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Par
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Economic and environmental benefits from crop-livestock complementarities through local legume production

A modelling approach for western France

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PhD thesis

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Résumé

Depuis le milieu du XXe siècle, l'agriculture européenne tend à se spécialiser, avec une déconnexion entre les productions végétales et les productions animales. Néanmoins, la faible résilience économique des exploitations agricoles et des régions spécialisées, ainsi que leurs impacts négatifs sur l'environnement soulèvent de plus en plus de questions. En effet, la plupart des avantages économiques et environnementaux des agroécosystèmes diversifiés sont perdus lors de la spécialisation. En particulier, la production jointe de services écosystémiques est limitée, tout comme la valorisation des complémentarités techniques entre cultures et élevage.

L'objectif général de ma recherche doctorale est d'étudier les complémentarités techniques culture-élevage afin d'améliorer la durabilité de l'agriculture. Cette recherche se concentre sur une étude de cas de l'ouest de la France (Bretagne et Pays de la Loire). L'hypothèse principale est que les légumineuses améliorent ces complémentarités grâce à la production conjointe de produits végétaux riches en protéines et d'azote pour les cultures suivantes. Plusieurs leviers qui peuvent favoriser la production et l'utilisation des légumineuses en alimentation animale sont étudiés. Les impacts économiques et environnementaux de la production de légumineuses sur les complémentarités sont évalués à différentes échelles.

À l'échelle de la rotation, je montre à travers une revue de la littérature que les légumineuses sont économiquement attractives: leurs coûts d'opportunité sont nuls ou négatifs grâce à leur effet précédent. À l'échelle de l'exploitation d'élevage, je montre que l'augmentation de la production de légumineuses et leur utilisation dans l'alimentation animale conduisent à des bénéfices environnementaux limités lorsque le chargement animal reste élevé. Permettre l'épandre des effluents d'élevage sur les légumineuses peut aider à atteindre une production plus élevée de légumineuses, mais cela n'a pas d'impact positif, car les gains liés à la réduction des apports en azote sont presque compensés par l'augmentation de la lixiviation des nitrates, due à une fertilisation excessive des légumineuses.

La principale contribution de cette recherche est le développement du modèle bioéconomique SYNERGY qui étudie les complémentarités à l'échelle régionale. Ce modèle prend en compte trois types d'exploitations agricoles dans l'ouest de la France: laitière, porcine et de grandes cultures. Il représente les échanges locaux de cultures (y compris de légumineuses) et d'effluents entre les exploitations d'élevage et les exploitations de grandes cultures. Ce modèle représente l'effet précédent des légumineuses au sein de rotations, ainsi que des rations alternatives avec des légumineuses. SYNERGY peut être utilisé à deux fins. Premièrement, il peut aider à comprendre les impacts économiques et environnementaux de changements ambitieux. Par

exemple, en fixant un pourcentage élevé de légumineuses (10%) dans l’ouest de la France, je démontre que l'utilisation de légumineuses en alimentation animale augmente dans les exploitations laitières et que l'utilisation d'engrais azotés de synthèse diminue (-7%). Cependant, l’augmentation de la production de légumineuses entraîne également une baisse des bénéfices du secteur agricole (-4%), sans amélioration substantielle des indicateurs environnementaux. Les échanges d’effluents peuvent aider à développer la production de légumineuses dans certaines fermes porcines, mais ils conduisent également à une intensification de la production porcine. Deuxièmement, SYNERGY peut aider à identifier les leviers économiques, technologiques et réglementaires les plus pertinents pour atteindre des objectifs spécifiques, en particulier la transition vers des systèmes agricoles plus durables. Par exemple, je démontre que les aides couplées aux légumineuses ont peu d'influence sur l'utilisation des légumineuses en alimentation animale dans l'ouest de la France, tandis que l'augmentation de la demande en produits animaux certifiés sans OGM conduit à un changement technologique substantiel en alimentation animale, grâce à une substitution presque complète des rations à base de soja vers d’autres des rations à base de légumineuses. Cependant, la production de légumineuses et les échanges locaux restant faibles dans cette situation, les légumineuses sont largement importées de l'extérieur de la région. Ainsi, les résultats économiques et environnementaux ne s'améliorent pas à l'échelle régionale, ni l'autonomie en protéines.

Enfin, parallèlement à la production et à l'utilisation de légumineuses à l'échelle de l’exploitation et de la région, j'étudie les relations verticales à l'échelle des filières agroalimentaires. A partir d'études de cas, je montre que les légumineuses sont caractérisées par des coûts de transaction élevés. Ces coûts ne sont pas suffisamment réduits par les contrats existants entre producteurs et collecteurs, notamment parce que les incertitudes de prix restent élevées. Des initiatives visant à réduire ces incertitudes devraient être mises en place pour favoriser la production et les échanges locaux de légumineuses et ainsi améliorer les complémentarités entre productions.

Abstract

Since 1950s, European agriculture has experienced a trend of specialization, with a disconnection between crop and animal production. Nevertheless, the low economic resilience of specialized farms and regions and their negative environmental impacts have raised questions about this trend. Indeed, most economic and environmental benefits of diversified agroecosystems are lost during specialization. In particular, joint production of ecosystem services is restricted, as is enhancement of technical complementarities between crops and livestock.

The general objective of my doctoral research is to study crop-livestock technical complementarities to improve the sustainability of agriculture. This research focuses on a case study of western France (i.e., Brittany and Pays de la Loire). The main hypothesis is that legumes improve these complementarities through the joint production of protein-rich crops and nitrogen for subsequent crops. Several levers to foster legume production and use in feed are studied. Economic and environmental impacts of legume production on complementarities are assessed at different scales.

At the rotation scale, I demonstrate through a literature review that legumes are economically attractive: their opportunity costs are zero or negative due to their pre-crop effect. At the livestock-oriented farm scale, I show that the increase in legume production, and their use in feed, leads to limited environmental benefits when the livestock stocking rate remains high. Allowing manure spreading on legumes can help reaching higher legume production but it does not lead to further benefits, since the benefits of lowering nitrogen inputs are nearly offset by the increase in nitrate leaching due to overfertilization of legumes.

The main contribution of this research is the development of the bio-economic model SYNERGY that studies complementarities at the regional scale. This model encompasses three type of farms in western France: dairy farm, pig farm and crop farm in western France. It represents local exchanges of crops (including legumes) and manure between crop-oriented farms and livestock-oriented farms. This model represents the pre-crop effect of legumes in rotations and includes alternative rations with legumes. SYNERGY can be used for two purposes. First, it can help to understand economic and environmental impacts of ambitious changes. For example, by setting a high legume percentage (i.e., 10%) in the region of western France, I demonstrate that the use of legumes in dairy feed increases and the use of synthetic N fertilizers decreases (-7%). However, this increase in legume percentage also leads to a decrease in profit of the farming sector (-4%), without substantial improvement in environmental

indicators. Manure exchanges can help increase the percentage of legumes on some pig farms, but it also leads to intensification of pig production. Second, SYNERGY can help to identify the most relevant economic, technological and regulatory levers to achieve specific objectives, in particular the shift to more sustainable farming systems. For example, I demonstrate that coupled support to foster legume production has little influence on legume use in feed in western France, while increasing demand for GMO-free animal products leads to substantial technological change in animal feeding through a nearly complete shift in rations from soybean-based to legume-based. However, in this situation, since the production of legumes and the simulated local exchanges remain low, legumes are largely imported from outside the region. Thus, the economic and environmental results do not improve at the regional scale, neither the protein self-sufficiency.

Finally, alongside the production and use of legumes at farm and regional scales, I study vertical relationships at the agro-food chain scale. From case studies, I show that legumes suffer from high transaction costs. These costs are not sufficiently decreased by the existing contracts between producers and collectors, in particular because uncertainties in price remain high. Initiatives to decrease such uncertainties should be set up to foster production and local exchanges of legumes and thus improve complementarities between production.

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Synthèse

Chapitre 1. Introduction

Depuis le milieu du XXe siècle, l'agriculture européenne tend à se spécialiser, avec une déconnexion entre les productions végétales et les productions animales. Ce phénomène a pu être observé à différentes échelles. D’une part, les exploitations agricoles se sont spécialisées dans un certain type de production, élevage ou grandes cultures, bénéficiant ainsi des économies d'échelle liées aux progrès techniques (Chavas 2008). D’autres part, certaines régions agricoles ont vu se concentrer les exploitations d’élevage, ou de grandes cultures, du fait d’avantage comparatifs liés aux conditions pédoclimatiques et aux économies d'agglomération qui peuvent apparaître lorsque des entreprises d’un même secteur se retrouvent sur un même territoire (Gaigné et al. 2012; Roguet et al. 2015). Néanmoins, depuis les années 2000, la faible résilience économique des exploitations agricoles et des régions spécialisées quant aux aléas économiques et climatiques ont remis en question cette tendance, tout comme leurs impacts négatifs sur l’environnement (Naylor et al. 2005). En effet, la spécialisation de l'agriculture va de pair avec son industrialisation, dont les conséquences sur l'environnement sont largement reconnues: pollution de l'eau, dégradation des sols, réduction de la biodiversité, émissions de gaz à effet de serre (Donald et al. 2006; Moss 2008; Baude et al. 2019; Garnier et al. 2019). Ainsi, la plupart des avantages économiques et environnementaux des agroécosystèmes diversifiés sont perdus lors de la spécialisation. En particulier, la production jointe de services écosystémiques est restreinte, tout comme la valorisation des complémentarités techniques entre culture et élevage.

Ce manque de valorisation des complémentarités techniques culture-élevage a conduit à d’importantes modifications de la production et de la gestion de l’azote. Les exploitations et régions spécialisées en grandes cultures sont caractérisées par un déficit en N, qui doit être compensé par des achats d'engrais azotés synthétiques. Au contraire, les exploitations et les régions spécialisées en élevage sont caractérisées par un excès d’azote issus des effluents d’élevage (fumier, lisier), dont une partie de cet excédent est perdu dans l'environnement. Par ailleurs, la question de la distribution de l’azote comprend aussi celle de la disponibilité des protéines étant donné que l’azote est l’élément de base de ces molécules. Les exploitations et les régions spécialisées en élevage doivent acheter des aliments riches en protéines (par exemple le tourteau de soja), remplaçant partiellement les aliments produits sur l’exploitation (Naylor et al. 2005). Ainsi, les échanges d'intrants riches en azote, comme les engrais synthétiques et les tourteaux ont augmenté à travers le monde (Lassaletta et al. 2014). Outre les impacts environnementaux (par exemple, la pollution de l'eau ou la déforestation), la faible autonomie en protéines de l'Union Européenne (UE) est considérée comme une menace pour son économie (European Parliament 2011). Compte tenu de ces enjeux, il est nécessaire de réduire les échanges mondiaux d'intrants azotés.

Pour se faire, un des leviers identifiés est de développer la production de légumineuses (Schneider and Huyghe 2015). Le principal avantage de ces cultures réside dans leur capacité à fixer le l'azote atmosphérique, permettant ainsi la production jointe de partie aériennes riches en azote, qui peuvent être utilisée en alimentation animale, et d'azote dans le sol pour les cultures suivantes grâce via les résidus des cultures (Wossink and Swinton 2007; Peoples et al. 2009). Ainsi, des complémentarités techniques peuvent apparaître entre les légumineuses et les cultures suivantes, ainsi qu'entre les légumineuses et les animaux d'élevage. Cependant, la production de légumineuses dans les exploitations d'élevage peut être limitée par des contraintes de gestion des effluents. Une solution consisterait donc à valoriser les complémentarités techniques non pas à l'intérieur des exploitations agricoles, mais entre les exploitations d'une même région: les exploitations de grandes cultures pourraient produire et vendre des légumineuses aux exploitations d'élevage, qui peuvent utiliser ces cultures pour nourrir les animaux. En contrepartie, les exploitations d'élevage peuvent exporter des effluents vers des exploitations de grandes cultures qui manquent d'azote pour la fertilisation. Cet exemple d'économie circulaire peut représenter un levier intéressant pour diminuer les impacts négatifs de la spécialisation agricole tout en profitant de ces avantages économiques.

L'objectif général de ma thèse est d'étudier les complémentarités techniques culture-élevage, de l'échelle de la rotation à l'échelle régionale, afin d'améliorer la durabilité de l'agriculture. L'hypothèse principale est que les légumineuses améliorent ces complémentarités techniques. À cette fin, j'étudie (i) les leviers potentiels pour augmenter la production de légumineuses et renforcer les complémentarités techniques et (ii) les conséquences potentielles - économiques et environnementales - de telles innovations. De plus, étudier les complémentarités techniques culture-élevage, je me concentre principalement sur les légumineuses utilisées en alimentation animale (en tant que produits intermédiaires), même si les légumineuses comme cultures de rente (en tant que produits finaux) sont également considérées. L'objectif général est décomposé en plusieurs questions de recherche (figure 1.2), qui sont traitées dans les différents chapitres de cette thèse.

Q1 : Quels sont les coûts d'opportunité des légumineuses à l'échelle de la parcelle et de la rotation?
La production de légumineuses reste limitée au sein de l'UE. À l'échelle de la parcelle, les légumineuses sont considérées comme moins rentables à court terme que les autres cultures courantes car leur marge brute annuelle est généralement plus faible et qu'il est difficile de quantifier la valeur monétaire de l'effet précédent (von Richthofen et al.2006a). De plus, les légumineuses sont considérées comme plus risquées que les cultures plus courantes en raison de leurs rendements plus variables d'une année à l'autre, bien qu'il n'y ait pas de consensus sur ce point dans la communauté scientifique (Peltonen-Sainio et Niemi 2012; Cernay et al.2015). Ainsi, due à l'aversion au risque des agriculteurs, les marges des légumineuses sont pénalisées par une prime de risque plus élevée (c'est-à-dire le montant qu'un agriculteur serait prêt à payer pour éliminer tous les risques) que celles des autres cultures, ce qui diminue encore plus leur profitabilité relative.

Cependant, du fait de la production jointe d'azote par les légumineuses, une première complémentarité technique apparaît à l'échelle de rotation entre légumineuses et les autres cultures. Or, plusieurs études ont examiné les performances agronomiques et environnementales des légumineuses (Dequiedt et Moran 2015; Cernay et al.2015; Lötjönen et Ollikainen 2017), mais peu se sont concentrées sur les légumineuses d'un point de vue économique (Bridet-Guillaume et al.2010). En particulier, peu d'études ont examiné les coûts d'opportunité des légumineuses, même si cette question reste une priorité pour les agriculteurs lors du choix de leur plan de culture. Le chapitre 3 analyse les données de la littérature sur l'attractivité économique des légumineuses à l'échelle de la parcelle (c'est-à-dire pendant un an) et à l'échelle de rotation.

Q2: Quels sont les coûts d'opportunité des légumineuses à l'échelle de l'exploitation d'élevage?
Au sein des exploitations d'élevage, une autre complémentarité technique apparaît : les légumineuses, qui sont riches en protéines, peuvent être utilisée pour nourrir les animaux. Les légumineuses représentent alors un bien intermédiaire dont le coût d'opportunité dépend de leurs coûts d'opportunité intrinsèques et des performances de la production animale. Or les rations à base de légumineuses n'ont pas encore été suffisamment observées pour être estimées économétriquement.

Les modèles de programmation mathématique peuvent permettre une analyse *ex ante* en évaluant de tels changements techniques, même s'ils n'ont pas encore été introduits à grande échelle (Jacquet et al.2011; Böcker et al.2018). Ces modèles sont généralement basés sur des fonction de production, combinées à un objectif économique (par exemple, la maximisation le profit). Parmi les modèles de programmation mathématique, les modèles bioéconomiques combinent des données économiques et biologiques, ce qui est particulièrement pertinent pour représenter la production jointe des légumineuses. Ces modèles permettent également d'identifier des compromis entre les considérations économiques et environnementales (Janssen et van Ittersum 2007). La diversité des modèles bioéconomiques est décrite dans le chapitre 2. À ce jour, seuls quelques modèles bioéconomiques ont étudié les légumineuses en tant qu'aliments pour les animaux dans les exploitations d'élevage (Helming et al. 2014; Schläfke et al. 2014; Gaudino et al. 2018).

De plus, un facteur qui peut affecter l'introduction de légumineuses dans ces exploitations n'est pas pris en compte: la gestion des effluents. Les légumineuses n'ayant pas besoin d'être fertilisées, l'épandage d'effluents sur celles-ci n'est pas cohérent d'un point de vue agronomique. Cela se traduit par la Directive Nitrates qui est appliquée différemment selon les pays européens. Par exemple, dans l'ouest de la France, l'application de cette directive interdit l'épandage d'effluents sur la plupart des légumineuses. À l'échelle de l'exploitation, une modification de cette réglementation pourrait permettre d''épandre des effluents sur les légumineuses tant que le bilan azoté à l'échelle de l'exploitation est cohérent, comme cela est pratique en Allemagne. Ce changement pourrait améliorer les interactions entre les politiques agricoles qui soutiennent les légumineuses, comme les aides couplées (pilier I de la PAC) et les politiques environnementales, comme la Directive Nitrates. Les modèles bioéconomiques analysant les impacts de la Directive Nitrates sont courants (Belhouchette et al.2011; Kuhn et al.2019). Cependant, à ma connaissance, aucune étude n'a analysé les interactions potentielles entre les mesures de soutien direct aux légumineuses et l'application de la Directive Nitrates. Le chapitre 4 aborde cette question en appliquant le modèle bioéconomique FarmDyn à des exploitations laitières représentatives en France et en Allemagne.

Q3: Les complémentarités techniques entre exploitations agricoles encouragent-elles la production de légumineuses à l'échelle régionale? Quelles en sont les conséquences économiques et environnementales?

Une autre solution pour développer l'utilisation des légumineuses dans les exploitations d'élevage serait d'étudier cette question à l'échelle régionale. À cette échelle, les exploitations spécialisées pourraient échanger leurs produits (Peyraud et al. 2014b; Martin et al. 2016). Les exploitations d'élevage pourraient exporter des effluents vers les exploitations de grandes cultures voisines qui manquent d'azote pour la fertilisation. En retour, les exploitations de grandes cultures pourraient vendre des légumineuses aux exploitations d'élevage et fournir ainsi des cultures riches en protéines pour l'alimentation animale. Les complémentarités entre légumineuses et productions animales seraient ainsi renforcées à l'échelle régionale grâce aux principes de l'économie circulaire.

Pour étudier les échanges entre exploitations au sein d'une région, il a été nécessaire de construire un modèle bioéconomique répondant à différentes caractéristiques. Ces caractéristiques et les problèmes méthodologiques qu'elles peuvent soulever sont décrits dans le chapitre 2. En particulier, le modèle bioéconomique doit intégrer plusieurs échelles, de l'exploitation à la région. De tel modèles ont déjà été développés, principalement pour étudier les conséquences de politique publiques sur la production agricole (Chopin et al. 2015; Gocht et al. 2017). À ma connaissance, aucun modèle bioéconomique à grande échelle ne se concentre sur la production de légumineuses ni 'analyse les échanges entre exploitations, à l'exception du modèle de Helming et Reinhard (2009), qui inclut des échanges d'effluents. Il est nécessaire de souligner que les échanges d'effluents ont également été étudiés théoriquement (Djaout et al.2009) ou en utilisant d'autres outils, tels que les modèles multi-agents (Happe et al.2011).

Le chapitre 5 détaille le modèle bioéconomique que j'ai créé lors de ma thèse. Ce modèle, SYNERGY, intègre de cultures, dont les légumineuses, et d'effluents entre exploitations agricoles. Il analyse (i) les impacts de la production de légumineuses dans l'ouest de la France (Bretagne et Pays de la Loire) et (ii) la complémentarité technique légumineuses/élevage à l'échelle régionale à travers des échanges locaux entre exploitations agricoles. SYNERGY intègre de nombreuses données provenant de différentes sources. Le chapitre 5 comprend également un *data paper* qui présente les données utilisées dans ce modèle.

Q4: Quels sont les coûts de transaction liés aux échanges de légumineuses entre producteurs et collecteurs? La contractualisation peut-elle réduire ces coûts?

J'ai créé SYNERGY pour répondre à la question précédente (Q3), mais ce modèle représente seulement les relations horizontales entre exploitations agricoles, sans tenir compte des problématiques d'organisation verticale (c'est-à-dire la coordination d'entreprises opérant à différents niveaux de la filière agroalimentaire). Or l'organisation verticale est une problématique cruciale pour la filière des légumineuses, car étant des cultures de diversification, les légumineuses peuvent être associées à des coûts de transaction élevés (Meynard et al.2018). Il est donc nécessaire d'analyser les relations verticales qui peuvent exister pour limiter ces coûts de transaction et créer des marchés innovants pour les légumineuses. Les échanges de cultures entre exploitations agricoles, y compris celles de légumineuses, sont confrontés à d'importantes contraintes logistiques. Les collecteurs tels que les coopératives, peuvent limiter ces contraintes en jouant le rôle d'intermédiaires entre les exploitations en collectant, transformant et commercialisant les légumineuses. Les échanges de légumineuses peuvent ainsi faire partie d'une filière agroalimentaire, de la production dans l’exploitation agricole à la commercialisation par la coopérative.

La nouvelle économie institutionnelle étudie le rôle joué par les institutions (c'est-à-dire l'ensemble des règles et normes qui régissent les comportements) dans la coordination économique (Coase 1998). Dans ce corpus, la théorie des coûts de transaction permet d'analyser les filières agroalimentaires comme des successions de transactions. Cette théorie est basée sur l'hypothèse que les acteurs ont une rationalité limitée et un comportement opportuniste. Plus les coûts de transaction sont élevés, plus les acteurs sont enclins à choisir un mode de coordination intégré (Williamson 1979). Différents modes de coordination ont été décrits, allant du « marché » à la « hiérarchie » (dans lequel les transactions se déroulent de manière intégrée). La contractualisation est un mode de coordination « hybride » entre marché et hiérarchie (Ménard 2004). Comme mentionné, les échanges de légumineuses peuvent entraîner des coûts de transaction relativement élevés et la contractualisation est un moyen de les réduire.

De nombreuses études empiriques ont été réalisées sur la contractualisation dans le secteur agricole, aussi bien en production animale que végétale (Bouamra-Mechemache et al.2015; Cholez et al.2017; Bellemare et Lim 2018). Cependant, aucune étude ne se concentre en particulier sur la diversité des contrats de légumineuses en alimentation animale. Le chapitre 3 étudie les coûts de transaction liés à la commercialisation des légumineuses. Il analyse notamment les contrats de légumineuses pour l'alimentation animale proposés par différents collecteurs de l'ouest de la France.

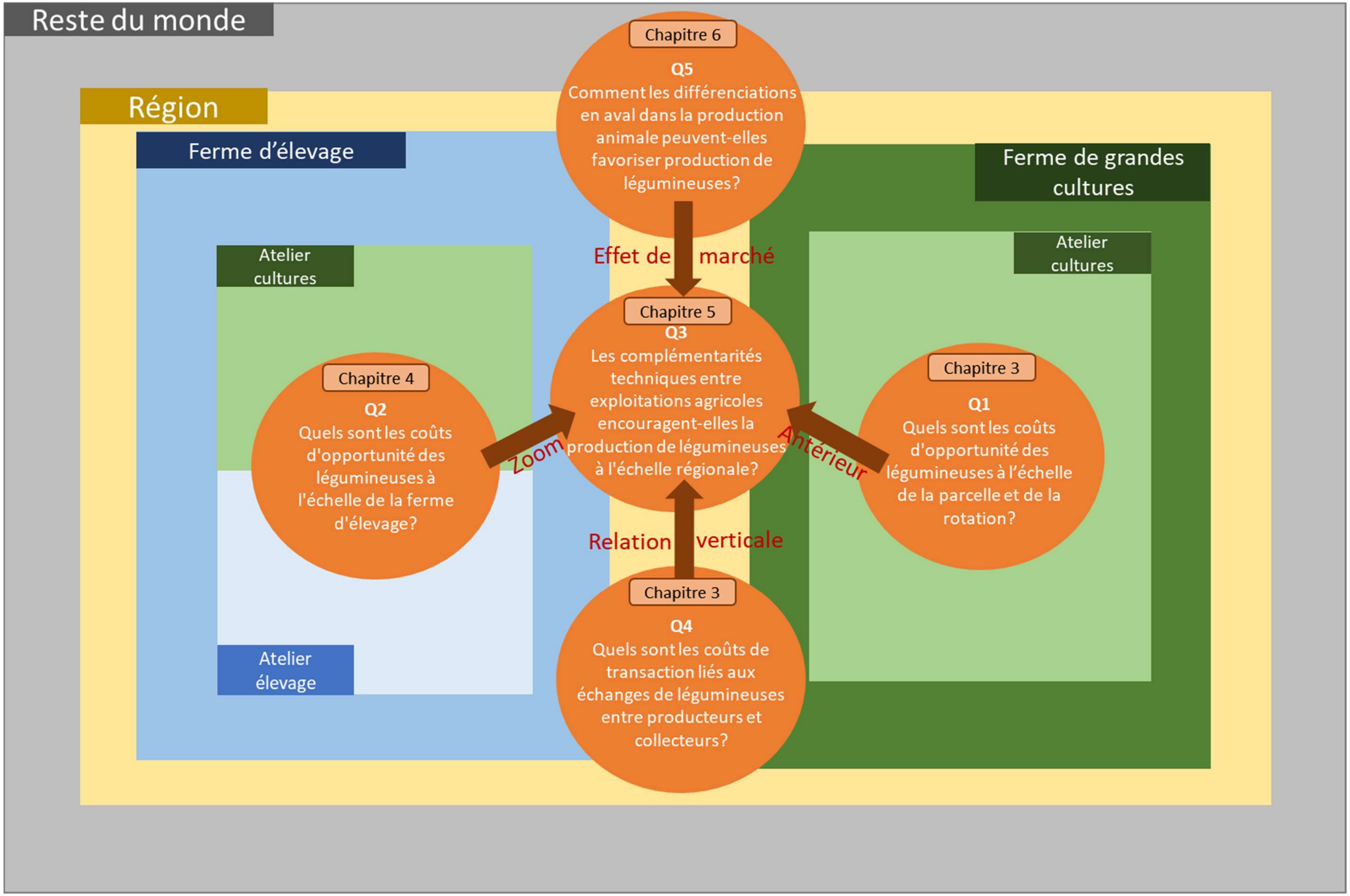
Q5: Comment les différenciations en aval de la production animale peuvent-elles favoriser production de légumineuses?

Enfin, concernant l'utilisation des légumineuses en alimentation animale, l'absence de différenciation entre les produits animaux pénalise ces cultures. En effet, les légumineuses sont facilement substituables par des aliments moins chers, comme les tourteaux de soja importé, ce qui limite considérablement l'incorporation de légumineuses dans les rations (Charrier et al. 2013). Une solution pour réduire cette substituabilité consiste à valoriser les avantages environnementaux et sociétaux de l'utilisation des légumineuses en alimentation animale. Ces avantages sont des attributs fondés sur la confiance: les consommateurs ne peuvent pas les évaluer avant ou après l'achat.

Pour réduire ces asymétries d'information, les décideurs politiques ou les entreprises privées peuvent donc développer des labels (Aprile et al. 2012), qui garantissent aux consommateurs des attributs de qualité basés sur des techniques de production spécifiques (Allaire 2012). Ce faisant, ils créent un marché de niche et permettent aux entreprises d'obtenir un prix supérieur basé sur un consentement à payer plus élevé (Loureiro et Hine 2002; Unnevehr et al. 2010). Le certification sans OGM représente une opportunité pour différencier les aliments pour animaux à base de légumineuses, car la plupart du soja produit dans le monde est génétiquement modifié (Castellari et al.2018). Ainsi, les produits animaux certifiés sans OGM (par exemple, le lait et la viande d'animaux nourris sans OGM) peuvent bénéficier de prix plus élevés, ce qui pourrait réduire le coût d'opportunité des légumineuses en alimentation animale et encourager la production de ces cultures. À ma connaissance, aucune étude n'a envisagé ce levier pour augmenter la production de légumineuses utilisées en l'alimentation animale.

Le chapitre 6 aborde cette question en analysant les conséquences d’une augmentation de la demande en produits animaux certifiés sans OGM, ce levier ayant été également identifié dans la prospective TERUnic. Pour ce faire, le modèle SYNERGY est associé à un modèle d'équilibre général calculable (EGC) existant (Gohin et al.2016). Ces deux modèles ne sont pas intégrés dans une chaîne de modélisation, car la mise en œuvre du modèle EGC sort du cadre de mes recherches. Néanmoins, ce travail en collaboration avec d'autres scientifiques a permis d'introduire les effets macro-économiques prédits par le modèle EGC dans le modèle SYNERGY, qui réalise ensuite une évaluation économique et environnementale à l'échelle de la région. En comparaison, les impacts d'une augmentation des aides couplées aux légumineuses sont également étudiés.

Figure S1. Vue d'ensemble du cadre de recherche



Chapitre 2. Démarches méthodologiques

Les modèles bioéconomiques sont des modèles de programmation mathématique qui capturent les interactions entre les processus biophysiques et économiques. Ils décrivent les relations entre les intrants et les produits en utilisant explicitement une démarche basée sur les fonctions de production d'ingénieur (Flichman et Allen 2013). Le fondement de cette démarche est donc le processus de production, qui est appelé activité. Une activité est définie par un ensemble de coefficients techniques qui représentent la quantité d'intrants nécessaires pour produire des biens, liée à une unité d'un facteur fixe (par exemple, la quantité d'azote nécessaire par hectare pour produire du blé). Comme d'autres modèles de programmation mathématique, un modèle bioéconomique maximise (ou minimise) une fonction objective soumise à des contraintes. L'un des points forts des modèles bioéconomiques est leur capacité à considérer de nombreuses technologies qui peuvent être utilisées simultanément ou se remplacer les unes les autres, en fonction des contraintes liées à la disponibilité des intrants (Ridier 2001). Un autre de leurs atouts est que chaque bien (par exemple, le grain de blé) peut être produit par plusieurs activités (par exemple, une rotation blé-blé-maïs, blé dans une rotation pois-blé-maïs), et chaque activité peut produire plusieurs biens (par exemple, un porc produit de la viande et des effluents) (Flichman et al. 2011). Ainsi, les modèles bioéconomiques sont capables de représenter la complexité des agroécosystèmes en incorporant des productions jointes (Havlik et al. 2005). De plus, ces biens étant représentés par des quantités physiques et non monétaires, il est donc possible de considérer des produits intermédiaires (ex: effluents) et des services écosystémiques partiellement non commercialisables (ex: azoté fixé par les légumineuses) et ainsi de mettre en évidence des complémentarités techniques.

Construire des modèles bioéconomiques implique de faire des choix et des compromis autour de différentes caractéristiques. En premier lieu, l'objectif de l'étude influence fortement le choix des autres caractéristiques : les modèles bioéconomiques sont construits différemment selon qu'ils visent à évaluer les impacts des politiques publiques ou à adopter des innovations techniques. L'étude des politiques publiques peut nécessiter de représenter la diversité et la représentativité des systèmes agricoles à l'échelle locale ou nationale. Comme il est difficile de modéliser des exploitations individuelles à de telles échelles, des exploitations représentatives (ci-après, types d'exploitations) sont utilisées. Une question difficile est de choisir les types de production à inclure et dans quelle mesure la diversité des systèmes agricoles devrait être représentée. En revanche, l'étude des innovations techniques implique de développer un large éventail de coefficients techniques afin de représenter la diversité des technologies (Townsend et al. 2016). Par exemple, il peut être utile de différencier la production conventionnelle et la production biologique. De plus, la construction d'un modèle bioéconomique nécessite de choisir une méthode de calibration, pour que le modèle reproduise le comportement observé des agents. Cependant, selon l'objectif de l'étude et les données disponibles, l'étalonnage peut être limité aux niveaux de production (par exemple, la superficie cultivée) ou aller plus loin pour inclure les technologies observées. Enfin, le choix de l'échelle représente également un enjeu stratégique: selon l'objectif, étudier à petite échelle permet d'évaluer des changements techniques détaillés, mais extrapoler les résultats aux décideurs peut être difficile, car ces changements n'ont été modélisés que pour des types d'exploitations spécifiques. Néanmoins, les données permettant d'élaborer des coefficients techniques ne sont pas toujours disponibles à toutes les échelles, ce qui peut également influencer le choix de l'échelle. En termes plus pratiques, la plupart des choix méthodologiques représentent un compromis entre l'utilisateur, la science et les données: à quelle échelle l'utilisateur (par exemple, décideur, décideur) effectue-t-il l'évaluation? Quelles données sont disponibles? Quelles ressources (humaines et techniques) sont allouées à l'étude?

Tableau S1. Caractéristiques du modèle SYNERGY et d'autres modèles bioéconomiques représentation des productions animales et végétales

Nom du modèle	Source	Echelle	Processus décisionnel	Productions agricoles modélisées	Typologie	Méthode de calibration	Indicateur environnemental	Caractéristiques particulières
AROPAj	De Cara and Jayet (2000)* Galko and Jayet (2011)	groupe d'EA > régions > UE	max. marge brute de chaque groupe d'EA	1 074 groupes d'EA 32 activités végétales 21 activités animales	positiviste	ré-estimation de coefficient techniques	gaz à effet de serre	grande variété d'EA et d'activités
DRAM	Helming (1998)* Helming and Reinhard (2009)	régions (=grande EA) > pays	(1) min. fertilisation (2) max. revenus régionaux : somme des revenus nets des EA	19 activités végétales 15 activités animales	-	PMP standard	solde N et P	échanges de fourrages et d'effluents
FSSIM-DEV	Louhichi et al. (2010)* Louhichi and Gomez y Paloma (2014)	ménage > région	max. utilité régionale : somme pondérée des utilités des ménages	12 activités végétales 9 types d'EA [a]	positiviste	méthode de max. entropie and données inter-section	not inclus [b]	agrégation à différentes échelles échanges entre EA
ILM	Schönhart et al. (2011)	EA & paysages > région	max. marge brute de chaque EA	20 EA avec production animale et végétale 20 cultures 4 itinéraires techniques	-	-	C organique du sol pertes sédimentaires index de diversité Shannon	grande variété de rotations modélisation spatiale d'éléments du paysage
IMF - CAP	Louhichi et al. (2017)	EA individuelles > UE	max. profit de chaque EA	37 activités végétales 16 activités animales	-	données inter-section and prior information	not inclus	grande variété d'EA et d'activités EA individuelles modélisées
MODAM	Zander (2003)* Schläfke et al. (2014)	région = 1 grande EA	max. marge brute régionale	106 activités végétales 1 activités animales	-	pas de calibration	érosion	effet précédent inclus dans els activités végétales
MOSAICA	Chopin et al. (2015)	parcelles > EA > région	max. utilité régionale : somme des utilités des EA (fonction Markowitz-Freund)	36 activités végétales 8 types d'EA (1 spécialisé en élevage)	positiviste	aversion au risque	pesticides biodiversité qualité de l'eau émissions de CO_2	agrégation à différentes échelles spatialement explicite
SYNERGY	Jouan et al. (en révision)	EA > sous-régions > région	max. profit régional	3 types d'EA 156 activités végétales 44 activités animales	mixte	"double calibration" avec PMP standard	pertes potentielles en N (SynB) efficience azotée (SyNE)	agrégation à différentes échelles échanges de cultures et d'effluents grande variété de rotations

* Étude originale présentant le modèle pour la première fois; [a]: la production animale n'a pas été introduite dans le cas d'étude mais l'est dans le modèle générique; [b]: l'évaluation environnementale n'a pas été introduite dans le cas d'étude mais peut l'être dans le modèle général en utilisant le modèle de biophysique APES; EA : exploitation agricole ; Tous les modèles inclus dans ce tableau ont les caractéristiques suivantes: modèle bioéconomiques positifs, statiques, sans prise en compte du risque, qui visent à évaluer les politiques agricoles.

Chapitre 3. Intérêts économiques de la production de légumineuses et de leur utilisation en alimentation animale

Ce chapitre vise à aborder les intérêts économiques de la production de légumineuses pour l'alimentation animale, à l'échelle de la parcelle et de la rotation, et à l'échelle de la filière. Pour ce faire, il analyse comment l'attractivité économique des légumineuses peut être influencée par deux facteurs: les coûts d'opportunité et les coûts de transaction. La méthode est divisée en trois parties. Tout d'abord, j'ai construit une base de données des coûts d'opportunité des légumineuses à partir d'une revue de la littérature. Deuxièmement, j'ai caractérisé qualitativement les coûts de transaction associés à l'échange de légumineuses entre producteurs et collecteurs. Troisièmement, j'ai analysé qualitativement si les contrats actuellement proposés dans l'ouest de la France diminuaient ces coûts de transaction. À titre de comparaison, les coûts de transaction des graines de lin ont également été étudiés.

Nos résultats montrent que l'attractivité économique des légumineuses se révèle à l'échelle de la rotation: ces cultures ont un coût d'opportunité nul ou négatifs seulement si l'on calcule la marge brute à l'échelle de la rotation. De plus, lors des échanges, les coûts de transactions de légumineuses sont élevés du fait d'incertitudes environnementales et économiques élevées pour les producteurs, ainsi que d'actifs spécifiques importants engagés par les collecteurs. Enfin, concernant les contrats de légumineuses étudiés, seulement la moitié d'entre eux assurent un prix de vente (ou une marge) au producteur à la signature du contrat, transférant ainsi les risques économiques vers les collecteurs. Les contrats apparaissent donc comme un moyen efficace pour inciter les producteurs à cultiver des légumineuses à condition que les prix soient fixés à l'avance. Ce partage du risque-prix est cependant possible uniquement lorsque le collecteur créé de la valeur ajoutée en aval à travers des filières différenciées.

Tableau S2. Analyse de l'évolution des coûts de transaction au sein des contrats de légumineuses et de graines de lin, par rapport à ceux sans contractualisation, pour les cinq collecteurs interrogés (A-E)

Evolution des coûts de transaction Sous contractualisation		**A**	**B**	**C**	**D**	**E**
		Luzerne	**Féverole**	**Pois**	**Lupin**	**Lin**
Nature des contrats		**Commercialisation**[a]	**Production**[b]	**Commercialisation**	**Production**	**Production tripartite**[c]
Incertitudes sur le volume	Pour le producteur	**Constant** Paiement en fonction du tonnage	**Légèrement diminué** Paiement en fonction du tonnage mais suivi technique significatif	**Constant** Paiement en fonction du tonnage	**Légèrement diminué** Paiement en fonction du tonnage mais suivi technique significatif	**Légèrement diminué** Paiement en fonction du tonnage mais suivi technique significatif
Incertitudes sur le volume	Pour le collecteur	**Constant** L'engagement du producteur est basé uniquement sur la surface	**Légèrement diminué** L'engagement du producteur est basé sur la surface mais suivi technique significatif	**Légèrement diminué** L'engagement du producteur est basé sur le volume mais pas de pénalité en cas de non-conformité	**Légèrement diminué** L'engagement du producteur est basé sur la surface mais suivi technique significatif	**Légèrement diminué** L'engagement du producteur est basé sur la surface mais suivi technique significatif
Incertitudes sur la qualité	Pour le collecteur	**Diminué** La culture est acceptée si elle contient plus de 20% de protéines brutes	**Constant** Aucun paiement en fonction de la qualité	**Constant** Aucun paiement en fonction de la qualité	**Constant** Aucun paiement en fonction de la qualité	**Légèrement diminué** Paiement en fonction de la teneur en oméga3
Incertitudes de prix	Pour le producteur	**Constant** Le prix est fixé chaque année en fonction du prix du blé	**Diminué** Garantie de marge brute	**Légèrement diminué** Garantie d'un complément de prix (8€.t^{-1}), mais avec un prix de base fixé à la récolte	**Diminué** Prix et bonus fixés lors de la signature du contrat	**Diminué** Prix "tunnel" avec un minimum garanti lors de la signature du contrat
Incertitudes de prix	Pour le collecteur	**Constant** Les contrats n'ont aucune influence				
Incertitudes de marché	Pour le collecteur	**Constant** Les contrats n'ont aucune influence				

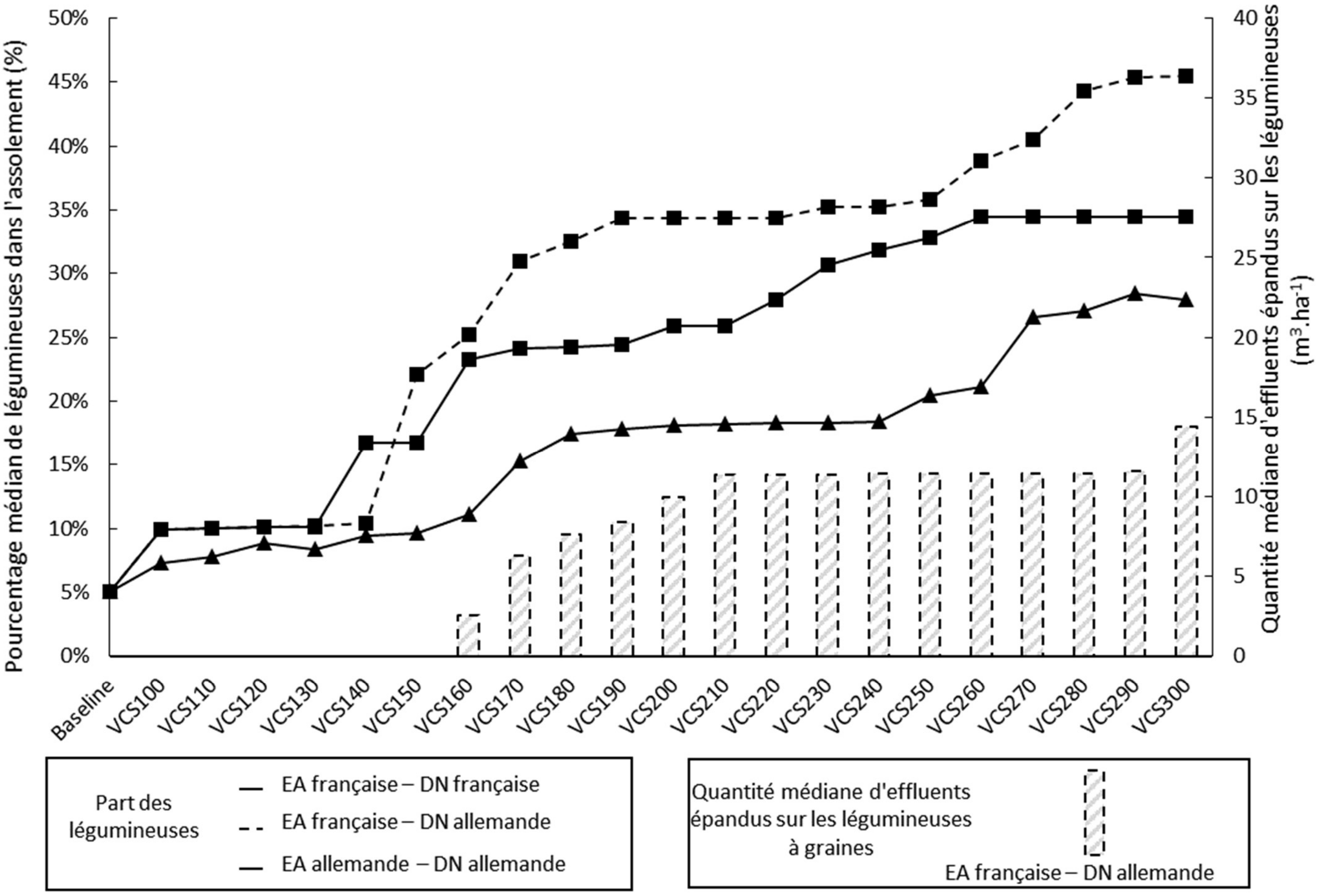
Note: [a] Les contrats de commercialisation ne spécifient que les conditions de vente (par exemple, les méthodes de détermination des prix et des montants, ainsi que les dates et méthodes de livraison). [b] Les contrats de production ne spécifient que les conditions de vente et les pratiques agricoles utilisées pour influencer la qualité finale du produit (par exemple, achats de semences et de pesticides spécifiques; opérations obligatoires à des dates et à une fréquence spécifiques). [c] Contrat de production tripartite entre le producteur, l'intermédiaire qui collecte et le transformateur (regroupé ici en tant que collecteur)

Chapitre 4. Production de légumineuses et utilisation en alimentation animale dans une exploitation de polyculture-élevage : les leviers de politiques publiques

Ce chapitre étudie la production et l'utilisation de légumineuses en alimentation animale à l'échelle de l'exploitation agricole. Il vise à analyser comment les politiques publiques agricoles et environnementales peuvent affecter la production de légumineuses à cette échelle. En particulier, il se concentre sur deux politiques publiques: les aides couplées aux légumineuses et la Directive Nitrates. Pour ce faire, j'ai utilisé le modèle bioéconomique FarmDyn, paramétré pour deux exploitations laitières faisant office de cas-types, en France et en Allemagne. En effet, la France a mis en place des aides couplées pour encourager la production de légumineuses, alors que l'Allemagne ne l'a pas fait. Cependant, l'Allemagne prévoit une application plus favorable de la Directive Nitrates pour les légumineuses en permettant l'épandage d'effluents sur ces cultures. Dans le modèle FarmDyn, j'ai introduit les légumineuses comme cultures de rente et aliments du bétail, mettant en évidence les interactions entre cultures et productions animales. J'ai analysé différents niveaux d'aides couplées à l'hectare, en comparant l'application française et allemande de la Directive Nitrates.

Les résultats suggèrent que les aides couplées entraînent une augmentation de la production de légumineuses mais de manière plus limitée dans l'exploitation allemande que dans celle française, en raison de coûts d'opportunité plus élevés en Allemagne. Dans les deux exploitations, l'augmentation de la production de légumineuses entraîne une amélioration limitée des indicateurs environnementaux: le lessivage de l'azote et le potentiel de réchauffement climatique diminuent légèrement. Dans l'exploitation agricole française, l'application allemande de la Directive Nitrates favorise la production de légumineuses. Je montre ainsi que permettre l'épandage d'effluents sur les légumineuses permet d'atteindre une production plus élevée de légumineuses dans les exploitations d'élevage. Cependant, cela n'entraîne pas d'impacts positifs sur l'environnement, car les avantages liés à la réduction des intrants azotés (engrais, aliments riches en protéines) sont presque compensés par l'augmentation du lessivage des nitrates due à la fertilisation excessive des légumineuses. L'épandage d'effluents sur les légumineuses devrait donc être justifié par d'autres objectifs tels que l'amélioration de l'autonomie en protéines à l'échelle de l'exploitation agricole.

Figure S3. Pourcentage de légumineuses dans l'assolement (hors prairies) et quantité d'effluents épandus sur les légumineuses à graines (médianes), par exploitation et application de la Directive Nitrates (DN), selon différent niveaux d'aides couplées aux légumineuses (ex : VCS100 équivaut à une aide couplée de 100€.ha^{-1})

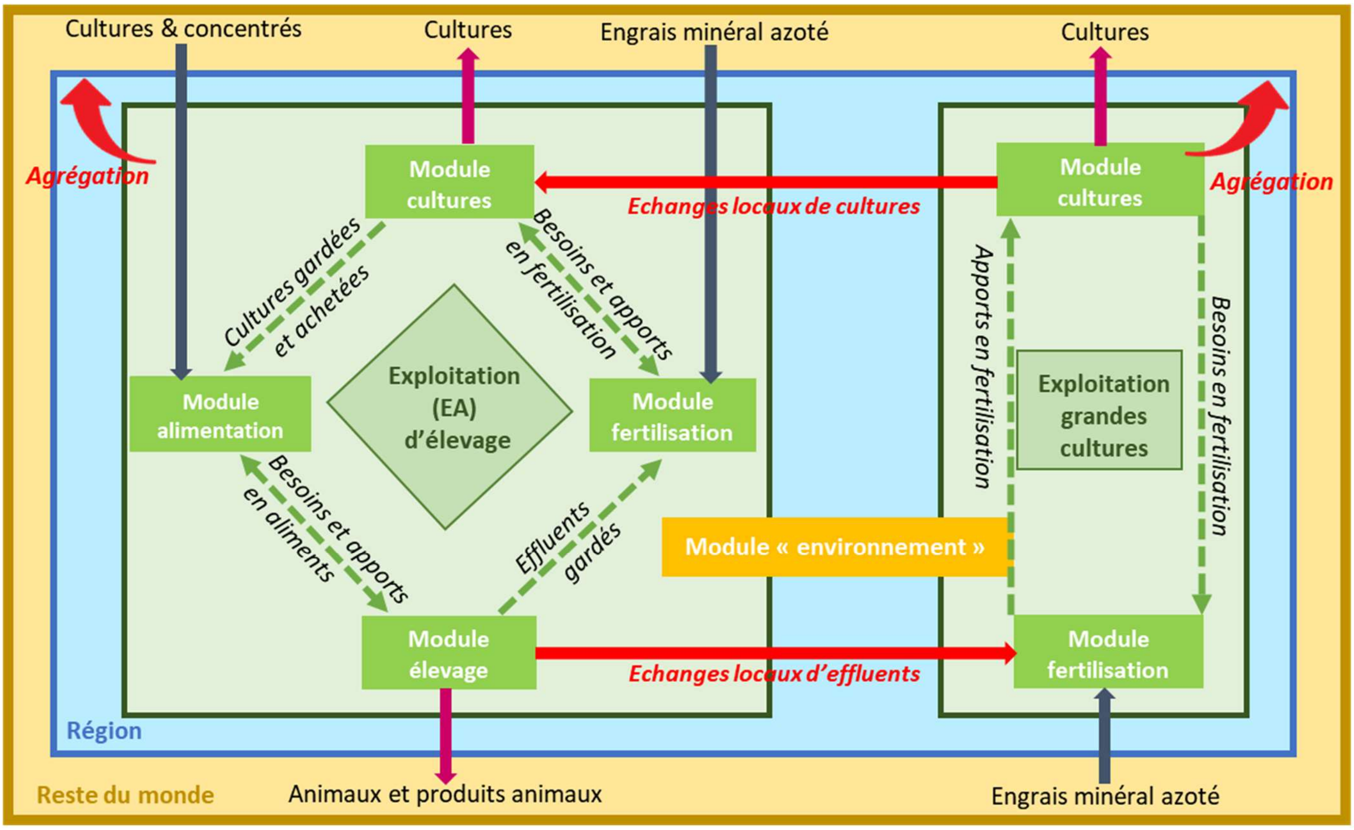


Chapitre 5. Le modèle SYNERGY : analyse de la production de légumineuses, et des complémentarités entre exploitations agricoles, en tant que leviers pour améliorer la durabilité de l'agriculture à l'échelle régionale

Ce chapitre se concentre sur le modèle bioéconomique SYNERGY que j'ai construit durant ma thèse. Ce modèle permet d'étudier les complémentarités techniques culture-élevage à l'échelle régionale en représentant explicitement les échanges entre exploitations de cultures, dont les légumineuses, et d'effluents. Pour permettre de tels échanges, il comprend plusieurs échelles, de l'exploitation à la région. Ces échanges sont représentés par un marché d'équilibre local pour les cultures et les effluents. Une autre spécificité de SYNERGY est de prendre en compte l'effet précédent des légumineuses. En effet, les activités végétales sont définies comme des combinaisons d'une culture et d'une rotation, il est donc possible de réduire les besoins en azote des cultures qui suivent les légumineuses par rapport à celles qui n'en suivent pas. Le modèle représente également des rations innovantes pour le bétail comprenant des légumineuses à graines et fourragères, en substitution du tourteau de soja importé. Ainsi, SYNERGY comprend une grande variété de technologies, tant en production végétale qu'en production animale. En intégrant plusieurs échelles, les complémentarités sont étudiées à l'échelle régionale mais aussi aux échelles de la rotation et d'e l'exploitation.

SYNERGY résulte d'un travail interdisciplinaire en économie et agronomie, ce qui me permet de réaliser une évaluation intégrée à l'aide d'indicateurs économiques et environnementaux. La deuxième partie du chapitre 5 détaille les données utilisées dans SYNERGY. Après un aperçu des données et de leurs sources, je présente comment les données sur les légumineuses ont été introduites dans SYNERGY, ainsi que le calcul de deux indicateurs environnementaux. SyNE (valeur de 0 à 1) évalue l'efficacité avec laquelle les systèmes agricoles transforment les intrants azotés en produits agricoles. SyNB (en kg N.ha-1) reflète les pertes potentielles d'azote des systèmes agricoles, y compris ceux issus du processus de production des intrants (Godinot et al 2014).

