneuses prédominantes	3.12.3.12	STH/b	PoorPastures	Permanent grassland	
PTF	Pomme de terre féculière	5.11.2	TUB/12	PotatoStarch	Tuber crops	
PTC	Pomme de terre de consommation	5.11.3	TUB/13	PotatoConsumption	Tuber crops	
TOP	Topinambour	5.12	TUB/2	Sunchoke	Tuber crops	

SM1.4 Input tables

Table SM1. 7 Coefficients from Anglade et al. (2015) used to estimate the biological nitrogen fixation ($\psi_{i,t}$) of leguminous crops and according to the classification of the study.

Plant ID	Plant name	alpha	beta	NHI	BGN	A
FOUR/21	PolyphytedGrassland	0.78	3.06	0.9	1.7	0.3
FOUR/23	ArtificialGrassland	0.81	-13.9	0.9	1.7	1
LEG/41	GreenBean	0.7	1.01	0.75	1.3	1
LEG/42	GardenPea	0.66	4.32	0.75	1.3	1
LEG/6	DryLegumes	0.7	1.01	0.75	1.3	1
OL/23	Soya	0.7	1.01	0.75	1.3	1
PR/31	Pea	0.66	4.32	0.75	1.3	1
PR/32	FabaBean	0.78	3.06	0.9	1.7	1
PR/33	Lupine	0.78	3.06	0.9	1.7	1
STH/a	PermanentGrassland	0.78	3.06	0.9	1.7	0.15
STH/b	LowProductiveGrassland	0.78	3.06	0.9	1.7	0.15

Table SM1. 8 Biological nitrogen fixation per plant and per FS estimated based on the equation by Anglade et al. (2015) for maximum plant yield.

Plant ID	Biological nitrogen fixation ψ_i [kg/ha]	FS
FOUR/21	43.33	Bocage Bourbonnais
FOUR/23	272.04	Bocage Bourbonnais
LEG/41	71.53	Bocage Bourbonnais
LEG/6	82.40	Bocage Bourbonnais
OL/23	188.40	Bocage Bourbonnais
PR/31	124.67	Bocage Bourbonnais
PR/32	151.15	Bocage Bourbonnais
PR/33	196.95	Bocage Bourbonnais
STH/a	14.65	Bocage Bourbonnais
STH/b	6.31	Bocage Bourbonnais
FOUR/21	43.33	Bretagne Centrale
FOUR/23	272.04	Bretagne Centrale
LEG/41	71.53	Bretagne Centrale
LEG/42	111.79	Bretagne Centrale
PR/31	124.67	Bretagne Centrale
PR/32	151.15	Bretagne Centrale
PR/33	196.95	Bretagne Centrale
STH/a	14.65	Bretagne Centrale
STH/b	6.31	Bretagne Centrale
FOUR/21	43.33	Plateau Picard
FOUR/23	272.04	Plateau Picard
LEG/41	71.53	Plateau Picard
LEG/42	111.79	Plateau Picard
LEG/6	82.40	Plateau Picard
OL/23	188.40	Plateau Picard
PR/31	124.67	Plateau Picard
PR/32	151.15	Plateau Picard
STH/a	14.65	Plateau Picard

Table SM1. 9 Animal-sourced food production coefficients according to FS, species, and livestock products (in kg of nitrogen per livestock unit).

FS	Species	Milk production in nitrogen (kg/LU)	Meat production in nitrogen (kg/LU)	Egg production in nitrogen (kg/LU)
Bocage Bourbonnais	Cattle	1.25	4.44	0.00
Bretagne Centrale	Cattle	19.59	3.80	0.00
Plateau Picard	Cattle	13.29	3.51	0.00
Bocage Bourbonnais	GoatSheep	0.72	2.46	0.00
Bretagne Centrale	GoatSheep	0.58	3.31	0.00
Plateau Picard	GoatSheep	0.47	2.49	0.00
Bocage Bourbonnais	Pig	0.00	10.57	0.00
Bretagne Centrale	Pig	0.00	11.40	0.00
Plateau Picard	Pig	0.00	9.83	0.00
Bocage Bourbonnais	Poultry	0.00	14.25	2.72
Bretagne Centrale	Poultry	0.00	6.27	7.86
Plateau Picard	Poultry	0.00	12.49	8.13

Table SM1. 10 C:N ratios and humification coefficients according to species and type of effluents.

Type of effluent	Group of species	Species	C:N ratio	Humification coefficient
Manure	ruminants	cattle	18.7	46%
Manure	ruminants	goatSheep	11.7	46%
Manure	monogastrics	pigs	22.8	46%
manure	monogastrics	poultry	9.2	46%

Table SM1. 11 Biophysical and soil annual mean values per FS

Annual averaged values per FS of	Bocage Bourbonnais	Bretagne Centrale	Plateau Picard
Irrigation in agriculture [mm]	31.9	91.5	31.8
Water pH [-]	6.0	6.0	7.2
Clay content [g/kg soil]	18.6	17.9	19.8
Calcium carbonate [CaCO ₃] content [g/kg soil]	12.0	11.2	65.8
Potential evapo-transpiration [mm]	800.14	807.75	770.69
C:N ratio - cropland [-]	10.9	11.2	9.7
C:N ratio – permanent grassland [-]	22	22	20
Cumulative rainfall [mm]	854.0	944.7	744.8
Daily temperature [°C]	12.2	12.5	11.7
Soil organic carbon stocks in agricultural land – in 2010 [tC/ha]	89.70	67.65	72.40

Table SM1. 12 Repartition coefficients of harvested and transformed biomass (shares) for the three FS (national values).

Plant name	Plant ID	Harvested biomass to humans $v_i^{H^H}$	Harvested biomass to livestock $v_i^{H^A}$	Harvested biomass to industry $v_i^{H^I}$	Harvested biomass used the year after for sowing $v_i^{H^S}$	Harvested biomass to transformation $v_i^{H^T}$	Harvested biomass transformed to livestock as oil $v_i^{T,LO}$	Harvested biomass transformed to livestock as meal $v_i^{T,LM}$	Harvested biomass transformed to industry $v_i^{T^I}$	Harvested biomass transformed to humans $v_i^{T^H}$
SoftWheat	CER/11/a	0.4	0.4	0.15	0.05	0	0	0	0	0
DurumWheat	CER/11/b	0.85	0.1	0	0.05	0	0	0	0	0
Barley	CER/12	0.05	0.9	0	0.05	0	0	0	0	0
Oat	CER/13	0	0.95	0	0.05	0	0	0	0	0
Triticale	CER/14	0	0.95	0	0.05	0	0	0	0	0
Rye	CER/15	0.15	0.8	0	0.05	0	0	0	0	0
Maize	CER/16	0.05	0.7	0.2	0.05	0	0	0	0	0
Sorghum	CER/17	0	0.95	0	0.05	0	0	0	0	0
Rice	CER/18	0.85	0.1	0	0.05	0	0	0	0	0
OtherCereals	CER/19	0	0.95	0	0.05	0	0	0	0	0
MaizeFodder	FOUR/11	0	1	0	0	0	0	0	0	0
OtherFodder	FOUR/19	0	1	0	0	0	0	0	0	0
FodderRoots	FOUR/2	0	1	0	0	0	0	0	0	0
ArtificialGrassland	FOUR/23	0	1	0	0	0	0	0	0	0
TemporaryGrassland	FOUR/22	0	1	0	0	0	0	0	0	0
PolyphytedGrassland	FOUR/21	0	1	0	0	0	0	0	0	0
TemperateFruits	FRU	1	0	0	0	0	0	0	0	0
Apricot	FRU/01/a	1	0	0	0	0	0	0	0	0
Cherry	FRU/01/b	0	0	0	0	1	0	0	0	1
Peach	FRU/01/c	0	0	0	0	1	0	0	0	1
Plum	FRU/01/d	0	0	0	0	1	0	0	0	1
Olive	FRU/01/e	0	0	0	0	1	0	0	0	1
Apple	FRU/02/a	1	0	0	0	0	0	0	0	0
CiderApple	FRU/02/b	0	0	0	0	1	0	0	0	1
Pear	FRU/02/c	0	0	0	0	1	0	0	0	1
Citrus	FRU/03	1	0	0	0	0	0	0	0	0
OtherNuts	FRU/04	0	0	0	0	1	0	0	0	1
Walnut	FRU/04/a	1	0	0	0	0	0	0	0	0
Almond	FRU/04/b	1	0	0	0	0	0	0	0	0
Chestnut	FRU/04/c	1	0	0	0	0	0	0	0	0
Hazelnut	FRU/04/d	1	0	0	0	0	0	0	0	0
RedBerries	FRU/05	1	0	0	0	0	0	0	0	0
TropicalFruits	FRU/06	1	0	0	0	0	0	0	0	0
Vineyard	FRU/07/a	0	0	0	0	1	0	0	0	1

Table SM1. 12 (continued).

Plant name	Plant ID	Harvested biomass to humans $v_i^{H^H}$	Harvested biomass to livestock $v_i^{H^A}$	Harvested biomass to industry $v_i^{H^I}$	Harvested biomass used the year after for sowing $v_i^{H^S}$	Harvested biomass to transformation $v_i^{H^T}$	Harvested biomass transformed to livestock as oil $v_i^{T^{LO}}$	Harvested biomass transformed to livestock as meal $v_i^{T^{LM}}$	Harvested biomass transformed to industry $v_i^{T^I}$	Harvested biomass transformed to humans $v_i^{T^H}$
Grapes	FRU/07/b	1	0	0	0	0	0	0	0	0
SugarBeet	IND/11	0	0	0.2	0	0.8	0.1	0	0	0.7
Linen	IND/21	0	0	0	0	1	0	0	0	1
Hemp	IND/22	0	0	0	0	1	0	0	0	1
Tobacco	IND/31	0	0	0	0	1	0	0	0	1
Hop	IND/32	0	0	0	0	1	0	0	0	1
Chicory	IND/33	0	0	0	0	1	0	0	0	1
Aroma	IND/42	0	0	0	1	0	0	0	0	0
Lavanda	IND/49	0	0	0	0	1	0	0	0	1
Vegetables	LEG	1	0	0	0	0	0	0	0	0
Artichoke	LEG/11	1	0	0	0	0	0	0	0	0
Asparagus	LEG/12	1	0	0	0	0	0	0	0	0
Celery	LEG/13	1	0	0	0	0	0	0	0	0
Cabbage	LEG/14	1	0	0	0	0	0	0	0	0
Endive	LEG/15	1	0	0	0	0	0	0	0	0
Spinach	LEG/16	1	0	0	0	0	0	0	0	0
Leek	LEG/17	1	0	0	0	0	0	0	0	0
Lettuce	LEG/18	1	0	0	0	0	0	0	0	0
	LEG/19	1	0	0	0	0	0	0	0	0
Strawberry	LEG/21	1	0	0	0	0	0	0	0	0
Eggplant	LEG/22	1	0	0	0	0	0	0	0	0
Watermelon	LEG/23/a	1	0	0	0	0	0	0	0	0
Melon	LEG/23/b	1	0	0	0	0	0	0	0	0
Squash	LEG/23/c	1	0	0	0	0	0	0	0	0
Cucumber	LEG/23/d	1	0	0	0	0	0	0	0	0
IndustrialTomato	LEG/24/a	0	0	0	0	1	0	0	0	1
Tomato	LEG/24/b	1	0	0	0	0	0	0	0	0
Pepper	LEG/25	1	0	0	0	0	0	0	0	0
Carrot	LEG/31	1	0	0	0	0	0	0	0	0
Turnip	LEG/32	1	0	0	0	0	0	0	0	0
Garlic	LEG/33	1	0	0	0	0	0	0	0	0
Onion	LEG/34	1	0	0	0	0	0	0	0	0
FodderBeet	LEG/35	1	0	0	0	0	0	0	0	0
Radish	LEG/36	1	0	0	0	0	0	0	0	0
Celeriac	LEG/37	1	0	0	0	0	0	0	0	0
Salsify	LEG/38	1	0	0	0	0	0	0	0	0

Table SM1. 12 (continued).