Figure S4. Vue d'ensemble du modèle bioéconomique SYNERGY



Dans le chapitre 5, SYNERGY est utilisé pour étudier des scénarios extrêmes en faisant évoluer certaines variables structurelles vers des situations extrêmes, sans s'intéresser aux leviers qui auraient pu conduire à de telles situations. Ce faisant, SYNERGY permet de comprendre les impacts économiques et environnementaux d'ambitieux changements recommandés pour parvenir à une agriculture durable. Par exemple, dans le chapitre 5, j'ai fixé un pourcentage élevé de légumineuses (10%) dans la région de l'ouest de la France.

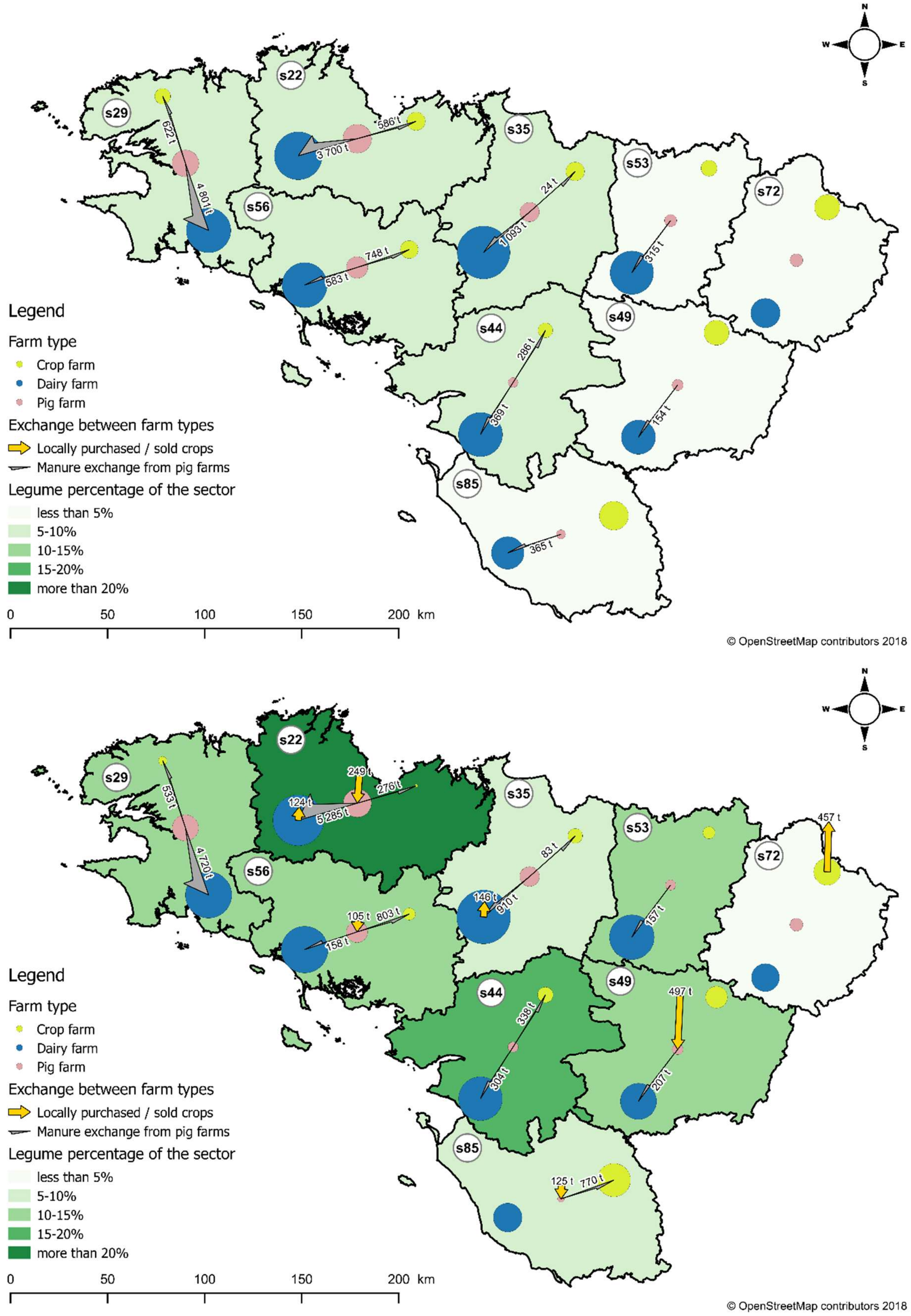
Dans cette situation, je montre que l'utilisation de légumineuses dans les exploitations laitières augmentent (pour atteindre 20% des vaches nourries avec légumineuses) et que l'utilisation d'engrais azotés diminue de 7%. Cependant, cette part importante de légumineuses entraîne également une baisse du profit des exploitations agricoles (-4%), sans amélioration sensible des indicateurs environnementaux. Les échanges d'effluents permettent d'augmenter le pourcentage de légumineuses dans certaines fermes porcines, mais ils conduisent également à une intensification de la production porcine. Les échanges de cultures restent limités et ne conduisent pas à une utilisation supplémentaire des légumineuses en alimentation animale. Pour favoriser la production et l'utilisation de légumineuses, une solution serait d'améliorer la profitabilité de ces cultures en créant de la valeur ajoutée pour le bétail nourri avec.

Chapitre 6. La production de légumineuses et leur utilisation en alimentation animale : analyse de leviers pour améliorer l'autonomie protéique définis à partir de scénarios prospectifs

Ce chapitre va au-delà de l'échelle régionale et examine l'influence des marchés et de la labellisation des aliments sur la production de légumineuses et leur utilisation en alimentation animale. En effet, ce chapitre vise à définir et évaluer des leviers pour augmenter l'autonomie protéique dans l'ouest de la France via l'utilisation de légumineuses. Pour ce faire, j'ai supervisé une prospective régionale, définissant ces leviers innovants. L'un des principaux leviers identifiés est l'augmentation de la demande en produits issus filières agroalimentaires labellisées, comme les produits animaux certifiés sans OGM. En comparaison, j'ai également étudié un autre levier: l'augmentation des aides couplées aux légumineuses. Pour analyser ces leviers, j'ai mis en place un travail de modélisation original. Il combine un modèle d'équilibre générale calculable et le modèle régional SYNERGY. Dans ce cas, SYNERGY est donc utilisé pour étudier différents types de leviers afin de quantifier leur impact sur les variables structurelles et sur les indicateurs économiques et environnementaux.

Les résultats montrent qu'une augmentation des aides couplées aux légumineuses entraîne une augmentation de la production de légumineuses, mais que cela n'a aucune influence sur l'autonomie protéique ou sur d'autres indicateurs, car les légumineuses ne sont pas plus utilisées en alimentation animale. Lorsque la demande en produits animaux sans OGM augmente, la production de légumineuses, y compris les prairies associées (70% ray-grass italien et 30% trèfle blanc), augmente considérablement et la plupart des animaux sont nourris avec des légumineuses. Cependant, dans les exploitations porcines, l'autonomie en protéines diminue car la production de légumineuses n’est pas suffisante par rapport aux besoins des exploitations porcines. Les échanges locaux de cultures entre exploitations restent limités. Le profit régional augmente, mais les indicateurs environnementaux ne s'améliorent pas, en partie à cause de l'augmentation des importations de légumineuses de l'extérieur de la région. Ainsi, dans une région aussi spécialisée en élevage que l’Ouest de la France, les possibilités d’'amélioration de l'autonomie en protéines semble relativement limitées. Une diminution des productions animales devrait être envisagée afin d’atteindre cet objectif et d’améliorer les résultats environnementaux.

Figure S.3. Production de légumineuses et échanges entre exploitations de cultures et d'effluents dans l'ouest de la France, dans la situation initiale (a) et avec une augmentation de la demande en produits animaux sans OGM



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Le pourcentage de légumineuses inclut les légumineuses cultivées pures (pois, féverole, Luzerne) et les prairies associées. Les cercles sont proportionnels aux surfaces des exploitations dans chaque secteur. Les échanges de cultures inférieurs à 600 t ne sont pas représentés.

Chapitre 7. Discussion générale

L'objectif général de ma thèse était d'étudier les complémentarités techniques culture-élevage à différentes échelles, en particulier grâce à l'utilisation de légumineuses. Pour cela, différentes approches ont été développées, comme le modèle bioéconomique SYNERGY. Cependant, plusieurs limites à cette étude peuvent être identifiées.

En premier lieu, la portée de l'étude est restreinte. Les productions bovin viande et volaille n'ont pas été incluses dans SYNERGY, ni le tourteau de colza comme substitut au soja importé. De plus, SYNERGY, comme la plupart des autres contributions, ne s'applique qu'à l'ouest de la France. Cette approche régionale se justifie au regard de l'organisme de financement et du temps nécessaire à la collecte des données nécessaires. Cependant, l'ouest de la France a une production animale élevée compte tenu de sa superficie agricole disponible, ce qui limite la valorisation des complémentarités techniques culture-élevage. Il serait donc intéressant d'étendre la zone d'étude à l'ensemble de la France, y compris aux régions plus tournées vers la production végétale. La deuxième limitation est liée à l'analyse de sensibilité des paramètres clés. Pour représenter les échanges locaux de cultures entre exploitations, un différentiel de 10% a été fixé entre les cultures achetées localement et les cultures achetées sur le marché mondial. De même, la plupart des coefficients techniques (par exemple, les prix, les coûts, les rendements) sont basés sur une moyenne de 5 ans. Une approche complémentaire consisterait donc à effectuer une analyse de sensibilité sur les hypothèses de différentiel de prix et sur les variations de prix ou de rendement afin d’améliorer la robustesse du modèle. Enfin, l’évaluation environnementale développée dans SYNERGY pour être améliorée en introduisant d'autres indicateurs, tels que l'utilisation de pesticides, les émissions de gaz à effet de serre. Ce dernier indicateur devrait inclure les émissions provenant du changement d'affectation des terres afin de prendre en compte le problème de la déforestation importée.

Au cours de cette thèse, un obstacle important à la production de légumineuses n'a pas été étudié: le temps de de travail. En effet, la diversification des cultures peut entraîner une augmentation du temps de travail ou des pics de travail, en particulier pour les légumineuses fourragères (Meynard et al. 2013; Schneider et Huyghe 2015). Or, le secteur agricole est confronté à un problème démographique: en France, près d'un tiers des agriculteurs ont plus de 55 ans et prendront leur retraite d'ici 3 ans (Forget et al.2019; Le Monde 2019). Pour répondre à ces enjeux, certaines organisations proposent de réformer fondamentalement le Pilier I de la PAC, en assurant des paiements de base non plus à l'hectare mais par unité de travail agricole (France Stratégie 2019). Cette réforme favoriserait une transition vers une agriculture qui nécessite plus de main-d'œuvre, ce qui pourrait créer des emplois. Au-delà du temps de travail, la question se pose de la place des légumineuses dans la prochaine PAC, en lien avec le « Green Deal », dont l'objectif est de rendre l'UE climatiquement neutre d'ici 2050. En effet, les légumineuses peuvent contribuer directement à limiter le changement climatique en diminuant l'utilisation d'engrais synthétiques azotés, qui sont l'un des principaux émetteurs de GES dans l'agriculture après la production animale (Perez Dominguez et al.2016).

De plus, l'une des principales contributions de cette thèse est de montrer que les subventions aux légumineuses encouragent leur production mais pas nécessairement leur utilisation en alimentation animale. Par conséquent, il serait de développer d'autres outils pour favoriser l'introduction des légumineuses dans les rations animales, tels que des investissements structurels pour réduire les coûts de transaction entre les producteurs et les collecteurs. Cependant, les rations à base de légumineuses sont généralement moins efficientes en protéines que les rations à base de soja. A technologie constante, plus de terres sont donc nécessaires pour produire du bétail. Il s'agit d'un problème fondamental, car une part importante des terres agricoles (65% dans l'UE) est déjà consacrée à la production animale (Leip et al. 2015). Il existe donc un dilemme entre l'utilisation d'aliments hautement efficaces reposant sur des échanges mondiaux ou des aliments moins efficaces mais produits localement. Néanmoins, un consensus émerge qui remet en question l'importance de l'élevage et de la consommation de viande: dans les pays développés, la réduction de la consommation de produits d'origine animale semble nécessaire pour aligner les régimes alimentaires sur les objectifs de santé publique et écologiques (Hedenus et al.2014; Bryngelsson et al.2016 ; Willett et al.2019). Dans ce contexte, SYNERGY pourrait être utilisé pour simuler un déclin substantiel de la production animale afin d'évaluer les compromis potentiels entre les impacts économiques et environnementaux.

En outre, dans les scénarios simulés par SYNERGY, les échanges de cultures restent faibles, ce qui limite la valorisation des complémentarités culture-élevage au niveau régional. Au-delà de l'écart de prix de 10% entre les cultures achetées localement et sur les marchés mondiaux, la question se pose de comment développer de tels échanges. Des canaux de commercialisation innovants basés sur des outils numériques semblent une solution prometteuse pour limiter les coûts de transaction. Par exemple, de nouveaux acteurs, comme le site Internet « Agriconomie », facilitent l'achat d'intrants, en proposant une large gamme de produits directement accessibles aux agriculteurs (Agra Presse 2018). Ces sites Web pourraient ainsi faciliter non seulement l'achat d'intrants (par exemple, les cultures) entre les détaillants et les agriculteurs, mais aussi directement entre les agriculteurs.

Enfin, cette thèse est le fruit d’une recherche interdisciplinaire, alliant économie et agronomie, afin de proposer une étude globale des complémentarités culture-élevage. En particulier, cette thèse développe une analyse économique des interactions qui sont connues pour être positives en agronomie (c'est-à-dire les complémentarités techniques culture-élevage) mais qui rencontrent des obstacles économiques dans leur mise en œuvre. Ces interactions positives et leurs déterminants techniques sont rarement étudiés en économie, tandis que leur rentabilité et leurs obstacles économiques sont rarement étudiés en agronomie. Au-delà de ce caractère interdisciplinaire, cette thèse résulte également d'une collaboration étroite avec les chambre d’agriculture, les instituts techniques et plusieurs coopératives de l'ouest de la France. Cette collaboration a permis de partager données et résultats, ainsi que de conduire des recherches conformes aux besoins des acteurs locaux. Valoriser de telles interactions entre la recherche académique et le monde professionnel constitue sans doute un élément déterminant pour développer une agriculture plus durable.

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List of abbreviations

EU	European Union
BEM	Bio-Economic Model
CAP	Common Agricultural Policy
CGE	Computable General Equilibrium
EFA	Ecological Focus Area
GHG	Greenhouse Gas
GM	Genetically Modified
GMO	Genetically Modified Organisms
GWP	Global Warming Potential
LHS	Latin hypercube sampling
MP	Mathematical Programming
N	Nitrogen
ND	Nitrates Directive
NIE	New institutional economics
NRW	North Rhine-Westphalia
PDL	Pays de la Loire
PE	Partial Equilibrium
PMP	Positive Mathematical Programming
UAA	Utilized agricultural area
VCS	Voluntary Coupled Support

Chapter 1.
General introduction

The classical economic theory developed by Ricardo and Smith defined labor, capital and land as the three essential factors of production and trade as the main source of benefits for nations. In the 20th century, neoclassical economic theory assimilated land into capital, making it substitutable with all other factors. Inherent to this theory, the continued growth of the economy represents the main objective of human action, which relegates the environmental stresses suffered by the Earth system to the periphery. However, the Earth system is a closed system: solar energy passes through it, but matter follows only cycles. In contrast, the economy is an open system in which finite or renewable resources are extracted from land (e.g., natural gas, wood) and from which waste must be removed (Raworth 2017). Redesigning the economy as an open subsystem in a closed Earth system was the major upheaval introduced by ecological economists (Daly 1990). They concede that the economy exceeds the Earth's regenerative capacity, over-exploiting land-based resources and generating pollution. In this respect, ecological economics integrates natural constraints that can limit growth (Arrow et al. 1995). To do so, a closer relation between economics and natural sciences has been developed. My research lies in a direct line with these considerations by proposing a multidisciplinary research, between economics and agronomy. It includes the complex processes of agroecosystems, involving multiple inputs and outputs (Chavas 2008), and highlights them in an economic research framework. This framework is particularly interested in European agriculture, whose structure changed greatly during the 20th century.

1.1. From specialization of agriculture to synergies between farms

1.1.1. Trends of agricultural specialization and its consequences

In the 19th century, the model of mixed crop-livestock farms, combining advantages of animal and crop production, spread in Europe to meet the growing demand for food. Thus, up until the 1950s, most farms in Europe were mixed crop-livestock farms (Jussiau et al. 1999). However, this model has since largely declined in favor of specialized farms, which represent 79% of farms in the European Union (EU) and 85% in France (Eurostat 2019a). Farm specialization has several roots (de Roest et al. 2018). In the 1960s, the Common Agricultural Policy (CAP) introduced price and market support (e.g., intervention prices) to improve food security by stabilizing producer prices. This encouraged farmers to specialize to reduce average production costs and thus satisfy the demand for less expensive food. **Economies of scale** thus emerged: the increase in the production of an output went along with a decrease in its average production costs. These economies of scale are intrinsically linked to technical progress, usually capital-intensive, which increases production and labor productivity and reduces input costs per unit of product. Under the hypothesis of bounded rationality of decision-makers (i.e., farmers), economies of scale can also be due to the lower complexity of specialized agro-ecosystems that generates labor productivity gains. Finally, technological change outside agriculture may have favored specialization: improvements in communication tools and lowered transport costs could have eased the access to specialists, thus allowing farmers to reduce the scope of their managerial activities (Chavas 2008).

In relation to this specialization at the farm scale, specialization also occurred at the regional scale: some EU regions have a concentration of animal production (e.g., western France, the Netherlands-North Germany-Denmark axis), while others have a concentration of crop production (e.g., the French region of Centre-Val de Loire). Many factors explain this concentration. For crop production and pasture-based livestock production, soil and climate conditions represent undeniable comparative advantages for production costs (Daniel 2003). Other elements play a substantial role, such as the saving of transport costs and the location of activities (Roguet et al. 2015). In particular, **economies of agglomeration** can occur when stakeholders in the same sector are located in the same territory (Fujita and Thisse 1996). Non-market interactions induced by geographical proximity also modify the relationship between costs and outputs by facilitating exchanges of information about markets and developing technical or organizational innovations. Frequent contacts between stakeholders within a region also decrease transaction costs (i.e., costs related to the search for information, the process of negotiation and verifications before and after the transaction (Coase 1937; Williamson 1979)). For example, in western France, the proximity of upstream and downstream industries (e.g., feed factories and dairy cooperatives), as well as harbors through which inputs and outputs pass, represent major drivers of livestock distribution (Gaigné et al. 2012).

Nevertheless, specialized farms and regions also have drawbacks. From an economic viewpoint, these systems suffer from higher vulnerability to production or price risks than mixed crop-livestock farms or regions (Seo 2010; Ryschawy et al. 2012). Other factors increase this economic vulnerability even more (OECD 2009). In addition to the volatility in input prices, the reduction of market support measures has increased agricultural products price volatility since 2000 (Chatellier 2011). Climate change is also increasing production volatility due to a rise in temperatures and more frequent extreme weather events (Schmidhuber and Tubiello 2007). In addition to its low economic resilience, specialized agriculture's environmental impacts are questioned (Naylor et al. 2005). Indeed, specialization of agriculture goes hand in hand with its industrialization, whose negative consequences for the environment are widely recognized: water pollution, soil degradation, reduction in biodiversity, greenhouse gas (GHG) emissions (Donald et al. 2006; Moss 2008; Baude et al. 2019; Garnier et al. 2019). However, these environmental damages reinforce the economic vulnerability of agriculture. Overall, most economic and environmental benefits of diversified agroecosystems are lost during the process of specialization (Kremen and Miles 2012). In particular, joint production of ecosystem services and recycling of nutrients through the complementarity of different agricultural production cannot be enhanced in specialized farms and regions.

1.1.2. Agroecology: enhancing joint production and complementarities of farms

Agroecology applies ecological theory to the design and management of sustainable agroecosystems (Altieri and Farrell 2018). These agroecosystems are expected to have high productivity per ha, require few chemical inputs and conserve resources. To do so, they are based on the valorization of biological processes that promote biodiversity, pest regulation and recycling of nutrients. From an economic viewpoint, these agroecological principles promote the emergence of joint production and technical complementarities.

Joint production refers to outputs that cannot be produced separately since they are joined by a common origin (Marshall 1959). It has been the core subject of multiple studies in production economics (Shumway et al. 1984; Leathers 1991). Different types of jointness are usually distinguished (OECD 2001). Among them, **non-allocable inputs** imply that one input produces multiple outputs (e.g., a sheep produces wool, meat and manure, and this last output can be recycled by fertilizing crops). Another type of jointness, **technical interdependencies,** implies that changes in the level of one output affect the levels of the other outputs. For example, bees depend on flowers to produce honey, while some flowers depend on bees for their pollination. If an increase in the supply of one output raises marginal input productivities[1] in the production of another, then the goods are **technically complementary**. If it decreases it, they are competing (Nilsson et al. 2008). In agriculture, this technical complementarity depends on positive interactions between types of production. Mixed crop-livestock farming is a good example: crops provide feed and straw to animals, which produce manure for crop fertilization (Peyraud et al. 2014b). Thus, an increase in the output "animals" increases the production of manure, which raises the marginal productivities of inputs used to produce crops since less synthetic nitrogen (N) fertilizer is needed.

Technical complementarities can also lead to **economies of scope** (Panzar and Willig 1981; Baumol et al. 1982). Economies of scope appear when producing outputs jointly costs less than producing them separately: they form the basis of multi-product firms (Chavas et al. 2010). In the agricultural sector, mixed crop-livestock farms are typically multi-product firms. In such farms, feed cost can be decreased by feeding animals with self-produced crops and fertilizer cost can be decreased by spreading manure instead of synthetic N fertilizers (Perrot et al. 2012). However, this multi-product nature can lead to some challenges, such as work management and maintaining the inherent productivity of the types of production (Moraine et al. 2014). For example, on a mixed crop-dairy farm, monitoring crop production closely can be difficult since dairy production monopolizes most of the workload, which can decrease the profitability of the crops. In addition, the inherent productivity of monogastric production (e.g., chickens and pigs) can be reduced greatly by using self-produced feeds instead of industrial feeds, because the latter are less effective at providing the nutrients needed by animals at the lowest cost.

In addition to the production of agricultural goods, recent studies have focused on applying joint production to the multifunctionality of agriculture (OECD 2001). Indeed, the **multifunctionality** of agriculture can be seen as the result of joint production, in which some of the outputs produced are ecosystem services (i.e., the benefits that people obtain from ecosystems) (Millennium Ecosystem Assessment 2005; Zhang et al. 2007). Most of them are

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[1] The term "marginal productivity" of an input refers to the additional output gained by adding one unit of this specific input, all other inputs held constant.

non-marketable outputs, since they have the characteristics of public goods. A good example of multifunctionality is grass-based beef production, which provides meat (i.e., a marketable good) and enhances biodiversity (i.e., non-marketable ecosystem services) (Dumont et al. 2019).

Specialization of agriculture, characterized by segregation of crop and animal production, has led to a neglect of joint production and technical complementarities. It has hampered proper recycling of essential nutrients between these two types of production (Nesme et al. 2015). In particular, production and management of N has been disturbed, leading to negative impacts. Indeed, according to the planetary boundary framework, N flows have already reached a critical state at the global scale, threatening human development (Rockström et al. 2009). This crossing of a threshold is due mainly to the specialization of regions in livestock production, where large quantities are N are produced by animals (i.e., manure), and some of it is lost to the environment (Steffen et al. 2015; Campbell et al. 2017) (Appendix A).

1.1.3. Agricultural specialization and nitrogen cycle

N input is essential to agriculture since it is the limiting element for plant growth in many agroecosystems. Thus, synthetic N fertilizers represent one of the main inputs of agricultural production, and the technology used to produce them and distribute them around the world has changed greatly in the 20th century (Galloway et al. 2008).

Until the middle of the 20th century, crop fertilization was based mainly on organic N fertilizers (e.g., animal manure[2]) and biological fixation (particularly that of forage legumes). In 1909, the invention of Haber-Bosch process made it possible to produce large quantities of synthetic N fertilizers from fossil fuels. Because of the development of these fertilizers, as well as progress in mechanization, plant protection and genetics, agricultural production increased, particularly that of cereals, and the technical complementarity of animals and plants was weakened (Erisman et al. 2008). A study based on long-term experiments and national statistics concluded that ca. 30-50% of the yield of major crops was due to synthetic N fertilization (Stewart et al. 2005). In 2010, consumption of synthetic N fertilizers in the EU stabilized at ca. 8 000 Gg N (Erisman et al. 2011).

Specialization of agriculture has led to an imbalance in the spatial distribution of N fertilizers. On crop-oriented farms and regions, N available for crops from natural processes (e.g., N

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[2] In the rest of the manuscript, I consider only organic fertilizers produced by animals; consequently, I use the term "manure".

mineralization from soil organic matter, N fixation by free-living organisms) may not meet crop needs. This leads to a deficit in N, which is offset by synthetic N fertilizers. On livestock-oriented farms and regions, however, the quantity of manure produced may exceed crop needs. This leads to an excess of N, some of which is lost to the environment. In addition, the issue of N distribution around the world is not limited to N fertilizers, but also includes N-rich feed, since N is the building block of proteins. In fact, specialization of agriculture has led to an increase in purchases of N-rich feeds (e.g., soybean meal), which have partly replaced feeds previously produced on farms (Naylor et al. 2005). Thus, exchanges of N-rich inputs have increased worldwide, with some regions exporting N-rich feed (e.g., soybeans from Brazil) and other regions importing it (e.g., soybeans to the EU). Indeed, soybean increased from 8% of protein N exchanges in 1960 to 44% in 2010 (Lassaletta et al. 2014). Exchange of N inputs also appeared between regions of the same country, some of which are specialized in crop production and others in animal production (Le Noë et al. 2016). Thus, agricultural specialization led to an increase in the production and exchanges of N inputs, favoring incoming and outgoing flows, which break the N cycle.

Regarding environmental impacts, the massive use of N fertilizers, especially from manure, causes N to accumulate in some environmental compartments and thus to damage ecosystems (e.g., water pollution by nitrates in a livestock region; Appendix B). The increased demand of N-rich feed is also held responsible for serious environmental issues: the concept of “imported deforestation” has highlighted how production of soybean to feed livestock, and the livestock production itself, are the main driver of tropical deforestation (Pendrill et al. 2019). Regarding economic impact, the dependence on N-rich feed is also questioned. The desire to increase feed self-sufficiency of farms has grown, related to the market instability of imported soybean (European Parliament 2011). This instability is due in part to the emergence of new customers for soybean suppliers, notably China, which recently became the main importer of N-rich feed in the world (Lassaletta et al. 2014). In addition to the instability, the soybean market also suffers from the negative perception of products made from genetically modified organisms (GMO) by European consumers; since most of soybean is genetically modified, its use in feed is increasingly questioned (Dolgopolova and Roosen 2018).

A reduction in worldwide exchanges of N inputs, such as synthetic N fertilizers and N-rich feed, could contribute to decreasing environmental damages and addressing economic concerns. Introducing legumes to farms, and enhancing complementarities between crops and livestock, represent valuable tools to reach this target.

1.1.4. Joint production and technical complementarities from legumes

Legumes are N-rich crops that belong to the Fabaceae family, which is the third largest plant family, with ca. 18 000 species (Schneider and Huyghe 2015). The main advantage of legumes lies in their ability to fix atmospheric N (N_2) through symbiosis with soil bacteria inside root nodules. Unlike other plants, most legumes do not need ammonium or nitrate for their development as soon as these nodules are formed. For this reason, they are usually self-sufficient in N fertilization. Furthermore, they can supply N to intercrops or subsequent crops through rhizodeposition[3] or mineralization of N-rich residues[4] (Peoples et al. 2009), reducing the use of N fertilizers for these crops. Thus, **legumes provide joint production of marketable outputs (i.e., N-rich food or feed) and a partially non-marketable ecosystem service (i.e., a source of N for intercrops or subsequent crops)** (Wossink and Swinton 2007). This specific jointness has received little attention in the field of agricultural economics (e.g., Hennessy (2006)), even though a monetary value can be estimated for this biological source of N. Indeed, this jointness makes it possible to decrease use of synthetic N fertilizers on intercrops or subsequent crops and, sometimes, even to increase yields or protein contents of the subsequent crops (i.e., the "pre-crop effect") (Beattie et al. 1974; Preissel et al. 2015). In addition to fixing N, legumes jointly produce other ecosystem services (Zander et al. 2016): they regulate pests by breaking the cycle of weeds and diseases (Angus et al. 2015), enhance field biodiversity and help improve soil structure (Peoples et al. 2009) and can reduce greenhouse gas (GHG) emissions by decreasing use of synthetic N fertilizers (Jensen et al. 2012).

In addition, legume production represents a concrete example of technical complementarity between successive crops **at the rotation scale**: increased production of one output (i.e., legume) leads to a reduced production cost of the other (i.e., the subsequent crop). **At the farm scale**, on mixed crop-livestock farms, legumes are also complementary with livestock. In fact, locally produced legumes can be introduced into rations as N-rich feed (Schneider and Huyghe 2015) and therefore replace imported N-rich feed. Consequently, introducing them can decrease expenses of feed purchases and increase the protein self-sufficiency of the farm (i.e., the ratio of crude protein produced and consumed on the farm to all crude protein consumed on the farm) (Gaudino et al. 2018).

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[3] N released by roots of organic compounds into their surrounding environment.

[4] N contained in the parts of the plants left on the ground, which are transformed into simple mineral compounds, assimilated by the subsequent crops.

Despite the advantages of legumes, their production has dropped sharply since the 1960s: from 1961 to 2017, the area of grain legumes decreased by 35% in the EU (from ca. 640 000 to 410 000 ha, respectively) (FAOSTAT 2019) (Appendix C). This decline is partly due to market factors such a high substitutability with other N-rich inputs (e.g., soybean meal) and lower short-term profitability than those of other crops (Zander et al. 2016). To increase legume production in the EU, several policies aim to increase the profitability of legumes and thus decrease their opportunity costs. In particular, the most recent CAP (2014) made it possible to implement voluntary coupled support for legumes (Pillar I). The "greening measures" (Pillar I) also encourage legume production by integrating these crops in plans for crop diversification and Ecological Focus Areas. In addition, Pillar II supports legume production through agri-environmental plans and support for organic production, in which the use of legumes is essential. Another way to increase legume production is to develop private initiatives: they can increase legume profitability, as final or intermediate goods, by labeling products made from legumes. In this case, added value is created along the entire agro-food chain.

However, on livestock-oriented farms, legume production may remain limited due to constraints on manure management. Since legumes do not need to be fertilized, spreading manure on them is inconsistent from an agronomic viewpoint, since it may lead to overfertilization and water pollution. This is translated into the EU Nitrates Directive, which EU countries apply differently. For example, in western France, application of the Nitrates Directive forbids spreading manure on legumes. In addition, the directive also limits the quantity of manure spread on all crops to 170 kg $N.ha^{-1}$. Thus, on livestock-oriented farms, introduction of legumes may complicate the valorization of manure while complying with this regulation. To facilitate introduction of legumes into livestock-oriented farms, one solution is to examine this issue at a larger scale.

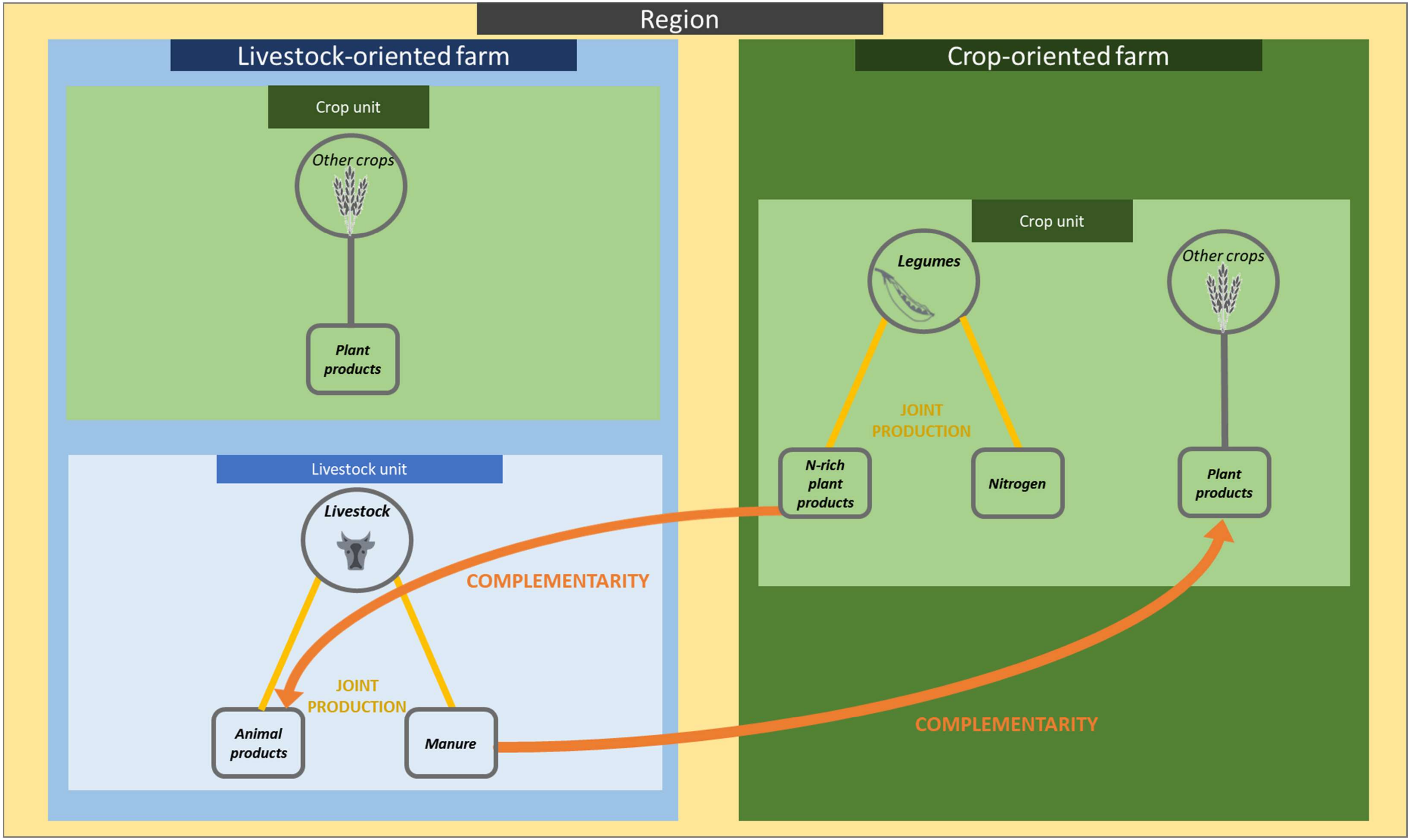
1.1.5. Farm-to-farm exchanges: scaling up agroecological principles to enhance technical complementarities

By scaling up agroecological principles, it is possible to highlight technical complementarities that appear not within a farm but between farms within a region: outputs of some farms become inputs of others. For example, crop-oriented farms produce and sell crops, especially legumes, to neighboring livestock-oriented farms, which use these crop products to feed animals (Figure 1.1). **Farm-to-farm exchanges** becomes particularly interesting when joint production of outputs that are considered negative externalities on one farm can be valorized as inputs by another farm. For instance, on some farms, high livestock densities lead to production of more manure than required by crops or allowed for spreading by environmental constraints. Thus, these farms can export their surplus manure to crop-oriented farms that are deficient in N for fertilization, which makes it possible for the latter to decrease purchases of synthetic N fertilizers. Thus, farm-to-farm exchanges of N-rich materials (legumes and manure) can facilitate their use on farms, decreasing worldwide purchases of N inputs, while taking advantage of the benefits of specialization (e.g., economies of scale).

Nevertheless, development of farm-to-farm exchanges faces several challenges. For one, manure exchanges usually have **high transport costs.** Because manure has lower N concentration than synthetic fertilizers, large quantities of manure need to be transported (Peyraud et al. 2014a). The challenge is even greater in regions with a high concentration of livestock production. The livestock-oriented farms that need to export manure compete with each other to find spreadable areas on other farms. Thus, they tend to spread it on more distant farms, which increases transport costs, these costs being paid only by the exporting farms in such regions. Regarding crop exchanges, the main issue is not transport costs but **transaction costs**. These costs are related to the search for information, the process of negotiation and verifications before and after transactions (Coase 1937; Williamson 1979). However, for legume exchanges, transaction costs can be especially high due to underdevelopment of the logistics or technical skills of cooperatives (or other collectors) that usually can decrease these transaction costs. This underdevelopment results from a “lock-in” situation that tends to favor cereals and oilseed crops instead of diversifying crops such as legumes (Magrini et al. 2016). This “lock-in” situation began when legumes were relegated to animal feed, placing them in direct competition with imported soybeans. Since then, a co-evolution of markets, agrochemical firms and public policies has favored increasing returns to adoption for cereals to the detriment of legumes.

Despite these issues, farm-to-farm exchanges represent a promising lever to apply the concept of a **circular economy**. This concept promotes adoption of production patterns that close the matter and energy loops between distinct structures in order to increase resource-use efficiency while decreasing the structures ‘environmental impacts (Ghisellini et al. 2016; Geissdoerfer et al. 2017).

Figure 1.1. Farm-to-farm exchanges at the regional scale to enhance technical complementarities



1.2. Problem statement, objective and research questions

Since 1950s, European agriculture has experienced a trend of **specialization**, with a disconnection between crop and animal production. This trend has occurred at several scales: farms specialized in one type of production take advantage of **economies of scale**, while some regions with concentrations of either crop- or animal-oriented farms take advantage of **economies of agglomeration**. Nevertheless, since 2000, the low economic resilience of specialized farms and regions and their negative environmental impacts have raised questions about this trend. Indeed, most economic and environmental benefits of diversified agroecosystems are lost during specialization. In particular, **joint production** of ecosystem services is restricted, as is enhancement of **technical complementarities** between crops and livestock. This leads to substantial modifications in the production and management of N. Crop-oriented farms and regions may suffer from a deficit in N, which must be offset by purchases of synthetic N fertilizers. In contrast, livestock-oriented farms and regions may suffer from an excess of N in manure, some of which is lost to the environment. Besides, the issue of N distribution encompasses the availability of proteins. Livestock-oriented farms and regions must buy N-rich feed (e.g., soybean meal) since the **opportunity cost** to produce it is too high. Thus, exchanges of N-rich inputs, synthetic N fertilizers and N-rich feed have increased worldwide. In addition to environmental impacts (e.g., water pollution, deforestation), the low protein self-sufficiency in the EU is seen as a threat to its economy. Given these concerns, it is necessary to reduce worldwide exchanges of N inputs. One lever that has been identified is to encourage **legume production**. The main advantage of legumes lies in their ability to fix atmospheric N, which lies behind joint production of N-rich crops and N for intercrops or subsequent crops. Thus, technical complementarities can appear between legumes and intercrops or subsequent crops, as well as between legumes and livestock, if legumes are used to feed animals. However, legume production on livestock-oriented farms may be limited by constraints on manure management. One solution would be to enhance technical complementarities between farms within a region: crop-oriented farms can produce and sell legumes to neighboring livestock-oriented farms, which can use these crop products to feed animals. In return, livestock-oriented farms can export manure to crop-oriented farms that are deficient in N for fertilization. This example of **circular economy** can represent an interesting lever for decreasing negative impacts of agricultural specialization while taking advantage of these economic benefits.

The general objective of my doctoral research is to study complementarities of crop and livestock production from rotation to regional scales to improve the sustainability of agriculture. The main hypothesis is that legumes improve these technical complementarities. To this end, I study (i) potential levers to increase legume production and enhance technical complementarities and (ii) potential consequences – economic and environmental – of such innovations. In addition, to connect crop and livestock production, I focus mainly on legumes used in animal feed (i.e., intermediate goods), even though the outlet of legumes as cash crops (i.e., final goods) is also considered.

The general objective is stated in several research questions (Figure 1.2), which are addressed in the following chapters of this thesis.

Q1: What are the opportunity costs of legumes at the field and rotation scales?

Legume production remains limited in the EU. At the field scale, legumes are considered less profitable in the short term than other common crops because their annual gross margin is usually lower and it is difficult to quantify the monetary value of the pre-crop effect (von Richthofen et al. 2006a). In addition, legumes are considered riskier than more common crops because of their more variable yields from year to year, though there is no consensus on this point in the scientific community (Peltonen-Sainio and Niemi 2012; Cernay et al. 2015). Thus, due to farmers' risk aversion, legume margins are penalized with a higher risk premium (i.e., the amount of money that a farmer is willing to pay to eliminate all risk) than those of other crops, which decreases their relative profitability even more. However, due to joint production of N in the soil caused by legumes in rotations, a first technical complementarity appears at the rotation scale between legumes and non-legume crops. Several studies have reviewed agronomic and environmental performances of legumes (Dequiedt and Moran 2015; Cernay et al. 2015; Lötjönen and Ollikainen 2017), but few focused on legumes from an economic viewpoint (Bridet-Guillaume et al. 2010). In particular, few studies examined opportunity costs of legumes, even though this issue remains a priority for farmers when choosing their cropping plan.

Chapter 3 analyzes literature data on the economic attractiveness of legumes at the field scale (i.e., for one year) and rotation scale. I tested the hypothesis that the opportunity costs of legumes are negative at the rotation scale due to the pre-crop effect, which reveals the technical complementarities between legumes and subsequent crops.

Q2: What are the opportunity costs of legumes at the livestock-oriented farm scale?

Farms that are specialized in livestock to differing degrees (e.g., mixed crop-livestock farms, livestock-oriented farms) have another technical complementarity: protein-rich legumes can be fed to animals. Legumes thus represent an intermediate good whose opportunity cost depends on their inherent opportunity costs and on the performance of animal production. Legume-based rations have not yet been sufficiently observed to be estimated econometrically. However, mathematical programming models can perform ex-ante analysis by assessing such fine technical changes, even though they have not yet been introduced at a large scale (Jacquet et al. 2011; Böcker et al. 2018). They are usually based on production function approaches, combined with an economic objective (e.g., maximizing profit). Among mathematical programming models, bioeconomic models combine economic and biological data, which is particularly relevant for representing joint production from legumes. These models also identify trade-offs between economic and environmental considerations (Janssen and van Ittersum 2007). The diversity of bioeconomic models is described in chapter 2. To date, only a few bioeconomic models have considered legumes as feed on livestock-oriented farms (Helming et al. 2014; Schläfke et al. 2014; Gaudino et al. 2018). In addition, one factor that may affect the introduction of legumes on these farms is not considered: manure management. Since legumes do not need to be fertilized, spreading manure on them is inconsistent from an agronomic viewpoint. This is translated into the Nitrates Directive, which EU countries apply differently. For example, in western France, application of the Nitrates Directive forbids spreading manure on legumes. At the farm scale, a change in regulations could allow manure to be spread on legumes as long as the N balance at the farm scale is not exceeded, as in Germany. This change would improve interactions between agricultural policies that support legumes, such as voluntary coupled support (Pillar I of the CAP) and application of the Nitrates Directive, which can limit legume production on livestock-oriented farms. Bioeconomic models analyzing impacts of the Nitrates Directive are common (Belhouchette et al. 2011; Kuhn et al. 2019). To the best of my knowledge, however, no study has analyzed considered potential interactions between CAP Pillar I measures related to legume production and implementation of the Nitrates Directive.

Chapter 4 addresses this issue by applying the bioeconomic model FarmDyn to representative dairy farms in France and Germany. I tested the hypothesis that allowing spreading of manure on legumes encourages legume production in France, which leads to positive environmental and economic implications at the farm scale. These positive implications result from the economies of scope allowed by the use of legumes in feed and from the ecosystem services jointly produced by legumes.

Q3: Do technical complementarities between farms encourage legume production at the regional scale? What are the economic and environmental consequences?

Another solution to encourage the use of legumes on livestock-oriented farms would be to study this issue at the regional scale. At this scale, specialized farms could exchange outputs (Peyraud et al. 2014b; Martin et al. 2016). Livestock-oriented farms could export manure to neighboring crop-oriented farms that are deficient in N for fertilization. Crop-oriented farms could sell legumes to livestock-oriented farms and thus provide N-rich crops for animal feed. Complementarities between legume and livestock production would thus be enhanced at the regional scale through circular economy principles.

To study exchanges between farms within a region, it has been necessary to build a bioeconomic model with specific features. The specifications and methodological issues they raise are described in chapter 2. In particular, the bioeconomic model must integrate multiple scales, from the farm to the region. Several cross-scale models have been developed, mainly to study policy changes that impact agricultural production (Chopin et al. 2015; Gocht et al. 2017). To the best of my knowledge, no cross-scale bioeconomic model focuses on legume production or analyzes farm-to-farm exchanges, except for the model of Helming and Reinhard (2009), who studied manure exchanges. It is necessary to emphasize that manure exchanges have also been studied theoretically (Djaout et al. 2009) and by using different tools, such as agent-based models (Happe et al. 2011).

Chapter 5 details the bioeconomic model I created during my doctoral research. This model, SYNERGY, integrates farm-to-farm exchanges of crops – including legumes – and manure. It analyzes (i) impacts of producing legumes widely in western France and (ii) the complementarity of legume and livestock production at the regional scale through local farm-to-farm exchanges. I tested the hypothesis that legume production and these exchanges enhance joint production of N-rich inputs, which benefits the agroecosystem both economically and environmentally. The SYNERGY model integrates many data from a variety of sources. Chapter 5 also includes a data paper that presents the data used in this model.

Q4: What are the transaction costs of exchanging legumes between producers and collectors? Can contracting reduce these costs?

I created SYNERGY to answer the previous question (Q3), but it represents only horizontal relationships from farm to farm, without considering issues of vertical organization (i.e., firms operating at different stages of the agro-food chain). However, vertical organization is important since legumes, as a diversifying crop, can suffer from high transaction costs (Meynard et al. 2018). It is thus necessary to analyze vertical relationships that may exist to lower these transaction costs and create innovative markets for legumes.

Farm-to-farm exchanges of crops, including legumes, face substantial logistical constraints. However, collectors such as cooperatives can play the role of intermediaries between farms by collecting, processing and marketing legumes. Exchanges of legumes can thus form part of an agro-food chain, from production on the farm to marketing in the cooperative. New institutional economics (NIE) studies the role played by institutions (i.e., the set of rules and norms that regulate behaviors) in economic coordination (Coase 1998). In NIE, the theory of transaction costs makes it possible to analyze agro-food chains as successions of transactions. This theory is based on the assumption that stakeholders have limited rationality and an opportunistic behavior. The higher the transaction costs, the more stakeholders are inclined to choose an integrated mode of coordination (Williamson 1979). Different modes of coordination have been described, ranging from "market" to "hierarchy" (in which transactions occur in an integrated manner). Contracting is a "hybrid" mode of coordination between market and hierarchy (Ménard 2004). As mentioned, exchanges of legumes can incur relatively high transaction costs, and contracting is a way to decrease them. Many empirical studies have been performed of contracting in the agricultural sector, for both animal and plant production (Bouamra-Mechemache et al. 2015; Cholez et al. 2017; Bellemare and Lim 2018). However, none of them focuses specifically on the diversity of contracts for legumes for animal feed.

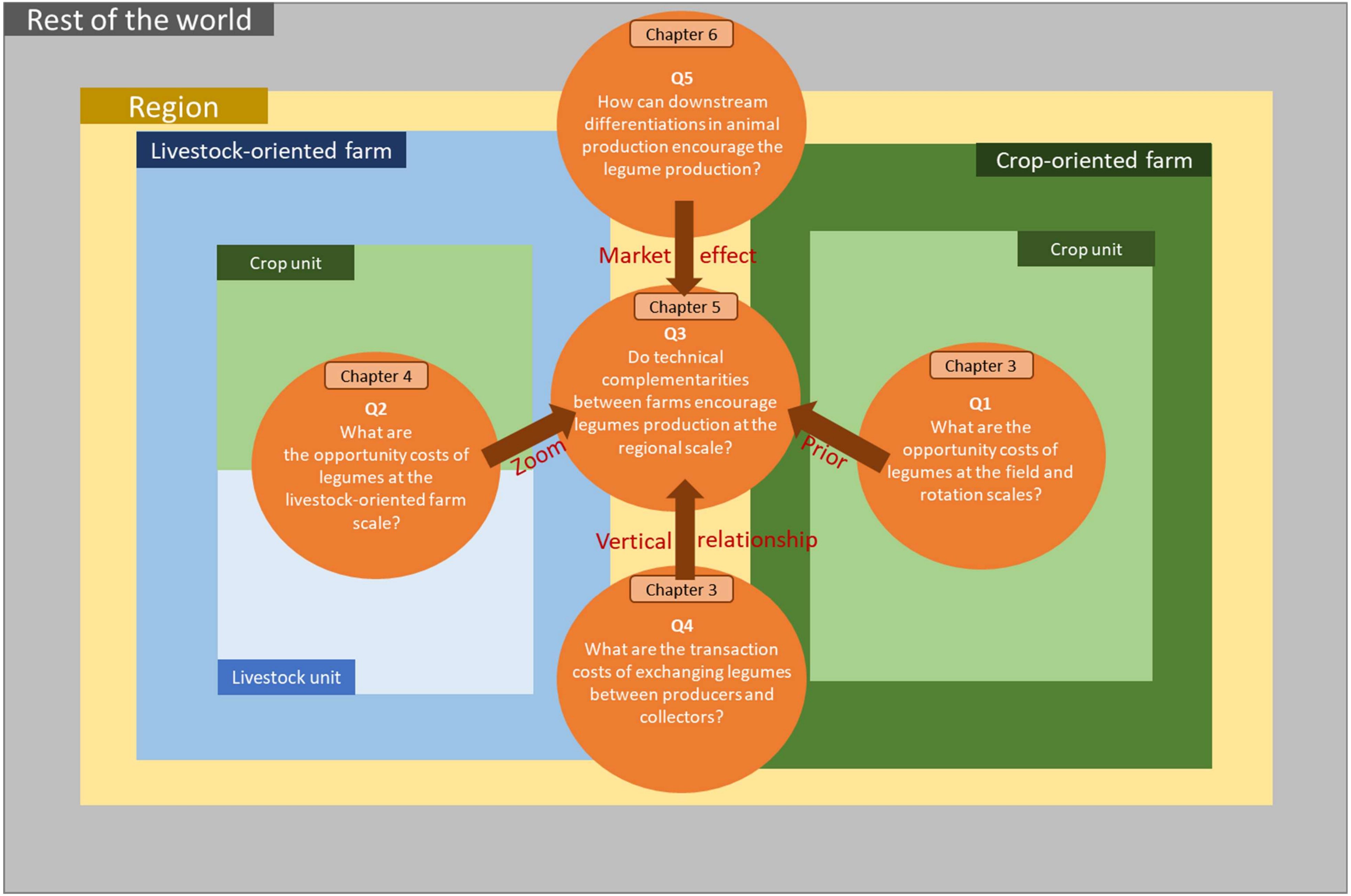
Chapter 3 studies transaction costs related to marketing of legumes. In particular, it analyses legume contracts for animal feed that are offered by cooperatives in western France. I first tested the hypothesis that transaction costs decrease the economic attractiveness of legumes the most, due to characteristics specific to exchanges of these crops. I then tested the hypothesis that contracting decreases transaction costs and thus encourages an increase in legume production.

Q5: How can downstream differentiations in animal production encourage the legume production?

Finally, regarding the use of legumes in animal feed, the lack of differentiation among animal products penalizes legume production. In fact, legumes are easily substitutable by cheaper ingredients, such as imported soybean meal, which considerably limits incorporation of legumes into rations (Charrier et al. 2013). One solution to reduce this substitutability is to highlight environmental and societal advantages of using legumes in feed. These values are credence attributes: consumers cannot evaluate them, whether before or after purchase. To decrease these information asymmetries, policy makers or private firms can introduce food labeling (Aprile et al. 2012), which ensures for the consumer attributes of quality based on specified production practices (Allaire 2012). By doing so, they create a niche market and allow firms to obtain a premium price based on higher consumer willingness to pay for these attributes (Loureiro and Hine 2002; Unnevehr et al. 2010). GMO-free labeling represents an opportunity to differentiate feed with legumes, since most soybean produced in the world is genetically modified (Castellari et al. 2018). Thus, GMO-free animal products (e.g., milk and meat from animals fed without GMOs) can benefit from higher prices, which might decrease the opportunity cost of legumes for feed and encourage legume production. To the best of my knowledge, no study has considered this lever to increase production of legumes used in feed.

Chapter 6 address this issue by implementing a foresight scenario in the SYNERGY model in which demand for GMO-free animal products has increased substantially. To do this, the SYNERGY model was associated with an existing computable general equilibrium (CGE) model (Gohin et al. 2016). These two models are not integrated into a modelling chain, since implementing the CGE model lay outside the scope of my research. Nonetheless, this collaborative work with other scientists made it possible to use the macro-economic effects predicted by the CGE model in the SYNERGY model, which performs economic and environmental assessment at the regional scale. I tested the hypothesis that an increased demand for GMO-free animal products leads to increase production of legumes and their use in feed, and thus to positive economic and environmental impacts. In comparison, I also studied the impacts of an increase in coupled support for legumes.

Figure 1.2. Overview view of the research framework



1.2. Outline of the PhD thesis

This PhD thesis comprises seven chapters, including this general introduction and a general discussion. Chapter 2 presents essential concepts on bio-economic models as well as the methodological approaches implemented in this PhD thesis. Chapter 3 approaches economic drivers of legume production at the rotation scale as well as the agro-food chain scale through the study of opportunity costs and transaction costs. Chapter 4 studies legume production and use in feed at the farm scale. In particular, it analyses how agricultural and environmental public policies can affect legume production and use in a typical dairy farm in France and Germany. Chapter 5 focuses on the SYNERGY model. The first part of this chapter presents this model and how technical complementarities between farms can be represented at the regional scale. The second part of this chapter details the data implemented in the SYNERGY model. Chapter 6 goes beyond the regional scale and looks at the influence of markets and food labelling in the production of legumes. Chapter 7 concludes this PhD thesis with a general discussion.

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Chapter 2.
Methodological approaches

Economic models are simplified representations of economic systems that organize production, allocation and distribution of goods and services. Based on mathematical equations, they represent essential characteristics of these complex systems to simulate various changes influencing them. These equations are founded on assumptions of the behavior of agents (e.g., producers, consumers), related to theoretical economic assumptions. In agricultural economics, models usually aim to assess changes in agricultural policies and technologies. These assessments, which can be performed either before (*ex-ante*) or after (*ex-post*) the changes, do not necessarily follow the same method or require the same data.

This Ph.D. thesis focuses on *ex-ante* assessments, for which models based on mathematical programming (MP) have been developed (Heckelei and Britz 2005). MP models are characterized by an explicit maximization (or minimization) problem, involving an explicit objective (e.g., expected profit, utility or costs), and subject to a set of constraints. These constraints may be technical (e.g., fertilization needs) or refer to limited quantities of quasi-fixed factors (e.g., land) (Carpentier et al. 2015). MP models are particularly useful for the agricultural sector to highlight relationships between inputs and outputs (Hazell and Norton 1986). Initially developed to calculate farm budgets, MP models progressively integrated the decision-making process of farmers, and some were expanded to provide assessment at global or national scales, not only the farm scale (Just 2007).

Computable general equilibrium (CGE) models are MP models applied at global or national scales that consider supply and demand functions of all economic sectors (not only agricultural ones) (Pelikan et al. 2015). In these models, changes in supply have a feedback effect on demand through income. However, CGE models have the disadvantage of using simple functional forms (e.g., constant elasticity of substitution) to represent substitutions between inputs or outputs (Carpentier et al. 2015). In addition, they have limited capacity to model the diversity of agricultural production (Britz and Hertel 2011).

Partial equilibrium (PE) models are MP models applied at national or regional scales. They also consider supply and demand but only for agricultural sectors (not all sectors of the economy) (Britz and Heckelei 2008). PE models represent the diversity of agricultural products in more detail than CGE models do (e.g., differentiating legume crops, while CGE models would represent them as a single "legume crop") (Britz and Hertel 2011). Since PE models are usually expressed in physical quantities, it is also easier to connect them to environmental indicators (Gocht et al. 2017). However, PE models can fail to represent innovative technologies (e.g., low-input cropping systems) in detail as well as the diversity of farming systems (Shrestha et al. 2016).

Supply models are MP models applied at regional or farm scales. Since they do not consider demand, the regions or farms represented are "price-taker": prices are exogenous and not influenced by supply (Ciaian et al. 2013). The main advantage of supply models is their ability to represent the diversity of farming systems as well as many technologies (Britz et al. 2012). Among supply models, **bio-economic models (BEMs)** can represent biophysical processes (e.g., N uptake by crops, soil erosion), which is essential to perform interdisciplinary and integrated assessments. This chapter reviews the literature on BEMs, highlights specific methodological issues and supports the methodological choices made during my Ph.D. research.

2.1. Bio-economic models: models to perform economic and environmental assessments

Breaking down barriers between disciplines is essential to perform integrated assessments. Economic models usually assess economic performance but fail to consider environmental impacts of agricultural systems in detail (Flichman and Jacquet 2003). In contrast, agronomic models usually focus on quantitative assessment of biophysical characteristics of agricultural systems, without evaluating economic performance (Blazy 2008). BEMs address this issue by connecting biophysical and economic data.

2.1.1. Bio-economic models: models based on mathematical programming

BEMs are **MP models** that capture interactions between biophysical and economic processes. As mentioned, BEMs describe relationships between inputs and outputs explicitly using an approach based on engineering production functions (Flichman and Allen 2013). This primal representation of technology facilitates interdisciplinary research on agri-environmental interactions and representation of multiple production processes (Ciaian et al. 2013).

The basic element of this approach is thus the production process, which is called an **activity**. An activity is defined by a set of **technical coefficients** that represent the quantity of inputs needed to produce outputs, which is related to one unit of a fixed factor (e.g., the quantity of N needed per ha to produce wheat). Like other MP models, a BEM is a constraint-optimization model that maximizes (or minimizes) an objective function subject to constraints. A generic formulation can be written as (Eq. 2.1-2.3) (Hazell and Norton 1986):

$$\max Z = \sum_{j=1}^{n} c_j X_j \tag{2.1}$$

$$\text{such that} \sum_{j=1}^{n} a_{ij} X_j \leq b_j \quad \text{all } i = 1 \text{ to } m \tag{2.2}$$

$$\text{and} \qquad X_j \geq 0 \qquad \text{all } j = 1 \text{ to } n \tag{2.3}$$

where X_j represents the level of the jth activity (e.g., area of wheat); n the number of possible activities; c_j the forecast of gross margin of a unit of the jth activity; a_{ij} the quantity of ith resource required to produce one unit of the jth activity; m the number of resources; and b_j the quantity of the ith resource available.

For each activity, these quantities are fixed, and the gross margin (and implicitly yields) are constants (e.g., wheat with a yield of 7 $t.ha^{-1}$ needs 30 kg $N.t^{-1}$ and is sold at $180€.t^{-1}$). Specification of input-output pairs can be thus likened to a simple Leontief production function (Gohin and Chantreuil 1999). One strength of BEMs, however, is their ability to consider many technologies that can be used simultaneously or replace each other, depending on the constraints related to the availability of inputs (Ridier 2001). The multiplication of technologies, and thus of activities, makes it possible to consider technical flexibility and limit jumpy behaviors and overspecialized solutions, which are important issues of linear BEMs (Louhichi et al. 2013).

Another strength of BEMs is that each product (e.g., wheat grain) can be produced by several activities (e.g., a wheat in wheat-maize rotation, wheat in a pea-wheat-maize rotation), and each activity can produce several products (e.g., a pig produces meat and manure) (Flichman et al. 2011). Thus, BEMs are able to represent **the complexity of agroecosystems by incorporating joint production through non-allocable inputs and technical interdependencies** (Havlik et al. 2005). In addition, since these products are represented by physical quantities and not monetary ones, it is possible to consider intermediate products (e.g., manure) and partially non-marketable ecosystem services (e.g., N fixed by legumes) and thus **highlight technical complementarities**.

2.1.2. Diversity of bio-economic models

BEMs generally follow a dual approach: mechanistic, based on explicit definition of cause-effect relationships, and empirical, resulting from more limited knowledge and based on experimental observation (Flichman and Jacquet 2003). According to the reviews of Janssen and van Ittersum (2007) and Reidsma et al. (2018), BEMs can be classified according to seven characteristics:

- The goal of the model's user, which determines whether a positive or normative approach is used. A positive approach is used if the user seeks to understand and describe as accurately as possible the actual behavior of agents (e.g., the farmer in a farm model). Such approaches are suitable to assess policy changes or technological innovations in the medium to short term. A normative approach is used if the user seeks to find solutions to a problem of resource management and allocation, to make recommendations. Normative models are thus based on a "norm" that does not correspond to the actual behaviors of agents for various reasons, such as imperfect information or risk aversion. However, they are particularly useful for assessing alternative farm configurations.

- The decision-making process of the agents modeled, which is described in the objective function of the model. The most classic function is profit maximization, which can include a risk factor. In multi-criteria approaches, objective functions are based on multiple objectives, including social or environmental objectives.
- Consideration of risk, since agricultural production faces economic and environmental uncertainties (e.g., variations in yields, prices). BEMs using only average data assume risk neutrality. Other BEMs represent risk in different ways. When risk is non-embedded, agents cannot respond to uncertainties to reduce the final risk. When risk is embedded, agents can exercise some control by making sequential decisions, thereby influencing the final risk (e.g., by decreasing irrigation for crops if their prices drop during the season).
- Time: most BEMs are static because they do not represent time explicitly (i.e., they model a period with one time step). In contrast, dynamic models consider time explicitly to capture some of the decision variables as functions of time.
- Calibration, to make the model reproduce the observed behavior of agents before using it for simulations. Many methods of calibration are available, such as risk-aversion-based, Positive Mathematical Programming (PMP) and maximum entropy (section 2.4).
- Scale: most BEMs represent a single scale (e.g., farm, region, country). Some BEMs are considered "cross-scale BEMs" since they combine several scales (e.g., multiple farms in a region). These scales can be associated with greater or lesser degrees of complexity using different aggregation or disaggregation processes (section 2.3).
- The farming systems modeled: BEMs can focus on a single farming system (e.g., arable farm that produces only crops) or multiple ones (e.g., arable farm that produces only crops and livestock farm that produces only animal outputs), which can be connected to varying degrees through technical complementarities (e.g., between specialized farms, within mixed crop-livestock farms). These farming systems can also have a wide range of technologies (i.e., conventional or organic crop production). The ability to represent different farming systems and technologies is the main advantage of BEMs compared to other types of models.

Developing BEMs implies making choices and compromises for these characteristics. First, the **goal of the study** strongly influences the choice of the other BEM characteristics. Thus, BEMs are constructed differently depending on whether they aim to assess impacts of public polies or adoption of technical innovations. Studying public policies may require representing the diversity and representativeness of farming systems at local or national scales. Since it is difficult to model individual farms at such scales, representative farms (hereafter, **farm types**) are used. One difficult issue is to choose which types of production should be included (e.g., crops, dairy cattle, pigs) and to what extent the diversity of farming systems should be represented. In contrast, studying technical innovations implies developing a wide range of technical coefficients for a given farming system to represent the diversity of technologies (Townsend et al. 2016). For example, it can be useful to differentiate conventional and organic production. In addition, building a BEM requires choosing a calibration method, to make the model reproduce the observed behavior of agents. However, depending on the goal of the study and the data available, calibration may be limited to production levels (e.g., crop area) or go further to include the observed technologies. Finally, the choice of scale also represents a strategic issue: depending on the goal, studying at small scale makes it possible to assess detailed technical changes, but extrapolating results to policy makers may be difficult, since these changes were modeled only for specific farm types. Nevertheless, data to develop technical coefficients are not always available at all scales, which can also influence the choice of scale.

In practical terms, most methodological choices represent a compromise between the user, the science and the data: At what scale does the user (e.g., policy maker, decision maker) perform the assessment? What data are available? What resources (human and technical) are allocated to the study?

2.1.3. Model specifications to assess benefits from crop-livestock complementarities

The BEM that I developed during my Ph.D. research – SYNERGY – must have several specific features to address the general objective of my study: investigate the technical complementarities of crop and livestock production enhanced by legumes, from rotation to regional scales, to improve the sustainability of farming systems.

First, SYNERGY must model exchanges of crop and manure between farms to highlight technical complementarities not only within farms but also between farms. Second, it must include innovative technologies with legumes (i) in crop production (i.e., rotations with legumes) and (ii) in livestock production (i.e., rations with legumes). Third, it must include different scales, from farms to the region, to consider (i) the diversity of farming systems and technologies and (ii) the heterogeneity of soil and climate conditions. This is particularly important, since we assumed that legumes would not be introduced homogenously in all farming systems, and since soil and climate conditions influence the profitability of legumes. Fourth, it must perform **economic and environmental assessment** at these multiple scales. Specifically, we wanted to highlight potential positive environmental impacts of improving technical crop and livestock complementarities using legumes (in part due to joint production), without ignoring their opportunity costs at the rotation scale. Fifth, SYNERGY must simulate a variety of *ex-ante* scenarios (e.g., coupled support, technical improvements, changes in input and output prices), compared to a baseline scenario built from observed data.

Methodological choices were made regarding these specifications. In the following three sections about model scale, I present three issues related to methodological choices: representation of farming systems and technologies, the scale and aggregation to higher scales, and the calibration method. In the final section of the chapter, I explain the compromises in methodological choices made to build SYNERGY.

2.2. Choice of technologies and farming systems

2.2.1. Representing technical flexibility: from current to alternative practices

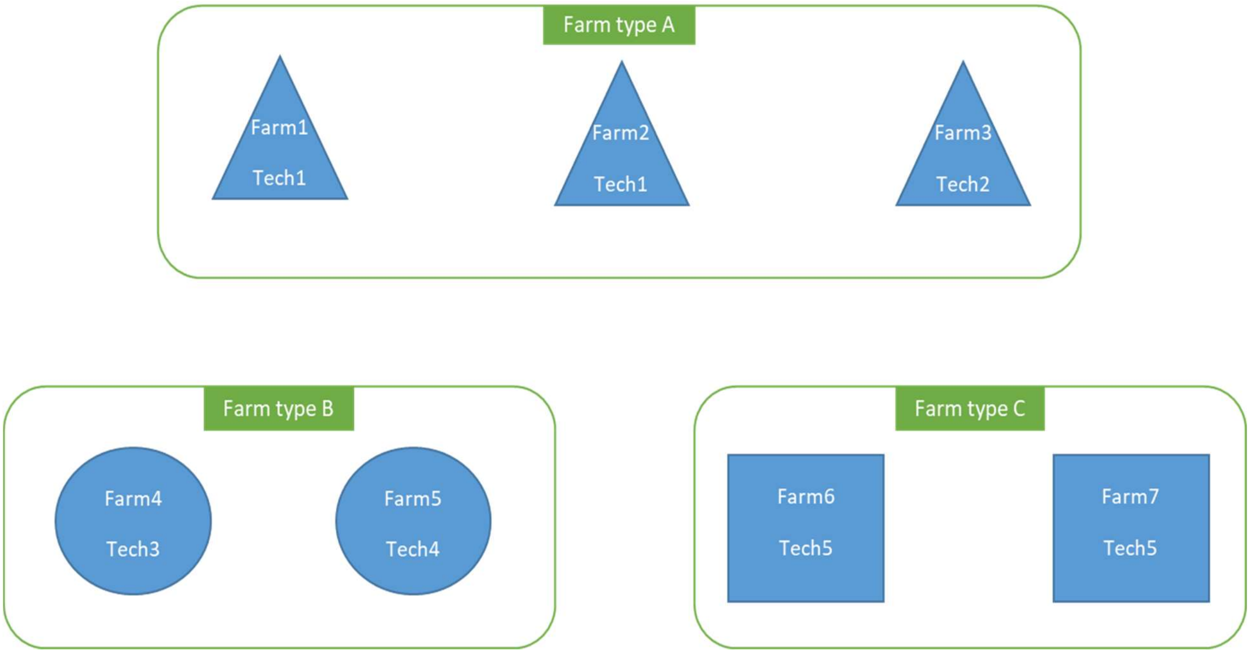
To assess technical innovations or policies that influence the choice of technologies, technical flexibility is essential. This flexibility relies on the range of technologies included in the BEM, and makes it possible to balance the interest of each technology while limiting overspecialized solutions. This range of technologies is represented by technical coefficients, which are developed depending on the types of technologies. If the technologies are well known, technical coefficients can be estimated from data on current management systems. For example, “irrigated” or “non-irrigated” crops can be described easily using technical coefficients in regions where both technologies are used. However, for alternative technologies, which are uncommon, it is difficult to define technical coefficients using data on current management systems. One solution is to call on experts who have thorough knowledge of such technologies and to develop technical coefficients based on their expert knowledge (Jacquet et al. 2011). Another way to introduce innovative technologies into BEMs is to use biotechnical simulators that generate technical coefficients. Representation of technologies shifts from an engineering-production function to a simulator-production function. These simulators can be based on a target-oriented approach that identifies an optimal combination of inputs to reach a given output level, based on knowledge of biophysical processes (e.g., developing a ration from multiple ingredients to reach a given milk yield) (van Ittersum and Rabbinge 1997). These simulators can also design new technologies by including a large number of constraints, based on expert knowledge, but without any undesirable arbitrariness (Dogliotti et al. 2003). Finally, a third option to integrate various technologies is to create a BEM as a coupling of two sub-models, an economic model and a biophysical model (e.g. crop growth model). In this case, the crop growth model is used to determine technical coefficients that are used as inputs in the economic model (Belhouchette et al. 2012). In other cases, the biophysical process is integrated directly into the BEM as a function (Böcker et al. 2018).

2.2.2. Representing farm diversity: use of typologies

To assess technical innovations or policies that are targeted to different farming systems, it is necessary to represent the diversity of farming systems. When it is difficult to obtain sufficient data to model all farms, one solution is to identify **farm types** using a typology.

To develop a typology, Escobar and Berdegué (1990) suggest maximizing the heterogeneity between types and the homogeneity of individuals (i.e., farms) within each type. A trade-off must also be made between the number of farms per farm type, to ensure the robustness of estimates, and the number of types, to limit aggregation bias (Day 1963; De Cara et al. 2005) (section 2.3.2). In practice, in line with the goal of the study, a farm typology can be built according to (i) **type of production** (based on the relative distribution of income from different types of production); (ii) their **environmental impacts** (e.g., GHG emissions) (Andersen et al. 2007); (iii) their soil and climate conditions (Antle and Stoorvogel 2006; Hazeu et al. 2011); and (iv) their technologies, such as crop or livestock management systems. These criteria can also be combined. For example, one farm type can be the combination of one type of production, one type of environmental impact and one type of technology. Such highly detailed typologies are particularly relevant when the studied policies are farming-system oriented and aim to influence the technologies used (Gocht and Britz 2011). However, creating such a typology implies that the farm sample is large enough and describes the technologies and environmental impacts in detail.

Figure 2.1. Diagram of the grouping of individual farms, each with different farming systems and technologies, into farm types.



Blue shapes represent farming systems. A given shape (e.g., triangle) represents similar farming systems (e.g., dairy-oriented farms), which are grouped into farm types (e.g. “dairy”). Tech: technique (e.g., rations)

Different methods to build a farm typology exist (Maton et al. 2005). In the **positivist method**, farm types are built from statistical analysis of farm surveys. A two-step statistical procedure is usually performed (Blazy et al. 2009): a principal component analysis reduces the number of variables, which are then analyzed in ascending hierarchical clustering to divide the population into homogeneous groups. This method has the advantage of creating homogenous groups, but the explanatory variables can difficult to understand, which can limit dissemination of results. In the **constructivist method**, farm types are built from assumptions based on expert knowledge (Perrot and Landais 1993; Girard et al. 2001). Users can understand the explanatory variables easily, but the farm types created have no statistical basis. In the **mixed method**, farm types are defined from both expert knowledge and statistical analysis, which provides both understandable explanatory variables and a statistical basis for justifying farm types (Righi et al. 2011). The mixed method limits bias, since the explanatory variables chosen by expert knowledge must be consistent with the statistical analysis.

2.3. Choice of model scale

The choice of scale (e.g. field > farm > watershed > region > country) is a critical issue, since agricultural systems have many inter-related components. These components are often shaped not only by biophysical factors but also by socio-economic ones. Thus, agricultural systems can be viewed as a set of sub-systems of different dimensions (Ewert et al. 2011). For example, a farm has a biophysical dimension related to ongoing biophysical processes, but also an economic dimension because of the economic decisions made within it and its economic performances. Therefore, developing BEMs to perform integrated assessment implies considering these dimensions while understanding connections between the scales.

2.3.1. Farm, regional and hybrid models: from single-scale to large multi-scale models

In **farm-scale BEMs**, the lowest scale is a farm. The farm's specific characteristics (e.g., soil and climate conditions, crop and livestock management systems, fixed endowments) are included, as are technological changes. Farm-scale models are all the more relevant since farmers make decisions at this scale and most environmental regulations also set constraints at this scale (Janssen and van Ittersum 2007; Godinot et al. 2014). However, extrapolating results to larger scales is difficult due to the usually small sample size of farms, which limits the sample's representativeness.

In aggregated **regional BEMs**, the lowest resolution is a region, which is considered as a single farm (Leip et al. 2007). In more detailed regional models, the region is divided into sub-regions, each of which is considered as a farm (Henseler et al. 2009). These detailed regional models are useful for assessing *ex-ante* agro-environmental policies at large scales since they partially represent the heterogeneity of soil and climate in the region and the diversity of farming systems. However, this representation of diversity is only partial, and they fail to consider decision-making processes at the farm scale.

Hybrid BEMs address this issue (Britz et al. 2012). In these models, the lowest scale is the farm and the highest one is the region. A variety of farming systems are represented by farm types. Decision-making and technical changes are represented at the farm scale, while aggregated indicators can be calculated at the regional scale. Thus, agro-environmental policies are assessed at different scales by considering the diversity of farms and the heterogeneity of soil and climate conditions in the region. By modeling multiple farms in the same region, hybrid models also allow for interactions between farms.

2.3.2. Scaling methods

Scaling refers to the process of extrapolating or translating information across scales (Blöschl and Sivapalan 1995). Scaling methods can be distinguished by how they transfer the information. A "bottom-up" approach is defined as a lower scale influencing a higher scale through aggregation. In contrast, a "top-down" approach is defined as a higher scale influencing a lower scale through disaggregation (Ewert et al. 2011; van Delden et al. 2011).

Several issues may arise from scaling methods, such as mismatching between scales and differing responses of processes to input variables (Ewert et al. 2006). In bottom-up models, one main issue is aggregation bias due to intra-scale heterogeneity (Hazell and Norton 1986). Indeed, aggregation implies assuming a homogenous environment for larger areas, where variability is much higher (Hansen and Jones 2000). For example, in a hybrid model representing farms in a region, it is impossible to model each farm in the region. In practice, farm types are usually used, which can remove the heterogeneity of farms and thus lead to aggregation bias. Several authors studied how to minimize aggregation bias (Day 1963; Miller 1966; Spreen and Takayama 1980; Chen and Önal 2012), but the conditions they cite are restrictive. According to Day (1963), farms of a farm type should be technologically, institutionally and economically homogeneous; thus, all technical coefficients, resource constraints and expected revenues should be the same. Although it is impossible to eliminate aggregation bias, typologies are designed to minimize it. Some calibration methods, such as PMP, also reduce it.

2.4. Choice of calibration methods

Calibration methods aim to make BEMs reproduce the observed behavior of farmers before using the BEMs for simulations. These methods can apply to farm-scale or regional BEMs. In the latter, the observed behavior of farmers is represented by the observed crop area and/or animal numbers. This section describes two calibration methods: one based on minimizing risk in the objective function, and another based on PMP.

2.4.1. Calibration based on risk-aversion

The risk-aversion method calibrates the model by approaching the observed data, but without reaching perfect calibration. To do so, it adds risk-factor minimization to the profit maximization already in the objective function. The sources of risk usually included are variabilities in price or yield. By assuming risk-adverse farmers, the decision-making process considers the highest expected profit and its variability (Mosnier et al. 2017). The objective function can be written as follow (2.4):

$$\text{Max E(U)} = \sum_{f} \mathrm{E}(\pi_{f}) - \Phi_{f}\mathrm{V}(\pi_{f}) \qquad (2.4)$$

where $E(\pi_f)$ represents expected farm profit f; $V(R_f)$ represents the variance of profit; and Φ_f is a risk-aversion coefficient that can vary by farm.

This risk-aversion coefficient is the calibrating parameter of the model: its value is set so that the estimated production level (e.g., area of crops) is as close as possible to the observed level. This calibration method has been applied by linearizing the variance term (MOTAD formulation) (Hazell 1971).

One advantage of the MOTAD calibration method is that the objective function remains linear. However, it does not make the model reproduce the observed data perfectly. To assess the quality of the calibration, a percentage of absolute deviation can be calculated, which must be less than 15% at the regional scale (Hazell and Norton 1986). Another disadvantage of this method is that risk-aversion coefficients may be set arbitrarily to fulfill this condition of percentage of absolute deviation. Thus, these coefficients are not usually parameters of absolute psychological preference that could be revealed using experimental economics methods. Finally, this calibration method may be inefficient for calibrating crop production and livestock production simultaneously in regional models because risk-aversion coefficients do not provide enough flexibility to calibrate both crop area and animal numbers.

2.4.2. Calibration based on positive mathematical programming

The PMP method, developed by Howitt (1995), calibrates BEMs and mitigates their common problems: overspecialization and jumpy behavior. It is based on the idea that differences between model predictions and observed farmer behaviors mean that some technical constraints and cost (or yield) specification have not been considered. Thus, these parameters must be estimated using additional information from observed production levels (e.g., areas) and included in the objective function using a non-linear cost (or production) function (Louhichi et al. 2013). The original PMP approach has three steps (Appendix D):

1. Develop a linear model and add calibration constraints that bound the production levels to those observed during a reference period.
2. Use the duals[5] of the calibration constraints to estimate parameters of a non-linear (usually quadratic) cost function.
3. Remove the calibration constraints from the first step and add the quadratic cost function to the objective function.

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[5] A dual is the shadow price of a constraint: it equals the amount that the objective function changes when the constraint is released by one unit.

The PMP model can then be used for simulations. In a regional cross-scale model that represents only crop farms, the objective function can be written as (Eq. 2.5):

$$Max\ Z = \sum_{f}\sum_{c} (R_f - (d_{c,f} + 0.5Qc_{c,f}.X_{c,f})) \tag{2.5}$$

where Z is the objective function value; R_f is the revenue of farm *f;* $d_{c,f}$ is the vector of intercepts of the cost functions; $Q_{c,f}$ is the vector of slope of the cost function; and $X_{c,f}$ is the non-negative vector of crop area for crop c on farm *f*.

This standard PMP approach has been widely used since its creation in 1990s, in particular to calibrate models including crop production. Several improvements have been made since (e.g., Heckelei and Britz (2005), Louhichi et al. (2013) and Frahan et al. (2007) for critical reviews of these approaches). For example, some PMP methods are now based on multiple observations (e.g., pooling of farm data), such as the maximum entropy-PMP approach (Heckelei and Britz 2000). Other PMP approaches are still based on a single observation but use exogenous information to address problems of zero-marginal cost for the least profitable activities and avoid arbitrary parameter specifications (Helming et al. 2001; Kanellopoulos et al. 2010). In addition, Röhm and Dabbert (2003) used an improved approach to calibrate not only types of production, but also technologies. It is based on the assumption that the elasticity of substitution between variants of the same type of production (e.g., a given crop irrigated or rain-fed) is higher than that between types of production (e.g., two different crops). This is particularly useful when the goal of the modeling framework is to study technical innovations, which can be considered as variants of a given type of production. Compared to the standard approach, the Röhm and Dabbert approach adds calibration constraints to variants, which bounds levels of activities (i.e., a production-variant pair) to the observed levels (Appendix D).

To conclude, a specific PMP method must to be chosen according to a variety of considerations, in particular the goal of the modeling framework and the data available: Is the model developed to assess policies at a large scale or technical innovations at a smaller scale? Are data available for several years or for different technologies?

2.5. From model specification to the SYNERGY model

Based on the model specification (section 2.1.3), methodological choices were made to build the SYNERGY model, concerning (i) representation of technologies and farming systems, (ii) model scale and (iii) the calibration method.

First, SYNERGY can represent exchanges of crops and manure between farms. To do so, profit is maximized at the regional scale, and farm-to-farm exchanges are represented through a local equilibrium in which local demand for crops and manure equals the local supplies. Due to this local equilibrium, SYNERGY converges to a partial equilibrium model. It differs from this type of model, however, by keeping an exogenous price for locally exchanged crops, since we assume that crops produced locally did not differ from those purchased outside the region. In addition, we assume that farms exporting manure pay any transport cost, while the importing farms import it at no cost. This representation of manure exchanges is related to the specific characteristics of the study area, where the animal density is so high that manure is considered as a waste to be eliminated rather than a resource to be valued. Second, SYNERGY represents innovative technologies such as rotations with legumes and legume-based rations. It also include dominant technologies (e.g., soybean-based rations). Technologies have been defined using biotechnical simulators and expert knowledge. Third, SYNERGY encompasses multiple scales, from the farm to the region, to represent the diversity of farming systems and technologies and the heterogeneity of soil and climate conditions. To this end, it represents multiple farm types, and the region is divided into several sub-regions (i.e., French departments). Since SYNERGY is used to study a variety of scenarios of both public policies and technical innovations, a compromise was made between the diversity of farming types and the diversity of technologies. Fourth, SYNERGY performs economic and environmental assessment using economic and environmental indicators. Economic indicators focus on the profitability of the farming systems and technologies through gross margin and income. Environmental indicators focus on N management by calculating potential N losses and N efficiency (Godinot et al. 2014). These indicators make it possible to assess the potential progress made by developing legume production and manure exchanges, which can decrease the use of synthetic N fertilizers and losses of N to the environment. Fifth, SYNERGY can simulate a variety of scenarios and compare their results to observed data by performing calibration based on the PMP method. Since the PMP method has rarely been used to calibrate crop-livestock BEMs (e.g., Helming (1998)), an innovative feature of SYNERGY is to use an improved version of the standard PMP approach that performs "double calibration" for crop production and livestock production.

Given these characteristics, SYNERGY can be considered a regional, cross-scale, pseudo-hybrid BEM. It was built to study technical complementarities of crop and livestock production in a specific region: western France. A comparison of SYNERGY to other BEMs that represent crop and livestock production shows some of its advances (Table 2.1).

Table 2.1. Characteristics of the SYNERGY model and other bio-economic models that represent crop and livestock production

Model name	Source	Scale	Decision making process	Agricultural production modeled	Typology	Calibration method	Environmental indicator	Specific features
AROPAj	De Cara and Jayet (2000)* Galko and Jayet (2011)	farm groups > regions > UE	max. gross margin of each farm group	1 074 farm groups 32 crop activities 21 livestock activities	positivist	coefficient re-estimation based	greenhouse gas emissions	wide range of farms and actives
DRAM	Helming (1998)* Helming and Reinhard (2009)	regions (i.e., single farms) > country	(1) min. fertilization (2) max. regional income: sum of net farm income	19 crop activities 15 livestock activities	-	standard PMP	N and P balances	exchanges of fodder and manure
FSSIM-DEV	Louhichi et al. (2010)* Louhichi and Gomez y Paloma (2014)	households > region	max. regional utility: weighted sum of farm households' utility	12 cropping systems 9 farm types [a]	positivist	maximum entropy method and cross-sectional data	not included [b]	aggregation at different scales exchanges between farms
ILM	Schönhart et al. (2011)	farms & landscapes > region	max. gross margin of each farm	20 farms with crop and livestock production 20 crops 4 input intensity levels	-	-	soil organic carbon soil sediment losses Shannon diversity index	wide range of crop rotations spatial modeling of landscape elements
IMF - CAP	Louhichi et al. (2017)	individual farms > EU	max. profit of each farm	37 crop activities 16 animal activities	-	cross-sectional data and prior information	not included	wide range of farms and activities individual farms modeled
MODAM	Zander (2003)* Schläfke et al. (2014)	region = 1 large farm	max. regional gross margin	106 cropping activities 1 livestock activities	-	no calibration	erosion	pre-crop effect included in cropping activities
MOSAICA	Chopin et al. (2015)	fields > farms > region	max. regional utility: sum of farmers' utility (Markowitz-Freund function)	36 cropping systems 8 farm types (1 livestock-oriented farm type)	positivist	risk-aversion based	pesticide contamination biodiversity water quality CO_2 emissions	aggregation at different scales spatially explicit
SYNERGY	Jouan et al. (in review)	farms > sub-regions > region	max. regional profit	3 farm types 156 cropping activities 44 animal activities	mixed	"double calibration" by standard PMP	potential N losses (SynB) N efficiency (SyNE)	aggregation at different scales exchanges of crops and manure wide range of crop rotations

* Original study presenting the model for the first time; a: livestock production was not included in the case study but was included in the generic model; b: environmental assessment was not included in the case study but can be included in the general model using the biophysical field model APES; All models included in this table have the following characteristics: positive, static, no-risk integrated BEMs, that aim to assess agricultural policies.

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Chapter 3.
Economic drivers of legume production and its use as feed

This chapter aims to approach economic drivers of legume production as animal feed at the field and rotation scales, and at the regional scale. To do so, it analyses how the economic attractiveness of legumes may be influenced by two factors: opportunity costs and transaction costs. The method is divided into three steps. First, I built a database of opportunity costs of legumes from a literature review. Second, I qualitatively characterized transaction costs associated with exchange of legumes between producers and collectors. Third, I qualitatively analyzed if contracts currently offered in western France decreased transaction costs. For comparison, transaction costs of linseed were also studied. The results indicate that legumes are economically attractive at the rotation scale due to zero or negative opportunity costs, but that their transaction costs are high. The contracts studied do not decrease these transaction costs sufficiently, in particular because uncertainties in price remain high in half of these contracts. Downstream differentiation seems necessary to decrease transaction costs by creating added value along the entire agro-food chain.

This chapter is based on my first article: “Economic drivers of legume production: approached via opportunity costs and transaction costs”. It was co-written with Aude Ridier and Matthieu Carof, and published in the peer-review journal Sustainability, in 2019.

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3.1. Introduction

Crop diversification is one of the main mechanisms identified for developing a more sustainable agriculture (Kremen and Miles 2012). Many positive impacts on agronomic systems are associated with it: improving biodiversity (Kennedy et al. 2013), increasing resilience of agronomic systems (Lin 2011; Gaudin et al. 2015) and decreasing the use of pesticides (Butault et al. 2010; Lechenet et al. 2014). Legumes, both grain legumes (pea, faba bean, lupin, soybean) and forage legumes (alfalfa, white clover, red clover), are interesting diversifying crops to add to crop rotations (Voisin et al. 2014). Unlike other crops, legumes can fix atmospheric nitrogen; thus, they need no nitrogen fertilization. Under certain conditions, legumes can also supply nitrogen to the soil, thus decreasing application of nitrogen inputs for the subsequent crop, or even increasing its yield (Cernay et al. 2018). In addition to their ability to fix nitrogen, legumes also have the interesting agronomic characteristics of breaking weed cycles and improving soil structure (Schneider and Huyghe 2015). The issue of support for legumes (and oilseed crops) is particularly striking in the European Union (EU) since the Blair House agreement of 1992, which has led to a decrease in their production there. In 2014, the EU enabled its member states to establish area-based subsidies for legumes, such as supports coupled to production and green payments related to the presence of legumes on a farm, without any production target. These recent measures have reversed the decreasing trend, and the area of grain legumes, including soybean, increased by 75% from 2013–17 (Eurostat 2018). Nonetheless, production of grain legumes remains low, covering only 2% of utilized agricultural area in the EU in 2017 (4% if including forage legumes) (Eurostat 2018).

Other economic factors, which differ according to the scale of action in which they appear and according to their nature, can explain this situation (Zander et al. 2016). The scale of action can be the farm, where production occurs, but also the agri-food chain, where problems of processing or lack of markets can appear, thus limiting demand for the producer. Regarding nature, economic factors can be identified as opportunity costs of legumes, which reflect their economic attractiveness compared to other crops already produced or marketed. In contrast, other economic factors have to do with other types of costs, which are difficult or impossible to quantify, related to asymmetric information about new crops and uncertainty during their production and marketing. These indirect costs include transaction costs (Coase 1937).

First, for opportunity cost at the farm scale, farmers often consider legumes as less profitable in the short term than other more common crops on the farm (e.g., wheat, rapeseed) (von Richthofen et al. 2006a), even though this assessment must be balanced in certain cases (e.g., organic farming) (Carof et al. 2019) or in areas with a climate more favorable to these types of production. In contrast, at the rotation scale, if one considers the decreased inputs (e.g., nitrogen fertilizers) and/or increased yields of subsequent crops, the profitability can be increased. In addition, legumes are considered riskier than more common crops because of their more variable yields from year to year, though there is no consensus on this characteristic in the scientific community (Peltonen-Sainio and Niemi 2012; Cernay et al. 2018). Because of farmers' risk aversion (von Richthofen et al. 2006a), legume margins are penalized with a higher risk premium (i.e., the amount of money that a farmer is willing to pay to eliminate all risk) than those of other crops, which decreases their relative profitability even more. Finally, for opportunity costs at the scale of processing industries, the lack of added value and of differentiation in the legume agro-food chain can penalize legume production; for example, in the animal feed market, legumes are easily replaced by other, less expensive raw materials, which greatly decreases their inclusion in rations (Charrier et al. 2013).

For indirect costs at the agro-food chain scale, certain authors note that legume production has not developed due to a "lock-in" situation, previously analyzed for other sectors in the economics of innovation (David 1985). For the agricultural sector, this lock-in appears to result from a co-evolution of markets, agrochemical companies and public policies that tends to favor cereal and oilseed crop agro-food chains (Magrini et al. 2016; Meynard et al. 2018). Today, this hegemony of a few cereal and oilseed crops limits development of diversifying crops such as legumes, since cooperatives and companies have not developed sufficient logistics or technical skills to produce them at a large scale. Large transaction costs can thus appear during exchanges. The theory of transaction costs, introduced by Coase (1937) in "The nature of the firm" and then theorized by Williamson (1979), explains that these costs are related to the search for information, the process of negotiation and verifications before and after the transaction. The higher the transaction costs, the more actors are inclined to choose an integrated mode of coordination. Different modes of coordination have been described, ranging from "market" to "hierarchy" (in which transactions occur in an integrated manner). Contracting is a "hybrid" mode of coordination between market and hierarchy that aims to decrease transaction costs related to the exchange of new crops such as legumes (Ménard 2004; Meynard et al. 2013). Many empirical studies have been performed on contracting in the agricultural sector, on both animal and plant production (Key and McBride 2003; Bouamra-Mechemache et al. 2015; Roussy et al. 2018; Bellemare and Lim 2018), but few of them have focused on contracting in the legume agro-food chain. In the study (Cholez et al. 2017), production contracts for field crops were analyzed between cooperatives and their members, some of whom produced legumes. They showed that these contracts can incite farmers to diversify their crops by offering an attractive payment system and that collecting these new crops requires specific investments by cooperatives. Nonetheless, their study did not focus specifically on the diversity of contracts within the legume agro-food chain.

The objective of the present study was to analyze how the economic attractiveness of legumes to farmers may be influenced by two factors: opportunity costs and transaction costs. Our first hypothesis was that transaction costs decrease the economic attractiveness of legumes the most, due to characteristics specific to exchanges of these crops. Our second hypothesis was that contracting can decrease transaction costs and thus promote an increase in legume production. The main conclusions are that legumes are economically attractive at the rotation scale, but that their transaction costs are high. The contracts studied do not decrease these transaction costs sufficiently, in particular because uncertainties in price remain high in half of these contracts.

3.2. Materials and methods

3.2.1. Analysis of opportunity costs of crops

Opportunity cost is defined as the net benefits of the next best alternative that are forgone when a specific activity is chosen. It can be expressed as the difference between the net benefits of the next best alternative and those of the chosen alternative (Caplan 2006). We calculated the opportunity cost of a legume as the margin of the crop it replaced (a cereal or oilseed crop, which represents the next best alternative), minus the margin of the legume (i.e., the chosen alternative). Therefore, if the opportunity cost of the legume is negative, the legume is preferable. Different types of margin can be used in the calculation. Gross margin considers the revenue from selling the crop minus the variable costs of inputs (seeds, fertilizers and pesticides). In accounting rules, coupled support can also be included in revenue, yielding “gross margin with subsidies”. Other margin indicators also include additional costs, such as the machinery or labor directly related to the crop, yielding the “semi-net margin” or “gross margin after machinery costs”. Likewise, margins can be calculated at the scale of a crop or a crop rotation. In the latter case, the rotation margin is estimated as the average of the margins of each crop in the rotation. One calculates average annual gross margin from the gross margins earned over several years, usually without considering a depreciation of capital costs. This approach is particularly useful for rotations in which certain crops provide agronomic benefits to others, as occurs for rotations with legumes. Finally, margins can be calculated in two ways. In the first, a margin can be defined a priori by including in the calculation the yields, prices, and costs available in databases of public statistics and agricultural organizations. It is a difficult approach, however, since these data vary among regions and years and are not necessarily published (especially costs of a given crop). In the second way, a margin can be defined a posteriori by including in the calculation observed accounting information: revenue from selling crops and costs of crops. However, these accounting data often remain confidential. The analytical breakdown of revenue and costs is also specific to each farm and is not performed the same way for all farm accounts, which often stop at the scale of the farm or the subsystem (Desbois 2006).

A database of opportunity costs of legumes was built from a literature review. To do this, we searched for pairs of keywords formed from a crop ("legume", "protein crop", "pea", "lupin", "soybean", "faba bean", "alfalfa" and "lucerne") and an economic term ("gross margin", "profitability" and "profit") in the databases of the Web of Science, Google Scholar and Google. This search was also performed using the same pairs of keywords in French. Depending on the article analyzed, we calculated opportunity costs of legumes from gross margins at the scale of the crop or the rotation, either a priori or a posteriori.

3.2.2. Analysis of transaction costs

3.2.2.1. Surveys of collectors of legumes or linseed

Farmers who produce and market legumes may, in addition to production costs, pay transaction costs related to marketing. To assess the level of these transaction costs, we surveyed five organizations in western France (Brittany and Pays de la Loire): four cooperatives (A to D) that collect and market one or more legumes and, for comparison, Collector E, which has developed a local market for linseed for animal feed (Table 3.1). Since linseed and legumes have many characteristics in common (Carof et al. 2015), we compared the mature market of linseed with the budding markets of legumes. Four legumes under contract were studied: the two main legumes produced in the region (i.e., pea and alfalfa) and two others that are less developed. To simplify the analysis, we present results for only one crop per organization (hereafter, "collector") (Table 3.1). Collector E does not collect linseed directly but rather uses an intermediary for collecting. Semi-directed interviews of one hour were performed over three months and covered (i) the legumes (or linseed) collected and the contracts offered; (ii) management of uncertainties in volume (i.e., lower yield than expected), price and quality; and (iii) marketing of and markets for the contracted products.

Table 3.1. Collectors surveyed that collect legumes or linseed.

Collector	Size	Product	Activities
A	1 000 members	Dehydrated **alfalfa** (90 000 t.yr^{-1})	Advice, supply, harvest, transport, alfalfa dehydrating, marketing
B	4 000 members	**Faba bean** (1 800 t.yr^{-1})	Advice, collection, production and marketing of animal feed
C	16 000 members	**Pea** (2 000 t.yr^{-1}), Faba bean, Lupin	Advice, collection, marketing
D	29 000 members	**Lupin** (3 000 t.yr^{-1}), Faba bean, Pea	Advice, collection, marketing
E	120 employees	**Linseed** (60 000 t.yr^{-1}), Faba bean	Processing, link between producers and processors

Bold text indicates the crop analyzed for each collector

3.2.2.2. Analysis of asset specificity and uncertainties during transactions

To characterize the transaction costs associated with the exchange of legumes (or linseed), we developed an analysis framework based on the theory of transaction costs. In the approach of Williamson (1996), transaction costs depend on three characteristics of the transaction: the specificity of the assets invested during it, the uncertainty surrounding it and its frequency.

We studied different types of asset specificity during legume (or linseed) transactions: (i) human assets, which depend on the specific knowledge and know-how (of both the producer and the collector) used to produce and process the crops; (ii) the material assets, which depend on the specific investments of both the producer and collector; and (iii) the location of the collection zone, if it is limited, which also entails specific investment costs. This information came from interviews with employees of the collectors. Regarding uncertainties surrounding transactions, there are four main types: (i) uncertainties in volume due to potentially low yield of the crop collected, (ii) uncertainties in quality due to potentially low protein contents, (iii) uncertainties in prices due to a potential decrease in prices of crops and (iv) uncertainties in the markets for crops. These uncertainties were assessed from literature data on yields (Cernay et al. 2015), statistical data on crude protein contents (Government of Canada 2017; Terres Inovia 2018a, b) and on prices (FAOstat 2018; FranceAgriMer 2018; La Dépêche - Le Petit Meunier 2018) from 2013–17, and interviews to obtain information about markets. We qualitatively assessed uncertainties during transactions, as well as asset specificity, as “low”, “moderate” or “high” compared to those of wheat. Regarding transaction frequency, transactions occur during every growing season; so, we did not study it as an attribute specific to legumes (or linseed).

3.2.2.3. Analysis of the effectiveness of contracts at decreasing transaction costs

To determine whether contracting effectively decreased transaction costs during exchanges of legumes (or linseed), we developed an analysis framework of the variety of legume contracts offered by the collectors surveyed. Two types of contracts were analyzed: marketing contracts, which specify only selling conditions (e.g., methods for determining prices and amounts, as well as delivery dates and methods), and production contracts, which also specify at least one of the agricultural practices used, to influence the final quality of the product (Goodhue 2011). When a given collector offered different types of contracts for a given crop, only the production contract was studied because, being more comprehensive, it is more likely to reduce transaction costs. The analysis framework began with the characteristics of transaction costs without a contract and then studied how the contracts modified these characteristics (i.e., whether the contracts decreased the uncertainties examined and secured the specific asset). As for the characteristics of transaction costs, we qualitatively analyzed their variations.

3.3. Results

Many recent literature reviews examined agronomic and environmental performances of legumes (Dequiedt and Moran 2015; Cernay et al. 2015; Lötjönen and Ollikainen 2017; Pelzer et al. 2017). Nonetheless, few studies focused on legumes from an economic angle (Bridet-Guillaume et al. 2010). In particular, few data or scientific studies exist on the economic attractiveness of legumes, even though the issue of their opportunity costs remains a priority for farmers when choosing which crops to plant.

3.3.1. Opportunity costs of legumes

3.3.1.1. Opportunity costs of legumes: annual approach to the cropping system

The database from the literature review (Preissel et al. 2015) showed that the opportunity costs of legumes that replaced wheat (hereafter “legume-wheat”) were positive in 10 of the 12 case studies studied (i.e., mean annual a priori gross margins were lower than those of wheat). More recently, compared to an a priori gross margin of wheat, the a priori gross margin of pea was estimated to be 56% lower in southwestern France (Ridier et al. 2016), while another study estimated those of pea, lupin and faba bean in Brittany to be 50% lower (Carof et al. 2019). Therefore, legume-wheat opportunity costs in these studies were positive. It is interesting to note that this last study observed better economic performances of legumes in organic farming systems. For example, the a priori gross margin of organic faba bean reached 800 €.ha-1, nearly double that of conventional faba bean. Nonetheless, the difference in gross margin between organic pea and organic wheat remained large, which resulted in positive opportunity costs. From the data used in the study (Martin et al. 2014), we calculated a posteriori gross margins of legumes and wheat. These data confirm results of a priori studies: they reveal a positive legume-wheat opportunity cost, with the a posteriori gross margin of grain legumes being 46% lower than that of wheat. However, it is more relevant from an agronomic viewpoint to calculate opportunity costs between legumes and other potential head-of-rotation crops (i.e., a crop planted in the first year of a rotation because its agronomic characteristics benefit subsequent crops) such as canola (Preissel et al. 2015). In the review of Preissel et al. (2015), legume-canola opportunity costs were positive in 11 of 12 case studies studied. Likewise, positive opportunity costs were observed, with a priori gross margins of lupin and pea ca. 66% lower than those of canola (Xing et al. 2017).

3.3.1.2. Opportunity costs of legumes: multi-annual approach to the cropping system

Studying the opportunity cost of a rotation with legumes compared to one without legumes (hereafter, "with/without opportunity cost") is much more relevant: doing so accounts for the fact that legumes fix atmospheric nitrogen, which may lead to decreased application of nitrogen inputs for the subsequent crop, or even increases in its yield. Rotations with legumes generally have zero or even negative opportunity costs, with gross margins similar to or even greater than those of rotations without legumes. In the review of Preissel et al. (2015), with/without opportunity costs were close to zero for 35 of 53 rotations with legumes modeled a priori. This confirms an initial study in east-central France of rotations with canola, wheat and barley (over 3–4 years) (Carrouée et al. 2012). Results of this study indicated that all but one rotation with pea had a priori gross margins that were similar to or higher than those without pea (0–6% higher). More recently, another study showed that with/without opportunity costs of grain legumes were slightly positive, while those of forage legumes were zero or even negative, with a priori gross margins that were similar or slightly higher (Reckling et al. 2016a). Of the five studies we found of opportunity costs of rotations with legumes, only two analyzed the with/without opportunity cost of a forage legume (Hirth et al. 2001; Reckling et al. 2016a). The with/without opportunity cost of alfalfa was nearly zero, since the difference in a priori gross margin between rotations was low (Hirth et al. 2001). This lack of visibility of the profitability of forage legumes can be explained by the fact that they are rarely sold, which prevents gross margins from being calculated. In the study of Preissel et al. (2015), the gross margins of wheat and canola were calculated when they were included in rotations with legumes in southern Australia: a priori gross margins of the two crops in rotations with legumes were higher than those in rotations without legumes, as long as nitrogen fertilization was less than 75 kg N.ha 1. In another study, a potential increase in gross margin of 118 €.ha-1 was estimated for conventional rotations with grain legumes compared to those without (Carof et al. 2019). Finally, compared rotations with/without grain legumes were compared in three European regions (von Richthofen et al. 2006b). It was observed that rotations with grain legumes have slightly higher a priori gross margins than rotations with no legumes and 75% or more cereals. Therefore, in this study, rotations with grain legumes were characterized by negative with/without opportunity costs.

The economic incentive for growing legumes is closely related to their head-of-rotation function: they have a zero or negative opportunity cost only when studied at the scale of the rotation. Legumes thus do not degrade the competitiveness of farms in the middle term and, in addition, have other beneficial effects on the environment that are not included in the market (e.g., improvement of biodiversity and water quality).

3.3.1.3. Opportunity cost of legumes: multi-annual approach in mixed crop–livestock systems

The economic attractiveness of legumes can also be understood at a scale more encompassing than that of a rotation. In mixed crop–livestock systems, farmers can choose not to sell legumes, instead using them to feed animals on the farm. They thus replace other types of animal feed, and the opportunity cost of these feeds can be studied (Froidmont and Bartiaux-Thill 2004; Jezierny et al. 2010). Nonetheless, few studies have focused on economic consequences of these practices (Schilizzi and Pannell 2001). Mathematical programming models are useful tools for assessing impacts of introducing legumes into rations because they allow activities to compete based on the opportunity cost of the set of all production factors. To our knowledge, no model has focused specifically on the use of legumes except for the study (Jouan et al. 2018), which aimed to analyze consequences of introducing legumes onto mixed crop–livestock farms, from both economic and environmental viewpoints.

3.3.2. Transaction costs and organizational choice: case studies in western France

3.3.2.1. Transaction costs of exchanging legumes and linseed

Asset specificity during legume transactions was usually higher than those of main crops of the region, such as wheat (Table 3.2). First, the specificity of human assets involved was moderate for the producers but could be high for certain collectors who establish procedures for processing legumes, such as Collectors A and D. Similarly, the specificity of physical assets was low for producers, who do not need to keep specific equipment to produce legumes (or linseed). In contrast, collectors must often adapt their storage capacities, even more so if they sort products by quality. Collectors who established procedures for processing legumes also had high specificity of physical assets, given that investment in equipment is often necessary for processing. Finally, the specificity of location was particularly high for Collector A, whose collection zone for alfalfa is restricted to a 70 km radius around its dehydration factory due to logistical constraints.