Plant name	Plant ID	Harvested biomass to humans $v_i^{H^H}$	Harvested biomass to livestock $v_i^{H^A}$	Harvested biomass to industry $v_i^{H^I}$	Harvested biomass used the year after for sowing $v_i^{H^S}$	Harvested biomass to transformation $v_i^{H^T}$	Harvested biomass transformed to livestock as oil $v_i^{T^{LO}}$	Harvested biomass transformed to livestock as meal $v_i^{T^{LM}}$	Harvested biomass transformed to industry $v_i^{T^I}$	Harvested biomass transformed to humans $v_i^{T^H}$
GardenPea	LEG/41	1	0	0	0	0	0	0	0	0
GreenBean	LEG/42	1	0	0	0	0	0	0	0	0
SweetCorn	LEG/5	1	0	0	0	0	0	0	0	0
DryLegumes	LEG/6	0.9	0	0	0.1	0	0	0	0	0
Mushrooms	LEG/7	1	0	0	0	0	0	0	0	0
Rapeseed	OL/21	0.05	0.05	0	0	0.9	0.5	0	0.3	0.1
Sunflower	OL/22	0.05	0.1	0	0	0.85	0.5	0	0.05	0.3
Soya	OL/23	0	0.2	0	0	0.8	0.6	0	0.1	0.1
OtherOleaginous	OL/29	0	1	0	0	0	0	0	0	0
Pea	PR/31	0.1	0.8	0	0.1	0	0	0	0	0
FabaBean	PR/32	0.07	0.83	0	0.1	0	0	0	0	0
Lupine	PR/33	0.09	0.85	0	0.06	0	0	0	0	0
PermanentGrassland	STH/a	0	1	0	0	0	0	0	0	0
LowProductiveGrassland	STH/b	0	1	0	0	0	0	0	0	0
Potato	TUB/1	0.7	0.05	0	0.05	0.2	0.1	0	0	0.1
PotatoSeed	TUB/11	0	0	0	1	0	0	0	0	0
PotatoStarch	TUB/12	0	0	0	0	1	0.2	0	0	0.8
PotatoConsumption	TUB/13	1	0	0	0	0	0	0	0	0
OtherTubercules	TUB/2	0.75	0	0	0.05	0.2	0.1	0	0	0.1

Table SM1. 13 Boolean values by plant ID: synthetic fertilization, cropland, and annual crop

Plant ID	Fertilised with synthetic nitrogen	Annual crop	Cropland
CER/11/a	TRUE	TRUE	TRUE
CER/11/b	TRUE	TRUE	TRUE
CER/12	TRUE	TRUE	TRUE
CER/13	TRUE	TRUE	TRUE
CER/14	TRUE	TRUE	TRUE
CER/15	TRUE	TRUE	TRUE
CER/16	TRUE	TRUE	TRUE
CER/17	TRUE	TRUE	TRUE
CER/18	TRUE	TRUE	TRUE
CER/19	TRUE	TRUE	TRUE
FOUR/11	TRUE	TRUE	TRUE
FOUR/19	TRUE	TRUE	TRUE
FOUR/2	TRUE	TRUE	TRUE
FOUR/21	TRUE	TRUE	TRUE
FOUR/22	TRUE	TRUE	TRUE
FOUR/23	FALSE	TRUE	TRUE
FRU/01/b	TRUE	FALSE	TRUE
FRU/01/c	TRUE	FALSE	TRUE
FRU/01/d	TRUE	FALSE	TRUE
FRU/01/e	TRUE	FALSE	TRUE
FRU/02/a	TRUE	FALSE	TRUE
FRU/02/c	TRUE	FALSE	TRUE
FRU/03	TRUE	FALSE	TRUE
FRU/04	TRUE	FALSE	TRUE
FRU/04/a	TRUE	FALSE	TRUE
FRU/04/c	TRUE	FALSE	TRUE
FRU/04/d	TRUE	FALSE	TRUE
FRU/05	TRUE	FALSE	TRUE
FRU/06	TRUE	FALSE	TRUE
FRU/07/a	TRUE	FALSE	TRUE
FRU/07/b	TRUE	FALSE	TRUE
IND/21	TRUE	TRUE	TRUE
IND/22	TRUE	TRUE	TRUE
IND/31	TRUE	TRUE	TRUE
IND/42	TRUE	TRUE	TRUE
IND/49	TRUE	TRUE	TRUE
LEG/11	TRUE	TRUE	TRUE
LEG/13	TRUE	TRUE	TRUE
LEG/14	TRUE	TRUE	TRUE
LEG/15	TRUE	TRUE	TRUE

Table SM1. 13 (continued).

Plant ID	Fertilised with synthetic nitrogen	Annual crop	Cropland
LEG/16	TRUE	TRUE	TRUE
LEG/17	TRUE	TRUE	TRUE
LEG/18	TRUE	TRUE	TRUE
LEG/19	TRUE	TRUE	TRUE
LEG/21	TRUE	TRUE	TRUE
LEG/22	TRUE	TRUE	TRUE
LEG/23/a	TRUE	TRUE	TRUE
LEG/23/b	TRUE	TRUE	TRUE
LEG/23/c	TRUE	TRUE	TRUE
LEG/23/d	TRUE	TRUE	TRUE
LEG/24/a	TRUE	TRUE	TRUE
LEG/24/b	TRUE	TRUE	TRUE
LEG/25	TRUE	TRUE	TRUE
LEG/31	TRUE	TRUE	TRUE
LEG/32	TRUE	TRUE	TRUE
LEG/33	TRUE	TRUE	TRUE
LEG/34	TRUE	TRUE	TRUE
LEG/35	TRUE	TRUE	TRUE
LEG/36	TRUE	TRUE	TRUE
LEG/38	TRUE	TRUE	TRUE
LEG/41	TRUE	TRUE	TRUE
LEG/42	TRUE	TRUE	TRUE
LEG/5	TRUE	TRUE	TRUE
LEG/6	FALSE	TRUE	TRUE
OL/21	TRUE	TRUE	TRUE
OL/22	TRUE	TRUE	TRUE
OL/23	FALSE	TRUE	TRUE
OL/29	TRUE	TRUE	TRUE
PR/31	FALSE	TRUE	TRUE
PR/32	FALSE	TRUE	TRUE
PR/33	FALSE	TRUE	TRUE
STH/a	TRUE	TRUE	FALSE
STH/b	FALSE	TRUE	FALSE
TUB/12	TRUE	TRUE	TRUE
TUB/13	TRUE	TRUE	TRUE
TUB/2	TRUE	TRUE	TRUE

Table SM1. 14 Plant parameters following the study classification: nitrogen content, humification coefficients, carbon content, and C:N ratios of the different parts of the plants.

Plant ID	Shoot-to-root ratio SR (-)	Harvest index HI (-)	Carbon content (kg/kg fresh matter)	Nitrogen content of the harvested organ σ^H (kg/0.1 ton)	Nitrogen content of the aerial residues σ^{RA} (kg/0.1 ton)	Nitrogen content of the root residues σ^{RR} (kg/0.1 ton)	Humification coefficient of the aboveground residues ϕ^{RA}	Humification coefficient of the belowground residues ϕ^{RR}	C:N ratio of the aerial residues CN^{RA}	C:N ratio of the root residues CN^{RR}
CER/11/a	4,17	0,45	0,34	1,76	0,60	0,90	0,5	0,5	19,32	37,78
CER/11/b	4,55	0,45	0,34	2,24	0,60	0,90	0,5	0,5	15,18	37,78
CER/12	4,55	0,45	0,34	2,15	0,70	1,40	0,5	0,5	15,81	24,29
CER/13	2,50	0,41	0,34	2,90	0,70	0,60	0,5	0,5	11,72	56,67
CER/14	4,55	0,44	0,34	1,70	0,60	0,90	0,5	0,5	20,00	37,78
CER/15	4,55	0,43	0,34	1,80	0,50	1,10	0,5	0,5	18,89	30,91
CER/16	4,00	0,52	0,34	1,50	1,20	1,20	0,5	0,5	22,67	28,33
CER/17	5,00	0,50	0,34	1,90	0,70	0,90	0,5	0,5	17,89	37,78
CER/19	5,00	0,45	0,34	1,80	0,60	0,90	0,5	0,5	18,89	37,78
FOUR/11	10,00	0,80	0,43	1,00	1,00	1,00	0,5	0,5	43,00	43,00
FOUR/19	5,00	0,80	0,4	1,20	1,20	1,20	0,5	0,5	33,33	33,33
FOUR/20	10,00	0,80	0,032	0,36	0,36	0,36	0,5	0,5	8,89	8,89
FOUR/21	1,00	0,80	0,4	2,40	1,25	1,20	0,5	0,5	16,67	33,33
FOUR/22	1,25	0,80	0,4	1,25	1,25	1,20	0,5	0,5	32,00	33,33
FOUR/23	0,83	0,80	0,4	2,80	1,25	1,20	0,5	0,5	14,29	33,33
FRU/02/a	5,00	0,80	0,06	0,04	1,00	1,00	0,5	0,5	138,89	6,00
FRU/04/c	5,00	0,15	0,4	0,34	1,00	1,00	0,5	0,5	117,37	40,00
FRU/05	10,00	0,95	0,06	0,18	1,00	1,00	0,5	0,5	33,78	6,00
FRU/07/a	4,00	0,40	0,06	0,12	0,66	0,66	0,5	0,5	52,08	9,09
IND/21	5,00	0,50	0,4	0,35	0,35	0,35	0,5	0,5	114,29	114,29
IND/22	5,00	0,50	0,4	0,35	0,35	0,35	0,5	0,5	114,29	114,29
IND/42	5,00	0,80	0,04	1,00	1,00	1,00	0,5	0,5	4,00	4,00
LEG/13	5,00	0,80	0,04	0,24	0,24	0,24	0,5	0,5	16,67	16,67
LEG/14	1,30	0,80	0,04	0,43	0,43	0,43	0,5	0,5	9,30	9,30

Table SM1. 14 (continued).

Plant ID	Shoot-to-root ratio $SR (-)$	Harvest index $HI (-)$	Carbon content (kg/kg fresh matter)	Nitrogen content of the harvested organ σ^H (kg/0.1 ton)	Nitrogen content of the aerial residues σ^{RA} (kg/0.1 ton)	Nitrogen content of the root residues σ^{RR} (kg/0.1 ton)	Humification coefficient of the aboveground residues ϕ^{RA}	Humification coefficient of the belowground residues ϕ^{RR}	C:N ratio of the aerial residues CN^{RA}	C:N ratio of the root residues CN^{RR}
LEG/15	4,00	0,80	0,04	0,18	0,18	0,18	0,5	0,5	22,73	22,73
LEG/17	6,70	0,80	0,04	0,25	0,25	0,25	0,5	0,5	15,72	15,72
LEG/18	5,00	0,80	0,04	0,21	0,21	0,21	0,5	0,5	19,23	19,23
LEG/19	1,30	1,00	0,04	0,18	0,36	0,36	0,5	0,5	22,22	11,11
LEG/21	6,67	0,50	0,04	0,10	0,16	0,16	0,5	0,5	38,46	25,64
LEG/23/c	6,67	0,80	0,04	0,20	0,29	0,29	0,5	0,5	20,49	13,66
LEG/31	5,00	0,80	0,04	0,11	0,11	0,11	0,5	0,5	37,88	36,36
LEG/34	5,00	0,80	0,04	0,18	0,18	0,18	0,5	0,5	22,73	22,73
LEG/35	1,25	0,50	0,09	0,21	0,21	0,21	0,5	0,5	42,86	42,86
LEG/41	6,67	0,30	0,036	0,98	0,98	0,98	0,5	0,5	3,67	3,67
LEG/42	6,67	0,40	0,036	0,96	0,96	0,96	0,5	0,5	3,75	3,75
LEG/6	6,67	0,35	0,15	4,06	4,06	4,06	0,5	0,5	3,69	3,69
OL/21	5,00	0,29	0,35	3,50	1,40	1,40	0,5	0,5	10,00	25,00
OL/22	5,00	0,30	0,35	1,96	1,20	1,20	0,5	0,5	17,86	29,17
OL/23	2,56	0,35	0,35	6,00	0,80	0,80	0,5	0,5	5,83	43,75
OL/29	5,00	0,30	0,35	3,50	1,00	1,00	0,5	0,5	10,00	35,00
PR/31	10,00	0,39	0,36	3,50	0,80	0,80	0,5	0,5	10,29	45,00
PR/32	1,67	0,39	0,36	4,16	0,80	0,80	0,5	0,5	8,65	45,00
PR/33	5,30	0,35	0,36	5,76	0,80	0,80	0,5	0,5	6,25	45,00
STH/a	1,00	0,65	0,4	1,26	1,26	1,20	0,5	0,5	31,87	33,33
STH/b	0,63	0,50	0,4	1,25	1,25	1,20	0,5	0,5	32,00	33,33
TUB/12	1,25	0,60	0,09	0,26	0,26	0,14	0,5	0,5	35,16	64,29
TUB/13	1,25	0,60	0,09	0,26	0,26	0,14	0,5	0,5	35,16	64,29

Table SM1. 15 Feed intake in nitrogen (kg/livestock unit) per species, feed category, and FS.