Table 3.2. Analysis of the degree of asset specificity (high, moderate, low) during transactions of legumes and linseed of the five collectors surveyed, compared to those of wheat, except where noted.

Asset specificity		**A** **Alfalfa**	**B** **Faba bean**	**C** **Pea**	**D** **Lupin**	**E** **Linseed**
Human assets	For the producer	**Moderate** Specific farming practices, less well known but not particularly difficult				
Human assets	For the collector	**High** Dehydration technique and technicians specific to alfalfa	**Moderate** Training of personnel to recognize the cleanliness of a field	**Low** No specific advice or process	**High** Several techniques for processing lupin for agro-food and cosmetic uses	**High** Thermo-extrusion of linseed for animal feed and human food
Physical assets	For the producer	**Low** No specific equipment absolutely necessary				
Physical assets	For the collector	**High** Harvest equipment and dehydration equipment	**Moderate** Suitable storage capacity	**Moderate** Suitable storage capacity	**High** Two processing sites partly dedicated to lupin; suitable storage capacity	**High** Many silos to separate crops of differing quality; processing equipment
Location	For the producer	**High** 70 km around the dehydration factory	**Low** No zone specified			

Data and assessments come from interviews performed during the study, except where noted.

Uncertainties during transactions of legumes (or linseed) were moderate to high compared to those of main crops of the region, such as wheat (Table 3.3). First, volume uncertainties were particularly high for lupin, which had a standard deviation of yield anomalies (i.e., normalized yield residuals) of 0.32, much higher than that of wheat (0.06) (von Richthofen et al. 2006a). We found no data for the variability of alfalfa or linseed yields. Second, regarding variability in the quality of the crops studied, we found no specific data for alfalfa or lupin, but it appeared during the interviews that variability in crude protein contents was not considered a problem. However, according to our calculations, quality uncertainties were high for faba bean and linseed, which had a coefficient of variation (CV) of crude protein content of 0.028 and 0.036, respectively, compared to that of wheat (0.013). Quality uncertainties for pea were similar to those of wheat. Third, according to our calculations, price uncertainties were particularly high for faba bean, which had a CV of selling price of 0.221 from 2013–17, compared to that of wheat (0.155). For other crops, price uncertainties were lower than those of wheat, with pea and linseed even having CVs of selling price less than 0.1. Finally, market uncertainties for crops were low for alfalfa and pea, which are used in many feeds. Market uncertainties were greater for linseed, which depends on the Bleu-Blanc-Cœur market. The highest market uncertainties were for faba beans, which depend greatly on the Egyptian market, and lupin, which remains a niche market.

Table 3.3. Analysis of the level of uncertainties (high, moderate, low) during transactions of legumes or linseed by the five collectors surveyed (A–E), compared to those of wheat.

Uncertainties during transactions Outside of contracts		**A** **Alfalfa**	**B** **Faba bean**	**C** **Pea**	**D** **Lupin**	**E** **Linseed**
Volume	For the producer and collector	No data	**Moderate** SD[a] of yield anomalies = 0.09	**High** SD of yield anomalies = 0.12	**High** SD of yield anomalies = 0.32	No data
Quality	For the collector	No data	**High** CVq[b] = 0.028	**Moderate** CVq = 0.013	No data	**High** CVq = 0.036
Price	For the producer and collector	**Moderate** CVp[c] = 0.113	**High** CVp = 0.221	**Moderate** CVp = 0.093	No data	**Low** CVp = 0.066
Markets	For the collector	**Low** Used in many animal feeds	**High** Dependent on exports to Egypt	**Low** Used in many animal feeds	**High** Niche market; lack of visibility	**Moderate** Relatively dependent on the BBC[c] market

Therefore, from analysis of the interviews, legume exchanges appear to have higher transaction costs than those of wheat, due to high asset specificity and high uncertainties. Producers would thus be inclined to choose a mode of organization that is more integrated than the market in order to decrease transaction costs.

Based on these results, we tightened our second hypothesis focused our second hypothesis: contracts decrease transaction costs by (i) decreasing volume and price uncertainties and (ii) securing the specific assets, in which mainly collectors have invested. Evidence supporting this hypothesis is strengthened by the fact that most collection of linseed, which has characteristics similar to those of legumes, is already contracted before harvest.

3.3.2.2. Effectiveness of contracts at decreasing transaction costs related to exchange of legumes or linseed

Analysis of legume contracts implemented by the collectors surveyed revealed great diversity: two of the collectors offered marketing contracts with an area or volume commitment, while the three others offered production contracts (Table 3.4). We examined whether these contracts supported our tightened second hypothesis.

Table 3.4. Analysis of the evolution of transaction costs of legumes and linseed contracts (unchanged, slightly decreased, decreased), compared to those outside contracts, for the five collectors surveyed (A–E).

Evolution of transaction costs Inside contracts		**A** **Alfalfa**	**B** **Faba bean**	**C** **Pea**	**D** **Lupin**	**E** **Linseed**
Nature of the contracts		**Marketing**[a]	**Production**[b]	**Marketing**	**Production**	**Three-party production**[c]
Volume uncertainties	For the producer	**Unchanged** Payment as a function of tonnage	**Slightly decreased** Payment as a function of tonnage but significant technical monitoring	**Unchanged** Payment as a function of tonnage	**Slightly decreased** Payment as a function of tonnage but significant technical monitoring	**Slightly decreased** Payment as a function of tonnage but significant technical monitoring
Volume uncertainties	For the collector	**Unchanged** Producer's commitment based on area only	**Slightly decreased** Producer's commitment based on area only but significant technical monitoring	**Slightly decreased** Producer's commitment based on volume but no penalty in case of non-compliance	**Slightly decreased** Producer's commitment based on area only but significant technical monitoring	**Slightly decreased** Producer's commitment based on area only but significant technical monitoring
Quality uncertainties	For the collector	**Decreased** The crop is accepted when it contains more than 20% crude protein	**Unchanged** No payment as a function of quality	**Unchanged** No payment as a function of quality	**Unchanged** No payment as a function of quality	**Slightly decreased** Payment according to omega-3 content
Price uncertainties	For the producer	**Unchanged** Price is fixed each year as a function of the price of wheat	**Decreased** Guarantee of gross margin	**Slightly decreased** Guarantee of a price complement (8 €.t^{-1}), but with a base price fixed at harvest	**Decreased** Price and bonuses fixed when the contract is signed	**Decreased** Price "tunnel" with a minimum guaranteed when the contract is signed
Price uncertainties	For the collector	**Unchanged** The contracts have no influence				
Market uncertainties	For the collector	**Unchanged** The contracts have no influence				

Note: [a] Marketing contracts specify only selling conditions (e.g., methods for determining prices and amounts, as well as delivery dates and methods). [b] Production contracts specify only selling conditions and agricultural practices used to influence the final quality of the product (e.g., purchases of specific seeds and pesticides; mandatory operations at specific dates and frequency). [c] Three-party production contract between the producer, the intermediary that collects and the processor (grouped here as the collector)

Volume uncertainties were slightly decreased, for both producers and collectors, by contracts of Collectors B, D and E, whose technical monitoring limits variations in yields. In contrast, price uncertainties remained unchanged for collectors but were slightly decreased for producers by the contract of Collector C, which guarantees a price complement of 8 €.t-1, albeit based on a price fixed at harvest. The contracts of Collectors B, and D decreased price uncertainties for producers even more by guaranteeing a given gross margin (Collector B) or a fixed price before harvest (Collector D). This difference is related to the internal structures of the collectors (e.g., mutualizing risk among several products) and to contracts negotiated downstream, for which we had no information. Collector E offered a contract with a price "tunnel" that limits both positive and negative variation in prices. This greater decrease in price uncertainties is possible because Collector E directly marketed downstream the products from animals fed linseed in the Bleu-Blanc-Cœur market, in which nutritional qualities (omega-3 and -6 contents) of these products are recognized by consumers. Regarding market uncertainties for the collectors, they remained unchanged: the contracts do not secure their downstream markets.

Collector A decreased quality uncertainties by expecting a minimum crude protein content but did not appear to apply a penalty if it is not reached. Collector E had a bonus/penalty policy as a function of the content of certain fatty acids. In contrast, Collectors B, C and D did not calculate their payments for legumes as a function of quality. As for all field crops, standards of cleanliness and moisture content were expected for legumes. If they were not met, additional costs for drying could be billed to producers (Collectors B and C) or the crop could be refused (Collector D). Finally, securing of human and physical assets was related to a decrease in volume uncertainties: the more the contract decreased volume uncertainties, the more the collector's investments in producing and/or transforming legumes (or linseed) were secured. Therefore, human and physical assets were slightly secured for Collectors B, C, D and E.

3.4. Discussion

This study offers a fresh look at the concomitant and complementary character of two types of costs of producing and marketing crops: opportunity costs and transaction costs. It is focused particularly on diversifying crops—legumes and linseed—which, despite their agronomic advantages, remain relatively underdeveloped in Europe.

Regarding opportunity costs, the database built from the literature review shows that legumes have gross margins similar to those of dominant crops, as long as one examines them at the rotation scale. Regarding transaction costs during exchanges, they seem higher than those of other main crops (such as wheat). They have high specific assets because collectors have to invest greatly in both physical and non-physical assets. Additionally, they have relatively high uncertainties in volumes, qualities and prices. Therefore, the results are in line with our first hypothesis (i.e., transaction costs decrease the economic attractiveness of legumes the most).

Our second hypothesis was that contracting can decrease transaction costs and thus promote an increase in legume production. To decrease transaction costs, contracts must decrease uncertainties and secure specific assets. The contracts we studied allow us to conclude that volume uncertainties are (i) only slightly decreased for producers by contracts of Collectors B, D and E and (ii) decreased for Collectors B, C, D and E. Human and physical assets are secured by decrease of volume uncertainties. The largest decrease in uncertainties is in prices for producers, which are decreased by contracts of Collectors B, D and E, due to prices (or gross margins) being partially fixed before harvest. Quality uncertainties are decreased only by Collector A, who accepts only crops with more than 20% crude protein, and slightly decreased by Collector E. Therefore, the results are also in line with our second hypothesis because contracting can decrease transaction costs, even though this decrease is quite limited. It is interesting to note that the contracts reduce price and volume uncertainties only when collectors engage specific assets. Additionally, to achieve this decrease in uncertainties, production contracts, which aim to decrease volume uncertainties through significant technical monitoring, seem to be more effective than marketing contracts.

Nonetheless, legume contracting is less developed than in the agro-food chain used as a comparison: linseed. Only the contract of linseed implemented by Collector E is able to decrease transaction costs by influencing all characteristics of the transaction costs analyzed. Our results are consistent with those of Charrier et al. (2013), who concluded that contracts with guaranteed prices helped increase the spread of diversifying crops such as linseed. In addition, our results for transaction costs were similar to those of Cholez et al. (2017). Nonetheless, the contracts we studied seem to decrease transaction costs less than those in the sample of Cholez et al. (2017).

The originality of our study lies in different aspects. First, it focuses on legumes (and linseed) produced for animal feed, which differs from most other studies, which focus on legumes produced for human food. Second, it analyzes two types of costs: opportunity costs and transaction costs. Third, it uses different tools: a database built from a literature review of legume gross margins defined a priori or a posteriori and an analysis framework of transaction costs of legumes and linseed, allowing transaction costs to be assessed both outside and inside contracts. One of the main limitations of the study, however, was the small study zone for interviews: surveys were performed only in western France. Although some of these regional collectors have a national reach, it would be interesting to test our hypothesis using a national survey to confirm our conclusions. In addition, we did not have access to details of all the contracts studied. Nonetheless, this approach can be generalized to a larger scale: the analysis frameworks can be transposed to different crops and different agricultural contexts. It also may have been more appropriate to focus solely on production contracts, which seem the best suited to address transaction costs. In-depth analysis of the technical monitoring implemented, related to price formation and added-value creation, would be a promising research approach. Additionally, the studies we analyzed to calculate opportunity costs excluded machinery costs, which can significantly influence crop margins. Our qualitative analysis could also be complemented by more quantitative work that estimates transaction costs directly. Many interviews with farmers and collectors would need to be performed, however, which was not possible with the means at our disposal.

Regarding legume opportunity costs, this study highlights that they are negative or zero if they are calculated in a multi-annual approach at the rotation scale. Nonetheless, calculating them can be tedious, time-consuming and expensive, not only for farmers but for extension agents, who often calculate only annual gross margins for given crops. Substantial resources should thus be provided to disseminate such technico-economic results to farmers. This dissemination could take the form of popular articles or even training sessions for farmers and extension agents. Simple tools could also be developed to ease calculation of multi-annual opportunity costs. Dissemination of these results and development of suitable tools could be financed by public or private actors (e.g., extension agents from national or regional governments or from cooperatives).

Regarding legume transaction costs, one of the main costs observed is related to specific investments by collectors. These investments are necessary to increase storage and sorting capacities, even more so if the collector distinguishes crops by quality (e.g., protein content). This result agrees with Meynard et al. (2013), who identified that volume strategies for grain storage were an obstacle to crop diversification. From these results, it would seem appropriate to develop policies to support investment in storage and sorting infra-collectors, not only at the farm scale (as in the French 2014–20 “protein plan”) but also within cooperatives and other collectors. Such organizational supports, if they are large enough, long term and clearly identified by the actors concerned, would complement well the supports coupled to crop production.

It is important to note that opportunity costs and transaction costs are related to some extent. When crops are seen as a risky production, volume uncertainties are high, which increases transaction costs. Collectors can implement contracts (in particular, production contracts) to decrease uncertainties and thus transaction costs. This decrease in uncertainties can be interpreted as a way to decrease farmers' risk premium associated with the crop. If the risk premium is included in the opportunity cost, we can conclude that a decrease in transaction costs through contracting decreases opportunity costs.

Finally, regarding contracting, Collector E seems to offer the most effective contract for decreasing transaction costs. This is possible by differentiating downstream products in the Bleu-Blanc-Cœur market, which includes products from animals feed linseed whose nutritional qualities (omega-3 and 6 contents) are recognized by consumers. This differentiation of products decreases the substitutability of raw materials used in agricultural production (here, linseeds) and creates added value by tracing the nutritional advantages of these raw materials down to the consumer. More recently, positive impacts on the environment (e.g., decreasing greenhouse gas emissions of ruminants, improving biodiversity) have also appeared as arguments for differentiation within this market. This differentiation of products could also soon lead to non-acceptance of certain raw materials used for animal feed. For example, non-genetically modified (GM) products (e.g., soybean meals in animal feed) are increasingly popular among consumers. Agro-food businesses are diversifying their products to respond to this demand, both in Europe and the United States (Bain and Dandachi 2014; Castellari et al. 2018). These new products provide a unique opportunity to develop legumes, which can replace GM soybean meal; however, political and economic questions can arise with non-GM certification (McCluskey et al. 2018). In particular, segregating GM production from non-GM production can be an economic burden for businesses. Contracts thus appear as essential tools for segregating non-GM production in countries that allow GM production (Sykuta and Parcell 2003).

French soybeans, which are non-GM, could also represent an interesting alternative for the non-GM market. They are produced mainly in southwestern France, outside our study zone. Contacts between soybean producers and collectors have been established there. It would thus be interesting to study the different forms of contracts used for French soybeans, and other legumes, to guide development of these crops.

3.5. Conclusions

Despite the agronomic advantages of legumes, their production remains low in Europe. The objective of this study was to analyze how the attractiveness of legumes to farmers could be influenced by two factors: opportunity costs and transaction costs. The opportunity costs of legumes were zero or negative when studied at the scale of the rotation; from an economic viewpoint, rotations with legumes were as good as or better than rotations without them. Transaction costs were higher than those of wheat due to high asset specificity and high uncertainties. The surveys performed in the region did not allow us to conclude that the contracts used sufficiently decrease these transaction costs, in particular because the uncertainties in price remain high in half of the contracts studied. Downstream differentiation seems necessary to decrease transaction costs greatly. Nonetheless, it seems easier to develop downstream differentiation for legumes produced for human food than for animal feed, whose added value is diluted in a longer agro-food chain. Policies to disseminate results of opportunity costs and to help collectors invest in storage and sorting tools represent concrete mechanisms for developing the production and marketing of diversifying cultures such as legumes.

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Chapter 4.
Legume production and use as feed on mixed crop-livestock farms: public policy levers

This chapter studies legume production and use as feed at the farm scale. It aims to analyze how agricultural and environmental public policies can affect legume production at this scale. In particular, it focuses on two policies: Voluntary Coupled Support and the Nitrates Directive. To do so, I employed the bio-economic model FarmDyn, parameterized for a typical dairy farm in France and Germany. Indeed, France established Voluntary Coupled Support scheme to encourage legumes production, but Germany did not. However, Germany provides more favorable implementation of the Nitrates Directive for legumes by allowing spreading manure on these crops. In the FarmDyn model, I introduced legumes as cash crops and on-farm feed, highlighting interactions between crop and animal productions. I analyzed different levels of coupled support per hectare, comparing the French versus the German implementation of the Nitrates Directive. Results suggest that voluntary coupled support leads to an increase in legume production but to a lesser extend in the German farm than in the French farm, due to higher opportunity costs of legumes. In both farms, the increase in legume production leads to limited environmental benefits: nitrogen leaching and global warming potential slightly decrease. In the French farm, the German implementation of the Nitrates Directive fosters legume production. Thus, I show that allowing manure spreading on legumes can help reaching high legume production in livestock farms. However, this further increase in legume production does not lead to environmental benefits. Therefore, allowing manure spreading on legumes to increase their production should be justified by other goals such as improving the protein self-sufficiency of the farm.

This chapter is based on the article « Integrated assessment of legume production challenged by European policy interaction: a case-study approach from French and German dairy farms». It was co-written with Julia Heinrichs, Wolfgang Britz and Christoph Pahmeyer from the Institute for Food and Resource Economics (University of Bonn). It is published as a Discussion Paper of the University of Bonn (https://doi.org/10.22004/ag.econ.298428). It will be submitted in a peer-review journal early 2020.

4.1. Introduction

Increased legume production can limit the impact of agricultural systems on the environment in several dimensions (Drinkwater et al. 1998). As legumes can fix atmospheric nitrogen (N), they need no, or limited, N fertilization and may even supply N to the soil, reducing N fertilization needs of the following crop (Peoples et al. 2009). They can contribute to crop diversification and thus to reduced pesticide application (Nemecek et al. 2008). Additionally, legumes used as protein-rich feed can substitute vegetable meals, often derived from imported crops and linked to loss of natural habitats (Sasu-Boakye et al. 2014).

After decades of a declining trend, legumes, including forage legumes and soybeans, covered on average less than 4% of the utilized agricultural area (UAA) between 2012 and 2017 in the European Union (EU) (Eurostat 2018). That reflects firstly that their use in feed can mostly not compete against substitutes such as imported soybean meal (Häusling 2011). Second, at the scale of the European agro-food chain, legumes suffer from a lock-in situation that tends to favor cereal and non-legume oilseed crops (Magrini et al. 2016), while sales of legumes face high transaction costs (Jouan et al. 2019). Third, legumes are generally less profitable for farmers compared to other major crops such as wheat and rapeseed, even if, at the rotation scale, their profitability is equivalent (Preissel et al. 2015). Farmers are also reported to assess their production risk as higher (von Richthofen et al. 2006a), though there is no consensus in the scientific community that the yield variability of legumes exceeds that of other crops (Cernay et al. 2015; Reckling et al. 2018).

Since 2014, in the light of their advantages but low crop share, European member states can establish Voluntary Coupled Support (VCS) for legumes under the Pillar I of the European Common Agricultural Policy (CAP). That measure helped to reverse the downward trend in legume production but heterogeneously across member states and regions, reflecting that this measure was differently implemented. For instance, both France and Germany count legume acreage with a factor of 1 towards the Ecological Focus Area (EFA) requirement as part of "Greening". However, only France introduced VCS for legumes, reaching 145 million euros in 2017 (European Commission 2017a). The VCS might explain why the French area of legumes nearly doubled between 2013 and 2017 but only increased by 35% in Germany. It is also interesting to notice that the share of legumes in arable land in France is half as large in regions focused on livestock production compared to regions specialized in arable crops (Eurostat 2018). This may be due to the French implementation of the Nitrates Directive (latter called "French ND") (91/676/CEE), which prohibits manure application on most legumes, discouraging their production in farms with high stocking densities. The German implementation of the Nitrates Directive (latter called "German ND") allows spreading manure on legumes as long as the mandatory N fertilization planning at the farm scale is respected.

This study aims at assessing environmental and economic impacts of key policy measures affecting legume production, comparing in detail a French and German case study. We focus on the interactions of two different policy fields: VCS for legumes and national implementations of the European ND, while taking into account the "Greening" measures. Our hypothesis is that first, implementing a minimum VCS per hectare in France and Germany, will increase legume production in both countries. Second, that implementing the German ND in France, will lead to a further increase in legume production in France. Third, that these increases have positive environmental and economic implications at farm-scale. Fourth, that an increase in VCS would foster these developments. To test these hypotheses, we employ the bio-economic programming farm-scale model FarmDyn (Britz et al. 2014).

So far, only few studies analyzed policies directly designed to increase legume production with farm-scale models (Helming et al. 2014; Cortignani et al. 2017). Studies using bio-economic models to analyze the ND and nitrate related policies are more common (Peerlings and Polman 2008; Belhouchette et al. 2011; Kuhn et al. 2019). Other tools were also employed to study this directive, such as N flow models (Cardenas et al. 2011)) or agent-based models (Van der Straeten et al. 2011). Nevertheless, to the best of our knowledge, there is no analysis considering measures related to legume production, and the implementation of the ND, as an example for environmental policy interactions (Nilsson et al. 2012). Besides, impacts of legumes production are so far mostly analyzed in arable cropping systems (Nemecek et al. 2008; Reckling et al. 2016b), except for Schläfke et al. (2014), Helming et al. (2014) and Gaudino et al. (2018) who also considered legumes as feed in livestock farms. Finally, as far as we know, the study of Küpker et al. (2006) is the only one comparing in detail different farms in France and Germany, even though these countries being the main milk producers in EU. Other models at the European scale cover also the French and German productions (Louhichi et al. 2018), but as they are far more aggregated, they do not take into account detailed measures e.g. differentiated implementations of the ND according to countries. Thus, our study addresses several gaps in literature by (1) considering jointly multiple policies affecting legume production, (2) by introducing legumes as cash crops and on-farm feed, highlighting interactions between crop and animal productions, and (3) by developing an integrated assessment of representative dairy farms in two European countries, France and Germany, whose regulations on legumes and manure management differ.

The paper is structured as follows: the second section describes the method implemented by presenting the model FarmDyn, how we introduced data related to legume production and the ND, and by describing the two analyzed case studies. The third section presents the results. The fourth section includes a discussion where policy implications and the limitations of our approach are developed. Finally, the fifth section concludes by summarizing the main conclusions.

4.2. Method

4.2.1. Overview of the FarmDyn model

Mathematical programming models represent a valuable tool to analyze technical changes or the introduction of (new) crops as they describe in detail farm management and investment decisions (Jacquet et al. 2011; Britz et al. 2012). Among them, bio-economic models aim to assess both economic and environmental indicators and their trade-off by accounting for joint production of agricultural outputs and environmental externalities (Janssen and van Ittersum 2007). Bio-economic models have been introduced at different scales, from the field to whole regions (Lehmann et al. 2013; Gocht et al. 2017). At farm scale, bio-economic models have the advantage to simulate in detail the decision-making process of the farmer, considering technical as well as work-time or financial constraints. In the context of the European agriculture, farm bio-economic models are particularly used for assessing policies (Reidsma et al. 2018).

FarmDyn is a highly detailed single farm bio-economic model, building on fully dynamic mixed integer linear programming. It is written in the General Algebraic Modelling System (GAMS Development Corporation 2018). The model provides a framework for the simulation of economically optimal farm-level plans and management decisions, as well as related material flows and environmental indicators (Lengers et al. 2013). Thereby, farm management decisions such as adjustments of crop shares, feeding practices, fertilizer management and manure treatment are depicted with a monthly resolution. FarmDyn maximizes the farm net present value under (1) the farms' production feasibility set, (2) working-time and (3) liquidity constraints as well as (4) environmental and policy restrictions. By assuming a rational, fully informed and risk-neutral farmer, the simulation results entail best-practice behavior. The extension of the linear programming with a mixed integer approach allows capturing indivisibilities e.g., of stables and machines.

In the underlying study, the comparative-static version of FarmDyn is used. We consider that the machinery pool used for legumes is already available to manage the benchmark crop rotation. Thus, the use of the simpler static version model seems appropriate and eases model application and result analysis. Therefore, indivisibilities in investments are considered but investment costs in buildings and machinery are annualized and herd dynamics are depicted by a steady state model (e.g., the number of cows replaced in the current year is equal to the number of heifers raised for replacement).

Indicators on farm performance are implemented such as the total profit of the farm, the protein self-sufficiency (i.e., the ratio between protein produced to feed the herd, and total protein consumed by the herd), and different environmental indicators. The global warming potential (GWP) of the farm is calculated by measuring the emission of different greenhouse gases and expressing their GWP as a factor of carbon dioxide. Thereby, emissions arising on-farm (e.g., from fertilization and manure storage), as well as emissions related to the usage of inputs such as diesel or feeds are considered. Since the ND aims to protect water quality by preventing nitrates polluting water bodies, we include an indicator for nitrogen leaching (latter called "N leaching"). It calculates a probabilistic value for N leaching by considering different sources of N, e.g., fertilization and manure application, mineralization, as well as the nutrition deduction by the crops following the model SALCA -NO_3 (Richner et al. 2014).

4.2.2. Case-studies and data implemented

We analyze as case studies one French and one German intensively managed dairy farm (Table 4.1), located in Pays de la Loire (PDL) in France and North Rhine-Westphalia (NRW) in Germany. Intensive dairy farms where chosen as they combine features salient for the analysis: high quantities of manure produced per ha of land such that manure management restrictions from ND are relevant; the possibility of using both grain and forage legume as feed; and compared to pig farms, more constrained feed choices linked to structural characteristics of the farm (e.g., part of fodder area). The case studies are defined based on longer time series data from agricultural institutions and extension services. The French farm is based on the farm type "1b Pays de la Loire", from Inosys Réseaux d'Elevage (IDELE 2016) as one of the most common types of dairy farms in that region. Quite detailed data are available for this farm-type, such as crop rotation, stable inventory, and grass management. Besides, the crop rotation of this farm corresponds to the main crop rotation of PDL (Jouy and Wissocq 2011). The German farm is based on farm type « Niederrhein NR_SB » from (Steinmann 2012), one of the most common types of dairy farms in NRW. Since no information on typical crop shares is provided by that source, the crop rotation of the German farm is taken from Kuhn and Schäfer (2018) who derived typical crop rotations for different farm-types in NRW, based on data from agricultural census and expert interviews. For both farm types, yields are based on regional data, and input and output prices on national ones (mean 2013-2017) (French Ministry of Agriculture 2018a; La Dépêche - Le Petit Meunier 2018; AMI 2019; KTBL 2019; IT.NRW 2019).

The German farm has a lower share of grassland than the French farm as well as a higher stocking rate (Table 4.1). Further, the milk as well as the crop yields are higher for the German farm. Thus, overall, the German farm is managed more intensively than the French farm.

Table 4.1. Description of the dairy farms implemented in the FarmDyn model

	French farm	German farm
Arable land (ha)	49	60
Grassland (ha)	27	20
Number of dairy cows	62	75
Stocking rate (cow.ha-1)	0.82	0.94
Breed	Holstein	Holstein
Milk yield (kg.cow-1.year-1)	8 600	8 800
Crops	Grassland, wheat, silage maize	Grassland, wheat, silage maize

4.2.3. Introduction of legumes related data

We cover three legumes in FarmDyn model: peas, faba beans and alfalfa (Table 4.2). As for the other crops, data on yields, and on input and output prices based on (French Ministry of Agriculture 2018a; La Dépêche - Le Petit Meunier 2018; AMI 2019; KTBL 2019; IT.NRW 2019). German input prices for legumes that are rarely traded are calculated using the method available in (DLR Westerwald Osteifel 2011). Peas and faba beans can either be used as feed or sold as cash crops, while alfalfa can only be used as feed. In the French region, a cooperative offers a dehydration service to its members: alfalfa is harvested by the cooperative, dehydrated and then returned to farmers as a conserved fodder of high nutritional quality (Leterme et al. 2019). It is assumed that this technique could become available in Germany (Kamm et al. 2016). CO2eq emissions from the dehydration were taken into account in the model (Corson and Avadí 2016).

Table 4.2. Characteristics of legumes implemented in the FarmDyn model

		Alfalfa	Faba bean	Pea
Yield (t.ha^{-1})	France	10.2	3.0	4.1
	Germany	8.5	4.2	4.7
Selling price (€.t^{-1})	France	-	208	212
	Germany	-	177	198
Buying price (€.t^{-1})	France	-	270	246
	Germany	-	297	306
N from mineralization of residues	France	25	30	20
	Germany	20	10	10

One of the main advantages of legumes is their positive effect on following crops: legumes have the ability to fix nitrogen and hence fertilize the following crops by mineralizing their residues. Thus, N from legume residues enters in the fertilization balance, in addition to N from manure and synthetic fertilizers, as shown in equation (1).

$$Nneed_c.X_c \leq \mathrm{Nmanure}_c + \mathrm{Nsynt}_c + NLeg_c \tag{1}$$

Where, for each arable crop c, $Nneed_c$ is the need for N, X_c is the cropping area, and $\mathrm{Nmanure}_c$, Nsynt_c as well as $NLeg_c$ are, respectively, N available from manure, synthetic fertilizers, and mineralization of legume residues.

As the FarmDyn model is used as a comparative-static model, N stemming from mineralization of legume residues is introduced as an additional pool of N, integrated at the farm scale (equations 2 to 4) and not explicitly modelled by providing N to following crops:

$$\sum_c NLeg_c = NLegPool \tag{2}$$

With $$NLegPool = \sum_{leg} X_{leg}.NcarryOver_{leg} \tag{3}$$

$$NLeg_c < X_c.NcarryOver_{leg} \tag{4}$$

Where, for each arable crop c, $NLeg_c$ is N available from mineralisation of legume residues, $NlegPool$ is the pool of N available at the farm scale from mineralisation of legume residues; X_{leg} is the cropping area of each legume at the farm; $NcarryOver_{leg}$ is the quantity of N mineralised from residues of each legume. Data on N from mineralization of residues is based on national documentation on the balance of N fertilization (COMIFER 2011; BMEL 2017).

The mineralization of legume residues also adds another source of N that might pollute the environment through leaching. This additional source of N is integrated in the calculation of N leaching according to the model SALCA-NO3 (Richner et al. 2014).

4.2.4. Differentiated implementation of the Nitrates Directive in the FarmDyn model

As all European directives, the ND (91/676/CEE, (European Council 1991)) must be implemented into national laws, which implies differences across member states. For our analysis, we introduce the key aspects of the French and the German ND, which are implemented in PDL and NRW (BMEL 2017; DREAL Pays de la Loire 2018) into FarmDyn (Table 4.3). Apart from slightly different blocking periods for the application of manure, the main divergence relevant for this study is the possibility of spreading manure on legumes or not. In France, it is forbidden to spread manure on grain legumes (e.g., peas, faba beans) but not on forage legumes (e.g., alfalfa). In Germany, it is possible to spread manure on legumes as long as the surplus of the nutrient balance at the farm gate does not exceed 50kgN.ha^{-1}. Both, the French PDL region and the whole of Germany are designated as nitrate vulnerable zones where organic N application is limited to 170kgN.ha^{-1} on farm level.

Table 4.3. Main measures under the Nitrates Directive implemented in by France and Germany

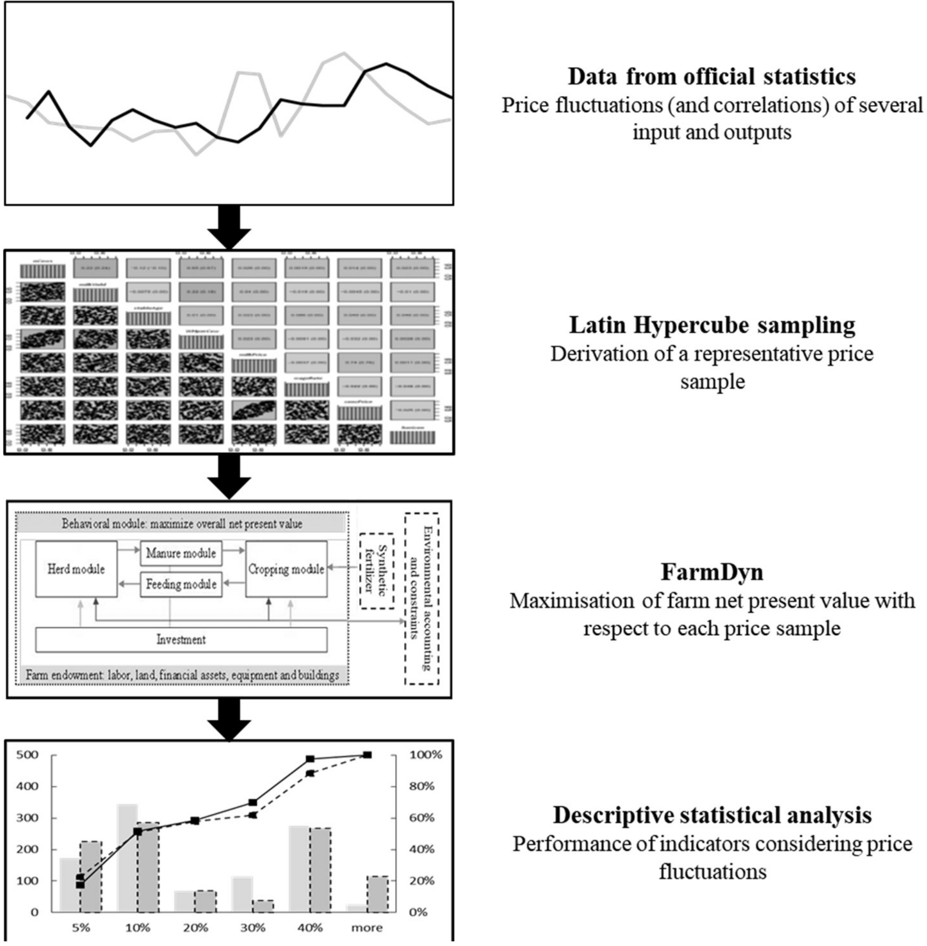
	France	Germany
Threshold of organic N application	170kgN.ha^{-1}	170kgN.ha^{-1}
Surplus of nutrient balance authorized at the farm gate	No regulation	50kgN.ha^{-1}
Threshold of organic N application on legumes	Alfalfa: 200kgN.ha^{-1} Grain legumes: 0kgN.ha^{-1}	No regulation
Fixed blocking periods of N application	Crop planted in autumn: 15.11-15.01 Crop planted in spring: 01.07-15.01 Pasture and alfalfa: 15.12-15.01 Rapeseed: 01.11-15.01	Grassland: 01.11-31.01 Arable land: 01.10-31.11
Minimum manure storage capacity	4 to 6.5 months	LSU^{f}.ha^{-1} <3: 6 months LSU.ha^{-1} >3: 9 months

4.2.5. Calibration procedure and sensitivity analysis

Each farm is calibrated by adjusting the working-hours available on the farm, as well as the grazing periods for the herd and the energy content of grass. In the German farm, the yield of wheat is adjusted within a 5% tolerance level. The size of the herd is fixed according to the number of dairy cows in the observed farm types.

A sensitivity analysis is conducted on the selling price of wheat and the buying prices of soybean meal and concentrated feeds, identified as being the main substitutes for legumes (Charrier et al. 2013). We adopt a meta-modelling approach (Lengers et al. 2014; Kuhn et al. 2019) to assess the effectiveness of the policy measures at different price levels (Figure 4.1). First, a representative price sample is generated by Latin hypercube sampling (LHS). The sampling is based on observed price fluctuations (between 1995 and 2017) derived from official statistics (Eurostat 2019b). The price fluctuations are applied on the initial average prices, giving price ranges for each good. For each tested policy scenario (see section 2.6), 1000 prices samples are randomly drawn out of the price ranges in order to obtain a representative sample. Thereby, price correlation between the respective goods is taken into account. Second, FarmDyn is used to simulate the optimal farm-level plan and maximize the farm net present value with respect to each price sample. Third, the results are used in a descriptive statistical analysis to determine the performance of key indicators considering feasible price fluctuations.

Figure 4.1. Overview of the sensitivity analysis performed, adapted from (Kuhn et al. 2019)



Data from official statistics
Price fluctuations (and correlations) of several input and outputs

Latin Hypercube sampling
Derivation of a representative price sample

FarmDyn
Maximisation of farm net present value with respect to each price sample

Descriptive statistical analysis
Performance of indicators considering price fluctuations

4.2.6. Scenarios

We define a baseline scenario (VCS0) with no VCS for legumes and with the French ND in the French farm and the German ND in the German farm. In the first scenario (VCS100), we implement a VCS for legumes in both countries, keeping the national implementations of the ND. Even though the total VCS budget for legume is stable among years in France, the VCS per hectare depends on the legume variety and on the total area of legume cultivated during the year. Therefore, we chose to implement the minimum level established in France[6]: 100€.ha^{-1} for peas, faba beans and alfalfa. In the second scenario (VCS100ge), the German ND is introduced in the French farm, the VCS of 100€.ha^{-1} still being available. Lastly, we define a set of scenarios where the VCS per hectare is increased in both farms, with steps of 10%, starting from 110€.ha^{-1} to 300€.ha^{-1} (VCS110 to VCS300), under the French or the German ND in the French farm, and the German ND in the German farm. This increase in VCS per hectare per is deliberately extreme in order to explore impacts of increasing VCS and the implications of resulting legume shares not yet observed in farms.

4.3. Results and Discussion

Unless specified, the following quoted values represent the median of our sample.

4.3.1. Legume shares and manure spreading

In the baseline scenario (VCS0), both farms produce three crops in addition to pasture: wheat, maize for silage, and one legume. However, the legume species is different according to the farm: while the French farm produces peas, the German farm produces faba beans. These legumes are present in the farms only to comply with the greening regulation and represent 5% of the arable land in both farms (Table 4.4). The introduction of VCS of 100€.ha^{-1} in the French and German farm increases the share of legumes in the arable land. However, the results of the sensitivity analysis suggest that the legume share of the German farm remains lower compared to the French Farm (Figure 4.2). The share of draws, where the German farm grows legumes only to comply with the greening regulation, is particularly high. This difference can also be observed through the median: in the French farm, the median of the legume share doubles to reach 10% of arable land, whereas the legume share in the German farm reaches 7% of arable

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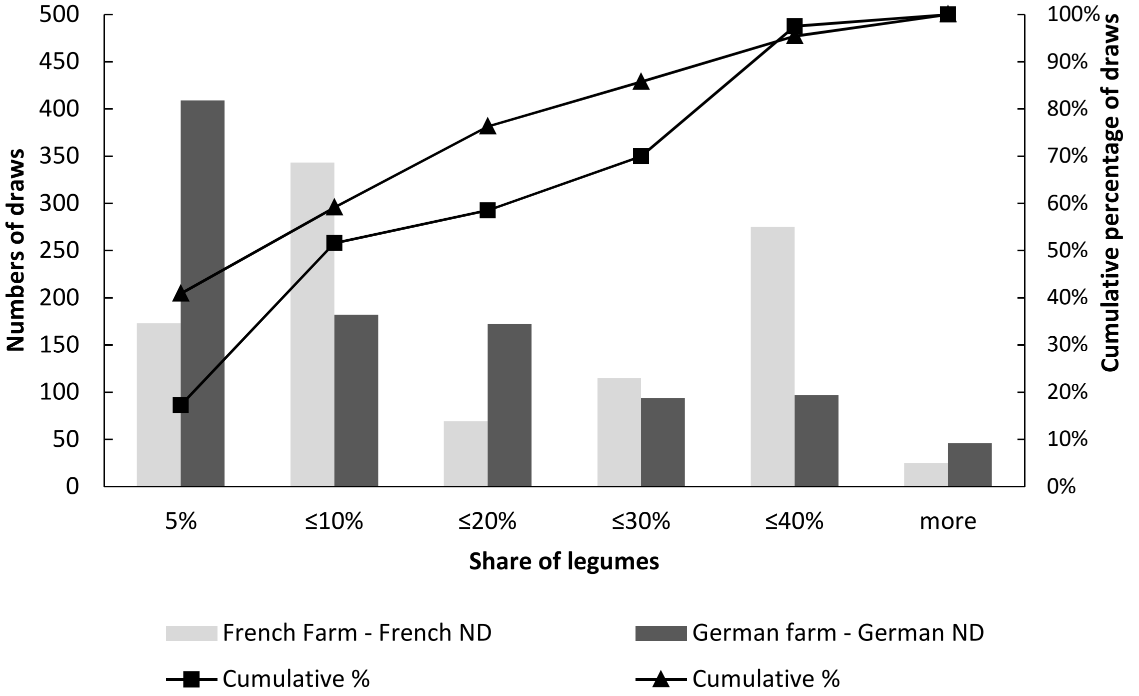
[6] The French VCS budget supports five species and usages of legumes (grain legumes, forage legumes, soybean, legumes for dehydration, and legumes for seed), each having its own sub-budget. While the VCS budgets are usually stable from year to year, the VCS per hectare vary with the acreage of each legume. Thus the VCS per hectare is usually different between grain legumes (e.g., peas, faba beans), and dehydrated alfalfa. However, a minimum per hectare for possibility of fungibility is implemented. It guarantees that, if a part of the VCS budget for legumes is assigned to another farming sector (e;g., sheep), the VCS per hectare of legumes is minimum of 100€.ha-1 (DGPE/SDPAC/2018-20).

land (Table 4.4). Legumes substitute mainly against wheat, while the acreage of maize remains quasi constant. Alfalfa is not yet produced with this level of VCS.

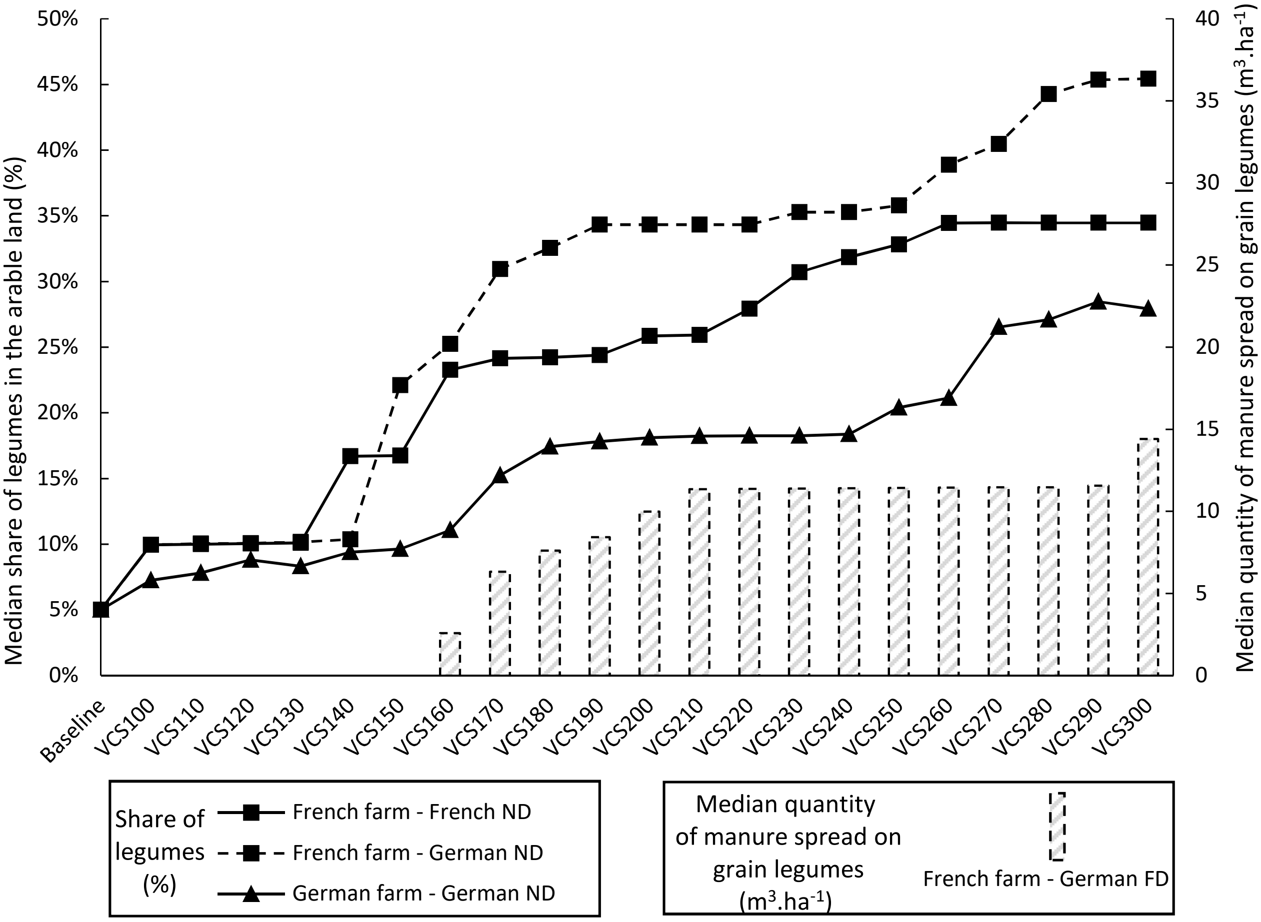
Figure 4.2. Distribution of share of legumes among the 1000 draws implemented in the sensitivity analysis, for the French farm and the German farm with VCS of 100€.ha^{-1}



When the VCS per hectare gradually increased from 100 €.ha^{-1} to 300 €.ha^{-1} (scenario VCS300), the legume share continues to increase (Figure 4.3). This increase is still more moderate in the German farm and, in the French farm, differences between the implementation of ND begin to appear after VCS130. Under the French ND, the legume share grows consistently from scenario VCS140 until the share reaches its maximum in VCS260 with 34% of arable land. Except of scenario VCS140, the legume share under the German ND is always significantly higher and reaches 45% of arable land in VCS300, which is 11 percentage points higher than under the French ND. This reflects that under the German ND, the increase in the legume share is not restricted by the need to keep spreadable areas, as it is possible to spread manure on grain legumes. Under the German ND, spreading of manure on grain legumes begins under VCS160 with 3m^3.ha^{-1} of manure, and reaches 14m^3.ha^{-1} in VCS300 (Figure 4.3). From VCS220 to VCS250, the gap of legume share is lowered between the ND: the share of alfalfa increases under the French ND, as spreading manure on alfalfa is allowed, even under the French ND. In all cases, the acreage of maize remains constant such that the share of wheat is reduced. In VCS140, the differences in the median of legume shares reflect different periods where manure spreading is allowed. Nevertheless, these differences are much more limited in their minimum and maximum values (see Table 4.4 for VCS150).

In the German farm, the legume share slowly increases to reach a maximum of 28% in VCS300 (Figure 4.3). As in the French farm, legumes (faba bean) substitute for wheat at quasi-constant maize production. The lower increase in the German farm is mainly due to the high prices and yields of wheat that increase the opportunity costs of legume in the German farm. It is interesting to notice that the median quantity of manure spread on legumes is equal to 0 in all scenarios (Table 4.4). Overall, the results suggest that VCS are an effective policy to foster substantially legume production, but to a lesser extend in Germany. These results are in line with findings of Helming et al. (2014) analyzing the effect of different policy measures aiming at fostering legume production in Europe. They found a maximum increase of +15% in legume area with subsidies from 210 €.ha^{-1} to 422€.ha^{-1} and thus concluded that besides other measures, subsidies on legumes are an effective tool to increase legume share. However, their study is limited in scope as the results are not detailed by type of farm. It is necessary to stress out that, in our study, the sensitivity analysis shows large ranges of legume shares in both farms. Thus, the effectiveness of the VCS still depends highly on the economic context. Besides, in the French farm under the German ND, the legume share reaches high level, with a median 45% (maximum at 63%) in scenario VCS300. Thereby, the share of grain legumes (38%) is above the recommended maximum share of legumes in the crop rotation (25%). However, such high shares do exist in organic systems in the EU (Pelzer et al. 2019).

Figure 4.3. Share of legumes and quantity of manure spread on grain legumes (medians), per farm and implementation of the Nitrates Directive (ND), under the Voluntary Coupled Support (VCS) scenarios for legumes



4.3.2. Input use and economic indicators

The increase in legume share decreases the use of inputs. On the one hand, the use of own-produced legumes in feed increases, which leads to a decrease in purchased feed, and thus a rise of the protein self-sufficiency (Figure 4.4). In the French farm, the protein self-sufficiency increases from 67% in the baseline scenario, to reach 71% in scenario VCS220, under both NDs. Then, up to VCS300, the German ND fosters an additional increase to 74% while it consistently remains at 71% under the French ND. This gap is mainly due to the upcoming production of alfalfa under the German ND that is mainly used for feed. The additional production of grain legumes is mainly sold under both ND and thus, does not promote a further increase in protein self-sufficiency. In the German farm, the increase in protein self-sufficiency is particularly high, with a baseline value lower than in the French farm: it increases from 60% in the baseline scenario, to 71% in VCS300. In both farms, most legumes are used as feed, and not sold to the market. This reveals a better profitability of legumes as intermediate goods (i.e., own-produced feed) than as final goods (i.e., cash crops). This is coherent with the results of

Schläfke et al. (2014) who found a higher potential of legumes in dairying as on-farm feed than as cash crop. However, with increasing subsidies, the production of grain legumes exceeds the herd's needs and thus, grain legumes are sold as cash crops.

On the other hand, the application of synthetic N fertilizer decreases, resulting from the first increases in the legume share. In the baseline scenario, the application of the synthetic N fertilizer per hectare (i.e., urea and ammonium nitrate) is higher in the German farm (183kg.ha^{-1}) than in the French farm (125kg.ha^{-1}). With VCS of 100€.ha^{-1}, it decreases by 16% in the French farm, and by 7% in the German farm. The decline in the application of synthetic N fertilizer continues and even accelerates with higher shares of legumes. With VCS of 300€.ha^{-1}, it is reduced by 73% and 81% in the French farm, respectively under the French and German ND, and by 66% in the German farm, compared to the baseline scenario. Two factors explain these decreases. First, legumes provide N through the mineralization of their residues. Second, the overall N demand is lower as there is less wheat produced, this crop having high fertilization needs.

4.3.3. Environmental and economic indicators

This increase in the legume share, associated to a decrease in the use of inputs, lead to a slight improvement of environmental indicators in both farms (Figure 4.4). In the French farm, N leaching decreases differently between the two NDs, from its initial value at 36kgN.ha^{-1}. Under the French ND, N leaching decreases almost continuously to reach a maximal decrease of 16% in VCS300, whereas, under the German ND, it decreases only by 5%. This is due to the spreading of manure on grain legumes, leading to over fertilization and thus, additional N leaching. GWP also decreases with higher share of legumes. It decreases by 5% in VCS300 under the French ND but only by 2% with German ND. This lower decrease in GWP under the German ND is explained by two factors: higher input purchases and a higher production of alfalfa that causes emissions trough the dehydration process.

Regarding farm profit, it increases by 4% under both NDs. However, the share of VCS in the farm profit also rises, to reach respectively 5.7% and 7.4% under the French and the German ND in VCS300. Overall, the total VCS allocated under the German ND is higher than under the French ND (as the legume share is higher), whereas the decrease in GWP is lower. Thus, the reduction costs diverge widely. Under the French ND, the costs increase from 26€.tCO_2eq in VCS100 to 130€.tCO_2eq in VCS300, whereas, under the German ND, the costs increase from 190€. tCO_2eq in VCS100 and reach 1,040€.tCO_2eq in VCS300

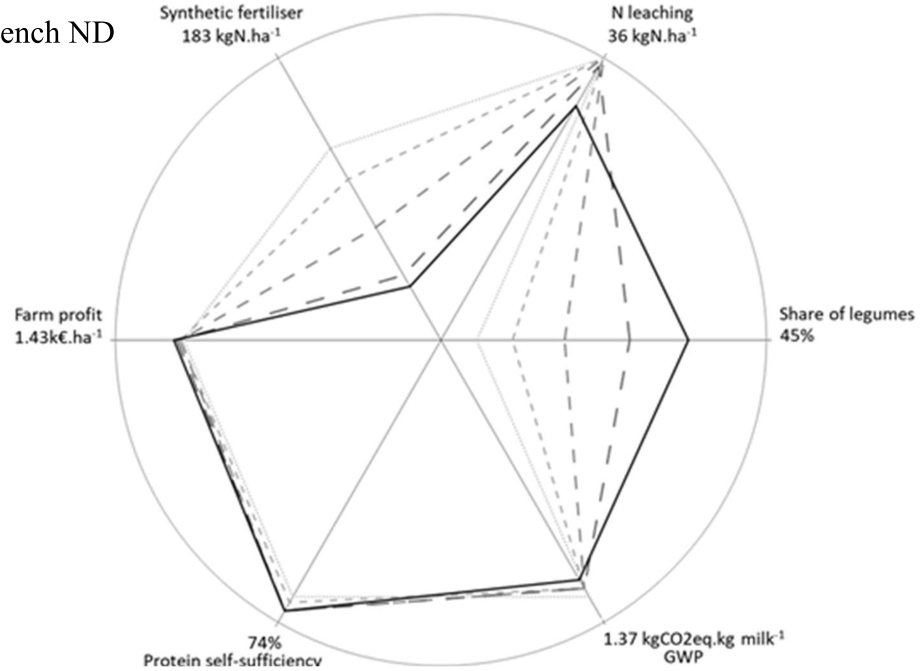
In the German farm, the improvement of environmental indicators is similar. Starting from a higher value than in the French farm (183kg.ha^{-1}), N leaching decreases by 5% between the baseline scenario and VCS300. GWP decreases by 7%, from 1.37 to 1.26 kgCO$_2$eq.kg milk^1. The farm profit slightly increases by 3%, with a simultaneously rising share of VCS in the profit from 0.4% in VCS100 to 4.4% in VCS300. Thus, the decrease in GWP in the German farm is similar to the French farm under French ND, but with lower VCS expenditure. Accordingly, the reduction costs of GWP are lower in the German farm, starting at 12€. tCO$_2$eq in VCS100 and increase to 81€. tCO$_2$eq in VCS300.

With currently 27€.tCO$_2$eq, the price of European Emission Allowances is almost always lower than the reduction costs of the French farm (European Energy Exchange 2019). In contrast, the costs of reduction of the German farm fall below the price of the European until VCS170.

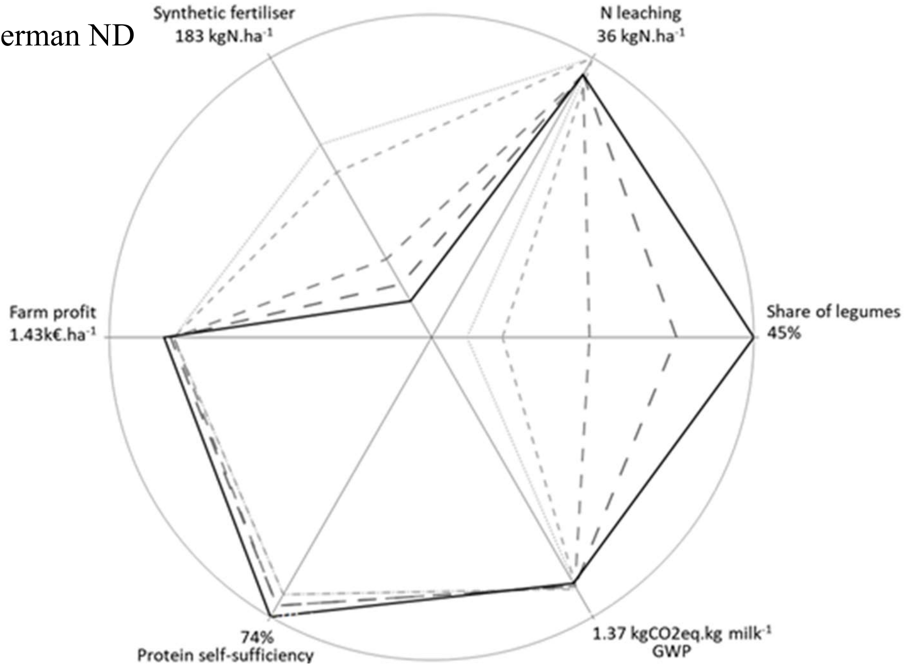
The increasing reduction costs reflects that the marginal environmental benefit of increasing VCS is limited: the main decrease in GWP takes place in the scenario VCS100. Indeed, as it is enteric fermentation and not inputs, or fertilization, that is the main source of GWP in the farms, the increase in the legume share has only limited impacts on this indicator. This is coherence with the study of Gaudino et al. (2018) in which the reduction in GHG was mainly achieved by herd reductions. Besides, the slight decreases in N leaching are coherent with the study of Nemecek et al. (2008), who focused on environmental impacts of legumes only in cropping systems. Similarly to the study of Dequiedt and Moran (2015), an in-depth economic analysis of the potential of legumes used as feed to mitigate climate change, and the cost associated will be necessary.

Figure 4.4. Integrated assessment of farms, across specific scenarios and Nitrates Directive (ND) implementation. Reference points of indicators are set by their maximum value observed in the study

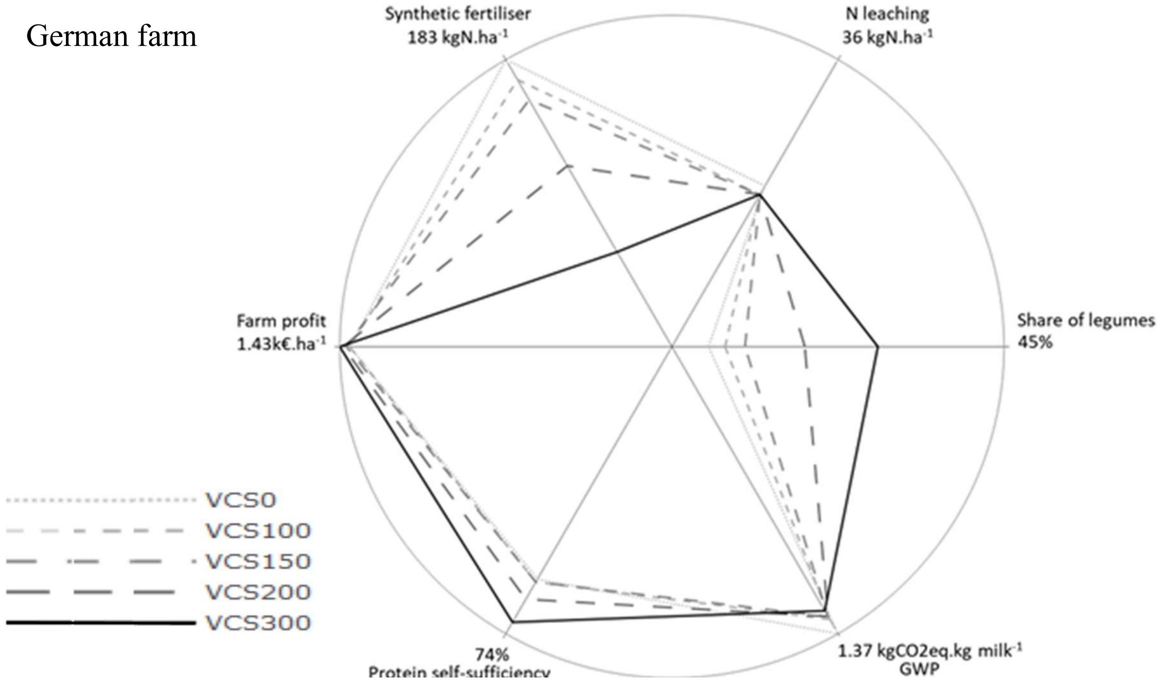
French farm – French ND



French farm – German ND



German farm



4.3.4. Policy implications and future research

This study is the first one assessing the interactions of two key policy measures affecting legume production in Europe: VCS for legumes and the national implementation of the ND. Thanks to the sensitivity analysis, different price contexts on five inputs or outputs are integrated. We found that VCS represent an effective tool to provoke a first increase in legume production. However, high VCS per hectare are needed to reach high share of legumes. Thus, we recommend a combination with other measures (e.g., taxation of N synthetic fertilizer) in order to foster legume production. Even though substantial reductions in input use are associated to high shares of legumes, linked with high VCS, improvements in the environmental indicators studied, N leaching and GWP, are rather limited. Thus, high VCS for legumes are not economically justified with regards to these indicators. However, other agronomic and environmental goals (e.g., pest management, biodiversity, protein self-sufficiency), could justify them. Besides, with lower VCS, the costs for first GWP reductions are rather limited, especially in the German farm, which is managed more intensively than the French farm. Compared to the price of the European Emission Allowance, VCS can thus be efficient tool.

Under certain conditions, the implementation of the German ND in the French farm leads to a further increase in the legume share: until + 7 percentage points. Even though this provokes a reduction in input use, it does not lead to an improvement of environmental indicators. However, the implementation of the German ND could be more relevant in farms facing higher stocking rates. In fact, allowing manure to be spread on legumes promotes further legume production, but only if manure spreading area becomes restricting. Thus, with higher stocking rates, the possibility of spreading manure on legumes could lead to the introduction of legumes in farms, and thus to first improvements of environmental indicators. Nevertheless, limits should thus be set regarding the maximum amounts of manure allowed on these crops in order to avoid a rise of N leaching.

The main limitation of the study is the restriction to two specific case studies at the farm scale. As the implementation of farms is based on various assumptions, results might differ with other farms types, in other regions, or under different price contexts. Nevertheless, the sensitivity analysis carried out makes it possible to integrate different price contexts on wheat as output, and on four inputs. Another solution would be to include multiple representative farms, which differ by their size and different mixes of resources, in order to aggregate the results at the regional scale (Weersink et al. 2002). However, working at the farm scale made it possible to study a poorly researched issue: the protein self-sufficiency. Indeed, producing legumes is one the main lever to decrease the purchases of protein-rich feed such as soybean meal. A will to increase feed self-sufficiency of farms is developing in the EU, linked with the market instability of imported protein-rich feed, and their impact on the environment (European Parliament 2011). The recent fires in the Amazonia, and the concept of imported deforestation, have highlighted the negative impact of soybean production to feed livestock, which is the first driver of tropical deforestation (Pendrill et al. 2019). Another limitation of the study is that policy feedback is not considered: the total VCS budgets for each legume species are upper bounded at national level. This level must be consistent with the ceiling of all productions benefiting from VCS in each Member State, in order to remain in compliance with the World Trade Organization "blue box" criteria (Regulation No 1307/2013). Thus, VCS per hectare depends on the overall national production of each legume. This introduces an additional risk on legume opportunity costs that is not integrated in the model.

In this study, we focused on the interaction between VCS and the ND, but further policy field could be considered such as interactions between VCS and pesticide policies. Conventional legume production still mostly relies on pesticides, while certain regulations ban pesticides on these crops such as UE 2017/1155 that forbids pesticides on legumes used as EFA. That restriction – which might lead to lower yields and/or higher costs for mechanical plant protection measures – is not considered in our analysis. Besides, as shown in our case studies it is more profitable to use legumes as own-produced feed than to sell them on markets. More studies analyzing the profitability of legumes used as feed, and not only as cash crops should be developed. Also, farmers' access to new techniques improving digestibility of legumes for livestock, such as toasting, should be strengthened. Beyond the farm level, it would be interesting to study crop-livestock integration through exchanges of legumes (i.e., crop farms selling legumes to livestock farms), or through the export of manure (i.e., livestock farm exporting manure to crop farms) (Willems et al. 2016; Moraine et al. 2016). Finally, we deliberately analyze high levels of VCS to explore implications of high legume shares not yet observed in conventional farms. Such legume shares make farm profit more dependent on subsidies, which is a questionable strategy at a time where high subsidies under the CAP are questioned. Alternatively, the profitability of legumes could be fostered by further development of dedicated agro-food chains. The emerging sector of GMO-free feed, using, among others, legumes produced in the EU, represents an interesting lever to increase legume production in dairy farms.

Table 4.4. Results of main indicators (median and range) used in the integrated assessment, for selected scenarios, per farm and implementation of the Nitrates Directive (ND)

	French farm - French ND					French farm - German ND					German farm – German ND				
	VCS0	VCS100	VCS150	VCS200	VCS300	VCS0	VCS100	VCS150	VCS200	VCS300	VCS0	VCS100	VCS150	VCS200	VCS300
Share of legumes	5% (5- 35)	10% (5- 46)	17% (5- 48)	26% (5-49)	34% (5- 59)	5% (5- 48)	10% (5- 49)	22% (5- 53)	34% (5- 58)	45% (5- 63)	5% (5- 44)	7% (5- 45)	10% (5- 59)	18% (5- 59)	28% (5- 62)
Grain legumes	*5%*	*7%*	*15%*	*24%*	*32%*	*5%*	*6%*	*20%*	*33%*	*38%*	*5%*	*5%*	*8%*	*18%*	*26%*
Protein self-sufficiency	67% (58- 86)	69% (58- 89)	71% (58- 91)	71% (58- 92)	71% (58- 92)	68% (58- 90)	68% (54- 92)	71% (58- 92)	71% (56- 92)	74% (59- 92)	60% (54- 88)	61% (49- 89)	61% (54- 90)	65% (49- 91)	71% (54- 92)
Manure on legumes (m^3.ha of legumes^{-1})	0 (0- 10)	0 (0- 15)	0 (0- 15)	0 (0- 15)	11 [a] (0- 15)	0 (0- 19)	0 (0- 20)	0 (0- 21)	10 (0- 21)	14 (0- 21)	0 (0- 14)	0 (0- 14)	0 (0- 20)	0 (0- 20)	0 (0- 21)
Synthetic fertilizer (kg.ha^{-1})	125 (35- 131)	105 (23- 131)	74 (22- 131)	42 (21- 131)	34 (11- 131)	127 (22- 134)	108 (21- 136)	52 (17- 134)	34 (13- 136)	24 (8- 134)	183 (34- 185)	170 (29- 188)	157 (18- 185)	116 (17- 189)	61 (11- 184)
Farm Profit (k€.ha^{-1})	1.13 (1.05 - 1.25)	1.14 (1.07 - 1.27)	1.15 (1.09 - 1.25)	1.16 (1.10 - 1.26)	1.17 (1.13 - 1.26)	1.14 (1.05 - 1.27)	1.15 (1.08 - 1.29)	1.15 (1.09 - 1.27)	1.16 (1.11 - 1.27)	1.18 (1.14 - 1.27)	1.39 (1.25- 1.64)	1.39 (1.27- 1.61)	1.40 (1.29- 1.63)	1.41 (1.31- 1.62)	1.43 (1.34- 1.63)
Share of VCS in profit	0.0% (0- 0)	0.6% (0.3- 2.4)	1.4% (0.4- 3.7)	2.9% (0.6- 5.0)	5.7% (0.9- 9.1)	0.0% (0- 0)	0.6% (0.3- 2.5)	1.9% (0.4- 4.0)	3.8% (0.6- 5.8)	7.4% (0.8- 9.6)	0.0% (0- 0)	0.4% (0.3- 2.1)	0.8% (0.4- 4.1)	1.9% (0.6- 5.5)	4.4% (0.8- 8.5)
N leaching (kgN.ha^{-1})	36 (22-41)	36 (19-41)	36 (19-41)	35 (19-41)	30 (18-41)	36 (20-39)	36 (19-42)	34 (19-48)	34 (19-48)	34 (17-52)	20 (7-23)	19 (7-23)	19 (6-31)	19 (6-32)	19 (6-36)
GWP (kgCO2eq.kg milk^{-1})	1.25 (1.06 - 1.69)	1.21 (1.04 - 1.69)	1.21 (1.03 - 1.69)	1.20 (1.02 - 1.69)	1.16 (1.01- 1.65)	1.23 (1.05 - 1.70)	1.23 (1.04 - 1.81)	1.22 (1.03 - 1.70)	1.22 (1.02 - 1.77)	1.21 (1.02 - 1.68)	1.37 (1.06 - 1.68)	1.30 (1.05 - 1.70)	1.29 (1.04 - 1.71)	1.29 (1.04 - 1.69)	1.26 (1.02 - 1.71)

[a] Manure spread only on alfalfa; The minimum and maximum values are in brackets;

4.4. Conclusion

Despite their contribution to a more sustainable agriculture, legume production remains low in the EU. This study is the first assessing economic and environmental impacts of two key policy measures affecting legume production in the EU: VCS for legumes and the national implementations of the ND. It compares in detail a French and German dairy farm, taking into account legumes as own-produced feed and as cash crop. When VCS are implemented, the legume production increases, but in a more limited in the German farm than in the French one, due to higher opportunity costs of legumes. In both farms, the increase in legume production leads to limited decrease in N leaching and GWP. In the French farm, the implementation of the German ND leads to a further increase in the legume share, but only when manure spreading area becomes restricting. Thus, we show that allowing manure spreading on legumes can help increasing the production of legumes in dairy farms with high stocking rates. However, environmental indicators are not substantially improved as it can lead to an over fertilization of legumes, and thus, additional N leaching. Therefore, allowing manure spreading on legumes to increase their production should be justified by others goals such as improving the protein self-sufficiency of the farm.

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Chapter 5.

The SYNERGY model: assessment of farm complementarities and legume production as levers to improve agricultural sustainability at the regional scale

This chapter focuses on the SYNERGY bio-economic model that I built during my Ph.D. research. The first part of this chapter presents the model, how it represents specialized farm types in a region and technical complementarities between them. To represent crop and livestock complementarities at the regional scale, SYNERGY models exchanges of crops and manure between these farms. In the study presented in this chapter, I applied the SYNERGY model to western France (Appendix E). I tested two levers to improve technical complementarities: developing farm-to-farm exchanges and increasing legume production. Economic, technical and environmental impacts were assessed. Results indicate that when legumes covered 10% of the region's utilized agricultural area (UAA), 20% of cows were fed legume-based rations, use of N fertilizers decreased by 7% and profit decreased by 4%. Environmental indicators did not change substantially at the regional scale, although they improved for some farms. Increasing manure exchanges led to intensification of pig production and worsened environmental indicators. Crop exchanges remained limited and did not lead to additional use of legumes as feed. To foster the latter, one solution would be to increase the profitability of legumes by creating added value for livestock fed these crops.

The first part of this chapter is based on the article "SYNERGY: a regional bio-economic model analyzing farm-to-farm exchanges and legume production to enhance agricultural sustainability", co-written with Aude Ridier and Matthieu Carof. It is in review in the peer-reviewed journal *Ecological Economics*. Extracts of the SYNERGY model, coded in GAMS, are available in Appendix F.

The second part of this chapter details the data used in SYNERGY. After an overview of the data and their sources, I present how legume data were included in SYNERGY and the calculation of two environmental indicators, SyNE and SyNB. This data paper will be submitted to the journal *Data*.

5.1. SYNERGY: a regional bio-economic model analyzing farm-to-farm exchanges and legume production to enhance agricultural sustainability

5.1.1. Introduction

Over the past 50 years, European farms have increased in specialization and decreased in number due to an increase in productivity sustained by technological innovation and genetic improvement. While specialization has increased farm production, it has disconnected crop and livestock production in many regions (Naylor et al. 2005). This disconnect lies at the root of a double break in the closure of the global nitrogen (N) cycle (Galloway et al. 2008). The first break concerns the imbalance in N availability: on crop farms, N available for crops from natural processes may not meet crop needs, leading to a deficit in N, while on livestock farms, the animal manure produced may exceed crop needs, leading to an excess of N. The second break concerns the dependence of many farms on purchases of N in various forms, such as synthetic N fertilizers on crop farms and N-rich feed on livestock farms. In particular, N-rich feed relies heavily on soybean meal (European Commission 2017b), which raises questions about deforestation in countries where soybean is grown (Karstensen et al. 2013) and the security of supply for importing countries (Gale et al. 2014). Other issues arise from this double break, mainly due to N losses in ecosystems: water pollution (Parris 2011), loss of biodiversity (Bobbink et al. 2010) and atmospheric pollution, which negatively impacts the climate and human health (Bauer et al. 2016). These negative effects were estimated to cost €75-485 billion in the European Union (EU) in 2008 (Van Grinsven et al. 2013).

Two mechanisms can be identified to increase closure of the N cycle. The first is an increase in local production of legumes; because they can fix atmospheric N, they are N-rich crops that do not need N fertilizers. They can also reduce the amount of N fertilizers applied on the following crop (Nemecek et al. 2008; Preissel et al. 2015) and can be used as an on-farm N-rich feed to replace some feed purchases (Bues et al. 2013). Nonetheless, at the yearly scale, legumes are less profitable than cash crops such as wheat (Preissel et al. 2015) and their yields vary more in Europe (Cernay et al. 2015). In addition, regulatory constraints (e.g. EU Nitrates Directive 91/676/CEE) can discourage livestock farmers from producing legumes: for example, in some livestock regions in the EU, manure cannot legally be spread on most legumes. The second mechanism is local farm-to-farm exchanges. Livestock farms can export manure to crop farms deficient in N, while crop farms can produce legumes and sell them to livestock farms. This crop-livestock integration beyond the farm level (Leterme et al. 2019) would avoid regulatory constraints that prevent legume production on livestock farms.

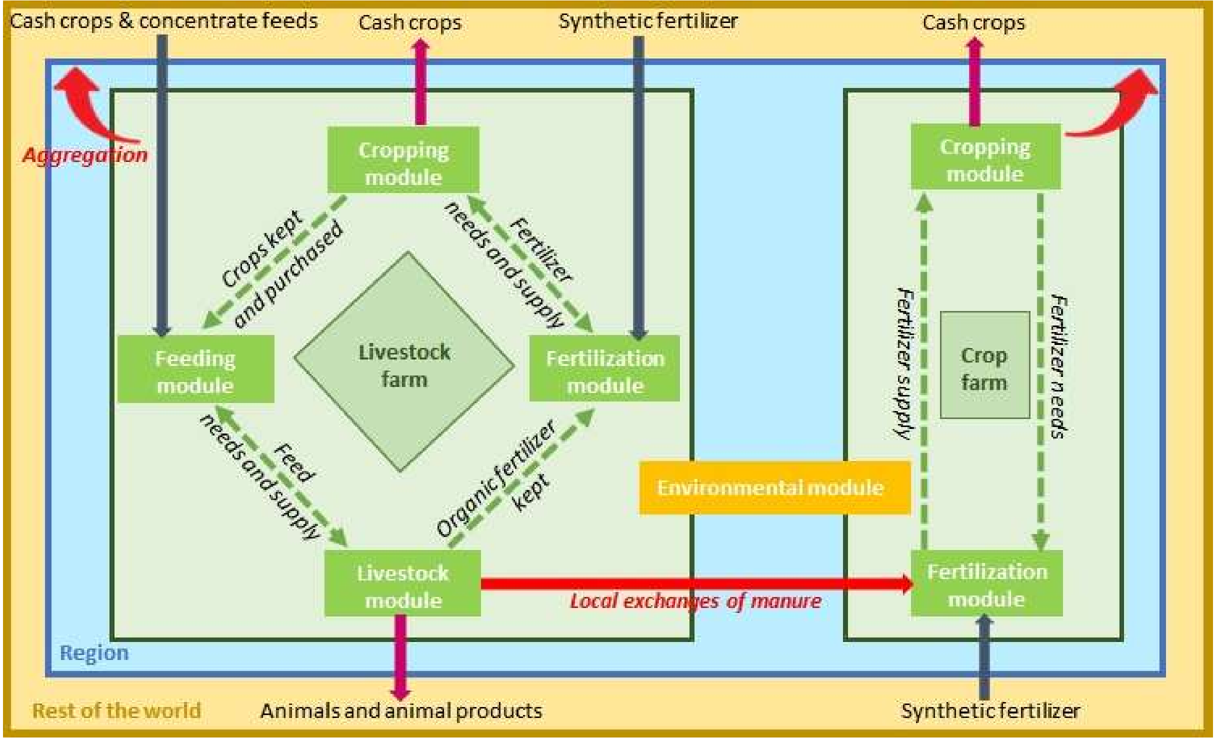
We hypothesized that legume production and local farm-to-farm exchanges enhance the joint production of N-rich inputs, which benefits the agroecosystem both economically and environmentally. In this study, we tested this hypothesis by developing and using a bio-economic model that considers (i) local production of legumes and (ii) local farm-to-farm exchanges of crops (including legumes) and manure at the regional level. Mathematical programming models perform ex-ante analysis that can assess changes in agricultural practices even if they have not yet been adopted over large areas (Delmotte et al. 2013; Böcker et al. 2018). Among such models, bio-economic models assess both economic and environmental impacts since they aim to identify trade-offs between economic and environmental considerations (Janssen and van Ittersum 2007). Several bio-economic models have been developed for legume production at the field level (Reckling et al. 2016a) and farm level (Schläfke et al. 2014). However, they fail to identify impacts at higher levels (e.g., region, country) that may be useful to policy makers. Hybrid models address this issue by aggregating results from the farm level to higher levels (Britz et al. 2012). Hybrid bio-economic models have been developed mainly to study policy changes that impact agricultural production (Chopin et al. 2015; Gocht et al. 2017). These models usually consider the diversity of farm types (e.g., crop, livestock) and technologies, but none of them focuses on legume production. Finally, exchanges of manure between farms can be simulated using agent-based models (Happe et al. 2011) or analyzed using mathematical programming models with supply and demand functions either explicitly or endogenously described (Spreen 2006; Helming and Reinhard 2009). The bio-economic model SYNERGY developed in this study is in direct line with these considerations. First, it is a hybrid model applied at the farm level and then aggregated to the regional level. Second, it considers multiple types of farms, soil and climatic conditions and technologies in the region to minimize aggregation bias. Third, it highlights the complementarity of farms by considering exchanges of crops and manure between them.

5.1.2. Method

5.1.2.1. Overview of SYNERGY

The bio-economic model SYNERGY (cross-Scale model using complementaritY betweeN livEstock and cRop farms to enhance reGional nitrogen self-sufficiencY) is a hybrid static non-linear programming model. SYNERGY represents specialized farm types (dairy cow, pig and crop) in a given region. Depending on the scenario, the total area allocated to each farm type may change, as may animal numbers and land use inside each farm type; however, farm types cannot change (e.g., a dairy farm cannot become a pig farm). SYNERGY is applied to a region that is divided into several sectors to consider a variety of soil and climate conditions. In each sector, arable land area is allocated among the farm types. Farm-level outputs are aggregated to the regional level by averaging total output of each farm type, weighted by its relative area in the region. In addition to being able to represent the high heterogeneity of multiple farm types and geographic sectors, SYNERGY can also represent multiple farm activities. Crop activities are defined as the combination of a crop and the rotation it belongs to, which determines the levels of inputs described in cropping and fertilization modules. Livestock activities are defined as the combination of an animal and its feed ration (e.g., legume-based), which determines (i) the levels of input use described in the feeding module and (ii) milk and meat yields described in the livestock module. The model represents many crop and livestock activities, making it possible to represent both widespread and alternative technologies (see section 3). SYNERGY's main originality lies in its ability to represent farm-to-farm exchanges of intermediate products (manure and crops), which occur on a local market (i.e., intra-sector or intra-region). SYNERGY is composed of several modules that detail crop and livestock activities, as well as their impacts on N efficiency and potential losses of N (Figure 5.1.1). It generates four types of indicators: (i) structural (e.g., crop areas, numbers of animals), (ii) technical (e.g., protein self-sufficiency, application of N fertilizers) (iii) economic (e.g., regional profit, farm income, farm-to-farm exchanges) and (iv) environmental (i.e., N efficiency and potential losses of N). These outputs are provided for each farm type at the sector and regional levels.

Figure 5.1.1. Conceptual diagram of the SYNERGY model (adapted from Jouan et al. (2017)).



Crop activities are described in cropping and fertilization modules, while livestock activities are described in livestock and feeding modules.

5.1.2.2. The objective function

SYNERGY's objective function is a quadratic function maximizing profit at the regional level that is solved under resource and production constraints. It yields an optimal allocation of arable land area of each farm type *f* in each sector *s*, and of crop and animal activities of each farm type. Profit equals farm income $R_{f,s}$ minus two cost functions, one for crops $FC_{c,f,s}(X_{c,r,f,s}).X_{c,r,f,s}$ and one for animals $FC_{a,f,s}(N_{a,ra,f,s}).N_{a,ra,f,s}$ (Eq. 5.1). These cost functions calibrate the model using Positive Mathematical Programming (PMP) (see section 2.4).

The quadratic profit-maximizing function is:

$$\text{Max } Z = \sum_{f}\sum_{s}\sum_{c}\sum_{a}\sum_{ra}\sum_{r}\left[R_{f,s} - FC_{c,f,s}(X_{c,r,f,s}).X_{c,r,f,s} - FC_{a,f,s}(N_{a,ra,f,s}).N_{a,ra,f,s}\right] \qquad (5.1)$$

where Z is regional profit; $R_{f,s}$ represents the income of farm *f*, in sector *s;* $X_{c,r,f,s}$ is the crop activity level (area allocated to each crop *c* associated with each rotation *r*, per farm *f* per sector *s*); $N_{a,r,f,s}$ is the animal activity level (number of each type of animal *a* associated with each ration ra, per farm f per sector s); $FC_{c,f,s}$ is the non-linear variable cost function for crops; and $FC_{a,r,f,s}$ is the non-linear variable cost function for animals.

Eq. (5.1) is subject to constraints:

$$\sum_{c}\sum_{r} Ac_{c,\mathrm{r},f,s} . X_{c,\mathrm{r},f,s} \leq Bc_{f,s} \tag{5.2.1}$$

$$\sum_{a}\sum_{ra} Aa_{a,ra,f,s} . N_{a,ra,f,s} \leq Ba_{f,s} \tag{5.2.2}$$

$$X_{c,\mathrm{r},f,s} \geq 0 \tag{5.3.1}$$

$$N_{a,ra,f,s} \geq 0 \tag{5.3.2}$$

where $Ac_{c,f,s}$ and $Aa_{a,r,f,s}$ represent respectively a matrix of input-output coefficients for crops and animals; and $Bc_{f,s}$ and $Ba_{f,s}$ represent respectively a matrix of resource availability for crops and animals.

Farm income $R_{f,s}$ is calculated from sales of crops, animal products and manure, minus purchases of crops, animals and synthetic N fertilizers, and minus the cost of exporting manure. The local and world markets have the same selling price of crops, but the local market has a lower purchase price than the world market because transport costs on the world market are not included on the local market (Eq. 5.4):

$$\begin{aligned} R_{f,s} = \sum_{c}\sum_{a}\sum_{ma}\sum_{ra}\sum_{r} & (WcropSale_{f,s,c,r} . ps_c - WcropBought_{f,s,c,r} . pb_c) \\ & + \left(LcropSale_{f,s,c,r} . ps_c -. LcropBought_{f,s,c,r} (pb_c - tc_c)\right) \\ & + \left(WanimalSale_{f,s,a,ra} . ps_{a,ra} - WanimalBought_{f,s,a,ra} . pb_{a,ra}\right) \\ & - \left(LfertiSale_{f,s,fe} . tc_{fe} + WfertiBought_{f,s,fe} . pb_{fe}\right) \end{aligned} \tag{5.4}$$

where $WcropSale_{f,s,c,r}$ and $WcropBought$ represent respectively sales and purchases of crops on the world market; $LcropSale_{f,s,c,r}$ and $LcropBought_{f,s,c,r}$ represent respectively sales and purchases of crops on the local market; $WanimalSale_{f,s,a,ra}$ and $WanimalBought_{f,s,a,ra}$ represent respectively sales and purchases of animals on the world market; $LfertiSale_{f,s,fe}$ and $WfertiBought_{f,s,fe}$ represent respectively local sales of fertilizers (i.e., manure) and purchases of synthetic N fertilizers on the world market; ps_c

and pb_c represent respectively the selling price and purchase price of crops; $ps_{a,ra}$ and $pb_{a,ra}$ represent respectively the selling price and purchase price of animals; pb_{fe} represents the purchase price of synthetic N fertilizers; and tc_c and tc_{fe} represent respectively the transport cost of crops and fertilizers purchased on the local market.

5.1.2.3. SYNERGY modules

❖ *Cropping module*

The cropping module sets the area of each crop activity for a farm type. Since SYNERGY is a static model, rotations are represented by combining different crops with constraints of crop share, which corresponds to each crop's minimum return period. The cropping module also sets the outlets of crop production: kept on the farm, sold on the local market or sold on the world market. The non-linear cost function considers costs of crop production (excluding fertilizer costs) and makes it possible to calibrate the model for the crop areas observed during a reference period (see section 5.2.4).

❖ *Fertilization module*

The fertilization module balances N-fertilization resources (manure and synthetic N fertilizers) with N-fertilization needs. It sets the quantity of manure produced by farm type and its outlets: kept on the farm to meet crop N requirements or exported locally. It also makes it possible to purchase and import the adequate quantity of manure from the local market and synthetic fertilizers from the world market. Farms import manure free of charge but those who export it bear transport costs. Fertilization needs were based on crop N requirements estimated by the French method COMIFER (COMIFER 2011), which considers multiple sources of N: fixed by legumes, produced in manure, purchased in synthetic fertilizers and mineralized in the soil. N mineralization comes from humus, grassland turnover and crop residues, among which legume residues are especially rich in N. For some crops, a maximum percentage of organic fertilization out of total fertilization is set to avoid fertilization with only manure, in accordance with current practices. The fertilization module also includes regulatory constraints (EU Nitrates Directive 91/676/CEE) that restrict the amount of manure spread on crops to 170 kg N.ha^{-1}. Thus, farms that reach this limit export their excess manure to other farms in the sector.

❖ *Animal module*

The animal module sets the activities that result in production of animals and milk. The quantity of milk produced per cow, as well as milk quality (i.e., protein and fat contents), depend on the ration. The animal module also sets the outlets of animals: kept on the farm or sold on the world market. Demographic constraints ensure that the number of animals is consistent with standard productivity. The non-linear cost function considers breeding costs and makes it possible to calibrate the model for the animal activities observed during a reference period (see section 5.1.2.4).

- *Feeding module*

The feeding module balances feed resources (crops produced and kept on the farm, crops purchased on the local or world markets, and concentrate feeds purchased on the world market) with feed needs. Feed needs are detailed by ration, which differ by animal and farm type. The feeding module calculates farm-protein self-sufficiency as the ratio of crude protein produced and consumed on the farm to all crude protein consumed on the farm.

- *Environmental module*

The environmental module uses two indicators developed by Godinot et al. (2014): SyNE (System N Efficiency) and SyNB (System N Balance). SyNE (range = 0-1) assesses the efficiency with which farming systems transform N inputs into desired agricultural products. SyNE is an improved indicator of N-use efficiency since it includes life cycle assessment of inputs and considers manure to be an intermediate product. As SyNE increases, farming-system efficiency increases. SyNB (kg N.ha^{-1}) reflects potential N losses from farming systems, including those during production of inputs; as SyNB increases, potential N losses from a farming system increase.

5.1.2.4. Calibration of the SYNERGY model

SYNERGY was calibrated using the PMP method, developed by Howitt (1995) and then improved by later authors (see Frahan et al. (2007), Heckelei and Britz (2005) and Louhichi et al. (2013)) for critical reviews of different PMP approaches). We used the standard approach of Howitt (1995) to calibrate crop areas and numbers of breeding animals. We did not calibrate rotations or rations since no robust data were available for the region studied.

The first step of PMP consists of creating a linear model and adding to the set of resource constraints (on land, feeding, herd demography, rotations and N management) an additional set of calibrating constraints that bound crop area and animal numbers to those observed during a reference period. Thus, in the first step, Eq. (5.5) was maximized, subject to constraints (5.2.1), (5.2.2), (5.3.1) and (5.3.2) and to PMP constraints (5.6.1) and (5.6.2).

$$\sum_{f}\sum_{s}\sum_{c}\sum_{a}\sum_{r}[R_{f,s}-co_{c,s}.X_{c,\mathrm{r},f,s}-co_{a,r}.N_{a,ra,f,s}] \tag{5.5}$$

$$\sum_{r} X_{c,\mathrm{r},f,s} \leq X^{0}_{c,f,s}.(1+\varepsilon_{c}) \qquad [\lambda c_{c,f,s}] \tag{5.6.1}$$

$$\sum_{ra} N_{a,ra,f,s} \leq N^{0}_{a,f,s}.(1+\varepsilon_{a}) \qquad [\lambda a_{f,s,a}] \tag{5.6.2}$$

where $co_{c,s}$ and $co_{a,r}$ represent respectively the linear-cost vector for crops and animal products; $X^{0}_{c,f,s}$ and $N^{0}_{a,f,s}$ represent respectively the non-negative vector of observed crop areas and animal numbers; and ε_{c}, ε_{a} are small positive vectors.

Then, in the second step of the PMP, the vectors of duals $\lambda c_{c,f,s}$ and $\lambda a_{f,s,a}$ are used to estimate parameters of non-linear cost functions that satisfy equations (5.7.1) to (5.9.2):

$$co_{c,s}+\lambda c_{c,f,s}=d_{c,f,s}+Q_{c,f,s}.X^{0}_{c,f,s} \tag{5.7.1}$$

$$co_{a,s}+\lambda a_{f,s,a}=d_{a,f,s}+Qa_{a,f,s}.N^{0}_{a,f,s} \tag{5.7.2}$$

$$d_{c,f,s}=co_{c,s}+\lambda c_{c,f,s}-kc.\lambda c_{c,f,s} \tag{5.8.1}$$

$$d_{a,f,s}=co_{a,s}+\lambda a_{f,s,a}-ka.\lambda a_{f,s,a} \tag{5.8.2}$$

$$Qc_{c,f,s}=\frac{kc|\lambda c_{c,f,s}|}{X^{0}_{c,f,s}} \tag{5.9.1}$$

$$Qa_{a,f,s}=\frac{ka|\lambda a_{f,s,a}|}{N^{0}_{a,f,s}} \tag{9.2}$$

where $d_{c,f,s}$ and $d_{a,f,s}$ represent respectively the vector of intercepts of the cost functions for crops and animals; $Q_{c,f,s}$, and $Qa_{a,f,s}$ represent respectively the vector of slope of the quadratic cost function of crops and animals; and kc and ka represent respectively the vector of parameters that determine the weights of the non-linear part of the cost function for crops and animals.

Finally, the two cost functions are written as:

$$FC_{c,f,s}(X_{c,\mathrm{r},f,s})=d_{c,f,s}+0.5Qc_{c,f,s}.\sum_{r}X_{c,\mathrm{r},f,s} \tag{5.10.1}$$

$$FC_{a,f,s}(N_{a,\mathrm{ra},f,s})=d_{a,f,s}+0.5Qa_{f,s,a}.\sum_{ra}N_{a,ra,f,s} \tag{5.10.2}$$

5.1.3. The case study

5.1.3.1. Overview of the case study

SYNERGY was applied to a region corresponding to two EU NUTS 2 sub-regions in western France: Pays de la Loire and Brittany. Although containing only 14% of France's UAA, this region contains 68% of its pig production and 38% of its cow milk production. Its area of grain legumes more than doubled from 2013-2017, but still represented only 1% of UAA in 2017 (French Ministry of Agriculture 2018a). Agricultural production location in the region is heterogeneous: most animal production lies in the north, while most crop production lies in the south. Appendix 5.1.A describes the sources of input data used. The region was divided into nine sectors, each representing an administrative department in the two sub-regions and numbered according to the French system (departments 22, 29, 35, 44, 49, 53, 56, 72 and 85).

5.1.3.2. Diversity of farms and activities

Three farm types were considered in the region: dairy cow, pig and crop. Dairy production had 20 potential rations, each differing in the main forage (i.e., forage maize, forage grass or both) and in the N-rich feed (soybean meal, peas, faba beans or dehydrated alfalfa). Regardless of the main forage, soybean-based rations were the basic rations used, based on regional references (IDELE - Inosys 2018). Legume-based rations were alternative ones created by replacing soybean meal with legumes (here, pea, faba bean or dehydrated alfalfa) using INRAtion® software (INRA 2003). If legumes could not replace all soybean meal due to nutritional constraints, some rapeseed meal was added. Appendix 5.1.B lists examples of compositions of the dairy rations used. Pig production had two potential rations, each differing in the N-rich feed (soybean meal or a mixture of pea and faba bean) and calculated using Porfal® software (IFIP 2018).

Crop production had 53 potential rotations, defined by expert knowledge, that included 11 crops. Some of these rotations were included improve model flexibility and calibration, but are not yet common in the region. Crop yields differed only by sector, not by rotation. Only N fertilization of each crop differed by both sector and rotation. For example, after a pea crop, N fertilization of wheat was lower than that after a maize crop due to the preceding crop effect of pea.

5.1.3.3. Data and calibration specifications

SYNERGY was calibrated for each farm type at the sector level. Animal numbers and areas of each farm type were calibrated using data from the most recent agricultural census in France

(French Ministry of Agriculture 2018b). Due to the PMP technique used, all crop areas were set to non-zero values to be able to evolve in the scenarios. Thus, for each legume studied (i.e., peas, faba beans and dehydrated alfalfa), the initial area was arbitrarily set at 0.5% of the area of each farm in each sector, which initialized the total legume share at 1.5% in each farm in each sector. Input and output prices were based on mean regional or national data for the reference years 2013-2017 (IFIP 2017; French Ministry of Agriculture 2018a; La Dépêche - Le Petit Meunier 2018).

5.1.3.4. Scenarios analyzed using the SYNERGY model

Four scenarios were analyzed using SYNERGY:

- BASE: The baseline scenario, which represents the situation observed after calibration. Manure is exchanged locally (i.e., intra-sector), but farms must meet regulatory constraints that restrict the amount of manure spread on crops to 170 kg $N.ha^{-1}$.
- LEG10: Legume area is set to 10% of the regional area, a share chosen according to a recent foresight (Poux and Aubert 2019) that explores the possibility of generalizing agroecology at the European level. The total amount of manure exchanged at the regional level is capped at the total amount predicted for BASE.
- LEG10+Ma: Legume area remains 10% of the regional area, and the total amount of manure exchanged can freely increase compared to those in BASE and LEG10.
- LEG10+MaC: Legume area remains 10% of the regional area, and local exchanges of crops are available in addition to exchanges of manure.

Results were analyzed either at the regional level or by farm type by averaging results of farms of the same type among sectors, weighted by the area of each farm type, or for a specific farm type by sector.

5.1.4. Results

5.1.4.1. Baseline scenario (BASE)

As set during initialization, legume share in BASE is 1.5% of the area of each farm in each sector. Grasslands and forage maize cover 53% of the regional area, while wheat covers 21%. Dairy farms cover 73% of the regional area. The region produces 736,110 hL of milk and 12 million pigs (Table 5.1.1).

The share of legume-based rations is low: 0.4% for pig farms and 4.8% for dairy farms. Sectors do not differ greatly, except for dairy farms in sector 35 (“Dairy35”), where the share of legume-based rations reaches 15.3%, mainly due to the large use of alfalfa (likely because the region’s only forage dehydration factory is located there). In the model, this large use is translated into PMP constraints that lead to small areas of forage maize relative to the number of cows. Consequently, the model favors alfalfa-based rations because they generate high milk yields while using the lowest amounts forage maize. Even so, 55% of the dehydrated alfalfa in sector 35 is purchased on the world market.

Protein self-sufficiency at the regional level reaches 58%, with large differences in the mean among farm types: 73% for dairy farms and 24% for pig farms. In almost all sectors, pig farms export their manure, mainly to dairy farms. Overall, 28% of pig manure produced in the region is exported to other farms. Although covering 73% of the region, dairy farms generate 64% of regional profit. Potential N losses are by far the largest for pig farms (mean SyNB = 267 kg N.ha^{-1}). Not surprisingly, crop farms are the most N efficient (mean SyNE = 0.55), followed by pig farms (0.41) and dairy farms (0.35).

5.1.4.2. LEG10 scenario

In the LEG10 scenario, legume area is set at 10% of the regional area, and the total amount of manure exchanged at the regional level is capped at the total amount predicted for BASE. Under these constraints, legume area is allocated among farms and sections, becoming higher on crop farms (22% of the area) than on dairy farms (8%) or pig farms (4%). Therefore, compared to BASE, legume share increases more in the south and east, where crop farms are widespread. Legume crops replace mainly temporary grasslands and forage maize. Multi-year rotations with legumes increase in number (+22%).

Compared to BASE, milk production decreases by a mean of 11% (Table 5.1.1) due to a decrease in herd size (-9%) and more extensive milk production. The share of legume-based rations for cows increases (by a mean of +15 percentage points), especially those with alfalfa. This increase is particularly high for Dairy35, with 100% of rations based on legumes (alfalfa or pea). Nonetheless, Dairy35's shift to alfalfa-based rations leads to a decrease in its protein self-sufficiency (-10 percentage points): it purchases large quantities of alfalfa because it does not produce enough of it.

Pig production decreases by 2% at the regional level, with the largest decreases for Pig35 (-18%) and Pig72 (-17%). Almost zero in BASE, the share of legume-based rations for pigs increases slightly (+2 percentage points) at the regional level, with the largest increase for Pig72 (+8 percentage points), whose relatively low stocking rate (36 pig.ha^{-1}) makes it have little need for areas on which to spread manure. Thus, the increase in legume area, which decreases the potential manure-spreading area, is not an issue for Pig72. Unlike for dairy farms, all legumes consumed by pigs are produced on the pig farms themselves. Finally, exports of manure from pig farms decrease by a mean of 5% due to the decrease in pig production.

The increase in the legume share is related to a decrease in purchases of synthetic N fertilizers: -7% at the regional level compared to BASE. Crop farms reduce synthetic N fertilization (-9% applied per ha) due to larger legume shares.

Compared to BASE, profit decreases by 4% at the regional level, with variability among farms. Income per L of milk decreases for most dairy farms, except when the share of legume-based rations exceeds 10% (i.e., for Dairy35, Dairy49, Dairy72 and Dairy85). Thus, a substantial use of legumes as feed can increase dairy incomes. Income per pig decreases for most pig farms, especially for Pig72 (by 6%) due to the legume-based ration, which is less efficient (more feed is needed to produce the same number of pigs). Finally, income per ha decreases by 6% for crop farms, reflecting a loss of crop profitability: with a legume share of 22%, crop farms lose a mean of 43 €.ha^{-1} compared to BASE.

Compared to BASE, SyNB (potential N losses) decreases by 5 kg N.ha^{-1} at the regional level. However, this small improvement hides larger changes at the farm level that offset one another. For example, SyNB decreases for dairy farms and crop farms in almost all sectors due to lower fertilization, but increases for Dairy35 and Crop35 due respectively to a high stocking rate and a large share of legumes (33% of area). SyNB increases slightly (mean = +3 kg N.ha^{-1}) for pig farms, with variability among sectors. SyNE increases slightly (+0.02) at the regional level due to higher SyNE for most dairy farms (mean = +0.02) and crop farms (+0.03). However, SyNE decreases the most for Dairy35 (-0.08) due to the use of alfalfa-based rations, which leads to large purchases of alfalfa, rich in N.

5.1.4.3. LEG10+Ma scenario

In the LEG10+Ma scenario, legume share is also set at 10% of the regional area, but the total amount of manure exchanged at the regional level can freely increase. Compared to LEG10, crop share at the regional level remains the same, but legume shares increase for Pig35 and Pig85 (respectively +19 and +6 percentage points), even though the total areas of these farms decrease (respectively -86% and -74%).

Simultaneously, pig production increases by 2% at the regional level, the opposite of the decrease predicted for LEG10 (Table 5.1.1). This increase is enabled by the increase in manure exports at the regional level, which increase by 22% compared to LEG10, with the largest increases for Pig35 (+469%) and Pig85 (+170%). Milk production increases by a mean of 1% for dairy farms because the share of grass-based rations (which generate lower milk yield) decreases in favor of legume-based rations, whose share remains similar to that in LEG10. The share of legume-based rations decreases slightly for Pig35 and Pig85, as does protein self-sufficiency (respectively -22 and -17 percentage points), due to a large decrease in legume area, which leads to an increase in purchases of crops for feed.

Despite the increase in manure exchanges, purchases of synthetic N fertilizers remain the same at the regional level as in LEG10. Application of synthetic N fertilizers also remains the same at the regional level but decreases for crop farms and dairy farms in sectors 35 and 85, where additional manure imports replace synthetic N fertilizers.

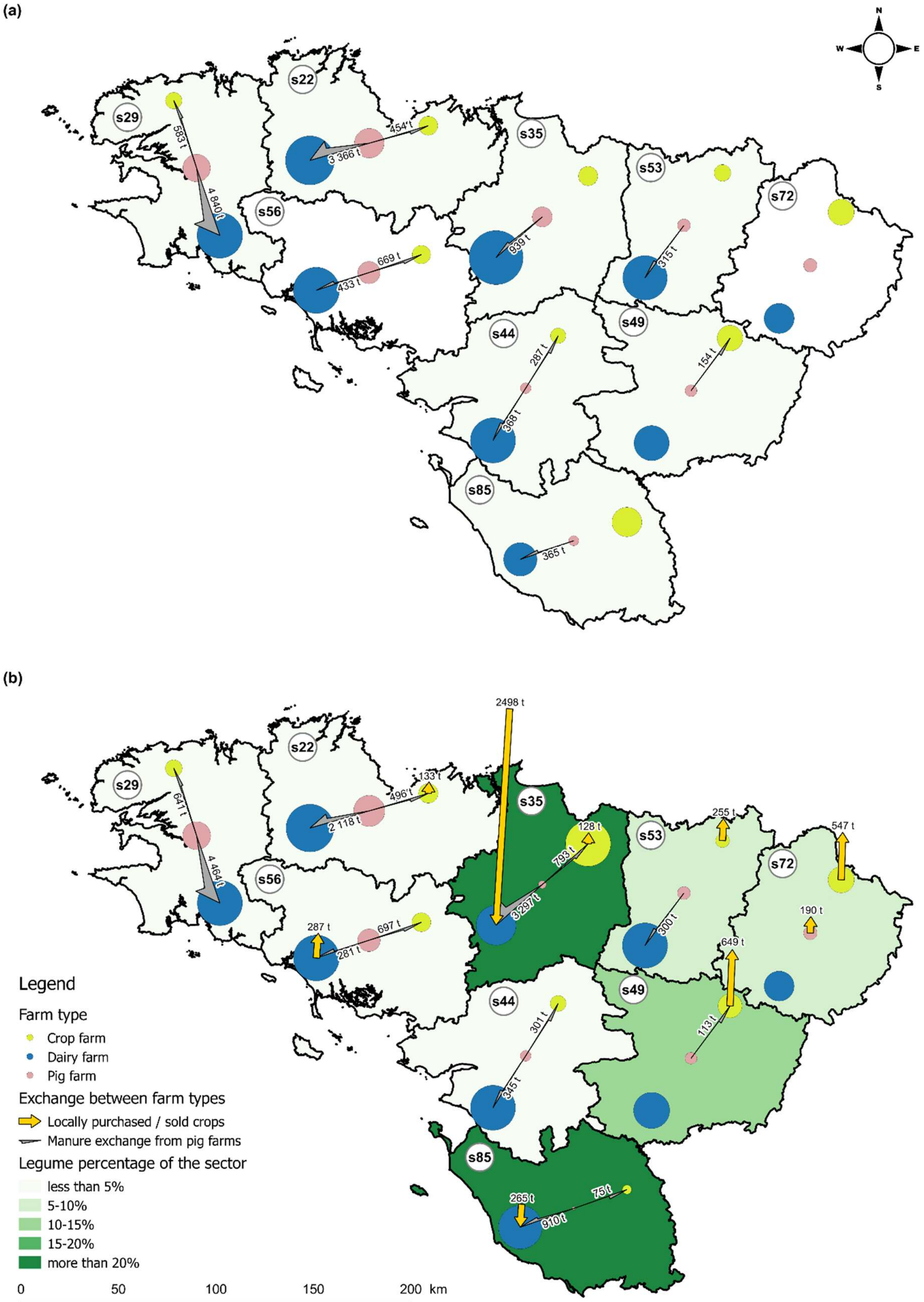
Compared to LEG10, profit increases slightly (+0.4%) at the regional level. Likewise, income per ha increases by a mean of 13 €.ha^{-1} for crop farms because of decreased use of synthetic N fertilizers, but it remains 18 €.ha^{-1} below the income predicted in BASE. The increase in pig production does not increase pig profit: income per pig decreases by a mean of 4%, especially for Pig35 and Pig85 (respectively -35% and -27%), due to the increases in feed expenses and manure exports, which represent additional costs for pig farms.