Feed category	Group of species	Species	Feed intake in nitrogen (kg/livestock unit)	FS
cereals	ruminants	cattle	8.11	Bocage Bourbonnais
cereals	ruminants	goatSheep	8.11	Bocage Bourbonnais
cereals	monogastrics	pigs	25.48	Bocage Bourbonnais
cereals	monogastrics	poultry	25.00	Bocage Bourbonnais
grass	ruminants	cattle	51.64	Bocage Bourbonnais
grass	ruminants	goatSheep	51.64	Bocage Bourbonnais
grass	monogastrics	pigs	0.00	Bocage Bourbonnais
grass	monogastrics	poultry	0.00	Bocage Bourbonnais
co-products	ruminants	cattle	0.00	Bocage Bourbonnais
co-products	ruminants	goatSheep	0.00	Bocage Bourbonnais
co-products	monogastrics	pigs	0.00	Bocage Bourbonnais
co-products	monogastrics	poultry	0.00	Bocage Bourbonnais
fodder	ruminants	cattle	40.41	Bocage Bourbonnais
fodder	ruminants	goatSheep	40.41	Bocage Bourbonnais
fodder	monogastrics	pigs	0.00	Bocage Bourbonnais
fodder	monogastrics	poultry	0.00	Bocage Bourbonnais
oil-protein	ruminants	cattle	0.79	Bocage Bourbonnais
oil-protein	ruminants	goatSheep	0.79	Bocage Bourbonnais
oil-protein	monogastrics	pigs	4.18	Bocage Bourbonnais
oil-protein	monogastrics	poultry	2.45	Bocage Bourbonnais
meals	ruminants	cattle	8.77	Bocage Bourbonnais
meals	ruminants	goatSheep	8.77	Bocage Bourbonnais
meals	monogastrics	pigs	19.63	Bocage Bourbonnais
meals	monogastrics	poultry	40.16	Bocage Bourbonnais
cereals	ruminants	cattle	11.64	Bretagne Centrale
cereals	ruminants	goatSheep	11.64	Bretagne Centrale
cereals	monogastrics	pigs	37.62	Bretagne Centrale
cereals	monogastrics	poultry	29.03	Bretagne Centrale
grass	ruminants	cattle	15.17	Bretagne Centrale
grass	ruminants	goatSheep	15.17	Bretagne Centrale
grass	monogastrics	pigs	0.00	Bretagne Centrale
grass	monogastrics	poultry	0.00	Bretagne Centrale
co-products	ruminants	cattle	0.00	Bretagne Centrale
co-products	ruminants	goatSheep	0.00	Bretagne Centrale
co-products	monogastrics	pigs	0.00	Bretagne Centrale
co-products	monogastrics	poultry	0.00	Bretagne Centrale
fodder	ruminants	cattle	66.74	Bretagne Centrale
fodder	ruminants	goatSheep	66.74	Bretagne Centrale
fodder	monogastrics	pigs	0.00	Bretagne Centrale
fodder	monogastrics	poultry	0.00	Bretagne Centrale

Table SM1. 15 (continued).

Feed category	Group of species	Species	Feed intake in nitrogen (kg/livestock unit)	FS
oil-protein	ruminants	cattle	0.46	Bretagne Centrale
oil-protein	ruminants	goatSheep	0.46	Bretagne Centrale
oil-protein	monogastrics	pigs	0.71	Bretagne Centrale
oil-protein	monogastrics	poultry	0.30	Bretagne Centrale
meals	ruminants	cattle	33.93	Bretagne Centrale
meals	ruminants	goatSheep	33.93	Bretagne Centrale
meals	monogastrics	pigs	28.18	Bretagne Centrale
meals	monogastrics	poultry	49.63	Bretagne Centrale
cereals	ruminants	cattle	11.08	Plateau Picard
cereals	ruminants	goatSheep	11.08	Plateau Picard
cereals	monogastrics	pigs	28.78	Plateau Picard
cereals	monogastrics	poultry	16.76	Plateau Picard
grass	ruminants	cattle	48.54	Plateau Picard
grass	ruminants	goatSheep	48.54	Plateau Picard
grass	monogastrics	pigs	0.00	Plateau Picard
grass	monogastrics	poultry	0.00	Plateau Picard
co-products	ruminants	cattle	1.23	Plateau Picard
co-products	ruminants	goatSheep	1.23	Plateau Picard
co-products	monogastrics	pigs	1.36	Plateau Picard
co-products	monogastrics	poultry	0.23	Plateau Picard
fodder	ruminants	cattle	33.15	Plateau Picard
fodder	ruminants	goatSheep	33.15	Plateau Picard
fodder	monogastrics	pigs	0.00	Plateau Picard
fodder	monogastrics	poultry	0.00	Plateau Picard
oil-protein	ruminants	cattle	30.60	Plateau Picard
oil-protein	ruminants	goatSheep	30.60	Plateau Picard
oil-protein	monogastrics	pigs	25.35	Plateau Picard
oil-protein	monogastrics	poultry	13.30	Plateau Picard
meals	ruminants	cattle	0.00	Plateau Picard
meals	ruminants	goatSheep	0.00	Plateau Picard
meals	monogastrics	pigs	0.00	Plateau Picard
meals	monogastrics	poultry	19.59	Plateau Picard

Table SM1. 16 Livestock numbers in livestock units per species and FS.

Species group	Species	FS	Livestock number in livestock units
monogastrics	pigs	Bocage Bourbonnais	394.3
monogastrics	pigs	Bretagne Centrale	261334.2
monogastrics	pigs	Plateau Picard	2300.1
monogastrics	poultry	Bocage Bourbonnais	7243.9
monogastrics	poultry	Bretagne Centrale	93905.6
monogastrics	poultry	Plateau Picard	3003.6
ruminants	cattle	Bocage Bourbonnais	137631.7
ruminants	cattle	Bretagne Centrale	59426.4
ruminants	cattle	Plateau Picard	16719.3
ruminants	goatSheep	Bocage Bourbonnais	402.1
ruminants	goatSheep	Bretagne Centrale	23.9
ruminants	goatSheep	Plateau Picard	24.8

Table SM1. 17 Plant area and yield per FS according to the study classification.

FS	Plant ID	Plant name	Cultivated area in ha	Typical crop yield in fresh matter (100 kg/ha)
Bocage Bourbonnais	CER/11/a	SoftWheat	20336,38	57,50
Bocage Bourbonnais	CER/11/a	Spelt	317,75	57,50
Bocage Bourbonnais	CER/11/b	DurumWheat	38,68	54,00
Bocage Bourbonnais	CER/12	Barley	7909,75	52,37
Bocage Bourbonnais	CER/13	Oat	383,44	42,27
Bocage Bourbonnais	CER/14	Triticale	8262,96	46,00
Bocage Bourbonnais	CER/15	Rye	109,60	37,67
Bocage Bourbonnais	CER/16	Maize	2974,42	94,90
Bocage Bourbonnais	CER/17	Sorghum	195,65	51,67
Bocage Bourbonnais	CER/19	Buckwheat	287,88	34,33
Bocage Bourbonnais	CER/19	CerealMix	1794,52	34,33
Bocage Bourbonnais	CER/19	Millet	90,96	34,33
Bocage Bourbonnais	CER/19	OtherCereals	25,42	34,33
Bocage Bourbonnais	FOUR/11	MaizeFodder	6703,99	92,83
Bocage Bourbonnais	FOUR/19	OtherFodder	172,41	107,40
Bocage Bourbonnais	FOUR/2	FodderBeet	38,76	333,18
Bocage Bourbonnais	FOUR/2	FodderRoots	16,44	333,18
Bocage Bourbonnais	FOUR/21	PoliphytedGrassland	4447,87	33,17
Bocage Bourbonnais	FOUR/22	Raygrass	393,67	33,17
Bocage Bourbonnais	FOUR/22	TemporaryGrassland	57412,50	33,17
Bocage Bourbonnais	FOUR/23	Alfalfa	1218,63	54,13
Bocage Bourbonnais	FOUR/23	ArtificialGrassland	13,63	54,13
Bocage Bourbonnais	FOUR/23	Clover	623,15	54,13
Bocage Bourbonnais	FOUR/23	FodderFaba	29,51	54,13
Bocage Bourbonnais	FOUR/23	FodderLegumes	166,77	54,13
Bocage Bourbonnais	FOUR/23	FodderPea	37,00	54,13
Bocage Bourbonnais	FRU/02/a	TemperateFruits	20,23	330,11
Bocage Bourbonnais	FRU/07/a	Vineyard	29,26	51,37
Bocage Bourbonnais	IND/42	Aroma	58,49	11,27
Bocage Bourbonnais	LEG/35	SugarBeet	18,90	202,83
Bocage Bourbonnais	LEG/41	GardenPea	10,00	72,67
Bocage Bourbonnais	LEG/6	Lentil	22,65	10,60
Bocage Bourbonnais	OL/21	Rapeseed	5346,54	31,83
Bocage Bourbonnais	OL/22	Sunflower	1134,01	25,00
Bocage Bourbonnais	OL/23	Soja	67,91	28,33
Bocage Bourbonnais	OL/29	Flax	46,93	16,47
Bocage Bourbonnais	PR/31	Pea	325,11	27,33
Bocage Bourbonnais	PR/31	PeaMix	696,97	27,33
Bocage Bourbonnais	PR/32	Faba	198,89	23,67
Bocage Bourbonnais	PR/33	Lupine	20,85	15,33
Bocage Bourbonnais	STH/a	Grassland	13071,72	50,00
Bocage Bourbonnais	STH/a	NaturalGrassland	100665,90	50,00
Bocage Bourbonnais	STH/b	OtherGrassland	172,74	20,00
Bocage Bourbonnais	STH/b	PoorPastures	6,97	20,00
Bocage Bourbonnais	TUB/13	PotatoConsumption	11,81	283,33
Bretagne Centrale	CER/11/a	SoftWheat	61712,04	73,13
Bretagne Centrale	CER/11/a	Spelt	10,46	73,13

Table SM1. 17 (continued).