Compared to LEG10, SyNB remains nearly the same (+2 kg N.ha^{-1}) at the regional level but increases most for Pig35 and Pig85, whose stocking rates increase (respectively +448% and +236%). SyNE remains the same at the regional level but increases for Pig35 (+0.10) and Pig85 (+0.08) because fewer legume-based rations are used and more manure is exported.

5.1.4.4. LEG10+MaC scenario

In the LEG10+MaC scenario, farm-to-farm exchanges of crops (including legumes) become possible. Alfalfa is exchanged locally between farms: 33% of alfalfa produced in the region is sold by several crop farms and pig farms to Dairy35 (Figure 5.1.2). Consequently, purchases of alfalfa on the world market decrease by a mean of 24% compared to LEG10+Ma. Some wheat, maize and rapeseed are also exchanged, but to a lesser extent. Regional protein self-sufficiency increases by 0.02 percentage points compared to LEG10+Ma. Unfortunately, farm-to-farm exchanges are not large enough to influence the other indicators greatly: areas and herd sizes remain nearly the same, as do economic and environmental indicators (Table 5.1.1).

Figure 5.1.2. Exchanges of manure between farms by sector (administrative department) in western France in (a) the baseline scenario and (b) the scenario LEG10+MaC (initial legume area = 10%, and local exchanges of crops are available in addition to manure exchanges).



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Circles are proportional to the area of each farm type in each sector. Arrows of crop exchanges are proportional to the absolute value of the balance "Purchases – Sales" (in t N), (only balances greater than or equal to 125 t N are represented)

Table 5.1.1. Results of the SYNERGY model for the main indicators, by scenario

	Baseline	LEG10	LEG10+Ma	LEG10+MaC
Legume share (input data)	1.5%	10.0%	10.0%	10.0%
Area of farms (ha)				
▪ *Dairy farms*	*1,128,399*	*1,085,642*	*1,087,053*	*1,084,768*
▪ *Pig farms*	*188,735*	*185,847*	*174,325*	*175,030*
▪ *Crop farms*	*239,242*	*284,887*	*294,998*	*296,579*
Milk production (hL)	736,110	656,015	660,548	660,003
Pig production (thousands of head)	12,178	11,915	12,108	12,104
Share of legume-based rations				
▪ *Dairy farms*	*4.8%*	*20.3%*	*20.6%*	*20.5%*
▪ *Pig farms*	*0.4%*	*1.7%*	*1.5%*	*1.4%*
Purchases of synthetic N fertilizers (t N)	121,033	112,720	113,141	112,338
Local exchanges of manure (t N)	12,775	12,199	14,909	14,831
Regional fertilizer self-sufficiency	56.5%	56.5%	56.6%	56.8%
Purchases of crops and concentrate (t N)	199,933	173,580	176,871	173,647
Local exchanges of crops (t N)	-	-	-	2,907
Regional protein self-sufficiency	57.8%	56.2%	55.4%	56.6%
Farm protein self-sufficiency				
▪ *Dairy farms*	*72.4%*	*72.1%*	*71.8%*	*71.8%*
▪ *Pig farms*	*23.7%*	*23.6%*	*21.9%*	*21.9%*
Regional profit (M€)	2,188	2,090	2,098	2,099
Dairy farm income				
▪ *Regional total (k€)*	*1,410,698*	*1,304,664*	*1,314,742*	*1,314,083*
▪ *Per hL of milk (€.hL^{-1})*	*1,916*	*1,989*	*1,990*	*1,991*
Pig farm income				
▪ *Regional total (k€)*	*612,234*	*601,138*	*588,821*	*589,237*
▪ *Per pig (€.pig^{-1})*	*50*	*50*	*49*	*49*
Crop farm income				
▪ *Regional total (k€)*	*164,747*	*184,064*	*194,268*	*195,295*
▪ *Per ha (€.ha^{-1})*	*689*	*646*	*659*	*658*
SyNB (System N Balance, kg N.ha^{-1})				
▪ *Dairy farms*	*122*	*116*	*118*	*117*
▪ *Pig farms*	*267*	*270*	*285*	*284*
▪ *Crop farms*	*93*	*91*	*92*	*93*
SyNE (System N Efficiency, range = 0-1)				
▪ *Dairy farms*	*0.35*	*0.37*	*0.37*	*0.37*
▪ *Pig farms*	*0.41*	*0.40*	*0.40*	*0.40*
▪ *Crop farms*	*0.55*	*0.58*	*0.58*	*0.57*

BASE: baseline. LEG10: Legume area set to 10% of the regional area, and manure exchanges are capped at the regional level. LEG10+Ma: Legume area remains 10%, and manure exchanges can increase. LEG10+MaC: Legume area remains 10%, and local exchanges of crops are available in addition to exchanges of manure that can increase.

5.1.5. Discussion & conclusion

SYNERGY was used to study interactions between specialized farms to highlight potential benefits of complementarities among them at the regional scale. We focused on legume production and how farm-to-farm exchanges of crops and manure can improve environmental and economic results. SYNERGY was applied to western France, a region that specializes in animal production but has a large amount of crop production in the south. In addition to the baseline scenario, three scenarios were analyzed with the regional legume share set to 10%, manure exchanges capped and then uncapped, and then crop exchanges added.

When the legume share is set to 10%, legume production increases more on crop farms than on livestock farms (i.e., dairy and pig farms), but only 25% of the legumes produced are kept to feed livestock. Thus, legumes are more profitable as a final product than as an intermediate one. This result contradicts the study of Schläfke et al. (2014), which showed that grain legumes have more economic potential on dairy farms as on-farm feed than as cash crops. This difference is due to two factors. First, the rotational constraints in SYNERGY limits the legume share on dairy farms: since forages represent a large share of area on dairy farms, legumes have to be included in long rotations with forages, which restrict their share. Indeed, if the rotational constraints are removed, the legume share on dairy farms becomes the same as that on crop farms. Second, application of the Nitrates Directive limits the legume share on pig farms: since spreading manure on legumes is prohibited, increasing the legume share decreases the potential manure-spreading area, which is an issue on pig farms because they produce large quantities of manure. The small share of legumes on pig farms explains the small shift to legume-based rations for pigs. In crop farms, the legume share reaches 22% but they lose a mean of 43 €.ha^{-1}. The opportunity costs of legumes are therefore positive even though the preceding crop effect is integrated. This result differs with the study of Jouan et al. (2019), which found zero or negative opportunity costs at the rotation scale. When the legume share is set to 10%, the environmental indicators SyNE and SyNB improve slightly, largely due to the decrease in use of synthetic N fertilizers. Nonetheless, it is difficult to compare these results to those of another study since no study has analyzed such a large increase in legume share at the regional level. Results for potential N losses are consistent with those of Reckling et al. (2016a) at the cropping-system level, even though the decrease in synthetic N fertilizer they estimated is greater than that in our study. N efficiency improves less in our study than in that of Plaza-Bonilla et al. (2017), partly because SYNERGY does not consider the potential increase in crop yield following a legume. This omission may also explain why SYNERGY predicts a decrease in regional profit and in income per ha for crop farms, while studies at the rotation level show that legumes are usually as profitable as other crops (Preissel et al. 2015).

The total amount of manure exchanged at the regional level is capped at the total amount predicted for BASE.

When the total amount of manure exchanged at the regional level can increase, the legume share increases for farms that can export more manure, since the Nitrates Directive is less binding. However, improvements in the environmental indicators are limited to a rebound effect (Figge and Thorpe 2019): larger farm-to-farm exchanges lead to intensification of production of some farms through an increase in the number of pigs produced per ha. This is consistent with results of Regan et al. (2017), who analyzed case studies of coupling dairy and crop production and observed intensification of production. However, the extreme intensification predicted by SYNERGY is not likely to happen, since high stocking rates on livestock farms require authorization in France, and it is unlikely that such rates would be allowed. Finally, adding local exchanges of crops has little influence on results. Dairy farms in sector 35 purchase alfalfa from other farms in the region, but doing so does not lead to large technical changes. The lower purchase price on the local market is a mechanism that is insufficient to promote legume-based rations in the region.

SYNERGY's main contribution is to address the issue of reclosing the N cycle by going beyond the farm level to highlight complementarities between farms. These complementarities are represented through different types of farms in a region, but the region we studied may be initially too specialized in livestock production for complementarities to become apparent. Therefore, it would be interesting to apply SYNERGY to French regions that are more specialized in crop production and have a larger N deficit. Methodologically, SYNERGY is generalizable and transferable to other geographic levels and other contexts by changing data for farms, crop activities and animal activities. Nonetheless, we considered only conventional production technology for crops. Interesting results may emerge by adding organic production, which prohibits the use of synthetic N fertilizers. Similarly, SYNERGY did not consider grassland associations of legumes and grass, even though they may be a useful tool to increase protein self-sufficiency of dairy farms. Another improvement of the model would be to add other environmental indicators. In particular, it would be more relevant to study nitrous oxide (N_2O), which is emitted in part by the use of synthetic N fertilizers and has a global-warming effect nearly 300 times as large as that of CO_2. Thus, decreasing synthetic N fertilizer use could dramatically reduce agriculture's impact on climate change. Finally, we did not use SYNERGY to test scenarios with different prices or public policies, but it could easily be used to do so. Thus, we did not question how a region could reach a legume share of 10%, but further studies should address it.

By modeling a large share of legume area, SYNERGY highlights multiple issues. First, it shows that promoting manure exchanges can lead to intensification and a slight increase in livestock production. Nonetheless, intensive animal production is increasingly questionable from a societal perspective. It would be interesting to study a scenario in which animal production cannot increase or even decreases, which would correspond to an external “shock” in consumer preferences. In this case, manure exchanges could represent a promising mechanism to improve environmental indicators. Second, even with large legume share in the region, soybean-based rations remain dominant; thus, it is still more profitable to produce milk and meat with soybean meal. However, the emerging market of GMO-free food may represent an opportunity for use of legumes in feed: it could create added value for milk and meat produced from animals fed locally produced legumes instead of imported soybean meal. However, the booming demand for vegetarian food strongly competes for the use of legumes. Indeed, legumes for human consumption often have a higher economic value than those for feed, which further limits the use of legumes in feed. Finally, the small improvements in environmental indicators raise questions about the utility of closing the N cycle by reconnecting animal production and feed production geographically. Feeding livestock locally produced crops may be less N efficient, but relying on ultra-optimized rations with imported feed (e.g., soybean meal produced in South America) may support deforestation. This dilemma reflects the many paths that agriculture can follow between agroecology and agro-industry.

5.1.6. Appendices

Appendix 5.1.A. Sources of the input data used in the SYNERGY model for the western France case study

Module	Data	Source
Selling price	FranceAgriMer, IDELE[a]	Selling price
Animal	Milk and meat yields and qualities	INOSYS Réseaux d'élevage[b], IFIP[c]
	Operating costs (insemination, vet)	INOSYS Réseaux d'élevage, IFIP
Cropping	Crop yields	FranceAgriMer
	Operating costs (seeds, pesticides)	Regional extension services, PEREL[d]
	Purchase price	IFIP
	Selling price	FranceAgriMer
Feeding	Standard and alternative dairy feed rations	IDELE, INRAtion software
	Standard and alternative pig feed rations	IFIP, Porfal© software
Fertilization	Need for fertilization (nitrogen)	COMIFER
	Quantity of nitrogen produced by animals	RMT livestock and environment (CORPEN)
	Calculation of nitrogen balance	COMIFER

[a] IDELE is the French Livestock Institute; [b]Inosys-Réseaux d'élevage, associated with IDELE, produces reference data for herbivore breeding systems and builds test case-studies of livestock management systems; [c] IFIP is the French Pig Research Institute; [d] PEREL is a tool to foster forage self-sufficiency

Appendix 5.1.B. Example of ration compositions used in the SYNERGY model. Dairy cow rations are based on forage maize; synthetic amino acids in rations are not included.

Ration	Forage	Crops (except legumes)	Legumes	Concentrate feeds
dairy cow_ soybean	76%	10%	0%	14%[a]
dairy cow_ faba	62%	9%	29%	0%
dairy cow_ pea	60%	9%	28%	4%[b]
dairy cow_ alfalfa	56%	10%	33%	1%[b]
Pig_soybean	0%	91%	0%	8%[a]
Pig_pea&faba	0%	82%	15%	3%[b]

[a] soybean meal; [b] rapeseed meal

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5.2. Data paper

5.2.1. Introduction

SYNERGY is a bio-economic model built to study crop-livestock technical complementarities beyond the farm scale (Jouan et al. in review). Technical complementarities are positive interactions between different types of agricultural production. If an increase in the supply of one output increases marginal input productivities[7] in the production of another, then the two types of production are technically complementary. SYNERGY focuses on technical complementarity related to legume production. The main advantage of legumes lies in their ability to fix atmospheric N, which is the source of joint production of N-rich crops and N for intercrops or subsequent crops. Thus, technical complementarities can appear between legumes and intercrops or subsequent crops: increased legume production can decrease the production cost of the subsequent crop. Technical complementarities can also appear between legumes and livestock: these crops can be introduced into rations and thus decrease the cost of N-rich feed (Schneider and Huyghe 2015).

SYNERGY assesses economic, technical and environmental impacts of producing legumes (e.g., faba bean, pea, alfalfa) on farms as final or intermediate goods (i.e., in livestock feed). To do so, it represents specialized farm types (dairy, pig and crop) in a region and models exchanges of crops (including legumes) and manure between them. As a bio-economic model, SYNERGY relies on an objective function that maximizes farmers' profit at the regional scale under resource and production constraints. It yields an optimal allocation in which the UAA, crop production, and livestock production of each farm type are defined.

SYNERGY was applied to a specific region – western France – which corresponds to two European Union (EU) NUTS 2 sub-regions, Pays de la Loire and Brittany (Appendix E). We decided to design this model for western France because it contains large percentages of French livestock production (68% of pigs and 38% of dairy cows), despite containing only 14% of France's UAA (French Ministry of Agriculture 2018a). Thus, 85% of western France's UAA is occupied by farms oriented to livestock production, especially in Brittany (French Ministry of Agriculture 2018b). In contrast, farms in the Pays de la Loire are more mixed, with a higher percentage of crop production (Draaf Bretagne 2019; Draaf Pays de la Loire 2019). Western

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[7] "Marginal productivity" of an input refers to the additional output gained by adding one unit of this specific input, all other inputs held constant.

France has an oceanic climate. Its crop production is divided mainly between pastures (38% of UAA) and field crops, especially wheat.

To study technical complementarities between crop and livestock production in western France, technical coefficients were generated from a wide variety of data: they represent the quantity of inputs needed to produce outputs (e.g., the quantity of N needed per ha to produce wheat). The data are either used directly in SYNERGY's optimization step (and thus considered inputs) or used in a second step, once the model has found an optimal solution. In the latter case, they used to generate additional results from model outputs (e.g., to estimate environmental impacts of land-use and production choices on the N cycle). This paper aims to present these data, their sources and how they were connected to be used in the model.

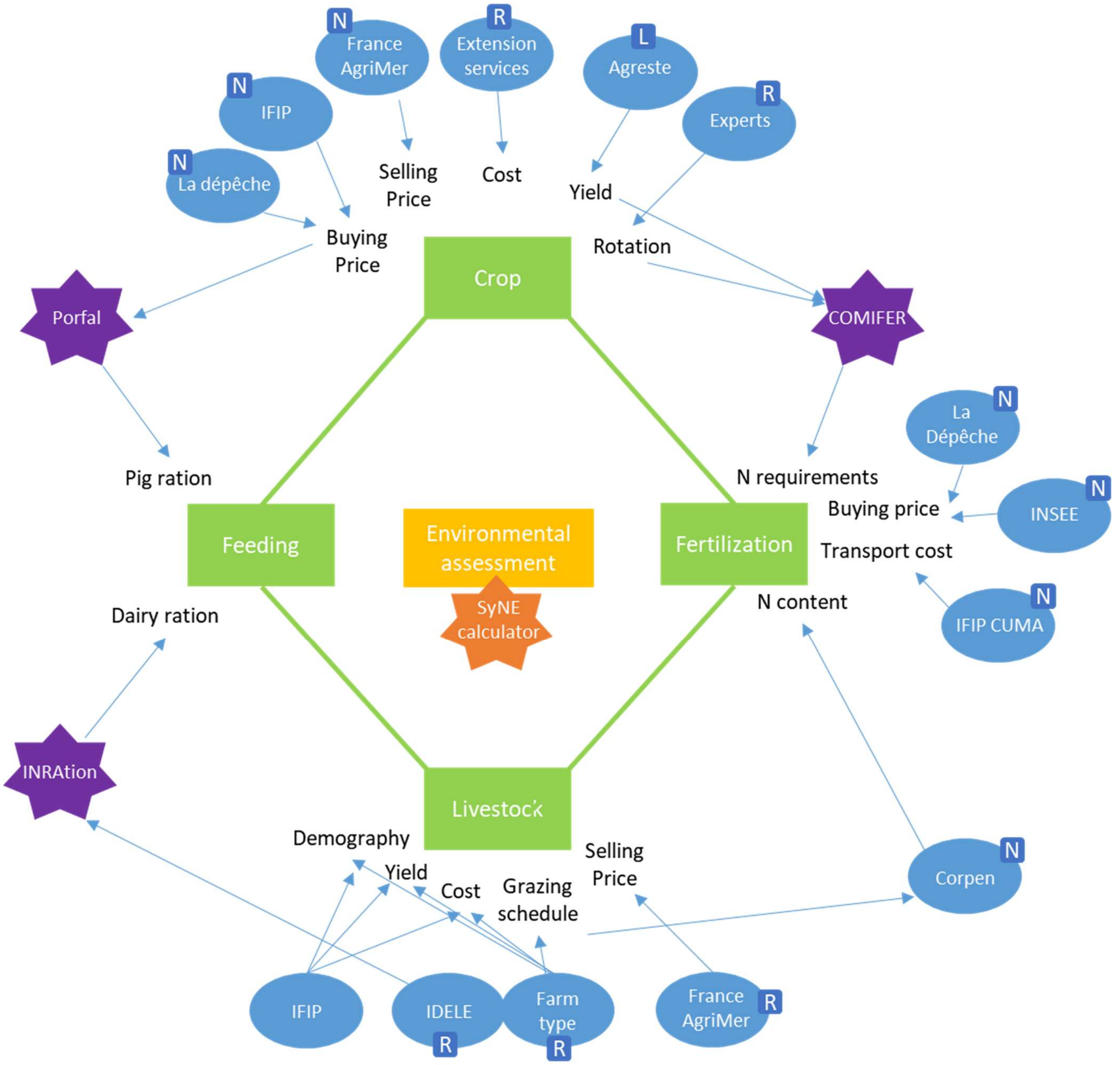
5.2.2. Overview of the data and their sources

Technical complementarities between crop and livestock appear through two main vectors: livestock feed (since some crops can be used to feed livestock) and fertilization (since livestock manure can be used to fertilize crops). Thus, to study these complementarities, it was necessary to collect data in four domains (hereafter, "modules"): crops, livestock, feed and fertilization. These types of data were used as inputs in SYNERGY. In addition, environmental impacts are estimated using indicators of N-use efficiency and N balance (SyNE and SyNB, respectively; Godinot et al., 2014), which were encoded directly in SYNERGY. They represent additional results that are calculated from outputs of the optimal solution, combined with additional data required to calculate the N balance (see section 5.2.4).

The data we used to implement SYNERGY were either secondary data collected from a variety of sources or primary data generated for the study using different tools (Figure 5.2.1). Data can also be differentiated by their scale: when possible, local data (i.e., administrative department) were collected to represent characteristics of the region as accurately as possible. Otherwise, data were regional or national. The collection and generation of data represented ca. 1 year of work due to the research for data sources, as well as the diversity of crops and livestock studied: for example, each set of crop data (e.g., mean yield) was collected for 11 crops. In addition, to improve the robustness of data, 5-year means were calculated for yields, costs and prices. Appendix G describes the data used to generate SYNERGY's technical coefficients and their sources.

One essential part of data collection was to differentiate feed cost by feed origin. For on-farm feed (i.e., cash crops and forage produced on livestock farms and fed directly to livestock), feed cost corresponds to production costs. For feed bought on the global market (e.g., cash crops, meals), feed cost corresponds to purchase costs. Since these costs were not available in public databases, they were collected from livestock technical institutes (IDELE 2016; IFIP 2017) and from a professional journal specialized in agricultural markets (La Dépêche - Le Petit Meunier 2018). Finally, feed produced on crop farms and sold to livestock farms in the same region costs 10% less than feed bought on the global market, to represent lower transport costs. This difference in cost was defined using data from La Dépêche - Le Petit Meunier (2018). Due to the journal's privacy policy, these data cannot be detailed here.

Figure 5.2.1. Overview of the main types of data and their sources used to study technical complementarities of crop and livestock production with the bio-economic model SYNERGY



Green boxes: modules of the SYNERGY model that use input data; yellow box: module performing post-optimization environmental assessment using the encoded SyNE and SyNB indicators (Godinot et al. 2014; Carof and Godinot 2018); blue circles: source of secondary data; purple stars: biotechnical simulators or calculation methods to generate primary data; L: local data (i.e., at the scale of administrative departments); R: regional data; N: national data.

5.2.3. Inclusion of legume data

Since this study focuses on legumes to enhance crop-livestock technical complementarities, it was important to represent the joint production of these crops: N-rich crops for feeding and N for fertilization of subsequent crops. A set of rotations, with and without legumes, was defined. Defining each crop within each rotation made it possible to differentiate expected yields and N requirements using a simplification of the COMIFER method (COMIFER 2011). In total, 26 of the 53 rotations defined contained legumes. N-rich crops were introduced as livestock feed in legume-based rations, which were built from standard rations using two tools: Porfal for pig rations (IFIP 2018) and INRAtion® for dairy cow rations (INRA 2003). Porfal generated standard and legume-based pig rations that fulfil nutritional requirements at the lowest cost. In comparison, standard dairy cow rations were based on IDELE rations that differed in the main forage ingredient (i.e., forage maize, forage grass or both). Legume-based dairy rations were then generated by replacing soybean meal with legumes (here, pea, faba bean, dehydrated alfalfa) using INRAtion®. If legumes could not replace all soybean meal due to nutritional constraints, some rapeseed meal was added. In total, 15 of the 20 rations for dairy cows and 1 of the 2 rations for pigs used in the model were legume-based.

5.2.4. Calculation of the SyNE and SyNB environmental indicators,

SYNERGY calculated two environmental indicators, SyNE and SyNB (Godinot et al., 2014). In brief, SyNE estimates N-use efficiency of a farming system (i.e., the extent to which N inputs of a farming system are converted into N outputs). In comparison, SyNB estimates potential N losses from a farming system (i.e., the sum of N inputs, N losses during production and transport of inputs, and change in soil N, minus N outputs). We encoded equations to calculate SyNE and SyNB in SYNERGY and collected data for them. Most of the data came from Godinot et al. (2014) and the SyNE calculator (Carof and Godinot 2018). However, additional work was performed to include products that were not present in the SyNE calculator, such as faba bean and pigs.

5.2.5. References

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Chapter 6.

Legume production and use in feed: analysis of levers to improve protein self-sufficiency from foresight scenarios

This chapter goes beyond the regional scale and looks at the influence of markets and food labelling in the production of legumes and their use in feed. Indeed, this chapter aims to define and assess levers to increase protein self-sufficiency in western France. To do so, I supervised a regional foresight, defining such innovative levers, in relation to legume production. One of the main lever identified was an increased in the demand for products from labeled agro-food chains, such as GMO-free animal products. In comparison, I also studied another lever: an increase in coupled support for legumes. To assess economic and environmental impacts of these levers, I developed a modeling framework. It combines a Computable Generale Equilibrium model and the regional model SYNERGY. Results showed that an increase in coupled support for legumes leads to an increase in legume production, but has no influence on protein self-sufficiency or other indicators, since legumes are not used in greater amounts in feed. When the demand for GMO-free animal products increases, the production of legumes, including multispecies grassland, increases substantially, and most livestock are fed legumes. However, on pig farms, protein self-sufficiency decreases because legume production does not meet the quantity needed by pig rations. Local exchange of crops between farms was limited. Regional profit increases, but environmental indicators do not improve, in part due to the increase in legume imports from outside western France. In such a highly specialized region, improvement in protein self-sufficiency seems relatively limited, and a decrease in livestock production should be considered to meet this objective and improve environmental results.

This chapter was co-written with Aude Ridier and Matthieu Carof. Claire Caraes performed the foresight under my co-supervision. This chapter is the basis of an article that will be submitted to Journal of Cleaner Production.

6.1. Introduction

The European Union (EU) relies on imports to feed its livestock due to a deficit in protein-rich feed, containing more than 15% protein. The self-sufficiency in protein for feed, defined as the ratio of protein produced to total protein consumed, reaches 79% in the EU, but the self-sufficiency in protein-rich feed reaches only 45% (European Commission 2019). Overall, 81% of EU imports of protein-rich feed are soybean meal, most of it genetically modified (ISAAA 2018; European Commission 2019). This situation raises questions about consumer expectations for GMO-free products (Boecker et al. 2008) and the EU security of supply (Gale et al. 2014). In addition, the recent concept of “imported deforestation” highlights environmental damages of soybean production in certain countries (Pendrill et al. 2019).

In this context, the Common Agricultural Policy (CAP), within the EU Protein Plan 2014, aims to improve the EU’s self-sufficiency in protein for feed by developing domestic legume production (e.g., faba bean, pea, soybean). The main interest of legumes lies in their ability to fix atmospheric nitrogen (N), which provides joint production of N-rich crops used for feed and food, and N as an input for subsequent crops. To increase legume production, the EU established several policies, such as the ability for member states to implement Voluntary Coupled Support (VCS) for legumes or to include them in Ecological Focus Areas. Following these reforms, the areas of sole-crop legumes increased by 88% from 2013-2018, reaching 4% of Europe’s utilized agricultural area (UAA) (Eurostat 2017). Nonetheless, EU self-sufficiency in protein-rich feed increased by only 4 percentage points during the same period.

Indeed, legumes for feed suffer from a double issue of economic attractiveness in the EU. On the supply side, their lower profitability in the short term than that of other crops limits their introduction on farms, even though their opportunity costs at the rotation scale can be zero or negative (Preissel et al. 2015; Jouan et al. 2019). On the demand side, their high substitutability with other protein-rich feeds, such as imported soybean meal, limits their incorporation into rations (Meynard et al. 2018). At the junction of supply and demand, legumes also have high transaction costs and experience a lock-in situation, favoring the development of a few main crops (e.g., wheat, maize, rapeseed) (Magrini et al. 2016; Jouan et al. 2019). Innovative solutions that improve the attractiveness of legumes must be developed to increase their use in animal feed in the EU and thus reduce reliance on imported protein-rich feed.

Foresights are systematic, participatory and multi-disciplinary approaches to explore futures and drivers of change through the use of scenarios (FTP 2014). Consequently, foresights can identify assets and constraints related to innovative solutions. However, few foresight studies have been performed in the agricultural sector (Gómez-Limón et al. 2009). Recent foresights on agriculture have considered legume production by studying either new market equilibria or development of agroecology (Le Mouël et al. 2018; Poux and Aubert 2019). The foresight of Uthayakumar et al. (2019) focuses on legumes, but more on their outlets in food than in feed. In addition, a complementary approach is to combine foresight studies with models to quantify the changes defined (van Vliet and Verburg 2012; Le Mouël et al. 2018; Poux and Aubert 2019). Such models, usually based on biomass balances, are adapted to the large scales of these foresights (e.g., European, global) and to the many changes implied in the scenarios defined. Nonetheless, they fail to consider the diversity of agricultural systems and technologies in detail or the heterogeneity of agricultural regions in the EU. Indeed, some European regions have specific types of agricultural production due to the processes of specialization and concentration of agricultural production (Chavas 2008). For example, western France (i.e., Brittany and Pays de la Loire regions) has a high density of animal production; due to the large number of animals compared to the regional UAA that can provide feed, the issue of protein self-sufficiency is even more critical there.

The aim of our study was to define levers to increase protein self-sufficiency in western France, without decreasing agricultural profitability but reducing negative environmental impacts of agricultural production. Local production of legumes, and their use in feed, is seen as one promising tool. A regional foresight called "TERUnic foresight" was performed to define innovative levers for legume production, which could improve protein self-sufficiency. It brings together many stakeholders from the many types of agricultural production of the region (e.g., farmers, cooperative managers). Then, a modeling framework was developed to estimate economic and environmental impacts of levers identified during the foresight analysis. This modeling framework combines a Computable Generale Equilibrium (CGE) model (Gohin et al. 2016) with the detailed regional-supply bio-economic model SYNERGY (Jouan et al. in review). In this way, the macro-economic effects calculated by the CGE model are used in SYNERGY, which performs detailed assessment at the regional scale (western France).

6.2. Method

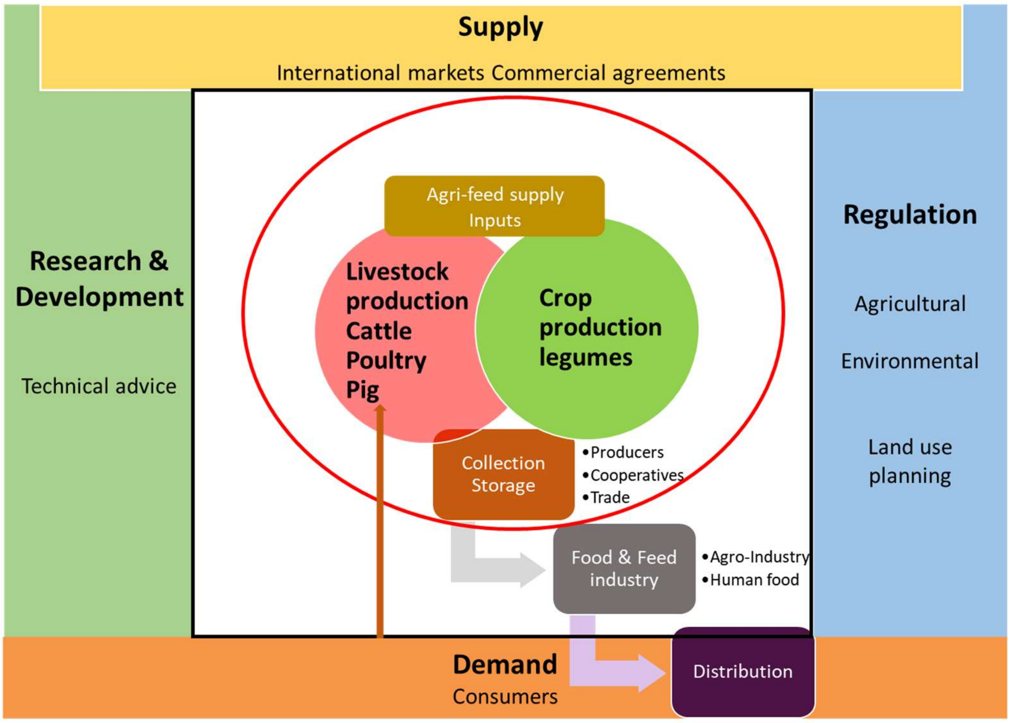
6.2.1. Regional foresight

Foresights aim to open the field of possibilities by developing scenarios, without prejudging their probable or desirable nature (Sebillotte et al. 2003). In the French approach, foresight is a participative and volunteer approach that relies on a group of experts to combine their diverse skills (Jouvenel 2004). The TERUnic foresight is based on a method commonly used for foresights in the agricultural sector in France: the SYSPAHMM method (Sebillotte and Sebillotte 2010). However, we reorganized the four steps of the original method into three steps, as detailed below. This three-step approach of the SYSPAHMM method, already implemented in a recent foresight (Aigrain et al. 2019), makes it possible to study contrasting scenarios that represent different evolutions of protein self-sufficiency.

6.2.1.1. Definition of study boundaries and representation of the system

The first step consisted of setting boundaries to the study, the time horizon and the structural trends (i.e., slow changes, observable over a long period and subject to strong inertia (Gaudin 2005)). The study of self-sufficiency in protein was restricted to dairy, beef, pig, and poultry sectors, under conventional and organic farming, in western France. Crop production is also included, with a focus on legumes. The time horizon chosen – 2040 – was a compromise reached by the stakeholders, which allows for sufficiently solid forecast of events, while avoiding those in the near future, such as the reform of the CAP or pre-existing innovations. The structural trends defined were climate change, an increase in human population, an increase in fossil fuel prices and stricter regulation of pesticides. Based on these elements, we defined the boundaries of the system (Figure 6.1) and set up the panel of 30 stakeholders (Appendix 6.A).

Figure 6.1. Boundaries of the system in the TERUnic foresight



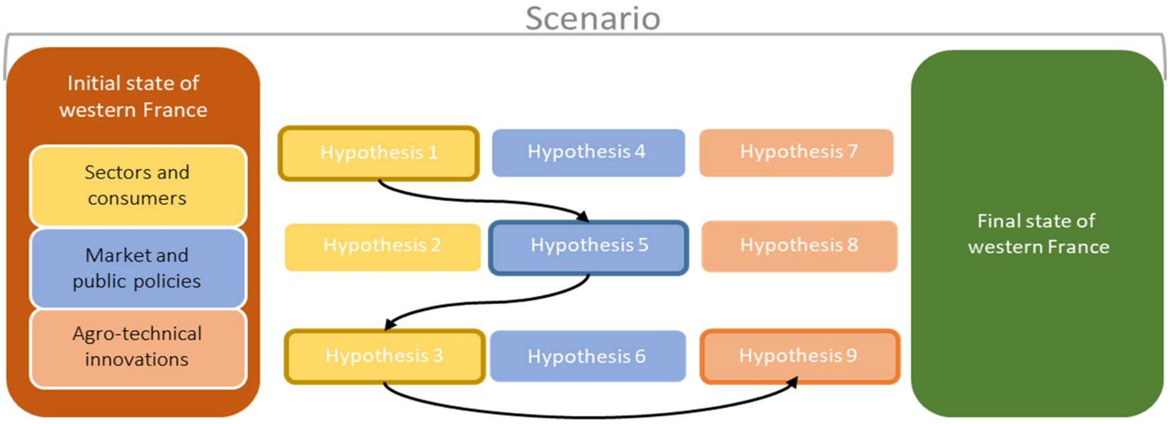
6.2.1.2. Definition of final states and hypothesis through a participatory approach

The second step consisted of defining the final states and formulating hypotheses (i.e., a short sentence that expresses an action likely to influence the trajectory of the system considered and whose inverse can also be expressed (FranceAgriMer 2018)). To this end, a first focus group was organized for half a day with most stakeholders on the panel. During this focus group, three distinct final states out of four that we had proposed were chosen. The three final states chosen were then defined using keywords (3 keywords per stakeholder). Then, for two months after this focus group, individual semi-structured interviews were held with a larger group of stakeholders to encompass the diversity of production types, sectors and stakeholders in the region (Appendix 6.A). Interview responses enabled us to identify the main obstacles and levers for protein self-sufficiency and to define hypotheses. After these interviews, we collected a pool of 64 hypotheses and classified them in three dimensions that correspond to three types of determinants influencing protein self-sufficiency: (i) agro-technical innovations, (ii) markets and public policies, and (iii) organization of the sectors and consumers' behavior.

6.2.1.3. Design of scenarios

The third step consisted of analyzing and connecting the hypotheses to shape different paths and design scenarios. To this end, a second focus group was organized with most stakeholders from the first one. The stakeholders were grouped in several roundtable discussions to bring together experts from different agricultural production types and organizations. In each roundtable discussion, one scenario had to be designed based on the pool of hypotheses classified in the three dimensions. Then, based on this work, we defined the final version of scenarios (Figure 6.2). These consistent combinations make it possible to explain the multiple steps leading to different final states of the system considered in 2040.

Figure 6.2. General principle of scenario design in TERUnic Foresight



6.2.2. The modeling framework

6.2.2.1. Overview of the CGE model used

The CGE model is based on the standard global trade analysis project (GTAP)-Agr model, containing social accounting matrices (i.e., matrices representing flows of economic transactions between economic agents) for many countries (Keeney and Hertel 2005). It was first adapted to analyze the agricultural and agro-food sector in France (Gohin et al. 2016). The CGE model represents firms' behavior in terms of supply of products, demand for inputs and use of factors (i.e., capital, labor or land for the agriculture sector) and household behavior in terms of final consumption of products and investment in enterprises. These behaviors depend on prices, technical and budgetary constraints, regulatory constraints and taxes or subsidies. Producers maximize their profits under the constraint of a production function, while consumers maximize their utility under budgetary constraints.

For this study, an updated social accounting matrix was built for the French economy, based on the method of Gohin et al. (2016). This matrix describes 26 agricultural products and 19 products from the agro-food industry. In particular, it was improved and specifically detailed by making the distinction between a GMO or non-GMO origin for certain products in agriculture and agro-food activities, whether they are produced, traded or consumed domestically. Since few data on products from animals fed with or without GMOs are available, the study of Tillie and Rodríguez-Cerezo (2015) was used to fill the social accounting matrix and to make assumptions about the quantities and prices of GMO-free products. The potential substitution between legumes and animal products to supply protein in food is not considered. Exchanges between western France and the "rest of the world" are made through export and import demand functions. Price elasticities are obtained from both the social accounting matrix and previous studies (e.g., Gohin (2009); Gohin et al. (2015)). The model is calibrated to reproduce the initial situation observed in 2011, which is the most recent year with complete data.

The CGE assessed four types of impacts: (i) those on crop and livestock production (ii) those on intermediate and final consumption of crop and animal products by firms and households, (iii) those on imports and exports of France and (iv) macroeconomic impacts such as labor demand and added-value. In addition, the CGE model also provides equilibrium prices for agricultural and agro-food products; these endogenous prices vary depending on the simulation.

6.2.2.2. Overview of the SYNERGY model used

The bio-economic model SYNERGY is a static non-linear programming model (Jouan et al. in review). It represents the supply of agricultural products focused on three specialized farm types (dairy cow, pig and crop) in western France. This region is divided into several sectors, corresponding to administrative departments, to consider the variety of soil and climate conditions. In each sector, the total area allocated to each farm type may change, as may animal numbers and land use within each farm type. SYNERGY's main originality lies in its ability to represent farm-to-farm exchanges of intermediate products (manure and crops), which occur on a local market (i.e., intra-sector for manure or intra-region for crops). In addition to this local market, exchanges can occur with the rest of the world (i.e., rest of France and other countries) at exogenous prices (see section 5.2 for a description of the data sample). However, although exogenous, these selling and buying prices can vary depending on the simulation of the CGE model (see section 6.2.2.3).

To the previous version of SYNERGY (Jouan et al. in review), a new crop, and its corresponding rotations and rations, was added: multispecies grassland (i.e., temporary grassland with 30% clover by cover). SYNERGY now includes 60 rotations and 12 crops. In addition, another feed was added: GMO-free soybean meal. Thus, two soybean meals are now available: a GMO-free version, produced in the rest of France, and a conventional version, imported from the rest of the world. It is assumed that soybean is not produced in western France, since only very early varieties are adapted to the hottest parts of this region (Terres Inovia 2017). GMO-free soybean meal is assumed to cost 80 €.t^{-1} more than conventional soybean meal (Feedsim Avenir 2019). Overall, GMO-free animal products come from animals fed rations containing GMO-free (i) soybean meal or (ii) other legumes (i.e., peas, faba beans, dehydrated alfalfa or multispecies grassland) (hereafter called "legume-based rations"). SYNERGY now includes 25 potential rations for dairy production and 2 potential rations for pig production.

The model is calibrated to reproduce the mean of observed crop areas and animal numbers in western France for the period 2013-2017. The initial area of each legume (i.e., alfalfa, faba bean and peas) was arbitrarily set at 0.5% of the area of each farm in each sector, thus covering a total of 1.5% of the area of each farm in each sector. Multispecies grassland was set at 15% of the total area of temporary grassland on dairy farms.

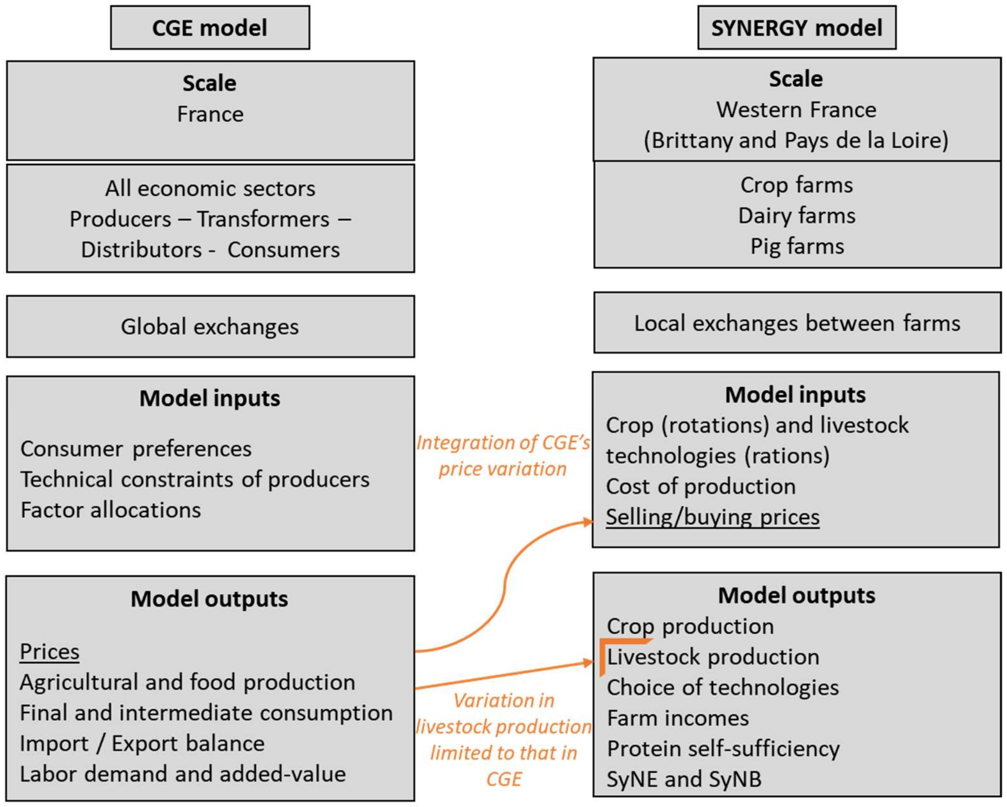
SYNERGY generates four types of indicators: (i) structural (e.g., crop areas, numbers of animals), (ii) economic (e.g., regional profit, farm profit, level of farm-to-farm exchanges), (iii) technical (e.g., protein self-sufficiency, application of N fertilizers) and (iv) environmental. SyNE (range = 0-1) assesses the efficiency with which agricultural systems transform N inputs into desired agricultural products and SyNB (kg $N.ha^{-1}$) reflects potential N losses from agricultural systems, including those during production of inputs (Godinot et al. 2014). All indicators are provided for each farm type at the sector scale and at the regional scale (average weighted by area), as well as at the regional scale, all types of farms combined average weighted by area).

Finally, one innovative feature of SYNERGY is to calculate protein self-sufficiency at the regional scale. Indeed, increased protein self-sufficiency at the farm scale can be low due to high numbers of animals relative to the available farm area. However, since SYNERGY can represent farm-to-farm exchanges, livestock farms can buy crops, such as legumes, from crop farms. In this case, protein self-sufficiency at the farm scale is constant, but that at the regional scale increases since less protein-rich feed is bought from the rest of the world.

6.2.2.3. Coupling the CGE model and SYNERGY

As mentioned, the CGE model provides endogenous prices for agricultural and agro-food products, which vary depending on the simulation. SYNERGY then uses these variations in prices: selling prices of outputs (e.g., milk) and buying prices of inputs (e.g., GMO-free soybean meal) (Figure 6.3). In addition, since the CGE model considers investment cost and labor demand, while SYNERGY does not, it was decided to limit the increase in livestock production in SYNERGY to the same range of variation as that observed in the CGE model.

Figure 6.3. Summary of CGE and SYNERGY models and their connections



6.3. Results

6.3.1. Results of the TERUnic foresight

6.3.1.1. Description of the three scenarios

The three scenarios defined by the stakeholders are the following:

- Scenario 1 ("Regional specialization and economies of scale") considers a decrease in protein self-sufficiency in western France by 2040. Consumption of labeled products has not developed. Specialization in livestock production and international competition has increased. Plant breeding of legume crops is limited, and the level of technical lock-in in legume storage and processing remains high.
- Scenario 2 ("Development of local agro-food chain") considers a moderate increase in protein self-sufficiency in western France by 2040. Consumers prefer products from labeled agro-food chains. Plant breeding of legume crops is strengthened, and cooperatives develop storage tools for them. Current CAP incentives such as VCS are maintained and adapted to local contexts.
- Scenario 3 ("Environment, complementarity and economies of scope") considers a huge increase in protein self-sufficiency in western France by 2040. Consumers prefer products

from labeled agro-food chains that protect the environment. Agricultural policy is driven by environmental goals. Strict regulations on the environment and animal welfare are implemented. Farms are less specialized, and the number of animals raised within the region decreases substantially. Agro-technical innovations have increased the use of legumes.

A detailed description of the three scenarios is available in Appendix H and in the study of Caraes (2018).

6.3.1.2. From scenarios to levers: modeling choices

Each scenario includes multiple levers, and simulating all of them simultaneously can make the results of economic models complex and confusing. Thus, we simulated only the main lever of scenarios 2 and 3, in which protein self-sufficiency increases: the demand for products from labeled agro-food chains. We chose to examine this lever by focusing on GMO-free animal products, since "GMO-free" was one of the main labels identified by stakeholders. Thus, the lever called "Le_GMO" is represented as an increase in demand for GMO-free animal products (by 50% for pork and 25% for milk and beef compared to the baseline situation (BASE)). This increase is introduced in the CGE model, which predicts variations in prices of inputs and outputs that are then used in SYNERGY (Table 6.1). The increase in livestock production was limited to the same variation as that in the CGE model: +2.5% for milk production and +1% for pig production.

Table 6.1. Increase in demand for GMO-free animal products in in the CGE model and the corresponding simulated variations in prices in in the SYNERGY model

Product	CGE model Increase in demand	SYNERGY model Variation in prices
GMO-free milk	+50%	7%
GMO-free beef	+50%	0%
GMO-free pork	+100%	7%
Conventional milk		-5%
Conventional beef		-3%
Conventional pork		0%
GMO-free soybean meal		16%
Conventional soybean meal		-1%

In addition, we studied another lever ("Le_SU"), which is represented as an increase in coupled support for legumes. Coupled support is set at 200 €.ha^{-1} for grain legumes (i.e., peas and faba beans), which is twice its minimum current value and corresponds to a 46% increase in the value of coupled support already set in BASE. A similar increase is set for alfalfa, leading to a coupled support of 182 €.ha^{-1} for this crop. In a first step, only this increase in coupled support is used in the CGE model, which decreases the price of legumes by 2%. In a second step, both this variation in price and the change in coupled support are used in SYNERGY.

6.3.2. Results of the modeling framework

6.3.2.1. Baseline situation (BASE)

Dairy farms cover 73% of the regional area (Table 6.2). Legumes as sole crops (alfalfa, faba bean, pea) cover 1.5% of the area of each farm in each sector, and multispecies grassland covers 15% of temporary grasslands of dairy farms. When multispecies grassland is recorded as "legume", the total percentage of legumes in the region reaches 5.1%. In addition, the percentage of multispecies grassland is higher in sectors where temporary grassland areas are higher, which corresponds to the northwestern part of the region (sectors s22, s29, s35, s44 and s56; Figure 6.4). Temporary pure grasslands, permanent grasslands and forage maize cover 50% of the regional area, while wheat covers 21% of the regional area.

The percentage of legume-based rations is low on pig farms (0.4% of pigs are fed legumes) but much larger on dairy farms (20.6% of dairy cows) because of rations based on multispecies grasslands. This percentage of legume-based rations is similar among dairy farms, except for dairy farms in sector 72 ("Dairy72"), where it is substantially lower (9.2%) due to less area of temporary grassland set after calibration, and thus less area of multispecies grassland. Protein self-sufficiency at the regional scale reaches 59%, with huge differences among farm types: on average, 74% for dairy farms and 24% for pig farms. In 8 of the 9 sectors, pig farms export their manure, mainly to dairy farms. There are no local exchanges of crops. Dairy farms generate 65% of regional profit, even though the profit per ha is higher on pig farms (3 342 €.ha^{-1}).

At the regional scale, for all farms, potential N losses (SyNB indicator) reach 127 kg N.ha^{-1}, and N efficiency (SyNE indicator) reaches 0.41, on average. For dairy farms, potential N losses differ greatly (53 kg N.ha^{-1}) between Dairy35 (84 kg N.ha^{-1}) and Dairy29 (137 kg N.ha^{-1}) due lower input of N fertilizer and N-efficient dairy cow rations on the former (Table 6.2).

6.3.2.2. Lever "Coupled support for legumes" (Le_SU)

When coupled support for legumes is set at 200 €.ha^{-1} for faba beans and peas and 182 €.ha^{-1} for alfalfa, the total area of these legumes increases by 13% at the regional scale, compared to BASE (Table 6.2). This increase is particularly high on crop farms (+33%, on average). However, since the percentage of legume area in the region is small in BASE (i.e., only 1.5 % of the regional UAA), this substantial increase does not lead to a high percentage of legume in

“Le_SU” (only 1.7%). In addition, when multispecies grassland is recorded as “legume”, the overall increase in legumes is more moderate (+3%): since the multispecies grassland is not subsidized, its area decreases by 1%, and the total percentage of legumes including multispecies grassland remains constant. There are no substantial impacts on livestock production, since the percentage of animals fed legumes does not change. The other indicators remain constant.

6.3.2.3. Lever “Increased demand for GMO-free animal products” (Le_GMO)

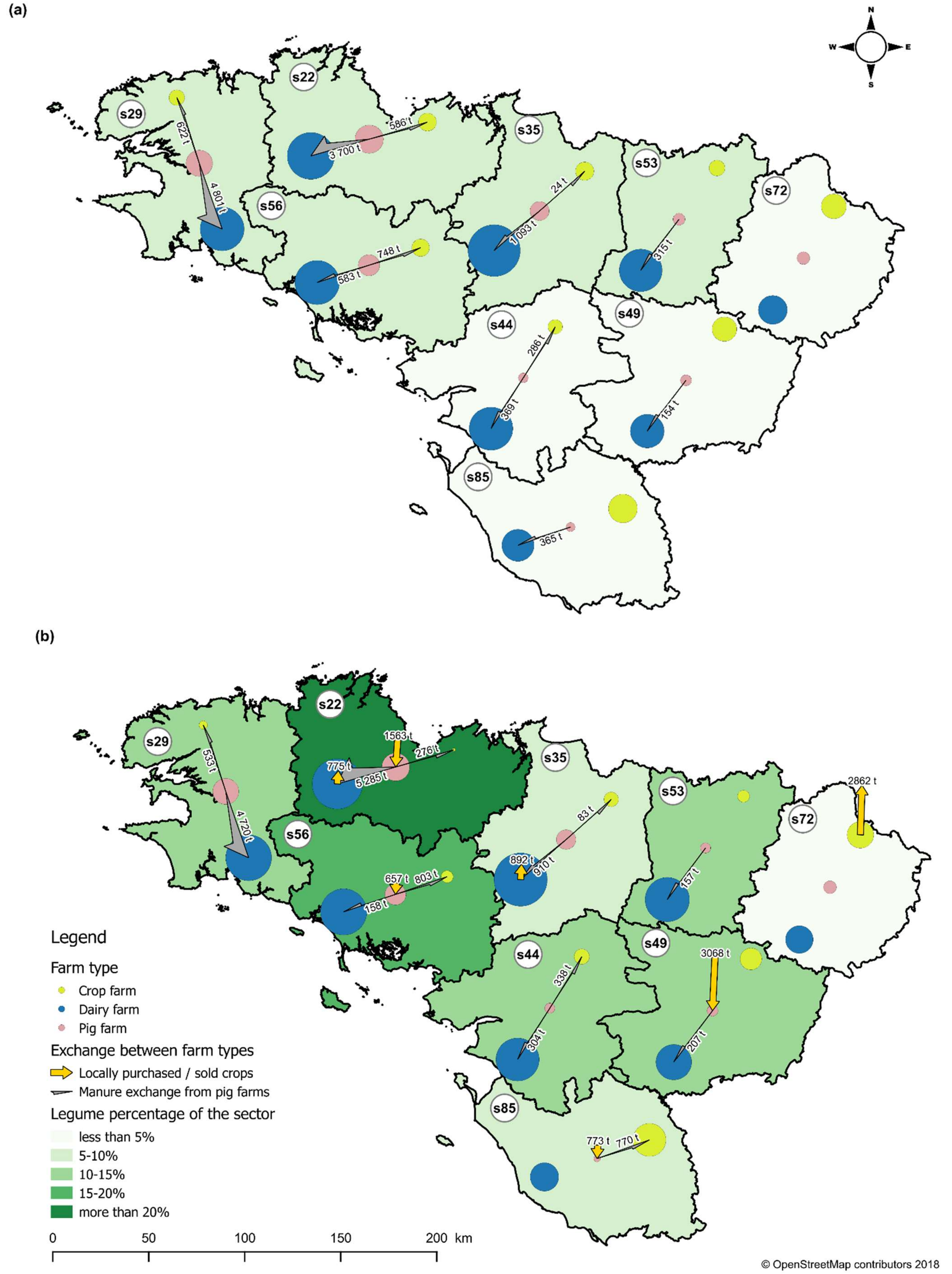
When this lever is applied, the area of sole-crop legumes increases by 14% at the regional scale, compared to BASE (Table 6.2). This increase is particularly high on dairy farms (+17% more area, on average). Like for the previous lever, legumes cover only 1.7% of the regional area. However, the increase in multispecies grassland is substantially higher (+194% more area), and the percentage of legumes, including multispecies grassland, reaches 12% of the regional area. Thus, the incentive to produce legumes for feed is an effective lever to increase production of multispecies grassland used in feed.

Compared to BASE, livestock production increases at the regional scale (+2.5% more milk produced and +1% more pigs produced). The increase in pig production is similar throughout the region, and the entire pig herd is fed legume-based rations. This shift in rations leads to an increased need for legumes that is not met by legume production in the region. Therefore, protein self-sufficiency decreases by 4 percentage points on pig farms, on average. The decrease in protein self-sufficiency is particularly high on Pig85 (-16 percentage points) due to a decrease in farm area (-42%) and an increase in pig production (+2%); thus, the stocking rate increases, as do feed purchases.

The increase in milk production varies more among sectors than the increase in pig production: milk production increases in the northwestern part of the region (particularly on Dairy35, with +10% more milk production) but decreases in the southern and eastern parts (particularly on Dairy72, with -19% more milk production). On dairy farms, the shift toward legume-based rations also varies more: 94% of cows are fed legumes, mainly multispecies grassland (48%) and alfalfa (33%). However, the remaining 6% of cows that are not fed legume-based rations are located on only three farms (Dairy44, Dairy53 and Dairy85) and are fed GMO-free soybean meal. Protein self-sufficiency on dairy farms remains constant on average, but substantial differences exist among farms. For example, when feed is based mainly on multispecies grassland and stocking rate decreases, protein self-sufficiency increases on Dairy22 and Dairy49 (by +9 and +8 percentage points, respectively). In contrast, when feed is based mainly on alfalfa, protein self-sufficiency decreases on Dairy35 (by -11 percentage points) because the farm produces less alfalfa than that needed for dairy cow rations.

Finally, due to the shift in rations that leads to an increased need for legumes on dairy and pig farms, imports of legumes from outside the region are multiplied by a factor of 18, and genetically modified soybean meal is no longer imported into the region. Also, local exchanges of crops appear, in particular of peas, faba beans and rapeseed (Figure 6.4). However, these exchanges represent only 1% of the quantities of these crops consumed in the region. Thus, exchanges of crops do not influence the protein self-sufficiency of the region.

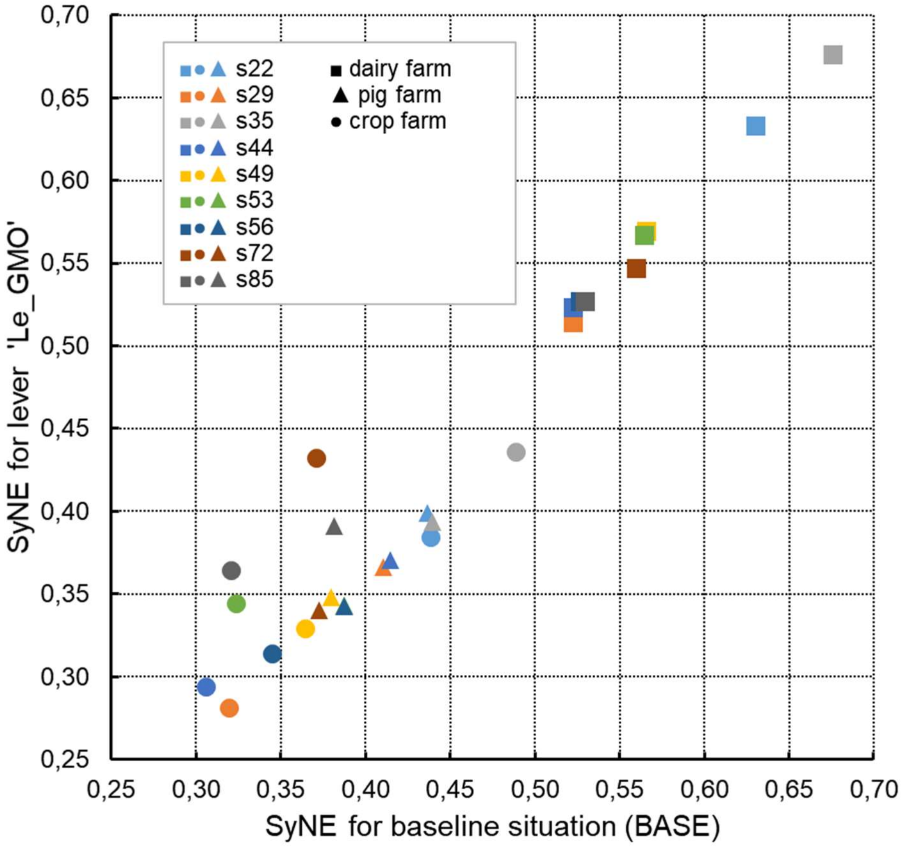
Figure 6.4. Legume production and farm-to-farm exchanges of crops and manure in western France in (a) the baseline situation and (b) under increased demand for GMO-free animal products (Le_GMO)



Legume percentage includes sole-crop legumes (peas, faba beans and alfalfa) and multispecies grassland. Circles are proportional to the area of each farm type in each sector. Crop exchanges less than 600 t are not represented.

Compared to BASE, the environmental results worsen slightly at the regional scale, despite the 9% decrease in synthetic N consumption. Indeed, SyNB increases by 10 kg N.ha^{-1}, and SyNE decreases by 0.02 points. These small decreases hide larger changes at the farm scale that offset each other (Figure 6.5). On pig farms, SyNB increases by 58 kg N.ha^{-1}, on average, mainly due to the increase in the stocking rate, which is not compensated by the increased exports of manure. SyNE also worsens (by -0.04 points, on average) due to legume-based rations for pigs that contain less N. These large decreases are partly compensated by smaller decreases on dairy farms, which cover a larger percentage of the regional area. On dairy farms, SyNB increases by only 5 kg N.ha^{-1}, and SyNE decreases by 0.03 points, on average. However, the results on dairy farms are very heterogeneous. Three of nine dairy farms (Dairy53, Dairy72 and Dairy85) have improved SyNB and SyNE due to an increase in the legume percentage that decreases purchases of N-rich inputs for fertilization (e.g., manure, synthetic N fertilizer) and feed (e.g., imported legumes). However, although high use of multispecies grassland increases protein self-sufficiency of farms, SyNE worsens because the feed ration is less efficient in N (i.e., more N in needed to produce the same quantity of outputs such as milk or meat). Otherwise, SyNB worsens on farms on which protein self-sufficiency decreases, due to an increase in feed purchases (e.g., alfalfa purchases on Dairy35). Environmental indicators on crop farms change little.

Figure 6.5. N efficiency (SyNE indicators) between the baseline situation (BASE) and under an increased demand for GMO-free animal products (Le_GMO), among farms and sectors



Compared to BASE, economic indicators improve: profit increases by 14% at the regional scale, with differences among farms. On pig farms, income per pig increases by 26% on average, with particularly high increases on Pig44 and Pig53 (+30%). On dairy farms, income per L of milk increases by 5% on average, with a particularly high increase on Dairy72 (+17%). Thus, it is possible to increase the profitability of milk production while improving protein self-sufficiency and environmental indicators. However, the trade-off between economic and environmental benefits does not always go in the same direction: on Dairy35, the increase in profitability goes along with a decrease in protein self-sufficiency and worsening of environmental indicators. Finally, on crop farms, income per ha decreases by 2% on average, with substantial differences among crop farms, from -6% on Crop29 to +3% on Crop22.

Table 6.2. Results for the main indicators of the SYNERGY model, under the two levers tested, Le_SU and Le_GMO, compared to the baseline situation (BASE)

Indicator	BASE	Le_SU	Le_GMO
Legume percentage	5.1%	5.2%	12.3%
Sole-crop legumes	*1.5%*	1.7%	*1.8%*
Multispecies grassland	*3.6%*	3.6%	*10.5%*
Area of farms (ha)			
Dairy farms	*1,128,399*	*1,130,106*	*1,093,793*
Pig farms	*188,735*	*189,277*	*185,236*
Crop farms	*239,242*	*236,993*	*277,347*
Milk production (hL)	741,807	741,17	760,353[a]
Pig production (thousands of head)	12,178	12,178	12,299 [a]
Percentage of legume-based rations			
Dairy farms	*20.6%*	*20.5%*	*94.0%*
Pig farms	*0.4%*	*0.5%*	*100.0%*
Purchases of GM soybean meal (t)	705,865	706,003	0[b]
Local exchanges of crops (t)	-	-	33,448
Regional protein self-sufficiency	59%	59%	59%
Farm protein self-sufficiency			
Dairy farms	*74%*	*74%*	*74%*
Pig farms	*24%*	*24%*	*20%*
Purchases of synthetic N fertilizers (t N)	315,845	315,518	287,743
SyNB (System N Balance, kg N.ha^{-1})			
Dairy farms	*112*	*112*	*117*
Pig farms	*260*	*259*	*318*
Crop farms	*90*	*90*	*92*
SyNE (System N Efficiency, range = 0-1)			
Dairy farms	*0.38*	*0.38*	*0.35*
Pig farms	*0.41*	*0.41*	*0.37*
Crop farms	*0.56*	*0.57*	*0.56*
Regional profit (M€)	2,191	2,293	2,607
Dairy farm income			
Regional total (k€)	*1,484,794*	*1,487,167*	*1,602,932*
Per hL of milk (€.hL^{-1})	*2,002*	*2,005*	*2,108*
Pig farm income			
Regional total (k€)	*630,689*	*631,286*	*802,932*
Per pig (€.pig^{-1})	*51.8*	*51.8*	*65.3*
Crop farm income			
Regional total (k€)	*175.987*	*174,536*	*199,987*
Per ha (€.ha^{-1})	*736*	*736*	*721*

BASE: baseline. Le_SU: coupled support for legume increased to 200€.ha^{-1} for peas and faba beans and 184 €.ha^{-1} for alfalfa. Le_GMO: demand for GMO-free animal products is increased in the CGE model, leading to several price variations. [a] the increase in milk and pig production is limited to that observed in the CGE model. [b] GMO-free soybean is purchased (18,405 t).

6.4. Discussion & conclusion

The aim of this study was to define and test levers to increase protein self-sufficiency in western France, without decreasing agricultural profitability and reducing, if possible, negative environmental impacts of agricultural production. Two levers related to the production or use of legumes in feed were tested: a policy-oriented lever (i.e., increase in coupled support for legumes) and a demand-oriented lever. Regarding the first lever, when coupled support increased, only crop production was impacted. Production of subsidized legumes (i.e., peas, faba beans and alfalfa) increased by 13% at the regional scale, in particular on crop farms. This increase occurred partly at the expense of multispecies grassland. However, with this lever, livestock production was not impacted by the increase in legume production: feed rations did not change. Since production of legumes remains low in the region, impacts on economic and environmental indicators are low. Thus, the policy-oriented lever does not influence the key indicators of this study, particularly protein self-sufficiency. This result differs from the study of Helming et al. (2014), who estimated a 4% increase in the use of legumes in feed when coupled support for grain legumes is provided. However, the level of this coupled support (at least 282€.ha^{-1}) is higher than that in our study, which may explain the difference. In addition, the increase in legume production, and its use in feed, could have been higher if multispecies grassland had also been subsidized.

Regarding the second lever, when demand for GMO-free animal products increased, production of sole-crop legumes increased by the same degree as that with the policy-oriented lever, particularly on livestock farms. However, the use of legumes in feed increased greatly. Indeed, in addition to an increase in livestock production, which was limited to account for investment and labor costs, rations became almost completely legume-based. On dairy farms, this shift went along with a stable protein self-sufficiency, on average: on farms using alfalfa, which was mainly imported from outside the region, protein self-sufficiency decreased, while it increased on farms using multispecies grassland, produced on farms. On pig farms, the impacts varied less: protein self-sufficiency decreased because legume production did not meet the quantity needed by pig rations. Therefore, regional areas are not large enough to feed the entire herd of pigs if it is converted to legume-based rations, given the possibility of importing feed. In addition to a demand-oriented lever, specific support for locally produced legumes would thus be necessary, as it is proposed in the foresight scenarios.

However, the economic situation of livestock farms improved, particularly on pig farms, because the selling price of non-GMO pigs increased more than their production cost. Unfortunately, environmental results were not as good: N efficiency and potential N losses worsened, on average. On dairy farms that used feed based on forage maize and multispecies grassland, N efficiency generally decreased, while protein self-sufficiency generally increased. Otherwise, when protein self-sufficiency decreased, potential N losses increased due to an increase in feed purchases. Finally, beyond protein self-sufficiency at the farm scale, regional protein self-sufficiency did not increase, since farm-to-farm exchanges of crops remained low (ca. 1% of the crops used in feed). The differential in price between local and global purchases seems to be too low to foster local exchanges. In addition, contrary to expectations, local exchanges occur more from the northwestern part of the region, oriented mainly toward livestock production, to the southeastern part of the region, oriented more toward crop production. Indeed, certain farms in the northwestern part produce more livestock than those in the southeastern part, but do so less intensively (i.e., fewer animals per ha). Thus, these northwestern farms can export feed, while the southeastern ones need to import it.

The main originality of this study is the identification of the close relation between the demand for animal products and effects on feed choice and crop production. From a regional case study, we analyzed the relation between increased demand for GMO-free animal products and improvement in protein self-sufficiency due to legume production. The GMO-free label was chosen as a lever to increase protein self-sufficiency because of collaborative work: the TERUnic foresight. This foresight relied on an original method whose initial steps defined final states (i.e., the level of protein self-sufficiency) qualitatively. Consequently, foresight participants looked to futures that differ substantially from current trends. In addition, the TERUnic foresight had the advantage of including a variety of experts from different types of livestock production, which differ in their constraints in the use of legumes for feed. Two of these types of livestock production were then represented in the modeling framework. This foresight was performed in less time (i.e., 6 months) than other foresights, however, which limited the complexity of scenarios.

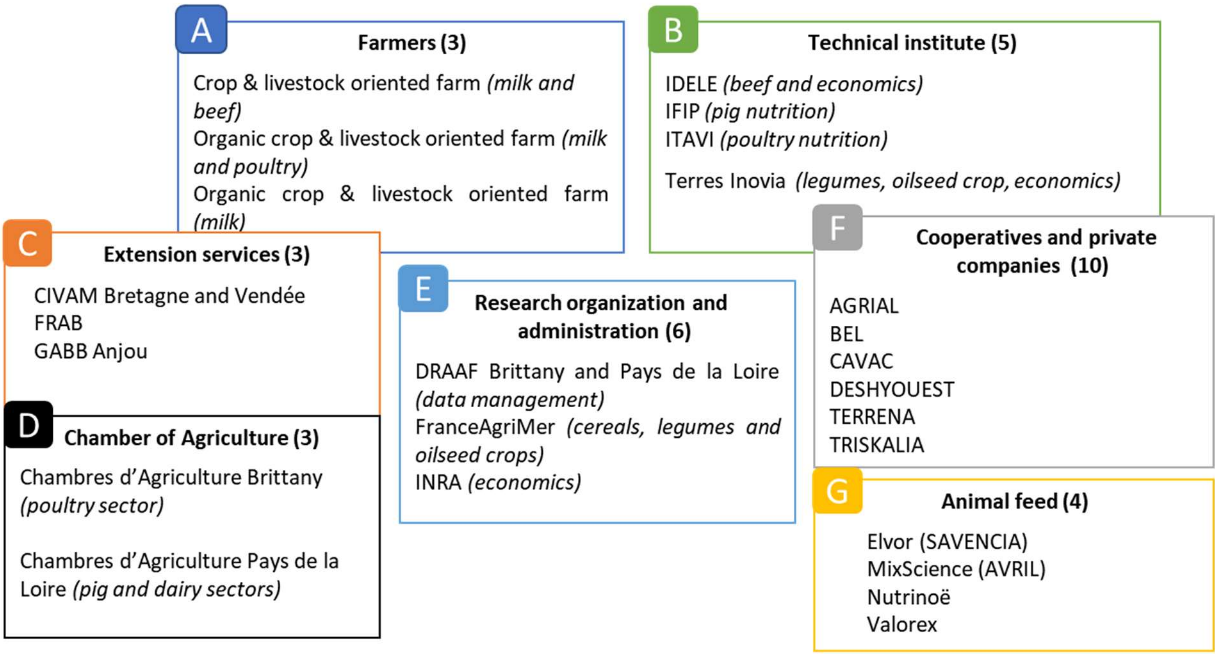
Another originality of this study is the modeling framework used to test the levers. It uses a CGE model to simulate market effects and then transfers these effects to the bio-economic model SYNERGY. The SYNERGY model has three main advantages. First, by simulating farm-to-farm exchanges, protein self-sufficiency can be studied not only at the farm scale but also the regional scale. To our knowledge, this is the first regional model to do so. Second, trade-offs between economic impacts, environmental impacts and protein self-sufficiency are highlighted. Third, by considering the region's heterogeneity, SYNERGY can differentiate development opportunities of protein self-sufficiency constrained by local characteristics, such as local crop yields and the level of livestock production. It is particularly relevant for dairy farms, on which forages (e.g., multispecies grassland) depend on the local characteristics as self-produced feed. However, this modeling framework had some limitations. In particular, the price differential between locally and world purchased crops was set at a realistic value of 10%, according to data from a professional journal. A change in this value might lead to different results. In particular, the price differential between locally and globally purchased crops was set at a realistic value of 10%. Similarly, due to a lack of data, multispecies grassland was assumed to cover 15% of temporary grassland on dairy farms. This strong assumption should be validated by future studies, and sensitivity analyses should be performed. In addition, the CGE and SYNERGY models do not use the same reference year due to the former's lack of data availability. However, coupling the two models provides a real added value. For example, had the increase in price of GM-free soybean meal simulated by the CGE model not been used in SYNERGY, the use of this meal would have been much higher, limiting the development of legumes.

The main conclusions of this study raise questions about the relevance of such high livestock production in light of environmental impacts and protein self-sufficiency. Even when using legume-based feed, protein self-sufficiency did not improve greatly, nor did environmental results. Indeed, due to the high livestock production, the ability to use feed based on legumes produced in the region is low compared to the need for N-rich feed, in particular for pig production. Thus, one way to improve protein self-sufficiency and environmental results could be to decrease the number of animals to be fed. To explore this option, we simulated a halving of dairy and pig production. The first results showed an increase in regional protein self-sufficiency by 12 percentage points, with a 34% increase in local exchanges of crops. Regional profit decreased by 18%, but environmental results improved substantially, with a decrease in potential N losses of 28 kg $N.ha^{-1}$ at the regional scale and, on average, 108 kg $N.ha^{-1}$ on pig farms. Such encouraging environmental results raise the question of whether the agricultural sector of western France, which is oriented mainly to exports, should change drastically. Further analysis could also be performed by targeting a certain level of protein self-sufficiency, as Gaudino et al. (2018) did. In addition, regarding dairy production, multispecies grassland seems a promising lever to increase protein self-sufficiency. Future studies should be performed to determine an adequate public policy that would foster its production.

Other N-rich feed should also be studied to improve protein self-sufficiency: for example, production of rapeseed (and its meal) is well developed in France, but rapeseed provides fewer ecosystem services than legumes. In addition, the issue of protein self-sufficiency must be addressed not only at the regional scale, but also at the national scale, in particular if exchanges between farms (or regions) are studied. In France, some regions are oriented more toward crop production, and it would be interesting to study exchanges of crops from these regions toward western France. These exchanges could be studied in SYNERGY by redefining sectors as French regions. Enhancing complementarities between French regions could thus be an interesting lever to increase protein self-sufficiency at the national scale.

6.5. Appendix

Appendix 6.A. Panel of stakeholders contributing to the TERUnic foresight



A **Farmers (3)**

Crop & livestock oriented farm *(milk and beef)*
Organic crop & livestock oriented farm *(milk and poultry)*
Organic crop & livestock oriented farm *(milk)*

B **Technical institute (5)**

IDELE *(beef and economics)*
IFIP *(pig nutrition)*
ITAVI *(poultry nutrition)*
Terres Inovia *(legumes, oilseed crop, economics)*

C **Extension services (3)**

CIVAM Bretagne and Vendée
FRAB
GABB Anjou

D **Chamber of Agriculture (3)**

Chambres d'Agriculture Brittany *(poultry sector)*

Chambres d'Agriculture Pays de la Loire *(pig and dairy sectors)*

E **Research organization and administration (6)**

DRAAF Brittany and Pays de la Loire *(data management)*
FranceAgriMer *(cereals, legumes and oilseed crops)*
INRA *(economics)*

F **Cooperatives and private companies (10)**

AGRIAL
BEL
CAVAC
DESHYOUEST
TERRENA
TRISKALIA

G **Animal feed (4)**

Elvor (SAVENCIA)
MixScience (AVRIL)
Nutrinoë
Valorex

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Chapter 7.
General discussion

7.1. Main contributions

The general objective of my doctoral research was to study technical complementarities of crop and livestock production at different scales, to improve the sustainability of agriculture. The main hypothesis was that **legumes improve these technical complementarities**. Indeed, the main advantage of legumes lies in their ability to fix atmospheric N, which lies behind **joint production of N-rich crops and N as input** for intercrops or subsequent crops. Thus, technical complementarities can appear between legumes and intercrops or subsequent crops. In a first approach, I studied technical complementarities at the **rotation scale**, by focusing on legumes and their N effect on subsequent crops (pre-crop effect). I demonstrated that **opportunity costs of legumes are zero or negative at the rotation scale due to their pre-crop effect**. In addition, since legumes are N-rich crops, technical complementarities can also appear at the farm scale between legumes and livestock: legumes can be used to feed livestock. However, production of these crops is still limited, in particular on livestock-oriented farms. Indeed, one factor may affect the introduction of legumes on these farms: manure management. Since legumes do not need to be fertilized, spreading manure on them is inconsistent from an agronomic viewpoint. This is translated into the Nitrates Directive, which is applied differently across the EU: in western France, spreading manure on legumes is forbidden (except of alfalfa). In a second approach, I studied at the farm scale how more flexible regulation of manure spreading can help increase production of legumes and their use in feed on livestock-oriented farms. I showed that **allowing manure spreading on legumes can help reach higher legume production on livestock-oriented farms**. The use of legumes in feed increases, and so does protein self-sufficiency. However, **it does not lead to positive environmental impacts** since the benefits of lowering N inputs are nearly offset by the increase in nitrate leaching due to overfertilization of legumes.

Another solution to encourage the use of legumes on livestock-oriented farms is to study this issue at a larger scale. These technical complementarities can be enhanced not within the farms, but between farms within a region: crop-oriented farms can produce and sell legumes to neighboring livestock-oriented farms to feed animals, and livestock-oriented farms can export manure to crop-oriented farms to fertilize crops. Thus, in the third approach of my doctoral research, I analyzed crop-livestock technical complementarities at the **regional scale** using the SYNERGY model that I built. SYNERGY studies such complementarities by explicitly representing farm-to-farm exchanges of crops – including legumes – and manure. To allow such exchanges, it encompasses multiple scales, from the farm to the region. These exchanges are represented through a local equilibrium market for crops and manure. Another specific feature of SYNERGY is to represent the pre-crop effect of legumes. Since crop activities in SYNERGY are defined as combinations of a crop and a rotation, it is possible to lower fertilizer needs of crops that follow legumes compared to those that do not. The model also represents innovative feed rations for livestock with grain and forage legumes, replacing imported soybean meal. Thus, SYNERGY includes a large variety of technologies, in both crop production and animal production. By encompassing multiple scales, complementarities are studied at the regional scale but also at the rotation and farm scales. SYNERGY results from **interdisciplinary work in economics and agronomy**; from this work, I created a model that performs an integrated assessment using economic and environmental indicators. During my doctoral research, I used SYNERGY **to study extreme scenarios by making structural variables evolve to extreme situations** (e.g., force a large percentage of legumes on agricultural land in the region), regardless of the levers that led to these situations. By doing so, SYNERGY helps to understand economic and environmental impacts of ambitious changes that are recommended to reach sustainable agriculture. For example (Chapter 5, p. 111), by setting a high legume percentage (i.e., 10%) in the region of western France, I demonstrated that the use of legumes in dairy feed increases and the use of synthetic N fertilizers decreases (-7%). However, this increase in legume percentage also leads to a decrease in profit of the farming sector (-4%), without substantial improvement in environmental indicators. Manure exchanges can help increase the percentage of legumes on some pig farms, but it also leads to intensification of pig production.

In addition, SYNERGY was used to **study different types of levers (i.e., policy, technological or market-oriented) to quantify their impact on structural variables, and on economic and environmental indicators**. By doing so, SYNERGY helps to identify the most relevant levers to achieve specific objectives, in particular enhancing crop-livestock technical complementarities. For example (Chapter 6, p. 141), I demonstrated that coupled support to foster legume production has little influence on legume use in feed in western France, while increasing demand for GMO-free animal products leads to substantial technological change through a nearly complete shift in rations from being soybean-based to legume-based. In both cases, however, legume production in the region remains relatively low (ca. 2% of the regional agricultural area), if multispecies grassland is not recorded as legume. Local exchanges of crop between farms are limited, and imports of legumes from outside the region increase. This leads to a slight decrease in environmental indicators, especially since legume-based rations are less N efficient and livestock production increases.

Finally, the last contribution of my doctoral research **is to study vertical organization of legume production**, which is not considered in SYNERGY. Based on case studies, I characterized transaction costs associated with exchange of legumes between producers and collectors in western France, and how the contracts currently offered decreased these transaction costs. I show that **exchanges of legumes do suffer from high transaction costs**. These costs are not sufficiently decreased by contracting, in particular because uncertainties in price remain high in the current contracts. Initiatives to decrease such uncertainties should be set up to foster production and local exchanges of legumes and thus improve complementarities between production.

7.2. Main limitations

The first limitation is related to the scope of the study. First, beef and poultry production is not included in SYNERGY, even though their production can use large amounts of soybean meal (Céréopa 2017). This is due to (i) a lack of time to include beef production, which may be added to an improved version of SYNERGY; (ii) the lack of relevance for including poultry production, since the feed is chosen at the sectorial scale (i.e., the downstream industry) rather than the farm scale. Indeed, for the poultry sector, few data were available, and the commitment of stakeholders on the issue of local legumes in feed was limited. In addition, it would have been interesting to consider rapeseed meal as a substitute of soybean, since rapeseed meal is rich in N, and its production is well developed in France (Terres Univia 2019). However, rapeseed provides relatively few ecosystem services and requires relatively large amounts of synthetic N fertilizers and pesticides (Lehuger et al. 2009; Bouchard et al. 2011). Also, SYNERGY, and most of the other contributions, are applied only to western France. This regional approach is justified in light of the funding organization and the time needed to collect the necessary data (Chapter 5, p. 126). However, western France has high livestock production given its available agricultural area. Thus, development of crop-livestock technical complementarities is limited if livestock production, especially pig production, is not assumed to decrease (Chapter 6, p. 149). Indeed, regarding the issue of protein self-sufficiency, it makes more sense to look at it at the scale of an entire country than at the scale of a region historically oriented toward livestock production. One future development of SYNERGY that is quite possible would thus be to expand the study area to the whole of France, including regions that are more oriented toward crop production. To do so, the sectors currently corresponding to administrative departments can be redefined as French administrative regions.

The second limitation is related to the sensitivity analysis of key parameters. To represent local exchanges of crops between farms, a 10% differential has been set between crops purchased locally and crops purchased on the global market. This difference in cost, which represents lower transport costs, is a strong assumption of SYNERGY. It was defined using data from a professional journal. However, SYNERGY's sensitivity to this parameter should be explored further: for example, a sensitivity analysis could be performed to determine the conditions under which local exchanges become substantial. This could encourage decision makers to take action to minimize local transport costs. Similarly, most technical coefficients (e.g., prices, costs, yields) are based on a 5-year mean in order to smooth the effect of market or climate variability on the simulations. A complementary approach would be to perform a sensitivity analysis of price or yield variations to improve the robustness of the model.

The third limitation is related to the structure of the objective function. SYNERGY would have been improved by using the Röhm and Dabbert approach of the PMP to calibrate not only animal numbers but also rations (Röhm and Dabbert 2003). This approach of the PMP has been applied, to the best of my knowledge, only to crop production by calibrating areas of crops and technologies used to produce them (Cortignani and Severini 2009). In attempting to adapt this approach to the calibration of rations, I encountered two problems. The first issue was the availability of data: the consolidated livestock-management database (French Ministry of Agriculture 2019), which describes the distribution of rations in the study area, was delivered much later than planned. Thus, I did not have time to use it to calibrate the model. The second issue was the decrease in model flexibility: when I tried to calibrate SYNERGY using the temporary livestock-management database (whose statistical representativeness was not yet validated) (French Ministry of Agriculture 2018), I realized that it no longer simulated substantial changes, even under extreme scenarios. In fact, by calibrating crop areas, animal numbers and feed rations simultaneously, the model loses its flexibility to modify areas, animal numbers and distribution of rations. It was thus decided to calibrate only crop areas and animal numbers using a double standard PMP approach. In addition, SYNERGY does not explicitly represent risk, even though risk is an important issue for legume production (Cernay et al. 2015). More generally, improvement in technical complementarities must lead to agricultural production that is more self-sufficient in inputs, increasing the resilience against economic shocks. However, fixed costs related to investments, which are particularly high in livestock production, and constraints of work availability, could have substantial impacts on the development of legumes. The static nature of SYNERGY does not allow these elements to be considered, but the model does represent the pre-crop effect of legumes, which is essential to assess advantages of developing legume production.

The fourth limitation is related to the inclusion of environmental indicators in SYNERGY. Currently, it assesses only N efficiency and N losses. It would be useful to add other indicators, such as the use of pesticides, an index of biodiversity or GHG emissions. This improvement could be made easily in a future version of SYNERGY. For example, GHG emissions could be assessed by adding indicators from the ECOALIM database (Wilfart et al. 2016). However, these new indicators should include GHG emissions from land-use change to capture the issue of imported deforestation. Besides, an alternative multi-criteria objective function might yield different results from maximizing profit under biotechnical and environmental constraints. In particular, it would be interesting to include SyNE and SyNB indicators directly in the optimization constraint of SYNERGY to test, for example, the double objective of increasing the demand of GMO-free products and improving values of these indicators.

7.3. Further considerations

During this Ph.D., an important obstacle to legume production was not studied: workload. Indeed, crop diversification can cause working time or peak labor to increase, in particular for forage legumes (Meynard et al. 2013; Schneider and Huyghe 2015). The issue of workload becomes even trickier with the development of organic production, which can be work-intensive (Midler et al. 2019). In contrast, the agricultural sector faces a demographic issue: in France, nearly one-third of farmers are over 55 years of age and will retire within 3 years. The profession of farming is thus aging and faces challenges due to decreased availability of agricultural land and a lack of attractiveness due to low expected incomes and high risks (Forget et al. 2019; Le Monde 2019). To address these issues, certain organizations propose reforming Pillar I of the CAP fundamentally, by providing basic payments no longer per hectare but per agricultural work unit (France Stratégie 2019). This reform would support a shift towards agriculture that requires more labor, which may create jobs. Beyond the issue of workload, the question arises about the place of legumes in the next CAP, in which the issue of climate change should be central. Indeed, the main objective of the “Green Deal”, recently led by the President of the European Commission, is to make the EU climate neutral by 2050. One aspect of this Green Deal is CAP reform, which must lead to a “farm to fork” strategy for sustainable food (von der Leyen 2019). Legumes can contribute directly to limit climate change by decreasing the use of synthetic N fertilizers, which are one of the main GHG emitters in agriculture after livestock production (Perez Dominguez et al. 2016). Indirectly, they can also help limit climate change by replacing animal products as the protein supply in human food, leading to a decrease in livestock production.

Nonetheless, competition between humans and livestock for legumes could appear, especially since legumes used for human food usually sell for higher prices (Schneider and Huyghe 2015). Thus, development of legumes for food could limit the development of legumes for animal feed and favor feed based on imported N-rich ingredients. Since most of these imported ingredients are genetically modified soybean, it raises questions about whether to import agricultural goods whose production does not follow EU regulations. The same holds true for pesticides that are prohibited in the EU but have been used increasingly in Brazil in recent years (Phillips 2019). In addition, one of the main findings of this Ph.D. thesis is that subsidies to legumes encourage their production but not necessarily their use in animal feed. Therefore, it would also be useful to develop support for adding them to feed, such as structural investments to lower transaction costs between producers and collectors that are also feed manufacturers. More innovative outlets for legumes, creating interesting by-products for the feed industry, could also foster their use in feed (Lienhardt et al. 2019). However, legume-based rations are usually less efficient in proteins than soybean-based rations; thus, more feed is needed when feeding legume-based rations. Under constant technology, more land is thus needed to produce livestock. This is a critical issue, since a large percentage of agricultural land (i.e., 65% in the EU) is already devoted to livestock production (Leip et al. 2015). There is thus a dilemma between using highly efficient feed relying on global exchanges or less efficient feed but locally produced. Nevertheless, a consensus is emerging that criticizes the extent of livestock production and meat consumption: in developed countries, reducing consumption of animal products seems necessary to align dietary patterns with public health and ecological goals (Hedenus et al. 2014; Bryngelsson et al. 2016; Willett et al. 2019). In this context, developing legume production to replace animal protein by crop protein in human food is essential. It would be interesting to consider the introduction of legumes for food (e.g., soybeans, lentils) in a simulation framework, as well as those already produced in western France (e.g., green beans, "coco de Paimpol"). Going further, SYNERGY could also simulate a substantial decline in animal production to assess potential trade-offs between economic and environmental impacts.

In the scenarios simulated by SYNERGY, exchanges of crops remained low, which limited the improvement in crop-livestock complementarities at the regional level. Beyond the 10% price differential between locally and globally purchased crops, the question arises of how to develop such exchanges. Innovative marketing channels based on digital tools seem a promising solution to limit transaction costs. For example, new stakeholders, such as the website "Agriconomie", are facilitating the purchase of inputs, offering a wide range of products for sale on the internet (Agra Presse 2018). Such websites could thus facilitate not only the purchase of inputs (e.g., crops) between retailers and farmers, but also directly between farmers. Similarly, exchanges of manure can benefit from progress in digital tools (e.g., decision-making tools to calculate fertilization value) (Arvalis 2019).

In addition, other innovative forms of crop-livestock complementarities that do not imply exchanges between farms could be developed. In particular, agroforestry (e.g. joint production of orchards and cattle) can represent an interesting solution to product fruit and meat while enhancing ecosystem services (Ridier and Képhaliacos 2006; Torralba et al. 2016). In addition, aquaponics, which is based on the production of aquatic animals (e.g., fish, shrimp) and plants, can also lead to sustainable agricultural production by improving crop-animal technical complementarities by looping the N cycle (Goddek et al. 2015).

Most of this Ph.D. thesis is devoted to the SYNERGY model and its applications. The model was built to study the specific issue of crop-livestock technical complementarities in western France. It can simulate farm-to-farm exchanges and considers specific regional characteristics (e.g., rotations, rations, soil and climate conditions). To enhance SYNERGY's value and the resources used to develop it, it seems essential to apply it to other issues or case-study regions. Indeed, the genericity and extension of BEMs is a key issue to improve research outcomes. Models such as FSSIM and CAPRI have been widely used and can be adapted to a variety of issues by adding specific modules (Louhichi et al. 2010; Gocht and Britz 2011; Weiss and Leip 2012; Gaudino et al. 2018). These models benefit from dedicated research teams, which saves time and increases robustness. They can also be included in chains of models, which widen their applications even more (van Ittersum et al. 2008; Pelikan et al. 2015). Thus, it would be judicious to continue the modeling framework started during this Ph.D. by providing adequate financial and human resources to improve SYNERGY and make it viable in the long term.

Concerns about use of BEMs can lead to questions about the objective function of most current BEMs. Indeed, these models reflect the dominant objective of continuous economic growth by maximizing profit or economic utility, even if they consider natural constraints. However, BEMs are in essence foresight tools, since they enable ex-ante assessments. Therefore, it would be relevant to use them to consider current reflections of some economists and other members of civil society, who argue that economic growth, even that claimed as “green growth”, is incompatible with sustainability (Raworth 2017; van den Bergh 2017; Parrique et al. 2019). Among this vast concept of degrowth (D’Alisa et al. 2014), some specific transitions related to agriculture and food could be assessed by BEMs, such as food self-sufficiency at different scales or regenerative designed technologies (Gomiero 2018).

Finally, this Ph.D. thesis results from interdisciplinary research: it combines economics and agronomy to offer a comprehensive approach to crop-livestock complementarities (Mitcham 2010). In particular, it performs economic analysis of interactions that are known to be positive in agronomy (i.e., crop-livestock technical complementarities) but that face economic obstacles in their implementation. These positive interactions and their technical determinants are rarely studied in economics, while their profitability and economic obstacles are rarely studied in agronomy. Beyond being interdisciplinary, this Ph.D. thesis also results from close collaboration with extension services, technical institutes and several cooperatives in western France. This collaboration enabled the sharing of data and results, and provided a research framework consistent with the needs of local stakeholders. Developing such interactions between academic research and the professional world can be a key element to develop a more sustainable agriculture.

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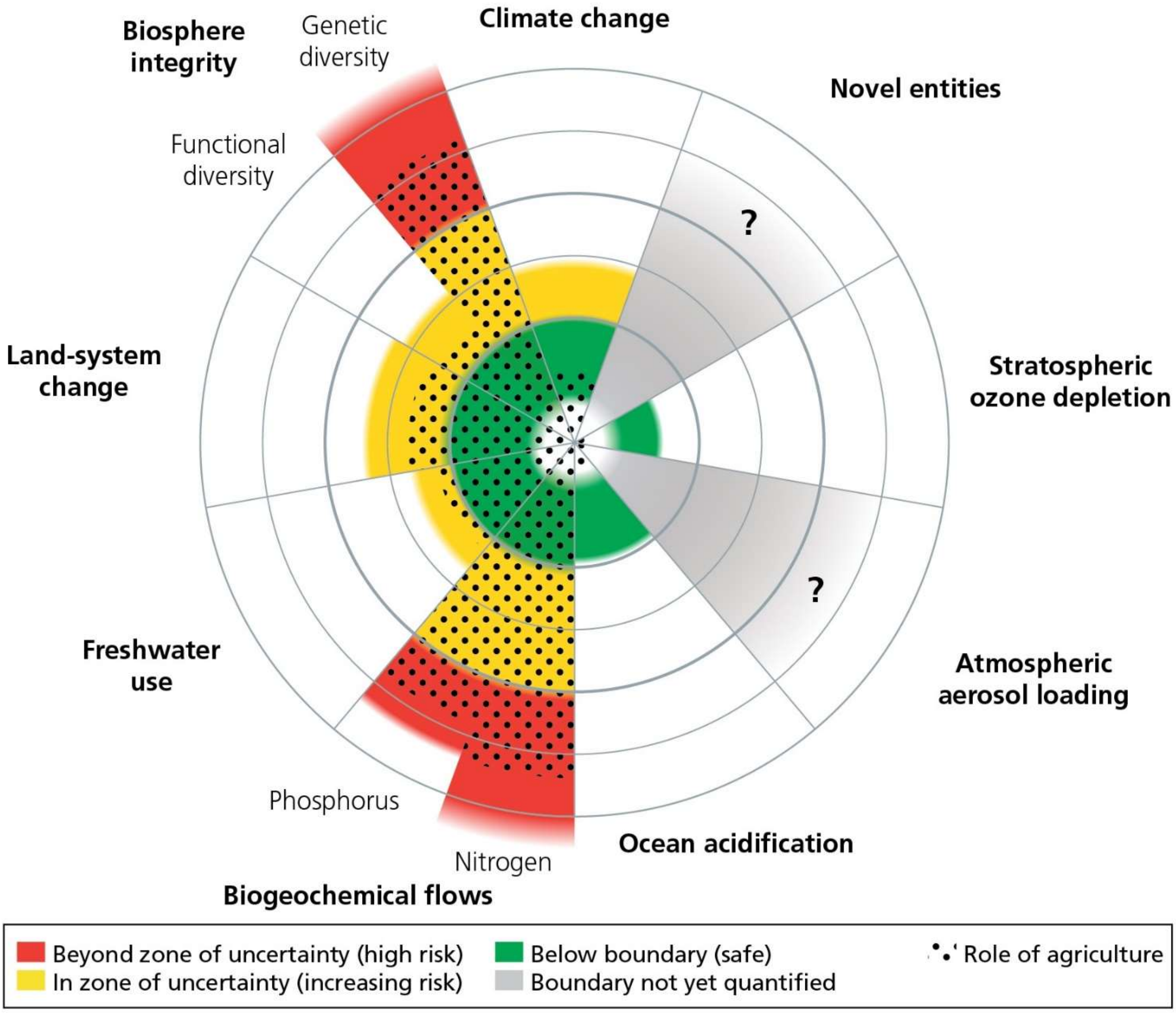
Appendices

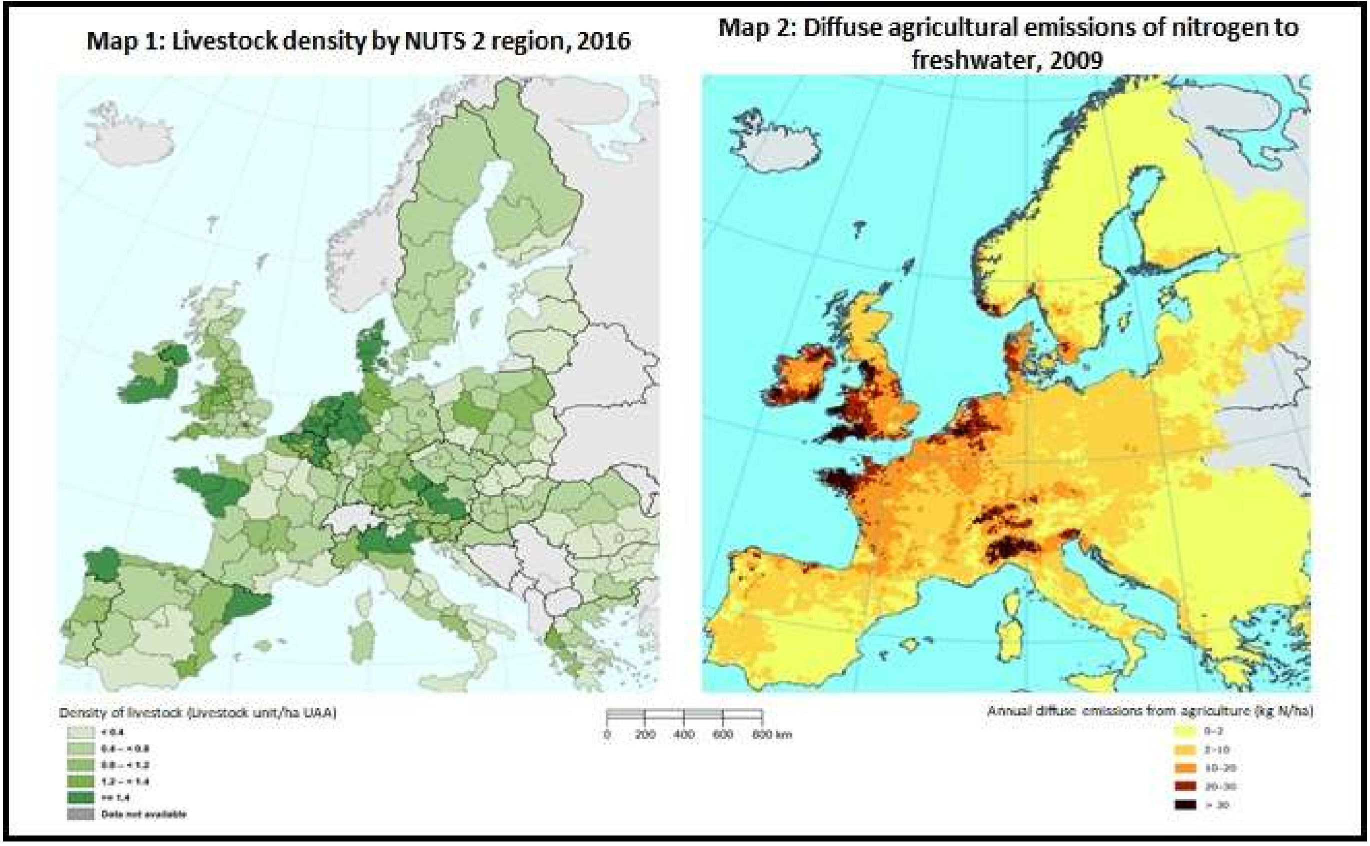
Appendix A.
The role of agriculture in the status of the nine planetary boundaries

Figure A1. The role of agriculture in the status of the nine planetary boundaries. Schema from Campbell et al. (2017), based on Steffen et al. (2015)



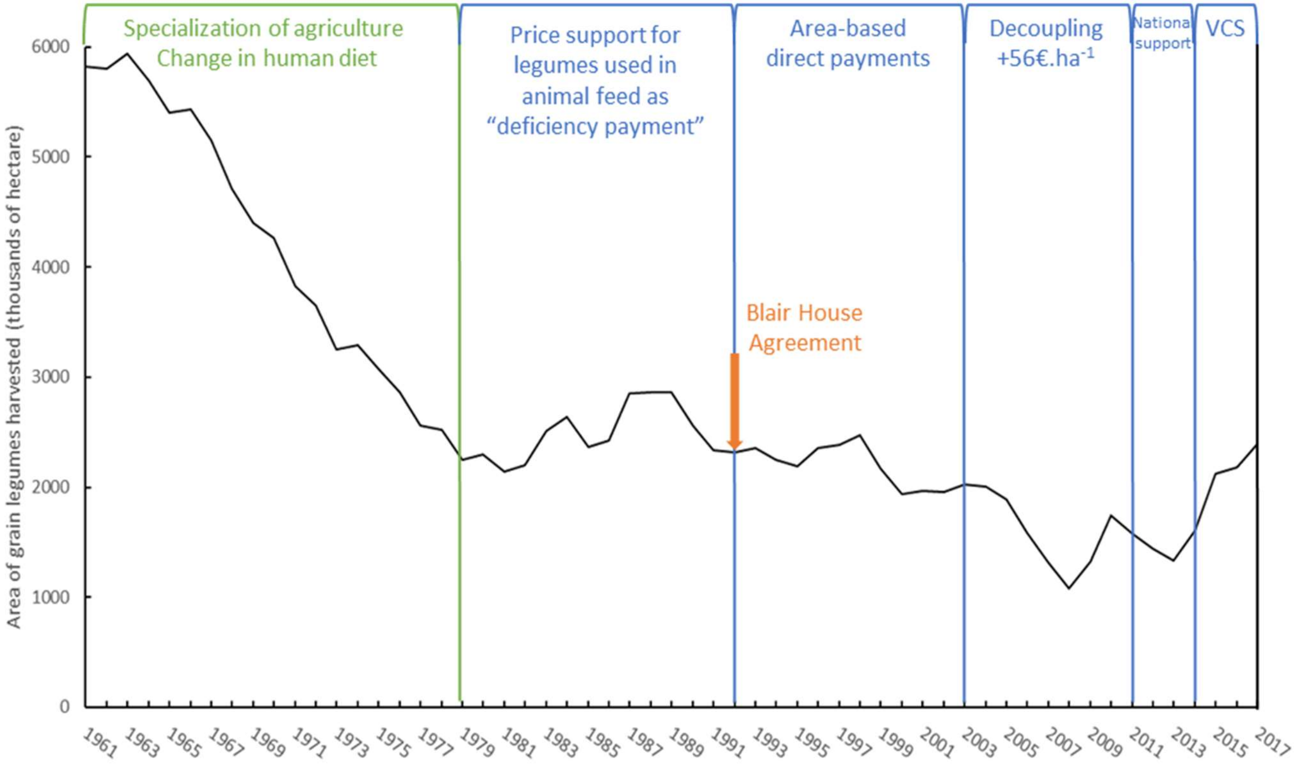
Appendix B.
Livestock density in EU and modelling of agriculture N emissions to freshwater

Figure B1. Livestock density in EU and modelling of agriculture N emissions to freshwater (Bouraoui et al. 2009; Eurostat 2019c)



Appendix C.
Evolution of harvested grain legume areas (i.e., pulses) in the EU

Figure C1. Evolution of harvested grain legume areas (i.e., pulses) in the European Union (28 members), in relation to structural and policy changes, based on (Bues et al. 2013; FAOSTAT 2019)



VCS: Voluntary Coupled Support

Appendix D.
PMP: from the standard approach to the Röhm and Dabbert's approach

The original PMP approach developed by Howitt (1995) comprises three steps. The first step consists in writing a linear model and adding a set of calibration constraints that bounds the production levels to the observed levels at a reference period (others resource constraints corresponding to the model itself are non-detailed here). In a regional cross-scale model that integrates only crop farms, this can be written as:

$$Max\ Z = \sum_{f} \sum_{c} (R_f - co_c . X_{c,f}) \tag{D.2}$$

$$X_{c,f} \leq X_{c,f}^0 . (1+\varepsilon) \qquad [\lambda c_{c,f}] \tag{D.2}$$

$$X_{c,f} \geq 0 \tag{D.3}$$

Where Z in the objective function value; co_c represent the linear cost vector for crops; $X_{c,f}^0$ is the non-negative vector of observed crop acreages for crop c in farm *f*; ε is a small positive vectors; $\lambda c_{c,f}$ is a vector of dual associated with the calibration constraint.

In the second step of the PMP, the dual $\lambda c_{c,f}$ is used for estimating parameters of the non-linear cost function satisfying equations (2.4) and (2.5):

$$co_c + \lambda c_{c,f} = d_{c,f} + Q_{c,f} . X_{c,f}^0 \tag{D.4}$$

$$Qc_{c,f} = \frac{kc|\lambda c_{c,f}|}{X_{c,f}^0} \tag{D.6}$$

Where $d_{c,f}$ represents the vector of intercepts of the cost functions for crops; $Q_{c,f}$ the vector of slope of the cost function of crops; kc is the vector of parameters that determine the weights of the linear part and the non-linear part of cost functions of crop production.