FS	Plant ID	Plant name	Cultivated area in ha	Typical crop yield in fresh matter (100 kg/ha)
Bretagne Centrale	CER/12	Barley	19588,99	65,70
Bretagne Centrale	CER/13	Oat	1405,68	52,63
Bretagne Centrale	CER/14	Triticale	3312,39	56,83
Bretagne Centrale	CER/15	Rye	26,43	43,07
Bretagne Centrale	CER/16	Maize	25016,69	92,13
Bretagne Centrale	CER/17	Sorghum	15,42	52,57
Bretagne Centrale	CER/19	Buckwheat	218,50	35,00
Bretagne Centrale	CER/19	CerealMix	363,26	35,00
Bretagne Centrale	CER/19	OtherCereals	23,41	35,00
Bretagne Centrale	FOUR/11	MaizeFodder	48504,62	134,00
Bretagne Centrale	FOUR/19	OtherFodder	44,54	107,40
Bretagne Centrale	FOUR/2	FodderBeet	328,00	333,18
Bretagne Centrale	FOUR/2	FodderCabbage	14,39	333,18
Bretagne Centrale	FOUR/21	PoliphytedGrassland	1755,00	42,17
Bretagne Centrale	FOUR/22	Raygrass	18395,62	42,17
Bretagne Centrale	FOUR/22	TemporaryGrassland	27542,03	42,17
Bretagne Centrale	FOUR/23	Alfalfa	1025,09	69,47
Bretagne Centrale	FOUR/23	Clover	123,41	69,47
Bretagne Centrale	FOUR/23	FodderFaba	41,66	69,47
Bretagne Centrale	FOUR/23	FodderLegumes	86,19	69,47
Bretagne Centrale	FOUR/23	FodderLupine	9,74	69,47
Bretagne Centrale	FOUR/23	FodderPea	44,93	69,47
Bretagne Centrale	FRU/02/a	TemperateFruits	520,44	308,51
Bretagne Centrale	FRU/04/c	Chestnut	6,41	8,72
Bretagne Centrale	FRU/05	RedBerry	6,32	37,73
Bretagne Centrale	IND/22	Hemp	88,17	57,52
Bretagne Centrale	IND/42	Aroma	13,91	11,27
Bretagne Centrale	LEG/13	Celery	35,39	161,00
Bretagne Centrale	LEG/14	Cabbage	149,42	151,53
Bretagne Centrale	LEG/15	Endive	31,53	218,84
Bretagne Centrale	LEG/17	Leek	14,53	129,47
Bretagne Centrale	LEG/18	Lettuce	9,08	206,17
Bretagne Centrale	LEG/19	Condiment	5,35	218,97
Bretagne Centrale	LEG/21	Strawberry	6,22	219,23
Bretagne Centrale	LEG/23/c	Zucchini	5,39	374,23
Bretagne Centrale	LEG/31	Carrot	5,61	501,67
Bretagne Centrale	LEG/34	Onion	17,72	212,87
Bretagne Centrale	LEG/41	GardenPea	139,75	67,43
Bretagne Centrale	LEG/42	GreenBean	537,44	97,67
Bretagne Centrale	OL/21	Rapeseed	9660,39	36,07
Bretagne Centrale	OL/29	Flax	141,96	21,07
Bretagne Centrale	OL/29	Mustard	5,94	21,07
Bretagne Centrale	PR/31	Pea	610,72	39,73
Bretagne Centrale	PR/31	PeaMix	415,77	39,73
Bretagne Centrale	PR/32	Faba	481,39	32,47
Bretagne Centrale	PR/33	Lupine	48,55	28,33
Bretagne Centrale	STH/a	Grassland	7428,85	50,00
Bretagne Centrale	STH/a	NaturalGrassland	6892,49	50,00

Table SM1. 17 (continued).

FS	Plant ID	Plant name	Cultivated area in ha	Typical crop yield in fresh matter (100 kg/ha)
Bretagne Centrale	STH/b	OtherGrassland	67,86	20,00
Bretagne Centrale	STH/b	PoorPastures	53,97	20,00
Bretagne Centrale	TUB/13	PotatoConsumption	334,69	255,30
Plateau Picard	CER/11/a	SoftWheat	99567,53	72,00
Plateau Picard	CER/11/a	Spelt	305,87	72,00
Plateau Picard	CER/12	Barley	19721,49	69,23
Plateau Picard	CER/13	Oat	369,68	58,27
Plateau Picard	CER/14	Triticale	133,32	53,67
Plateau Picard	CER/15	Rye	54,92	61,67
Plateau Picard	CER/16	Maize	4267,54	81,93
Plateau Picard	CER/19	Buckwheat	34,24	53,00
Plateau Picard	CER/19	CerealMix	12,74	53,00
Plateau Picard	CER/19	OtherCereals	122,26	53,00
Plateau Picard	FOUR/11	MaizeFodder	7375,21	140,67
Plateau Picard	FOUR/19	OtherFodder	288,20	107,40
Plateau Picard	FOUR/2	FodderBeet	224,09	333,18
Plateau Picard	FOUR/21	PoliphytedGrassland	141,94	58,53
Plateau Picard	FOUR/22	Raygrass	273,56	58,53
Plateau Picard	FOUR/22	TemporaryGrassland	1208,51	58,53
Plateau Picard	FOUR/23	Alfalfa	1230,58	87,53
Plateau Picard	FOUR/23	ArtificialGrassland	19,23	87,53
Plateau Picard	FOUR/23	Clover	168,25	87,53
Plateau Picard	FOUR/23	FodderFaba	56,56	87,53
Plateau Picard	FOUR/23	FodderPea	82,05	87,53
Plateau Picard	FRU/02/a	TemperateFruits	133,58	353,97
Plateau Picard	FRU/05	RedBerry	5,88	40,30
Plateau Picard	IND/21	Linen	2032,94	60,00
Plateau Picard	LEG/13	Celery	6,08	283,20
Plateau Picard	LEG/15	Endive	52,09	218,84
Plateau Picard	LEG/21	Strawberry	5,60	154,27
Plateau Picard	LEG/31	Carrot	94,73	581,10
Plateau Picard	LEG/34	Onion	255,23	315,93
Plateau Picard	LEG/35	SugarBeet	18431,73	357,40
Plateau Picard	LEG/41	GardenPea	1591,33	61,67
Plateau Picard	LEG/42	GreenBean	298,84	123,57
Plateau Picard	LEG/6	Lentil	41,40	11,13
Plateau Picard	OL/21	Rapeseed	24721,22	35,50
Plateau Picard	OL/22	Sunflower	15,36	24,67
Plateau Picard	OL/23	Soja	23,11	36,67
Plateau Picard	OL/29	Flax	224,89	20,70
Plateau Picard	OL/29	Mustard	48,53	20,70
Plateau Picard	PR/31	Pea	6841,99	37,67
Plateau Picard	PR/31	PeaMix	69,94	37,67
Plateau Picard	PR/32	Faba	1119,18	31,00
Plateau Picard	STH/a	Grassland	1421,82	50,00
Plateau Picard	STH/a	NaturalGrassland	11793,33	50,00
Plateau Picard	TUB/12	PotatoStarch	713,43	398,33
Plateau Picard	TUB/13	PotatoConsumption	2622,36	420,47

SM1.5 Uncertainties

Table SM1. 18 Uncertainties range (minimum and maximum) per parameter, considering the global sensitivity analysis done in R language with the FME package.

Parameter or variable name	Unit	Value (if applicable)	Min (absolute or relative) (NC: not considered)	Max (absolute or relative) (NC: not considered)
Biomass allocation coefficient to humans	%	NA	-20%	+20%
Biomass allocation coefficient to livestock	%	NA	-20%	+20%
Humification factor - Human effluent	%	70	60	80
Humification factor - Livestock effluent	%	NA	-20%	+20%
Humification factor - Aerial residues	%	NA	-20%	+20%
Humification factor - Root residues	%	NA	-20%	+20%
C:N ratio - Human effluent	-	10	8	12
C:N ratio - Livestock effluent	-	NA	-20%	+20%
C:N ratio - Aerial residues	-	NA	-20%	+20%
C:N ratio - Root residues	-	NA	-20%	+20%
Emission factors - Volatilisation during storage of housing facilities effluents	%	5	3	7
Emission factors - Volatilisation during excretion of effluents in housing facilities	%	30	20	40
Emission factors - N ₂ O emissions of effluents in housing facilities and during storage	%	1	0	2
Emission factors - Leaching of effluents during excretion and storage in housing facilities	%	10	5	15
Emission factors - N ₂ O emissions due to soil management	%	3	0	5
Emission factors - Soil mineral nitrogen lixiviation	%	20	10	30
Emission factors - N ₂ O emissions of synthetic fertilisers application	%	1	0	3
Emission factors - Volatilisation of organic fertilisers application	%	20	15	25

Table SM1. 18 (continued).

Parameter or variable name	Unit	Value (if applicable)	Min (absolute or relative) (NC: not considered)	Max (absolute or relative) (NC: not considered)
Emission factors - Volatilisation of synthetic fertilisers application	%	10	5	20
C:N ratio of the cropland soil	-	NA	-10%	+10%
C:N ratio of the grassland soil	-	NA	-10%	+10%
Shoot-to-root ratio	-	NA	-10%	+10%
Harvest index	-	NA	-10%	+10%
Typical yield	100kg/ha (fresh matter)	NA	-10%	+10%
Area cultivated	ha	NA	NC	NC
Biological nitrogen fixation	kg/ha	NA	-10%	+10%
Nitrogen content of the harvested organ	kg/100kg (fresh matter)	NA	-10%	+10%
Nitrogen content of the aerial residues	kg/100kg (fresh matter)	NA	-10%	+10%
Nitrogen content of the root residues	kg/100kg (fresh matter)	NA	-10%	+10%
Share of aerial crop residues exported as livestock bedding	%	35	25	45
Quantity of human excretion recovered and applied as sludge on field	kg	NA	NC	NC
Quantity of the feed consumed per livestock unit and per species	kg/LU	NA	-10%	+10%
Meat production coefficient per species	kg/LU	NA	-10%	+10%
Milk production coefficient per species	kg/LU	NA	-10%	+10%
Egg production coefficient per species	kg/LU	NA	-10%	+10%
Feed shortage threshold beyond which the livestock number is decreased	%	0.1	0.05	0.2
Atmospheric deposition on soil of NO _x	kg/ha	10	0	20
Initial number of livestock	LU	NA	NC	NC

Appendix 2 Supplementary Material of Chapter 2

SM2.1 Model description

See section II.3 in the General methodology.

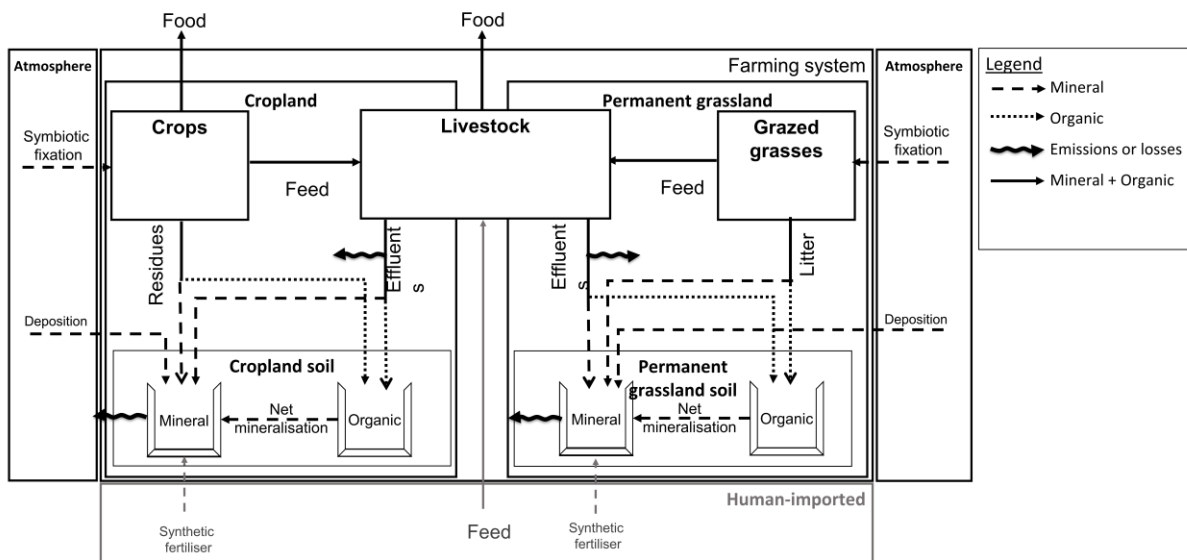


Figure SM2.1 Conceptual scheme of the model. Boxes are the compartments and arrows are the nitrogen flows. Nitrogen flows are of different types: mineral (dashed lines), organic (point lines), or mixed (full lines). The external flows that enter the FS come either from the atmosphere or are imported by humans (in grey). The wavy arrows represent gaseous or liquid losses of nitrogen. Figure adapted from Pinsard et al. (2021).

SM2.2 Results

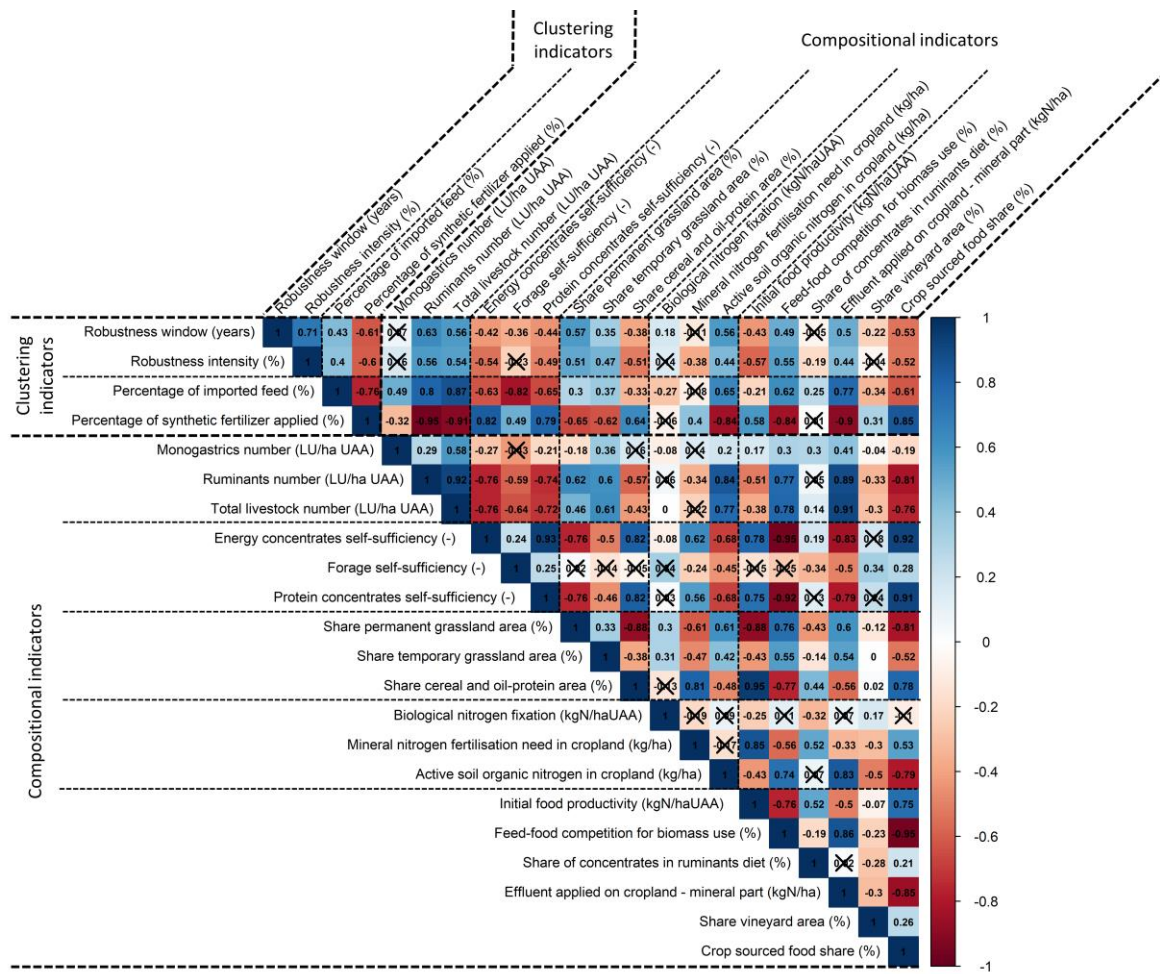


Figure SM2.2 Correlation matrix of robustness indicators and compositional indicators in France at the small agricultural region resolution, obtained with the package “stats” in R, with method “Spearman”. Robustness indicators (Robustness window and intensity) are defined in Figure 2 of the paper. We tested the significance of the correlations. A cross means that the correlation is not significant (p -value greater than 0.01).

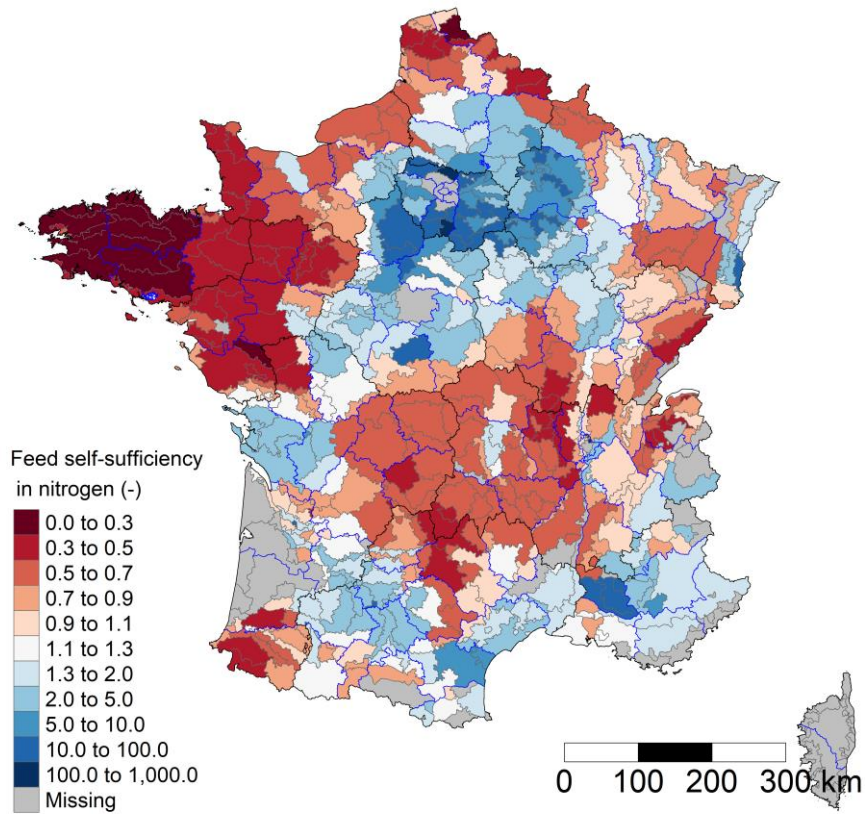


Figure SM2.3 Total feed self-sufficiency in mass of N per SAR. Feed production was assessed using national average allocation coefficients. This explains the highest feed self-sufficiency for the SARs around Paris. In these SARs, crops are first allocated to humans.

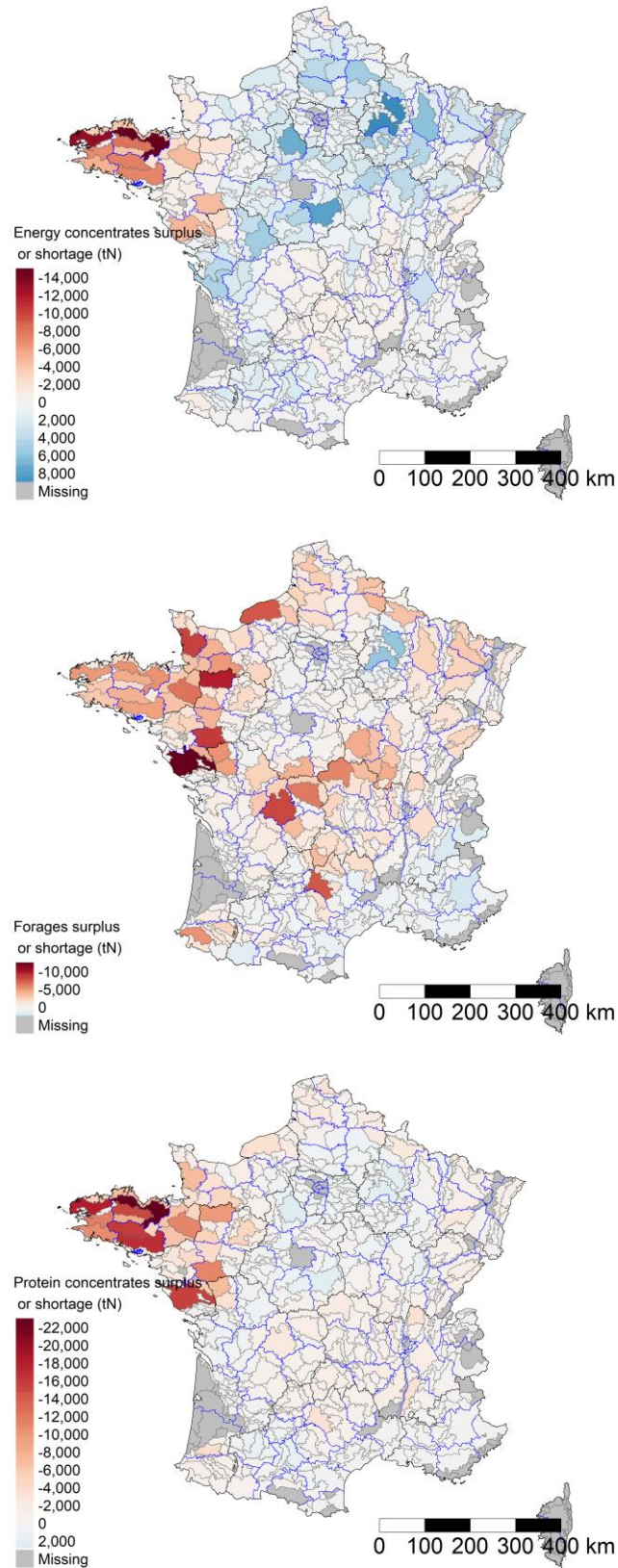


Figure SM2.4 Feed surplus or shortage in tons N per feed category and per SAR. Brittany has shortages in the three feed categories.

Appendix 3 Supplementary Material of Chapter 4

SM3.1 Material and methods

Table SM3. 1 Parameters description with data source and nominal value for non-multidimensional parameters.

Compartment	Parameter	Notation	Nominal value ¹	Unit	Source
GHG balance	CO ₂ emissions linked to the transportation of the feed imported	$\epsilon_{FI}^{CO_2}$	0.12	kgCO ₂ . (T. km) ⁻¹	(ADEME, 2012)
	CO ₂ emissions linked to the production and transportation of synthetic fertilizer	$\epsilon_{SF}^{CO_2}$	5.62	kgCO ₂ . kgN ⁻¹	(FAO, 2017)
	CH ₄ emissions from cattle effluent	$\epsilon_{eff}^{CH_4}$	1.3	%	(IPCC, 2019)
Soil and plant	Mineralisation rate	μ_i	13 or 5.5	%	(Clivot et al., 2019)
	Consumption index – Share of the harvested organ grazed by ruminants	CI_i	REP	%	(R. Teixeira et al., 2018)
	Shoot-to-root ratio	SR_i	REP	-	(Clivot et al., 2019)
	Harvest index	HI_i	REP	%	(Clivot et al., 2019)
	Typical yield	y_i^{TYP}	REP	100kg. ha ⁻¹	(Instituto Nacional de Estadística, 2020)
	Area cultivated	A_i	REP	ha	(Instituto Nacional de Estadística, 2020)
	Biological nitrogen fixation	\dot{n}_i^{BF}	REP	kgN. ha ⁻¹	(Anglade et al., 2015)
	Nitrogen content of the harvested organ	$\sigma_i^{N,H}$	REP	kgN. 100kg ⁻¹	(Clivot et al., 2019)
	Carbon content	σ_i^C	REP	kgC. kg ⁻¹	(Clivot et al., 2019)
	Nitrogen content of the aerial residues	σ_i^{N,R^A}	REP	kgN. 100kg ⁻¹	(Clivot et al., 2019)
	Nitrogen content of the root residues	σ_i^{N,R^R}	REP	kgN. 100kg ⁻¹	(Clivot et al., 2019)
	Humification factor - Aerial residues	$\Phi_i^{R^A}$	REP	%	(Fuchs et al., 2014)
	Humification factor - Root residues	$\Phi_i^{R^R}$	REP	%	(Fuchs et al., 2014)
	Volatilisation of organic fertilisers application	$\epsilon^{V^{ORG}}$	12	%	(IPCC et al., 2006)
	Volatilisation of synthetic fertilisers application	$\epsilon^{V^{SYN}}$	8	%	(IPCC et al., 2006)
	N ₂ O emissions due to soil management	$\epsilon^{N_2O,SM}$	1	%	(IPCC et al., 2006)
	N ₂ O emissions of synthetic fertilisers application	$\epsilon^{N_2O,APP}$	1	%	(IPCC et al., 2006)
	N ₂ O emissions due to legumes	$\epsilon^{N_2O,LEG}$	0.0125	kgN ₂ O. kgN ⁻¹	(IPCC et al., 2006)
	Soil mineral nitrogen lixiviation	$\epsilon^{L,APP}$	5	%	(Lin et al., 2001)
	Harvested biomass to cattle (after transformation or not)	$v_{i,k}$	100	%	(Instituto Nacional de Estadística, 2020)
Atmospheric deposition on soil of NO _x	\dot{n}^D	2	kgN. ha ⁻¹	(Norwegian Meteorological Institute, 2020)	

Table SM3. 1 (continued).

Compartment	Parameter	Notation	Nominal value ¹	Unit	Source
Beef cattle herd	Average live weight of cattle class a, s	$\bar{W}_{(a,s)}$	REP	kg live weight	(Marques et al., 2020)
	Live weight of cattle class a, s at the beginning of the year	$W_{(a,s)}^I$	REP	kg live weight	(Marques et al., 2020)
	Live weight of cattle class a, s at the end of the year	$W_{(a,s)}^E$	REP	kg live weight	(Marques et al., 2020)
	Share of the year the cattle of class a, s consumes the diet type m	$\tau_{(a,s),m}$	REP	%	(R. Teixeira et al., 2018)
	Share of the year spent by the cattle of class a, s grazing	$\tau_{(a,s)}^G$	REP	%	(R. Teixeira et al., 2018)
	Share of digestible energy for beef of the edible part of the plants	α_1^{DE}	REP	%	(INRA, 2018)
	Quantity of feed consumed per age and sex cattle class	$\hat{n}_{(a,s)}^{Feed,Need}$	75	kgN.LU ⁻¹	(Hou et al., 2016)
	Share of the feed category k in the diet m	$\alpha_{k,m}$	REP	%	(Costa et al., 2012)
	Calving ratio – Share of suckler cows giving birth	β	70	%	(Instituto Nacional de Estadística, 2020)
	Slaughtering ratio of young heifers	$\gamma_{(1,F)}$	50	%	(Instituto Nacional de Estadística, 2020)
	Slaughtering ratio of young steers	$\gamma_{(1,M)}$	10	%	(Instituto Nacional de Estadística, 2020)
	Slaughtering ratio of old heifers	$\gamma_{(2,F)}$	10	%	(Instituto Nacional de Estadística, 2020)
	Humification factor - Cattle effluent	$\Phi_{(a,s)}^E$	20	%	(Fuchs et al., 2014)
	Volatilisation during storage of effluents in housing facilities	ϵ^{VS}	5	%	(APA, 2018)
	Volatilisation during excretion of effluents on permanent pastures	ϵ^{VG}	10	%	(APA, 2018)
	Volatilisation during excretion of effluents in housing facilities	ϵ^{VB}	30	%	(APA, 2018)
	N ₂ O emissions of effluents in housing facilities and during storage	ϵ^{N_2O}	2	%	(APA, 2018)
	Leaching of effluents during excretion and storage in housing facilities	ϵ^L	10	%	(APA, 2018)
	Carbon to nitrogen ratio of cow milk	$C:N^{Milk}$	10.4	-	(R. Teixeira et al., 2018)
	Cattle carbon content	$\sigma^{C,C}$	0.467	kgC.kg live weight ⁻¹	(R. Teixeira et al., 2018)
Cattle nitrogen content	$\sigma^{N,C}$	0.114	kgC.kg live weight ⁻¹	(R. Teixeira et al., 2018)	

¹ REP: see data tables on the repository

Table SM3. 2 Model equation formulas according to the biogeochemical cycle, the compartment and land use considered and the item. Carbon quantities estimated from nitrogen quantities are filled in grey.

Number	Compartment / Land use	Item	Cycle	Equation formula
(4-1)	Soil	Organic pool	C	$c_{l,t+1}^{Soil} = c_{l,t}^{Soil} * (1 - \mu_l) + \dot{c}_{l,t}^{rA} + \dot{c}_{l,t}^{rR} + \dot{c}_{l,t}^E$, where $\dot{C}_t^E = \dot{C}_t^{EB} + \dot{C}_t^{EG} - \dot{C}_t^{CO_2,EFF} - \dot{C}_t^{CH_4,EFF}$
	Soil	Organic pool	N	$n_{l,t+1}^{Soil} = (n_{l,t}^{Soil} + \dot{n}_{l,t}^{rA} + \dot{n}_{l,t}^{rR} + \dot{n}_{l,t}^E) - (\mu_l * n_{l,t}^{Soil} - \dot{n}_{l,t+1}^I)$
(4-2)	Soil	Mineral pool - Cropland	N	$\dot{n}_{i,l,t+1}^{Fert,Av} = [\dot{n}_{l,t}^{OA} + (\mu_l * n_{l,t}^{Soil} - \dot{n}_{l,t+1}^I) + \dot{n}^D + \dot{n}_{i,t+1}^{Synth}] * (1 - \epsilon^{TOT}) - \dot{n}_{l,t}^{OA} * \epsilon^{V,ORG} + \dot{n}_i^{BF} * (1 - \epsilon^{N_2O,LEG}) - \dot{n}_{i,t+1}^{Synth} * \epsilon^{V,SYN}$, where $\epsilon^{TOT} = \epsilon^{L,APP} + \epsilon^{N_2O,APP} + \epsilon^{N_2O,SM}$ and $\dot{n}_{l,t}^{OA} = \dot{n}_{l,t}^{rA} + \dot{n}_{l,t}^{rR} + \dot{n}_{l,t}^E$
(4-2)	Soil	Mineral pool - Permanent pastures	N	$\dot{n}_{i,l,t+1}^{Fert,Av} = [\dot{n}_{l,t}^{OA} + (\mu_l * n_{l,t}^{Soil} - \dot{n}_{l,t+1}^I) + \dot{n}^D] * (1 - \epsilon^{TOT}) - \dot{n}_{l,t}^{OA} * \epsilon^{V,ORG} + \dot{n}_i^{BF} * (1 - \epsilon^{N_2O,LEG})$
	Plant	Residues application emissions - CO ₂	C	$\dot{C}_t^{CO_2,RES} = \sum_i \eta_{i,t} * A_i * (\sigma_i^{RA} * C : N^{RA} * (1 - \phi_i^{RA}) * \frac{1 - HI_i}{HI_i} + 1.65 * \sigma_i^{RR} * C : N^{RR} * (1 - \phi_i^{RR}) * \frac{1}{SR_i * HI_i})$
	Livestock - Herd	Population dynamics	NA (heads)	$\begin{cases} L_{(1,M),t+1} = 0.5 * \beta * L_{(3,F),t} * (1 - S_{(1,M),t+1}) \\ L_{(2,M),t+1} = L_{(1,M),t} * (1 - \gamma_{(1,M)}) \\ L_{(1,F),t+1} = 0.5 * \beta * L_{(3,F),t} * (1 - S_{(1,F),t+1}) \\ L_{(2,F),t+1} = L_{(1,F),t} * (1 - S_{(2,F),t+1} - \gamma_{(1,F)}) \\ L_{(3,F),t+1} = L_{(2,F),t} * (1 - \gamma_{(2,F)}) + L_{(3,F),t} * (1 - \gamma_{(3,F)}) \\ L_{offs,t+1} = \beta * L_{(3,F),t} \end{cases}$, where $\gamma_{(3,F)} = \frac{L_{(2,F),t} * (1 - \gamma_{(2,F)})}{L_{(3,F),t}} + S_{(3,F),t+1}$
(4-3)	Livestock - Herd	Meat production	NA (carcass weight)	$P_{t+1} = \beta * 0.5 * L_{(3,F),t} * (S_{(1,M),t+1} * W_{(1,M)}^I + S_{(1,F),t+1} * W_{(1,F)}^I) + L_{(2,M),t} * (1 - S_{(2,M),t+1}) * W_{(2,M)}^E + L_{(1,M),t} * \gamma_{(1,M)} * W_{(2,M)}^I + L_{(1,F),t} * (\gamma_{(1,F)} + S_{(2,F),t+1}) * W_{(2,F)}^I + L_{(2,F),t} * \gamma_{(2,F)} * W_{(3,F)}^I + L_{(3,F),t} * \gamma_{(3,F)} * W_{(3,F)}^I$
	Livestock - Individual	Feed intake	C	$\dot{C}_t^{Feed,Need} = \dot{N}_t^{Feed,Need} * \overline{C : N_{feed}}$, where $\overline{C : N_{feed}}$ is estimated using the carbon content of the feed intake

Table SM3. 2 (continued).

Number	Compartment / Land use	Item	Cycle	Equation formula
	Livestock - Individual	Feed intake	N	$\dot{N}_{(a,s),k,t}^{Feed,Need} = L_{(a,s),t} * \dot{n}_{(a,s)}^{Feed,Need} * \sum_m \alpha_{k,m} * \tau_{(a,s),m}$
	Livestock - Individual	Accumulation – Body weight gain	C	$C_{(a,s),t+1}^L = C_{(a,s),t}^L + L_{(a,s),t} * (1 - 0.65) * \sigma^{C,C} * (W_{(a,s)}^E - W_{(a,s)}^I)$
	Livestock - Individual	Accumulation – Body weight gain	N	$N_{(a,s),t+1}^L = N_{(a,s),t}^L + L_{(a,s),t} * (1 - 0.65) * \sigma^{N,C} * (W_{(a,s)}^E - W_{(a,s)}^I)$
	Livestock - Individual	Offsprings	C	$\dot{C}_{(3,F),t}^{Offs} = L_{Offs,t} * (1 - 0.65) * \sigma^{C,C} * (W_{Offs}^E)$
	Livestock - Individual	Offsprings	N	$\dot{N}_{(3,F),t}^{Offs} = L_{Offs,t} * (1 - 0.65) * \sigma^{N,C} * (W_{Offs}^E)$
	Livestock - Individual	Milk	C	$\dot{C}_{(3,F),t}^{Milk} = \dot{N}_{(3,F),t}^{Milk} * C : N^{Milk}$
	Livestock - Individual	Milk	N	$\dot{N}_{(3,F),t}^{Milk} = (L_{(1,M),t} * \dot{n}_{(1,M)}^{Feed,Need} + L_{(1,F),t} * \dot{n}_{(1,F)}^{Feed,Need}) * 0.5$
	Livestock	Excretion on permanent pastures	C	$\dot{C}_{t+1}^{EG} = \sum_{(a,s)} (\dot{N}_{(a,s),t}^{Feed,Need} - (N_{(a,s),t+1}^L - N_{(a,s),t}^L) - \dot{N}_{(a,s),t}^{Offs} - \dot{N}_{(a,s),t}^{Milk}) * \tau_{(a,s)} * C : N_{(a,s)}$
	Livestock	Excretion in housing facilities	C	$\dot{C}_{t+1}^{EB} = \sum_{(a,s)} (\dot{N}_{(a,s),t}^{Feed,Need} - (N_{(a,s),t+1}^L - N_{(a,s),t}^L) - \dot{N}_{(a,s),t}^{Offs} - \dot{N}_{(a,s),t}^{Milk}) * (1 - \tau_{(a,s)}) * C : N_{(a,s)}$
	Livestock	Excretion on permanent pastures	N	$\dot{N}_{t+1}^{EG} = \sum_{(a,s)} (\dot{N}_{(a,s),t}^{Feed,Need} - (N_{(a,s),t+1}^L - N_{(a,s),t}^L) - \dot{N}_{(a,s),t}^{Offs} - \dot{N}_{(a,s),t}^{Milk}) * \tau_{(a,s)}$
	Livestock	Excretion in housing facilities	N	$\dot{N}_{t+1}^{EB} = \sum_{(a,s)} (\dot{N}_{(a,s),t}^{Feed,Need} - (N_{(a,s),t+1}^L - N_{(a,s),t}^L) - \dot{N}_{(a,s),t}^{Offs} - \dot{N}_{(a,s),t}^{Milk}) * (1 - \tau_{(a,s)})$

Table SM3. 2 (continued).

Number	Compartment / Land use	Item	Cycle	Equation formula
	Livestock	Enteric fermentation - CH ₄	C	$\dot{C}_{t+1}^{CH_4,EF} = \frac{M_C}{M_{CH_4}} * (DMI_t * (a * \overline{DE} + b))$, where a and b are the coefficient of the linear interpolation of the Tier 2 IP CC equation for methane emission from enteric fermentation between CH ₄ yield and feed digestibility. M_C and M_{CH_4} are the molar masses for carbon and methane respectively. \overline{DE} corresponds to the average digestibility (-) of the feed intake by cattle. DMI_t corresponds to the dry matter intake (kg dry matter) by cattle at time t .
	Livestock	Respiration - CO ₂	C	$\dot{C}_{t+1}^{CO_2,Resp} = \dot{C}_{t+1}^{Feed,Need} - \dot{C}_{t+1}^{E^B} - \dot{C}_{t+1}^{E^G} - (C_{t+1}^L - C_t^L) - \dot{C}_{t+1}^{CH_4,EF} - \dot{C}_{t+1}^{Offs} - \dot{C}_{t+1}^{Milk}$
	Livestock	Effluent application emissions - CO ₂	C	$\dot{C}_t^{CO_2,EFF} = \sum_{(a,s)} (\dot{C}_{(a,s),t}^{E^G} + \dot{C}_{(a,s),t}^{E^B}) * (1 - \epsilon_{eff}^{CH_4}) * (1 - \phi_{(a,s)})$
	Livestock	Effluent application emissions - CH ₄	C	$\dot{C}_t^{CH_4,EFF} = \sum_{(a,s)} (\dot{C}_{(a,s),t}^{E^G} + \dot{C}_{(a,s),t}^{E^B}) * \epsilon_{eff}^{CH_4}$
	Livestock	Effluent management emissions - N ₂ O	N	$\dot{N}_{t+1}^{N_2O,EM} = \sum_{(a,s)} (\dot{N}_{(a,s),t}^{Feed,Need} - (N_{(a,s),t+1}^L - N_{(a,s),t}^L) - \dot{N}_{(a,s),t}^{Offs} - \dot{N}_{(a,s),t}^{Milk}) * \epsilon^{N_2O}$
	Plant	Legumes - N ₂ O	N	$\dot{N}_{t+1}^{N_2O,LEG} = [\sum_i \dot{n}_i^{BF} * A_i] * (\epsilon^{N_2O,LEG})$
	Soil	Soil management - cropland - N ₂ O	N	$\dot{N}_{l,t+1}^{N_2O,SM} = (\epsilon^{N_2O,APP} + \epsilon^{N_2O,SM}) * \sum_i A_i * [\dot{n}_{l,t}^{OA} + (\mu_l * n_{l,t}^{Soil} - \dot{n}_{l,t+1}^I) + \dot{n}^D + \dot{n}_{l,t+1}^{Synth}]$
	Soil	Soil management - permanent pastures - N ₂ O	N	$\dot{N}_{l,t+1}^{N_2O,SM} = (\epsilon^{N_2O,APP} + \epsilon^{N_2O,SM}) * \sum_i A_i * [\dot{n}_{l,t}^{OA} + (\mu_l * n_{l,t}^{Soil} - \dot{n}_{l,t+1}^I) + \dot{n}^D]$

SM3.2 Results

SM3.2.1 Beef cattle number

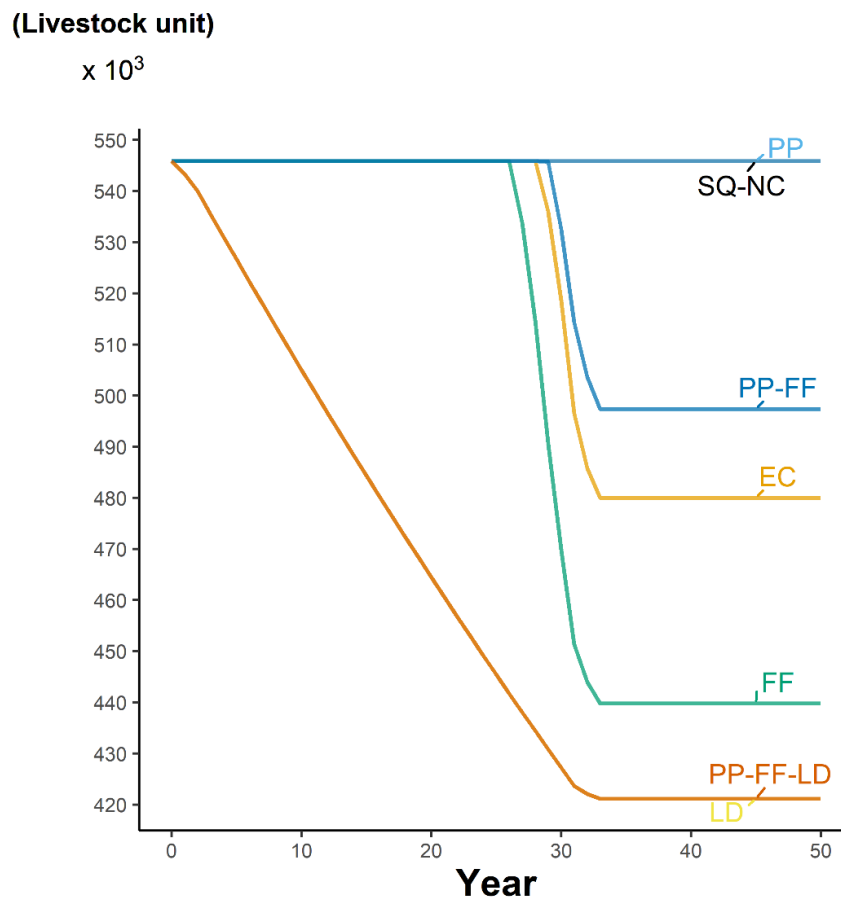


Figure SM3.1 Beef cattle number in livestock unit (converted from heads using coefficients from Eurostat) over time per scenario. The herd size decreases in scenarios with voluntary decrease of the herd, or in EC, FF and PP-FF scenarios. Initially the herd size is worth less than 550 000 livestock units.

SM3.2.2 Feed shortage for old steers

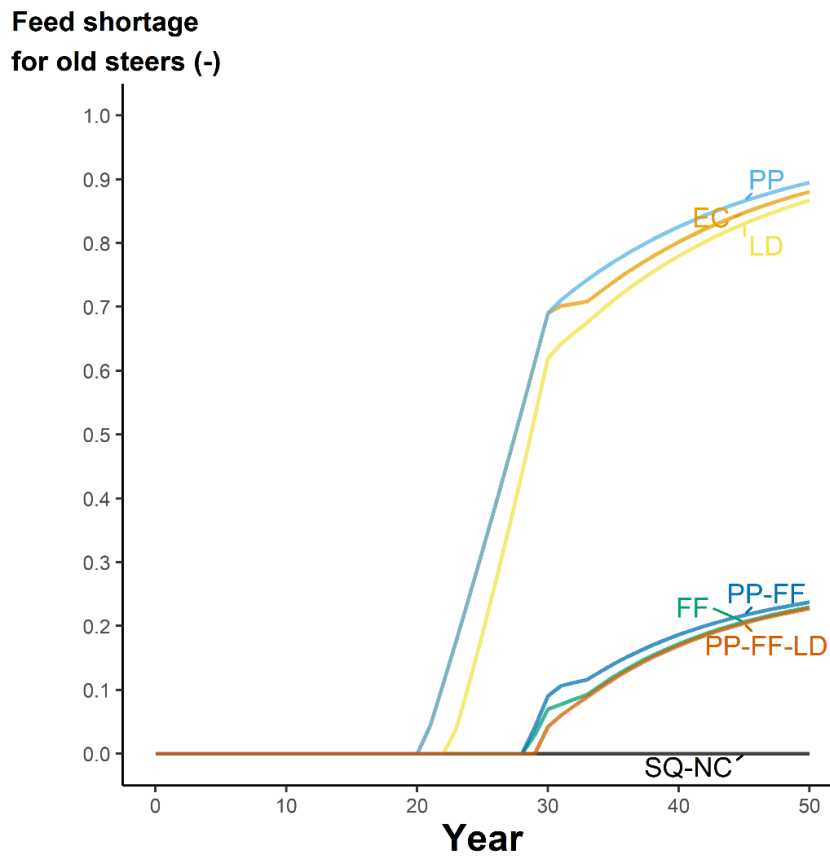


Figure SM3.2 Feed shortage share for old steers over time and per scenario. In scenarios with diet shift (FF, PP-FF, PP-FF-LD) the shortage is reduced (maximum 0.2 in year 50) in comparison to other scenarios with challenges (almost 1 in year 50).

SM3.2.3 Meat production vs. total GHG balance

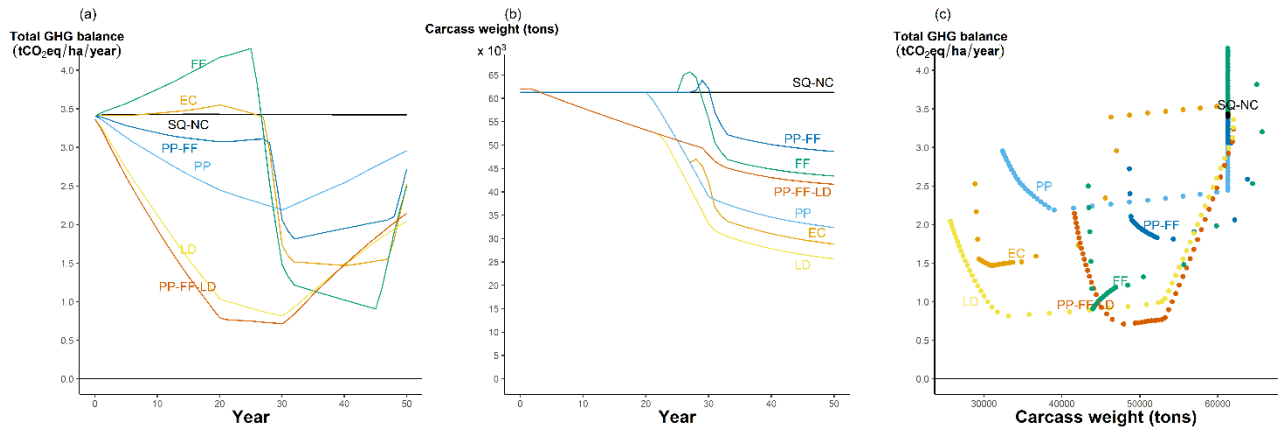


Figure SM3.3 Meat production vs. total annual GHG balance over time and per scenario (colors). (a) Total annual GHG balance in tCO₂eq/ha/year. (b) Meat production in tons/year of carcass. (c) Total GHG balance vs. meat production. Relation between total GHG balance and meat production are non-linear.

SM3.2.4 Global warming potential 100 years and star of methane emissions

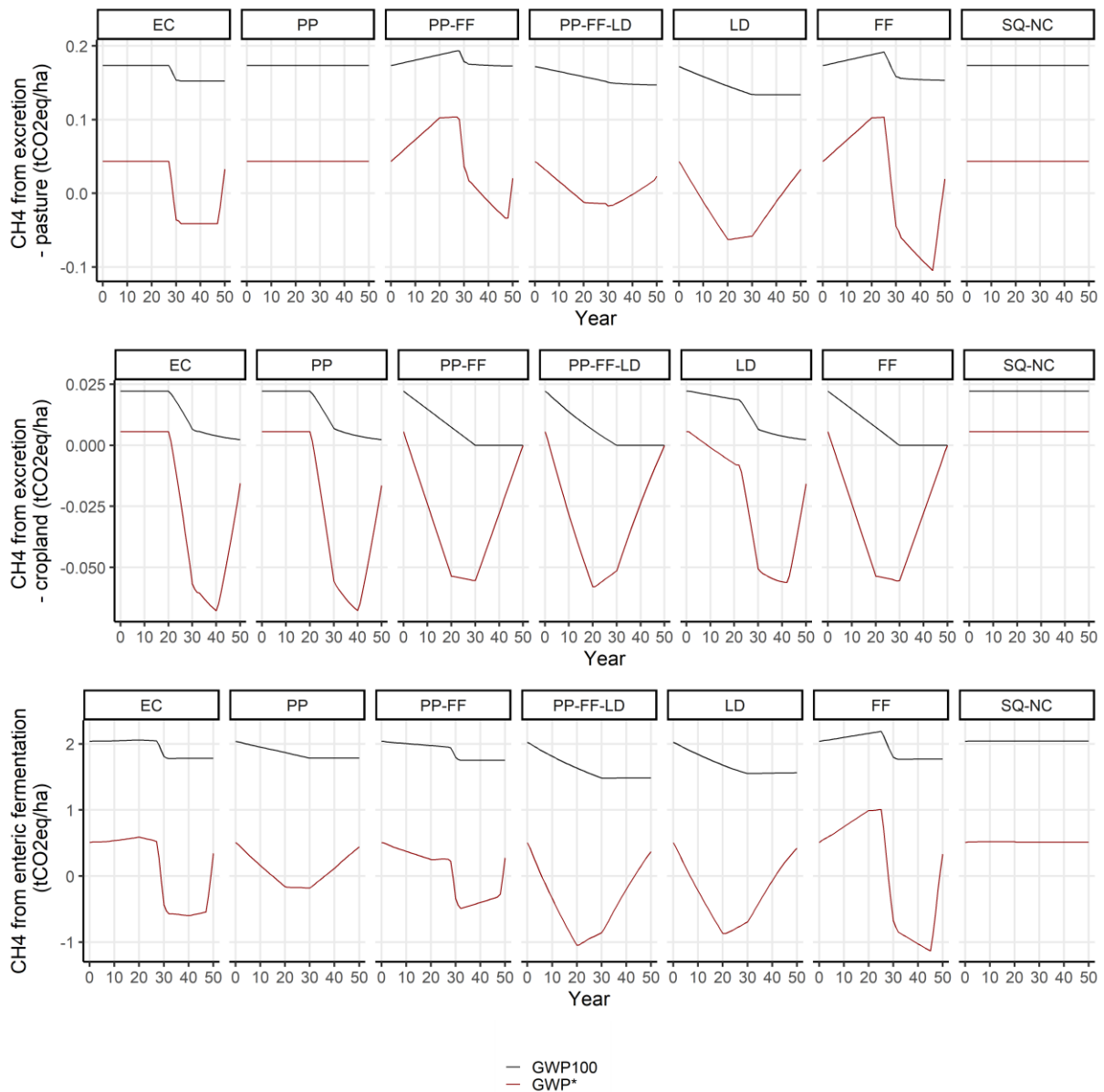


Figure SM3.4 Methane emissions (in tCO₂eq/ha) per scenario and per global warming potential coefficient type (GWP 100 years and GWP* (Lynch et al., 2020)). (a) Methane emissions from pasture excretions. (b) Methane emissions from manure application on cropland. (c) Methane emissions from enteric fermentation. The decrease in methane emissions generates a positive effect on the climate described only by the GWP* coefficient. At a constant emission rate, the effect of methane emissions on the climate is 3x lower with the GWP* coefficient than with the GWP₁₀₀ coefficient

SM3.2.5 Local sensitivity analysis

The local sensitivity analysis allowed identifying the parameters that particularly influence the meat production and the total GHG balance (with the GWP*) outputs among all the parameters. The results of the sensitivity analysis vary according to the scenarios for both outputs (Table SM3. 3 and Table SM3. 4).

SM3.2.5.1 Meat production

In all scenarios, the share of suckler cows giving birth leads to a very high sensitivity to meat production (~40 000 tons carcass in average), while the ratio of young heifers slaughtered leads to a tenfold lower sensitivity. Only in scenarios with forage shortage (EC and FF), specific crop parameters and emission factors influence meat production from +17 000 to -5 000 tons of carcass.

Table SM3. 3 Mean values from a local sensitivity analysis for the meat production (in ton carcass) per parameter (lines) and per scenario (columns). Parameters influencing meat production at least more than +2 000 tons carcass or less than -2 000 tons carcass in one scenario are shown. SBP stands for Sown Biodiverse Permanent Pasture Rich in Legumes and SNP for Semi-Natural Pasture.

Parameter	Scenario						
	SQ-NC	EC	PP	FF	LD	PP-FF	PP-FF-LD
Calving ratio – Share of suckler cows giving birth	59160.71	37186.11	42047.78	43122.47	37557.44	55240.92	47232.09
Emission factor - Soil mineral nitrogen lixiviation	0.00	-1550.29	-676.80	-2108.62	-579.23	-238.84	-185.32
Emission factor - Volatilisation of organic fertilisers application	0.00	-1493.60	-342.93	-2590.94	-281.29	-36.38	-25.73
Yield - SBP	0.00	7784.44	0.00	17084.80	0.00	0.00	0.00
Harvest index - SBP	0.00	-3258.10	0.00	-7140.07	0.00	0.00	0.00
Harvest index - SNP	0.00	4057.46	0.00	9057.53	0.00	0.00	0.00
Nitrogen content – harvested organ - SBP	0.00	5372.42	0.00	11798.88	0.00	0.00	0.00
Nitrogen content – harvested organ - SNP	0.00	2837.32	0.00	6355.14	0.00	0.00	0.00
Nitrogen content root residues - SBP	0.00	2200.51	0.00	4822.38	0.00	0.00	0.00
Nitrogen content root residues - SNP	0.00	-2210.10	0.00	-4937.36	0.00	0.00	0.00
Shoot-to-root ratio - SBP	0.00	-2200.51	0.00	-4822.38	0.00	0.00	0.00
Shoot-to-root ratio - SNP	0.00	2210.10	0.00	4937.36	0.00	0.00	0.00
Slaughtering ratio of young heifers	-4410.00	-3080.75	-4410.00	-1937.30	-3794.16	-4410.00	-3794.16

SM3.2.5.2 Total GHG balance

All parameters influence the total GHG balance in all scenarios. Aerial residues C:N ratios of SNP and SBP and nitrogen content of the harvested organ of SNP and SBP leads to the highest sensitivity for the annual total GHG balance (from -1 000 to +3 000 ktCO₂eq) while harvest indices and shoot-to-root ratios of SNP and SBP lead to a negative sensitivity between 0 and -1 000 ktCO₂eq except in scenario SQ-NC. These parameters, of the soil organic matter sub-model, impact the carbon sequestration value in the soil. The sensitivity of these parameters is already widely documented and discussed in the scientific literature (Clivot et al., 2019).

Table SM3. 4 Mean values from a local sensitivity analysis for the annual total GHG balance (in ktCO₂-e) per parameter (lines) and per scenario (columns). Parameters influencing the annual total GHG balance at least more than +200 ktCO₂-e or less than -200 ktCO₂-e in one scenario are shown. SBP stands for Sown Biodiverse Permanent Pasture Rich in Legumes and SNP for Semi-Natural Pasture.

Parameter	Scenario						
	SQ-NC	EC	PP	FF	LD	PP-FF	PP-FF-LD
Calving ratio – Share of suckler cows giving birth	1406.52	-61.67	604.86	-187.84	738.29	916.81	651.96
Aerial residues C:N ratio - SBP	1078.73	1110.36	2207.81	1124.28	1110.84	2076.50	2494.22
Aerial residues C:N ratio - SNP	1696.13	1720.63	1856.31	1752.04	1662.06	1817.22	1941.90
Share of digestible energy for beef of the edible part of SNP as forages	-212.26	355.09	927.72	350.40	458.41	732.32	1279.66
Emission factor - Soil mineral nitrogen lixiviation	298.56	-47.92	6.49	-90.54	272.32	5.79	7.44
Emission factor - N ₂ O emissions of synthetic fertilisers application	495.81	403.01	488.93	397.81	461.60	487.18	490.89
Emission factor - N ₂ O emissions due to soil management	495.81	403.01	488.93	397.81	461.60	487.18	490.89
Emission factor - Volatilisation of organic fertilisers application	403.97	-65.71	2.83	-122.72	353.99	1.12	1.25
Yield - SBP	-1813.48	1492.44	87.94	1873.92	-1306.63	8.38	353.88
Harvest index - SBP	945.64	-358.96	-287.11	-512.47	854.84	-287.19	-287.01
Harvest index - SNP	-2143.12	-497.45	-719.11	-287.14	-1965.16	-719.21	-718.98
Nitrogen content – harvested organ - SBP	-768.15	1746.38	825.00	2011.96	-51.21	514.69	1545.59
Nitrogen content – harvested organ - SNP	868.21	2351.43	1848.37	2525.24	1492.85	1711.64	2164.96
Nitrogen content root residues - SBP	-640.45	240.70	190.79	344.40	-579.09	190.85	190.71
Nitrogen content root residues - SNP	1188.38	292.63	409.21	177.51	1091.07	409.28	409.12
Shoot-to-root ratio - SBP	640.45	-240.71	-190.79	-344.40	579.09	-190.85	-190.71
Shoot-to-root ratio - SNP	-1188.38	-292.63	-409.21	-177.51	-1091.07	-409.28	-409.12
Slaughtering ratio of young heifers	-356.07	150.45	-193.77	202.90	-174.06	-190.78	-81.39
Share of digestible energy for beef of the edible part of wheat as concentrates	-26.95	188.29	187.99	213.05	190.11	212.26	213.90
Share of digestible energy for beef of the edible part of SBP as forages	-198.63	45.97	-880.34	53.64	85.58	-1069.18	-528.93