The quadratic cost function can be written as:

$$FC_{c,f,}(X_{c,f}) = d_{c,f} + 0.5 Qc_{c,f} . X_{c,f} \tag{D.7}$$

Finally, in the last step, the calibration constraints from the first step are removed and the quadratic cost function is added in the objective function. The PMP model is then usable for simulations.

$$Max\ Z = \sum_{f}\sum_{c} (R_f - (d_{c,f} + 0.5Qc_{c,f}.X_{c,f})) \tag{D.8}$$

This standard approach of PMP has been widely used since its creation in 1990's, in particular to calibrate models including crop production. Several improvements have been made since. In particular, Röhm and Dabbert (2003) implemented an improved approach to calibrate not only on productions, but also on technologies. It is based on the assumption that the elasticity of substitution between different variants of the same production (e.g., a same crop irrigated or not) is higher than between different productions (e.g., two different crops). This is particularly interesting when the goal of the modelling framework is to study technical innovations, which can be assimilated as different variants of a same production. Compared to the standard approach (equations D.2 to D.8), the Röhm and Dabbert approach adds calibration constraints on variants, bounding levels of activities (i.e., a couple production-variant) to the observed levels. Keeping as an example a regional cross-scale model that integrates only crop farms, this can be written as:

$$Max\ Z = \sum_{f}\sum_{c}\sum_{v}(R_f - co_{c,v}.X_{c,\mathrm{v},f}) \tag{D.9}$$

$$\sum_{v} X_{c,v,f} \leq \sum_{v} X^0_{c,v,f}.(1+\varepsilon_1) \qquad [\lambda 1_{c,f}] \tag{D.10}$$

$$X_{c,\mathrm{v},f} \leq X^0_{c,\mathrm{v},f}.(1+\varepsilon_2) \qquad [\lambda 2_{c,\mathrm{v},f}] \tag{D.11}$$

Where $co_{c,v}$ represents respectively the linear cost vector for crop activities; $X^0_{c,\mathrm{v},f}$ is the non-negative vector of observed crop activity levels; ε_1 and ε_2 are small positive number vectors ($\varepsilon_1 < \varepsilon_2$); $\lambda 1_{c,f}$ is the vector duals for crop acreages; $\lambda 2_{c,\mathrm{v},f}$ is the vector duals for crop activities

Then the vector duals $\lambda 1_{c,f}$ and $\lambda 2_{c,\mathrm{v},f}$ are used for estimating parameters of the non-linear cost function satisfying equations (D.12.) and (D.15):

$$co_{c,v} + \lambda 1_{c,f} + \lambda 2_{c,v,f} = d_{c,v,f} + Q1_{c,f}.\sum_{v} X^0_{c,v,f} + Q2_{c,v,f}.X^0_{c,v,f} \tag{D.12}$$

$$d_{c,v,f} = co_{c,v} + \lambda 1_{c,f} + \lambda 2_{c,v,f} - k.\lambda 1_{c,f} - k.\lambda 2_{c,v,f} \tag{D.13}$$

$$Q1_{c,f,} = \frac{k|\lambda 1_{c,f}|}{\sum_{v} X^0_{c,v,f}} \tag{D.14}$$

$$Q2_{c,v,f} = \frac{k|\lambda 2_{c,v,f}|}{X^0_{c,v,f}} \tag{D.15}$$

Where $d_{c,\mathrm{v},f}$ represents the vectors of intercepts of the cost functions for crop activities; $Q1_{c,f,}$ and $Q1_{c,v,f}$ and $Q2_{c,v,f}$ are, respectively, the vectors of slope of the cost function of each crop, and of each crop activity (i.e., variant of the same crop); k is the vector of parameters that determine the weights of the linear part and the non-linear part of cost functions of crop activities.

The two cost function can be written as:

$$FC_{c,v,f}(X_{c,v,f}) = d_{c,v,f} + 0.5Q1_{c,f}.\sum_{v} X_{c,v,f} + 0.5Q2_{c,v,f}.X_{c,v,f} \tag{D.16}$$

Appendix E.
Description of agricultural productions in western France

Western France corresponds to two EU NUTS 2 regions: Brittany and Pays de la Loire. It spanned 14% of French utilized agricultural area (UAA) in 2018. The agricultural sector is mainly oriented towards livestock production: 69% of pig produced in France are raised in western France, 46% of poultry (i.e., Gallus species) and 36% of dairy cows (French Ministry of Agriculture 2018c).

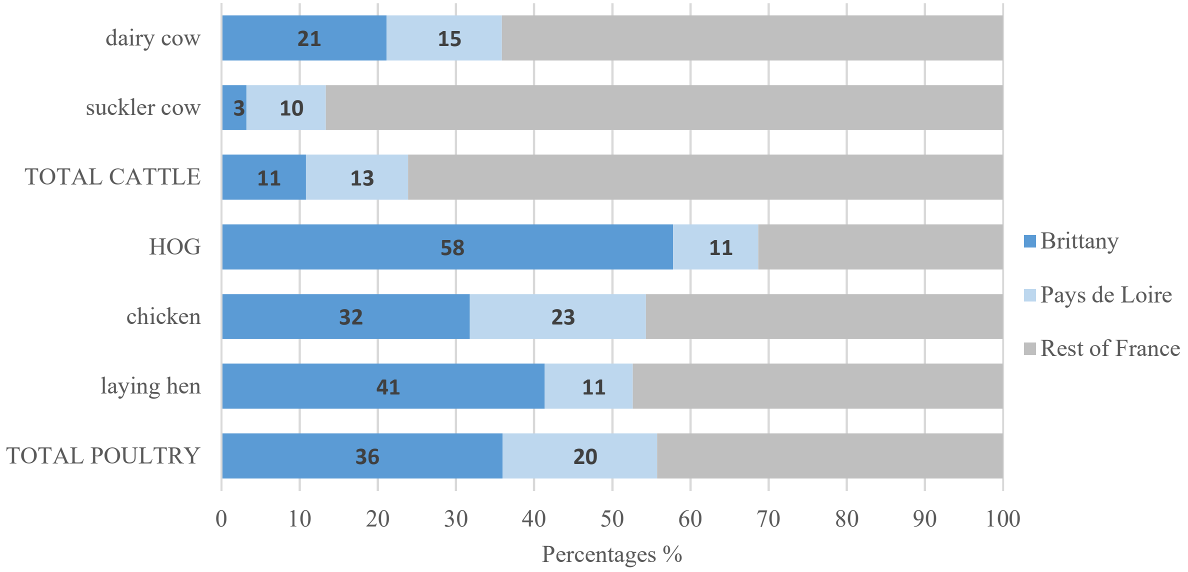
Regarding dairy production, milk deliveries have increased by 14% since 2000, to reach 91.4 million hectoliters in 2018. The dairy production is mainly located in Brittany that is the first dairy region in France. It has been substantially concentrated, with less farms producing more milk (e.g., -44% of milk-oriented farms in Brittany since 2000, but +14% of milk production) (Draaf Bretagne 2019). Dairy production also intensified with a decrease in dairy cow numbers of 8% during the same period in western France (French Ministry of Agriculture 2018c).

Regarding pig production, the herd of pig has increased by 4% since 2000, mainly due to the increase in Brittany. Brittany is the first pig-production region in France, far ahead Pays de la Loire that ranks second. Pig production has been substantially concentrated, with less farms producing more pigs (e.g., -26% of pig-oriented farms in Brittany since 2000, but +5% of pig production).

Overall, in western France, livestock production lies more the in the north, which corresponds to Brittany. Pays de la Loire is more oriented towards crop production, even though the dairy (and beef) production is substantial.

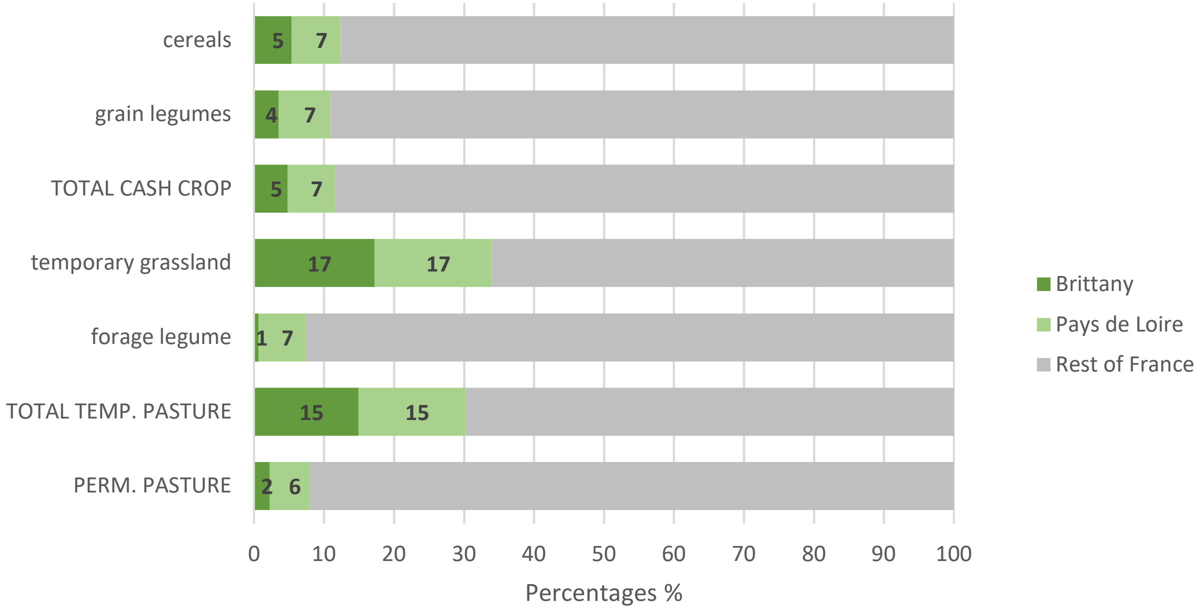
Regarding crop production, it represents 14% of the French crop production (DRAAF Pays de la Loire 2019). Cereals spanned 33% of western France UAA in 2018. This share has increased by 4 percentages points since 2000. However, crop production is mainly oriented to feed livestock: annual forage (mainly corn) represented in 2018 41% of the UAA, temporary pasture represent 25% of UAA, and permanent pasture 16%. Legume production remains low, with only 1.5% of UAA in western France (French Ministry of Agriculture 2018c).

Figure F1. Distribution of the main livestock productions (numbers of animals) in Brittany and Pays de la Loire compared to France (French Ministry of Agriculture 2018c)



Total poultry: only gallus species

Figure F2. Distribution of the main crop productions (areas) in Brittany and Pays de la Loire compared to France (French Ministry of Agriculture 2018c)



Cash crop: cereals, oilseeds and grain legumes ; Temp. pasture : temporary pasture ; Perm. pasture : permanent pasture

Appendix F.
Extracts from SYNERGY program coded under GAMS

```
*~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~MODELE SYNERGY~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*
$ontext
Name         SYN15c
Author       Julia JOUAN
Date        October 2019
Data        Imported from Excel file
$offtext
*~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*
option LP=conopt;
option NLP=conopt ;
option limrow=3000;
*********************************SETS*********************************
set
i          farm-type             /BL, PO, GC/
li(i)      livestock farm        /BL, PO/
cr(i)      crop farm             /GC/
k          states of nature    /k1, k2, k3, k4, k5, mean/
s          sector              /d22, d29, d35, d44, d49, d53, d56, d72, d85/
c          crop                 /barley, faba, lucerne, maizeF, maizeG, pastureP, pastureT, pea, rapeseed, sunflower, wheat/
cc(c)     cashcrops             /barley, faba, lucerne, maizeG, pea, rapeseed, sunflower,wheat/
leg(c)    legumes              /faba, lucerne, pea/
(…)
r         rotation             /ba_ba,fa_ba_ba, fa_fa, fa_ba_maF, fa_ba_maG, fa_maG_maG, fa_wh_maF, fa_wh_ba, fa_wh_maG,
                                fa_wh_maF_lu_wh_maF, fa_wh_maG_lu_wh_maG, fa_wh_ra_maF, fa_wh_ra_maG,
                                fa_wh_wh,lu_maF_wh, lu_lu, lu_maG_wh, lu_wh_maF, lu_wh_maG, lu_wh_wh, maF_maF, maG_maG,
                                maF_ba, maG_ba, maF_wh, maG_wh, maF_wh_ba, maG_wh_ba, maF_wh_sun, maG_wh_sun,
                                pea_pea, pea_wh, pea_ba_ba, pea_maG_maG, pea_wh_ba, pea_wh_maF, pea_wh_maG,
                                pea_maF_wh_ra_wh, pea_maG_wh_ra_wh, pea_wh_lu_maF, pea_wh_lu_maG, pea_wh_wh, PP_PP,
                                pt_pt, pt_maF, pt_maG, pt_maF_ba, pt_maG_ba, pt_maF_wh, pt_maG_wh, ra_ra, ra_wh_ba,
                                ra_maF_wh, ra_maG_wh, ra_wh_maF_wh, ra_wh_maG_wh, ra_wh_wh, sun_sun, wh_wh, wh_sun/
(...)
t         techniques           /conv/
gr        grass                /grassP, grassT, hayP, hayT, silageT/
co        concentrate         /Tsoybean, Trape, bran, Tsun/
fe        fertilizers         /manure_dairy, slurry_dairy, dropping_dairy, slurry_sow, slurry_pig, chemical/
ch(fe)    synthetic ferti.   /chemical/
ma(fe)    manure             /manure_dairy,slurry_dairy,dropping_dairy,slurry_pig,slurry_sow/
a          animals           /cow, heifer, calve, sow, pig/
(…)

ra         feed ration     /m_pl_std, m_pl_fab, m_pl_pea, m_pl_luc, m_br_std, m_br_fab, m_br_pea, m_br_luc, mh_pl_std,
                            mh_pl_fab, mh_pl_pea, mh_pl_luc, mh_br_std, mh_br_fab, mh_br_pea, mh_br_luc, h_std, h_fab,
                            h_pea, h_luc, std_hog, leg_hog/
(…)
ai(i,s,a,ra)   animal present on farm     /bl.(d22, d29, d35, d56).(cow,heifer,calve).(m_br_std, m_br_fab, m_br_pea, m_br_luc,
                                          mh_br_std, mh_br_fab, mh_br_pea, mh_br_luc, h_std, h_fab, h_pea, h_luc),
                                           bl.(d44, d49, d53, d72, d85).(cow,heifer,calve).(m_pl_std, m_pl_fab, m_pl_pea, m_pl_luc,
                                            mh_pl_std, mh_pl_fab, mh_pl_pea, mh_pl_luc, h_std, h_fab, h_pea, h_luc),
                                            po.(d22, d29, d35, d44, d49, d53, d56, d72, d85).(sow,pig).(std_hog, leg_hog)/

rc(c,r)     rotation possible    /barley.(fa_ba_ba, fa_wh_ba, fa_ba_maF, fa_ba_maG, maF_ba, maG_ba, maF_wh_ba,
                                  maG_wh_ba, pea_ba_ba, pea_wh_ba, pt_maF_ba, pt_maG_ba, ra_wh_ba),faba.(fa_ba_ba,
                                  fa_ba_maF, fa_ba_maG, fa_maG_maG, fa_wh_ba, fa_wh_maF, fa_wh_ra_maF,
```

```
                                          fa_wh_ra_maG, fa_wh_wh),
                                   lucerne.(lu_maF_wh, lu_maG_wh, lu_wh_maF, lu_wh_maG, lu_wh_wh, pea_wh_lu_maF,
                                            pea_wh_lu_maG),
                                   maizeF.(maF_maF, fa_ba_maF, fa_wh_maF, fa_wh_ra_maF, lu_maF_wh, lu_wh_maF, maF_ba,
                                           maF_wh, maF_wh_ba, maF_wh_sun, pea_wh_lu_maF, pea_wh_maF, pt_maF_ba, pt_maF,
                                           pt_maF_wh, pea_maF_wh_ra_wh, ra_wh_maF_wh, ra_maF_wh),
                                  maizeG.(maG_maG, fa_ba_maG, fa_maG_maG, fa_wh_maG, fa_wh_ra_maG, lu_maG_wh,
                                          lu_wh_maG, maG_ba, maG_wh, maG_wh_ba, maG_wh_sun, pea_maG_maG,
                                          pea_wh_lu_maG, pea_wh_maG, pt_maG_ba, pt_maG, pt_maG_wh, pea_maG_wh_ra_wh,
                                           ra_wh_maG_wh, ra_maG_wh),
                                  pastureP.(pp_pp),
                                  pastureT.(pt_pt, pt_maF, pt_maG, pt_maF_ba, pt_maG_ba, pt_maF_wh, pt_maG_wh),
                                  pea.(pea_ba_ba, pea_wh_ba, pea_wh_wh, pea_maF_wh_ra_wh, pea_maG_maG,
                                       pea_maG_wh_ra_wh, pea_wh_maF, pea_wh_maG),
                                  rapeseed.(ra_ra, fa_wh_ra_maF, fa_wh_ra_maG, pea_maF_wh_ra_wh, pea_maG_wh_ra_wh,
                                            ra_wh_ba, ra_wh_maF_wh, ra_wh_maG_wh, ra_wh_wh),
                                  sunflower.(maF_wh_sun, maG_wh_sun, wh_sun)
                                  wheat.(wh_wh, fa_wh_ba, fa_wh_wh, lu_wh_wh, fa_wh_maF, fa_wh_maG, fa_wh_ra_maF,
                                         fa_wh_ra_maG, lu_maF_wh, lu_maG_wh, lu_wh_maF, lu_wh_maG, maG_wh, maF_wh_ba,
                                          maG_wh_ba, maF_wh_sun, maG_wh_sun, pea_wh, pea_maF_wh_ra_wh,
                                          pea_maG_wh_ra_wh, pea_wh_lu_maF, pea_wh_lu_maG, pea_wh_maF, pea_wh_maG,
                                           pea_wh_ba, pea_wh_wh,maF_wh, pt_maF_ba, pt_maG_ba, pt_maF_wh, pt_maG_wh,
                                          ra_maF_wh, ra_maG_wh, ra_wh_ba, ra_wh_wh, wh_sun)/

sc          scenario                /sc_0/
;
**********************************SCALAR**********************************
scalar
fuel_conso          fuel direct consumption (Lperha)                            /150/
fuel_dir_emission fuel direct emissions (gNperL)                                /19/
fuel_indLoss        fuel indirection loss of N (gNperL)                         /1.4/
deposition          atmospherique deposition (kgNperha)                         /15/
no_symb_Nfix        non symbiotiq fixation of N (kgNperha)                      /5/
inorgfe_indloss     inorganic fe indirect loss of N (kgNperT)                   /8.2/
milk_density        milk density (kgperL)                                       /1.032/
milk_protein        protein content of FPCM milk (gperkg)                       /33/
milk_convprot       Nitrogen-to-protein conversion factor                       /6.38/
coeff_ex_c          coeff exchange of crops                                     /1/
coeff_ex_fe         coeff exchange of organic fertilisers                       /1/
tc                  transport cost of manure                                    /1.52/
epsilon1            perturbation                                                /0.00000001/
epsilon2            perturbation                                                /0.0000001/
;

**********************************PARAMETER**********************************
Parameter
chop_a(a,ra)                production costs of animal (€ per animal)
chop_c(c,r,t,s)             production costs (seeds and pesticides) of crops (€ per ha)
coeff_biomass_air(c)    coefficient aerial biomass ()
coeff_biomass_root(c) coefficient root biomass ()
coeff_ex_c_sc(sc)         coefficient exchange of crops()
coeff_ex_fe_sc(sc)        coefficient exchange of manure()
content_dryM_c(c)         content of dry matter in harvested crop (%)
content_dryM_co(co)  content of dry matter in concentrate (%)
content_dryM_gr(gr)   content of dry matter in grass (%)
content_dryM_seed(c) content of dry matter in seed crop (%)
density_seed(c,t)          density of seed (kgseed per ha)
dlandtot(s)                 total area of the region (ha)
indloss_N_a(a)             indirect loss of N in animals (kgN per Tdm)
indloss_N_c(c)            indirect loss of N in crops (kgN per Tdm)
```

```
indloss_N_co(co)        indirect loss of N in concentrates (kgN per Tdm)
indloss_N_seed(c)       indirect loss of N in seed production (kgN KgMs seed)
Keq_ma(c,r,ma)          effective synthetic fertilizer equivalence coefficient ()
mat_c(c)                crude protein of crops (kg per T or Tdm)
mat_co(co)              crude protein of concentrate (kg per T)
mat_gr(gr)              crude protein of fodder (kg per Tdm)
max_ma(c)               max percentage of fertilization by N from manure (%)
mh(c,i,s)               net mineralization of humus (kgNmin per ha)
mhp(c,r)                net mineralization by grassland overturn (kgNmin per ha)
mr(c,r)                 mineralization of crop residues from previous one  (kgNmin per ha)
mrci(c,r)               net mineralization of intermediate crop residues (kgNmin per ha)
nb_rot(r)               share of crop inside a crop rotation ()
need_c(a,ra,c)          animals' need in crops (kg per animal)
need_co(a,ra,co)        animals' need in concentrates (kg per animal)
need_gra(a,ra,gra)      animals' need in fodder (kg per animal)
prop_leg(c,s)           proportion of legumes in cultures (%)
pwb_a(a,k)              price of animal bought (€ per animal)
pwb_c(c,t,k)            price of crops bought on the world market (€ per T)
pwb_co(co,k)            price of concentrates bought on the world market (€ per T)
pwb_fe(fe,k)            price of fertilizers bought on the world market (€ per T)
pws_a(a,ra,k)           price of animal sold (€ per kgwl)
pws_c(c,t,k)            price of crops sold on the world market (€ per T)
pws_milk(ra,k)          price of milk sold (€ per L)
rate_clay(i,s)          rate of clay in soil (g per kg)
rate_CN_fe(fe)          C/N rate in fertilizer (kgC per T)
rate_Corg(i,s)          rate of C organic in soil (g per kg)
rate_cull(a,ra)         cull rate (%)
rate_N_a(a)             rate of N in animals (kgN per kgwl)
rate_N_c(c)             rate of N in crops (kgN per T)
rate_N_co(co)           rate of N in concentrates (kgN per T)
rate_N_fe(fe)           rate of N in fertilizers (kgN per T)
rate_N_seed(c)          rate of N in seeds (kgN per Tdm seed)
rate_prolif(a,ra)       prolificacy rate of animals (%)
rate_purchase(a)        purchase rate of animals (%)
rate_renew(a,ra)        renew rate of animals (%)
rate_sale(a)            sale rate of animals (%)
rf(c)                   quantity of Nmin in soil at balance closing (kgN per ha)
ri(c,r,s)               quantity of Nmin in soil at balance opening (kgN per ha)
su_c(c)                 coupled support for crops (€ per ha)
symb_Nfix(c)            N fixed by legumes (kgN per Tdm)
tb_milk(ra)             fat rate of milk (g per kgMilk)
Tmoy(i,s)               mean Temperature of sector (degrees Celsius)
time_c(c)               cultivation time (year)
tp_milk(ra)             protein rate of milk (g per kgMilk)
y_N(a,ra,ma)            production of manure from animals (T per animal)
y_c(c,t,s)              yield of crop (T ou Tdm per ha)
y_milk(a,ra)            yield of milk produced per cow (L per animal)
weight_a(a)             live weight of animals (kglv)
x_animal(a,ra,i,s)      calibration constraint on animals per ration ()
x_animal_tot(a,i,s)     calibration constraint on animals ()
x_culture(c,t,i,s)      calibration constraint on crops (ha)
x_culture_tot(c,i,s)    calibration constraint on crops (ha)
xxa(c,r,i,s)            crops' needs in fertilization (kgN per ha)
 (...)

nb_cr(c,r) crop       repetition in each crop rotation;
nb_cr(c,mono)$rc(c,mono)             =1;
nb_cr(c,uni)$rc(c,uni)              =1;
nb_cr(c,pluri)$rc(c,pluri)            =1;
nb_cr("barley","pea_ba_ba")           = 2;
```

```
nb_cr("lucerne","fa_wh_maF_lu_wh_maF")  = 3;
nb_cr("lucerne","fa_wh_maG_lu_wh_maG")  = 3;
nb_cr("lucerne","lu_maF_wh")           = 3;
nb_cr("lucerne","lu_maG_wh")            = 3;
(...)
Dlandtot(s) =  sum((c,i),x_culture_tot(c,i,s));
********************************VARIABLES********************************

positive variables
BL_C(c,t,i,s)              locally bought cultures (t)
BL_FE(fe,i,s)              locally bought fertilization (kgN)
BW_A(a,ra,i,s)             animals bought on world market (animals)
BW_C(c,t,i,s)              crops bought on world market (t)
BW_CO(co,i,s)              concentrates bought on world market (t)
BW_FE(fe,i,s)              synthetic fertilizers bought on world market (t)
BF_C(c,t,i,s)              cash crops kept in farm (tfm or tdm)
SF_C(c,t,i,s)              cash crops kept in farm (tfm or tdm)
K_FE(fe,i,s)               manure kept in farm (kgN)
K_C(c,t,i,s)               cash crops kept in farm (t)
K_GR(gr,i,s)               grass kept in farm (tdm)
K_N_nleg                   N fixed on annual crops (kgN)
K_N_fod                    N fixed on pasture (kgN)
N_a(a,ra,i,s)              number of animal produced  (animals)
number(i,s)                number of each type of farm  (farms)
Q_FE(ch,i,s)               quantity of N from ch ferti spread on crops (tN)
Q_MA(ma,i,s)               quantity of N from manure spread on crops (tN)
Q_FE_C(c,r,ch,i,s)         quantity of N from ch ferti spread on crops (tN)
Q_MA_C(c,r,ma,i,s)         quantity of N from manure spread on crop (tN)
SL_C(c,t,i,s)              locally sold culture (t)
SL_FE(fe,i,s)              locally sold fertilization (kgN)
SUBSIDIES(i,s)             coupled subsidies (€)
SW_A(a,ra,i,s)             animals sold on world market (animals)
SW_C(c,t,i,s)              crops sold on world market (t)
SW_milk(ra,i,s)            milk sold on world market (L)
X(c,r,t,i,s)               surface of culture (ha)
Xrot(r,t,i,s)              surface of rotations (ha)
;

Variables
GM_total(i,s)              gross margin (€)
GM_total_nlp(i,s)          gross margin (€)
U                          objective (€)
;

********************************EQUATION STATEMENT********************************
Equations
********objective ********
Objective                  objective function (€)
Profit_total               profit calculation
********cropping module********
Rota                       definition of rotations
Landtot1                   definition of acreages
Landtot2                   definition of acreages
Production_Cc              quantity of cash crops produced
Production_Foc             quantity of forage produced
Production_GrT             production of pastureT
Production_GrP             production of pastureP
Legume1                    constraint of minimum share of legumes
pasture1                   pasture specifications
pasture2                   pasture specifications
```

```
********animal module********
Demo_VL1              prolificacy of cattle
Demo_VL2              cull of cattle
Demo_PO1              prolificacy of pig
Demo_PO2              purchases of sow
Production_a          quantity of animals sold
Production_milk       quantity of milk sold
Numerous1             animal number specifications
********feeding module********
Alim_cc               animals' need of cash crops in standard ration
Alim_foc              animals' need of forage except grass
Alim_co               animals' need of concentrate
Alim_grass            animals' need of grass
Alim_silage           animals' need of silage
Alim_hay              animals' need of hay
********fertilisation module********
Fertilisation1        manure management
Fertilisation1bis     manure management
Fertilisation2        synthetic N fertilizer management
Fertilisation2bis     synthetic N fertilizer management
Fertilisation3        equilibrium need and supply of fertilization
Fertilisation4        constraint of spreadable area
Fertilisation5        manure specifications
Fertilisation6        manure specifications
Fertilisation7        manure specifications
Fertilisation8        manure specifications
Production_ma         quantity of manure produced
Need_n_culture        plants' need of fertilization
********local exchanges********
Exchange_C1           local exchanges of crops
Exchange_C2           local exchanges of crops
Exchange_C3           local exchanges of crops
Exchange_FE1          local exchanges of manure
Exchange_FE2          local exchanges of manure
********PMP********
Calib_a1              constraint calibration animal
Calib_c1              constraint calibration crop
Calib_c1bis           constraint calibration crop
;

********************************EQUATION WRITING*********************************

********************objective********************
Objective.. U=e=sum((i,s), GM_total(i,s)) ;
profit_total(i,s)..GM_total(i,s)=e= sum((cc,t), (SW_C(cc,t,i,s)*pws_c(cc,t,'mean'))-(BW_C(cc,t,i,s)*pwb_c(cc,t,'mean')))
                   +sum((c,t), (SL_C(c,t,i,s)*pws_c(c,t,'mean'))-(BL_C(c,t,i,s)*pwb_c(c,t,'mean')*0.9))
                   - sum((c,r,t)$rc(c,r),X(c,r,t,i,s)*chop_c(c,r,t,s))
                   -sum(ma,SL_FE(ma,i,s)*tc)- sum(ch, BW_FE(ch,i,s)*pwb_fe(ch,'mean'))
                   +sum((a,ra)$ai(i,s,a,ra),SW_A(a,ra,i,s)*weight_a(a)*pws_a(a,ra,'mean'))+
sum(ra,SW_milk(ra,i,s)*pws_milk(ra,'mean'))
                   -sum(co,BW_CO(co,i,s)*pwb_co(co,'mean'))-sum((a,ra)$ai(i,s,a,ra),BW_A(a,ra,i,s)*pwb_a(a,'mean'))
                   -sum((a,ra)$ai(i,s,a,ra),N_A(a,ra,i,s)*chop_a(a,ra))
                   +sum ((c,r,t)$rc(c,r), X(c,r,t,i,s)*su_c(c)) ;

********************Croping module********************
rota(c,r,t,i,s)$rc(c,r).. X(c,r,t,i,s)=e= nb_cr(c,r)*Xrot(r,t,i,s)*nb_rot(r);
Landtot1(s).. sum((r,t,i), Xrot(r,t,i,s))=l=Dlandtot(s);
Landtot2(s).. sum((c,r,t,i)$rc(c,r), X(c,r,t,i,s))=l=Dlandtot(s);
Production_Cc(cc,t,i,s).. sum(r$rc(cc,r), X(cc,r,t,i,s)*y_c(cc,t,s))=e= SW_C(cc,t,i,s)+SL_C(cc,t,i,s)+ K_C(cc,t,i,s);
Production_Foc(foc,t,i,s).. sum(r$rc(foc,r), X(foc,r,t,i,s)*y_c(foc,t,s))=e= SL_C(foc,t,i,s)+ K_C(foc,t,i,s) ;
```

```
Production_GrT(gr,i,s).. sum((r,t),
X('pastureT',r,t,i,s)$rc('pastureT',r)*y_c('pastureT',t,s))=e=K_GR('grassT',i,s)+K_GR('hayT',i,s)+K_GR('silageT',i,s)  ;
Production_GrTleg(gr,i,s).. sum((r,t),
X('pastureTleg',r,t,i,s)$rc('pastureTleg',r)*y_c('pastureTleg',t,s))=e=K_GR('grassTleg',i,s)+K_GR('hayTleg',i,s)+K_GR('silageTleg',i,s)
;
Production_GrP(gr,i,s).. sum((r,t), X('pastureP',r,t,i,s)$rc('pastureP',r)*y_c('pastureP',t,s))=e=K_GR('grassP',i,s)+K_GR('hayP',i,s)  ;
Legume1.. sum((leg,r,t,i,s)$rc(leg,r),X(leg,r,t,i,s))=g=sum(s,Dlandtot(s)*0.10);
pasture1(i,s).. sum((r,t),X('pastureP',r,t,i,s)$rc('pastureP',r))=l=x_culture_tot('pastureP',i,s)*1.01;
pasture2(i,s).. sum((r,t),X('pastureP',r,t,i,s)$rc('pastureP',r))=g=x_culture_tot('pastureP',i,s)*0.99;

********************animal module ********************
Demo_VL1(ra,i,s).. N_a("calve",ra,i,s)$ai(i,s,"calve",ra) =e=
N_a("cow",ra,i,s)$ai(i,s,"cow",ra)*rate_prolif("cow",ra)*(0.5+0.5*0.236);
Demo_VL2(ra,i,s).. N_a("heifer",ra,i,s)$ai(i,s,"heifer",ra) =e= N_a("cow",ra,i,s)$ai(i,s,"cow",ra)*rate_renew("cow",ra);
Demo_PO1(ra,i,s).. N_a("pig",ra,i,s)$ai(i,s,"pig",ra)=e= rate_prolif("sow",ra)*N_a("sow",ra,i,s)$ai(i,s,"sow",ra);
Demo_PO2(ra,i,s).. BW_A("sow",ra,i,s)$ai(i,s,"sow",ra)=e= rate_purchase("sow")*N_a("sow",ra,i,s)$ai(i,s,"sow",ra);
Production_a(a,ra,i,s).. SW_A(a,ra,i,s)$ai(i,s,a,ra) =e= N_a(a,ra,i,s)$ai(i,s,a,ra)*rate_sale(a) ;
Production_milk(ra,i,s).. SW_milk(ra,i,s) =e= sum(a$ai(i,s,a,ra), N_a(a,ra,i,s)$ai(i,s,a,ra)*y_milk(a,ra));
Numerous1(a,ra,cr,s).. N_a(a,ra,cr,s)$ai(cr,s,a,ra)=e=0 ;

********************feeding module********************
alim_cc(cc,i,s).. sum((a,ra)$ai(i,s,a,ra),(need_c(a,ra,cc)/1000)*N_a(a,ra,i,s)) =l= sum(t, BL_C(cc,t,i,s)+BW_C(cc,t,i,s)+ K_C(cc,t,i,s));
alim_foc(foc,i,s).. sum((a,ra)$ai(i,s,a,ra),(need_c(a,ra,foc)/1000)*N_a(a,ra,i,s))=l= sum(t,K_C(foc,t,i,s));
alim_co(co,i,s).. sum((a,ra)$ai(i,s,a,ra),(need_co(a,ra,co)/1000)*N_a(a,ra,i,s))=l= BW_CO(co,i,s);
alim_grass(i,s).. sum((a,ra)$ai(i,s,a,ra),need_gra(a,ra,'grass')*N_a(a,ra,i,s))=l=K_GR('grassT',i,s)+ K_GR('grassP',i,s);
alim_silage(i,s)..sum((a,ra)$ai(i,s,a,ra),need_gra(a,ra,'silage')*N_a(a,ra,i,s))=l=K_GR('silageT',i,s);
alim_hay(i,s)..sum((a,ra)$ai(i,s,a,ra),need_gra(a,ra,'hay')*N_a(a,ra,i,s))=l=K_GR('hayT',i,s)+ K_GR('hayP',i,s);

********************fertilisation module********************

Fertilisation1(ma,i,s).. Q_MA(ma,i,s)=e=K_FE(ma,i,s)+BL_FE(ma,i,s);
Fertilisation1bis(ma,i,s)..sum((c,r)$rc(c,r),Q_MA_C(c,r,ma,i,s))=e=Q_MA(ma,i,s);
Fertilisation2(ch,i,s)..  Q_FE(ch,i,s)=e=BW_FE(ch,i,s)*rate_n_fe(ch);
Fertilisation2bis(ch,i,s)..  sum((c,r)$rc(c,r),Q_FE_C(c,r,ch,i,s))=e= Q_FE(ch,i,s);
fertilisation3(c,r,i,s).. NEED_N(c,r,i,s)$rc(c,r)=e=sum(ma, Q_MA_C(c,r,ma,i,s)$rc(c,r)*Keq_ma(c,r,ma))+
sum(ch,Q_FE_C(c,r,ch,i,s)$rc(c,r));
fertilisation4(i,s)..sum(ma,K_FE(ma,i,s)+BL_FE(ma,i,s))=l=170*sum((c,r,t)$rc(c,r),X(c,r,t,i,s));
fertilisation5(nfod,r,i,s).. Q_MA_C(nfod,r,'dropping_dairy',i,s)$rc(nfod,r)=e=0;
fertilisation6(nspc,r,ma,i,s)..Q_MA_C(nspc,r,ma,i,s)$rc(nspc,r)=e=0;
fertilisation7(ma,s)..BL_FE(ma,'PO',s)=e=0;
fertilisation8(c,r,i,s)..sum(ma,Q_MA_C(c,r,ma,i,s)$rc(c,r))=l=max_ma(c)*(sum(ma, Q_MA_C(c,r,ma,i,s)$rc(c,r))+
sum(ch,Q_FE_C(c,r,ch,i,s)$rc(c,r)));
Production_ma(ma,i,s)..sum((a,ra)$ai(i,s,a,ra), N_a(a,ra,i,s)*y_N(a,ra,ma))=e= SL_FE(ma,i,s)+ K_FE(ma,i,s);
need_n_culture(c,r,i,s)..  NEED_N(c,r,i,s)$rc(c,r) =e= sum(t, X(c,r,t,i,s)$rc(c,r)*Xxa(c,r,i,s));

********************local exchanges********************

Exchange_C1(c,t).. sum ((i,s),SL_C(C,t,i,s))=e= sum((i,s),BL_C(c,t,i,s));
Exchange_C2(c,t).. sum ((i,s),SL_C(C,t,i,s))=e=  sum ((i,s),SL_C(C,t,i,s)*1);
Exchange_C3(c,t).. sum ((i,s),SL_C(C,t,i,s))=l= 0.001 ;
Exchange_FE1(ma,s).. sum (i,SL_FE(ma,i,s))=e= sum(i,BL_FE(ma,i,s)) ;
Exchange_FE2(ma,i,s).. SL_FE(ma,i,s)=e=SL_FE(ma,i,s)*1;

********************calibration********************
calib_a1(a_c,i,s)..       sum(ra$ai(i,s,a_c,ra),N_a(a_c,ra,i,s))=l= x_animal_tot(a_c,i,s)*(1+epsilon1);
calib_a1bis(a_c,i,s)..     sum(ra$ai(i,s,a_c,ra),N_a(a_c,ra,i,s))=g= x_animal_tot(a_c,i,s)*(1-epsilon1);
calib_a2(a_c,ra,i,s)..     N_a(a_c,ra,i,s)=l= x_animal(a_c,ra,i,s)*(1+epsilon2*100);
calib_c1(c,i,s)..         sum((r,t)$rc(c,r),X(c,r,t,i,s))=l= x_culture_tot(c,i,s)*(1+epsilon1);
calib_c1bis(fo,i,s)..     sum((r,t)$rc(fo,r),X(fo,r,t,i,s))=g= x_culture_tot(fo,i,s)*(1-epsilon1);
```

```
*********************************PMP*********************************
********************First step of PMP********************
model pmp_lp /objective,calib_c1,calib_c1bis,calib_a1,profit_total,rota,Landtot1
                        ,production_Cc,Production_Foc,Production_GrT,Production_GrP,Production_GrTleg
                        ,Demo_VL1,Demo_VL2,Demo_PO1,Demo_PO2,Production_a,Production_milk,Alim_cc
                        ,Alim_foc,Alim_co,alim_grass,alim_silage,alim_hay,alim_grassleg,alim_silageleg,alim_hayleg
                        ,Fertilisation1,Fertilisation1bis,Fertilisation2,Fertilisation2bis,fertilisation3
                        ,fertilisation4,fertilisation5,fertilisation6,fertilisation7,fertilisation8
                        ,Production_ma,need_n_culture,Exchange_C1, Exchange_C2
                        ,Exchange_FE1, Exchange_FE2, Numerous1,pasture1,pasture2,Landtot2/  ;

Parameter
alpha_a  intercept of the marginal cost function for animals
alpha_c  intercept of the marginal cost function for crops
beta_a1  slop of the marginal cost function for animals
beta_c   slop of the marginal cost function for crops
mu_a1    duals for animal calibration
mu_c     duals for crop calibration
;
(...)
solve pmp_lp using NLP maximizing U;
(...)

********************Second step of PMP********************
Equation calib_c2,calib_c2bis ;
calib_c2(c,r,t,i,s)$rc(c,r)..         X(c,r,t,i,s)=l= X_obs(c,r,t,i,s)*(1+epsilon1);
calib_c2bis(fo,r,t,i,s)$rc(fo,r)..     X(fo,r,t,i,s)=g= X_obs(fo,r,t,i,s)*(1-epsilon1);

model pmp_lp2 /pmp_lp - calib_c1 - calib_c1bis + calib_c2 + calib_c2bis /

parameter
alpha_a1
(...)
solve pmp_lp2 using NLP maximizing U;
(...)
SCALAR
alpha_an /0.5/
;
mu_c(c,r,t,i,s)$rc(c,r)               = calib_c2.m(c,r,t,i,s)+calib_c2bis.m(c,r,t,i,s);
alpha_c(c,r,t,i,s)$rc(c,r)            = mu_c(c,r,t,i,s) - alpha_cr(c)*abs(mu_c(c,r,t,i,s));
beta_c(c,r,t,i,s)$X_obs2(c,r,t,i,s)    = alpha_cr(c)*abs(mu_c(c,r,t,i,s))/x_obs2(c,r,t,i,s) ;
mu_a1(a_c,i,s)$ai2(i,s,a_c)             = calib_a1.m(a_c,i,s);
alpha_a1(a_c,i,s)                     = mu_a1(a_c,i,s)- alpha_an*abs(mu_a1(a_c,i,s));
beta_a1(a_c,i,s)$x_animal_tot(a_c,i,s)   = alpha_an*abs(mu_a1(a_c,i,s))/x_animal_tot(a_c,i,s);
(...)

********************Third step of PMP********************
variable
Z;
(...)

equation
obj_nlp  fonction objectif non lineaire
profit_total_nlp(i,s)
;

obj_nlp.. Z=e=sum((i,s), GM_total_nlp(i,s)) ;

profit_total_nlp(i,s)..GM_total_nlp(i,s)=e=
                   sum((cc,t),(SW_C(cc,t,i,s)*pws_c(cc,t,'mean'))-(BW_C(cc,t,i,s)*pwb_c(cc,t,'mean')))
```

```
            +sum((c,t), (SL_C(c,t,i,s)*pws_c(c,t,'mean'))-(BL_C(c,t,i,s)*pwb_c(c,t,'mean')))
            -sum((c,r,t)$rc(c,r),X(c,r,t,i,s)*chop_c(c,r,t,s))
            -sum((c,r,t)$rc(c,r),alpha_c(c,r,t,i,s)*X(c,r,t,i,s)+ 0.5*beta_c(c,r,t,i,s)*sqr(X(c,r,t,i,s)))
            -sum(ma,SL_FE(ma,i,s)*tc)- sum(ch, BW_FE(ch,i,s)*pwb_fe(ch,'mean'))
            +sum((a,ra)$ai(i,s,a,ra),SW_A(a,ra,i,s)*weight_a(a)*pws_a(a,ra,'mean'))
            +sum(ra,SW_milk(ra,i,s)*pws_milk(ra,'mean'))
            -sum(co,BW_CO(co,i,s)*pwb_co(co,'mean'))
            -sum((a,ra)$ai(i,s,a,ra),BW_A(a,ra,i,s)*pwb_a(a,'mean'))
            -sum((a_c),alpha_a1(a_c,i,s)*sum(ra$ai(i,s,a_c,ra),N_A(a_c,ra,i,s))
             +0.5*beta_a1(a_c,i,s)*sqr(sum(ra$ai(i,s,a_c,ra),N_A(a_c,ra,i,s))))
             -sum((a,ra)$ai(i,s,a,ra),N_A(a,ra,i,s)*chop_a(a,ra))
            +sum((c,r,t)$rc(c,r),su_c(c)*X(c,r,t,i,s));

model pmp_nlp /pmp_lp2 + profit_total_nlp + obj_nlp - profit_total - objective - calib_a1- calib_c2 - calib_c2bis/
(...)

solve pmp_nlp using NLP maximizing Z ;

model scenario1 /pmp_nlp /     ;
(...)
solve scenario1 using NLP maximizing Z ;
********************SYNE CALCULATOR********************
(...)
INPUT_atm(i,s,sc)=sum((c,r,t), X.l(c,r,t,i,s)*deposition);
INPUT_NfIX(i,s,sc)=sum((c,r,t), X.l(c,r,t,i,s)*no_symb_Nfix);
INPUT_BIO(i,s,sc)=sum((c,r,t), X.l(c,r,t,i,s)*y_c(c,t,s)*content_dryM_c(c)*prop_leg(c,s)*symb_Nfix(c));
INPUT_EN_DIR(i,s,sc)=sum((c,r,t),X.l(c,r,t,i,s)*fuel_conso*fuel_dir_emission/1000);
INPUT_EN_INDIR(i,s,sc)=sum((c,r,t),X.l(c,r,t,i,s)*fuel_conso*fuel_indLoss/1000);
INPUT_SEED_DIR(i,s,sc)=sum((c,r,t), X.l(c,r,t,i,s)/time_c(c)*density_seed(c,t)*rate_N_seed(c)/1000*content_dryM_seed(c));
INPUT_SEED_INDIR(i,s,sc)=sum((c,r,t),X.l(c,r,t,i,s)/time_c(c)*density_seed(c,t)*indloss_N_seed(c)/1000*content_dryM_seed(c));
INPUT_INORG_FE_DIR(i,s,sc)=sum(ch, BW_FE.l(ch,i,s)*rate_N_fe(ch));
INPUT_INORG_FE_INDIR(i,s,sc)=sum(ch, BW_FE.l(ch,i,s)*inorgfe_indloss);
INPUT_MANURE(i,s,sc)=sum(ma,BL_FE.l(ma,i,s)-SL_FE.l(ma,i,s));
FEED_LEG_DIR(i,s,sc)=(sum((hp,t),(BW_C.l(hp,t,i,s)+
BL_C.l(hp,t,i,s))*rate_N_c(hp)*content_dryM_c(hp))+sum(co,BW_CO.l(co,i,s)*rate_N_co(co)*content_dryM_co(co)));
CULTURE_LEG(i,s,sc)=(sum((hp,t),(SW_C.l(hp,t,i,s)+SL_C.l(hp,t,i,s))*rate_N_c(hp)*content_dryM_c(hp)));
FEED_LEG_INDIR(i,s,sc)=(sum((hp,t),(BW_C.l(hp,t,i,s)+
BL_C.l(hp,t,i,s))*indloss_N_c(hp)*content_dryM_c(hp))+sum(co,BW_CO.l(co,i,s)*indloss_N_co(co)*content_dryM_co(co)));
FLOW_HP(i,s,sc)= FEED_LEG_DIR(i,s,sc)-CULTURE_LEG(i,s,sc);
OUTPUT_HP_DIR(i,s,sc)= abs(FLOW_HP(i,s,sc))$(FLOW_HP(i,s,sc)<0);
INPUT_HP_DIR(i,s,sc)= abs(FLOW_HP(i,s,sc))$(FLOW_HP(i,s,sc)>0);
INPUT_HP_INDIR(i,s,sc)= (FLOW_HP(i,s,sc)*FEED_LEG_INDIR(i,s,sc)/FEED_LEG_DIR(i,s,sc))$((FLOW_HP(i,s,sc)>0) and
(FEED_LEG_DIR(i,s,sc)<>0));
FEED_NLEG_DIR(i,s,sc)=(sum((lp,t),(BW_C.l(lp,t,i,s)+ BL_C.l(lp,t,i,s))*rate_N_c(lp)*content_dryM_c(lp)));
CULTURE_NLEG(i,s,sc)=(sum((lp,t),(SW_C.l(lp,t,i,s)+SL_C.l(lp,t,i,s))*rate_N_c(lp)*content_dryM_c(lp)));
FEED_NlEG_INDIR(i,s,sc)=(sum((lp,t),(BW_C.l(lp,t,i,s)+ BL_C.l(lp,t,i,s))*indloss_N_c(lp)*content_dryM_c(lp)));
FLOW_LP(i,s,sc)= FEED_NLEG_DIR(i,s,sc)-CULTURE_NLEG(i,s,sc);
OUTPUT_LP_DIR(i,s,sc)= abs(FLOW_LP(i,s,sc))$(FLOW_LP(i,s,sc)<0);
INPUT_LP_DIR(i,s,sc)= abs(FLOW_LP(i,s,sc))$(FLOW_LP(i,s,sc)>0);
INPUT_LP_INDIR(i,s,sc)= (FLOW_LP(i,s,sc)*FEED_NlEG_INDIR(i,s,sc)/FEED_NLEG_DIR(i,s,sc))$((FLOW_LP(i,s,sc)>0) and
(FEED_NLEG_DIR(i,s,sc)<>0));
OUTPUT_milk(i,s,sc)=sum(ra,(SW_milk.l(ra,i,s)*milk_density*(0.337+(0.116*tb_milk(ra)/10)+(0.06*tp_milk(ra)/10))*(milk_protei
n/1000)/milk_convprot));
ANIMAL_BUY_DIR(i,s,sc) = sum(ra,BW_A.l('sow',ra,i,s)*113*rate_n_a('sow')/1000);
ANIMAL_BUY_INDIR(i,s,sc)=sum(ra,BW_A.l('sow',ra,i,s)*113*indloss_N_a('sow')/1000);
ANIMAL_SELL(i,s,sc) = sum((a,ra),SW_A.l(a,ra,i,s)*weight_a(a)*rate_n_a(a)/1000);
FLOW_ANIMAL(i,s,sc) = ANIMAL_BUY_DIR(i,s,sc)- ANIMAL_SELL(i,s,sc)   ;
OUTPUT_ANIMAL(i,s,sc)= abs(FLOW_ANIMAL(i,s,sc))$(FLOW_ANIMAL(i,s,sc)<0);
INPUT_ANIMAL_DIR(i,s,sc)= abs(FLOW_ANIMAL(i,s,sc))$(FLOW_ANIMAL(i,s,sc)>0);
```

```
INPUT_ANIMAL_INDIR(i,s,sc)=(FLOW_ANIMAL(i,s,sc)*ANIMAL_BUY_INDIR(i,s,sc)/ANIMAL_BUY_DIR(i,s,sc))$((FLOW_ANIMAL(i,s,
sc)>0) and (ANIMAL_BUY_DIR(i,s,sc)<>0));
CARBONE_A_FARM(i,s,sc)=(sum((a,ra,ma), N_a.l(a,ra,i,s)*y_N(a,ra,ma)*rate_cn_fe(ma)));
CARBONE_A_EXCHANGE(i,s,sc)=(sum(ma,(BL_FE.l(ma,i,s)-SL_FE.l(ma,i,s))*rate_cn_fe(ma)));
BIOMASS_C_AIR(i,s,sc)=sum((spois,r,t),
X.l(spois,r,t,i,s)*y_c(spois,t,s)*content_dryM_c(spois)*coeff_biomass_air(spois))+sum((r,t),X.l('pea',r,t,i,s)*3.5);
BIOMASS_C_ROOT(i,s,sc)=(sum((rootC,r,t),
X.l(rootC,r,t,i,s)*y_c(rootC,t,s)*content_dryM_c(rootC)*coeff_biomass_root(rootC))+sum((pois,r,t),X.l(pois,r,t,i,s)*2)
                   +sum((t,r),X.l("pastureP",r,t,i,s)*5)+sum((r,t),X.l("pastureT",r,t,i,s)*10/4)+sum((r,t),X.l("pastureTleg",r,t,i,s)*10/4));
Carbone_A_TOTAL(i,s,sc)=(CARBONE_A_FARM(i,s,sc)+CARBONE_A_EXCHANGE(i,s,sc))/1000;
Carbone_C_TOTAL(i,s,sc)= (BIOMASS_C_AIR(i,s,sc)+ BIOMASS_C_ROOT(i,s,sc))*40;
Carbone_actif(i,s,sc)=0.3*10000*1.3*rate_Corg(i,s)*(1-0.4);
F1(i,s,sc)=20/(1+(20-1)*exp(-0.120*(Tmoy(i,s)-15)));
F2(i,s,sc)=exp(-2.440*rate_clay(i,s)/1000);
F3(i,s,sc)=1+0.19*rate_clay(i,s)/1000;
h(i,s,sc)=0.166*F3(i,s,sc);
coeff_min(i,s,sc)=0.048*f1(i,s,sc)*F2(i,s,sc);
kca(i,s,sc)=Carbone_actif(i,s,sc)*coeff_min(i,s,sc)*sum((c,r,t), X.l(c,r,t,i,s));
hm(i,s,sc)=(h(i,s,sc)*Carbone_C_TOTAL(i,s,sc)*10)+(Carbone_A_TOTAL(i,s,sc)*1000*0.4);
stock_n_soil(i,s,sc)=((hm(i,s,sc)-kca(i,s,sc))/10);
TOTAL_INPUT_DIR(i,s,sc)=INPUT_atm(i,s,sc)+INPUT_NfIX(i,s,sc)+INPUT_BIO(i,s,sc)+INPUT_EN_DIR(i,s,sc)+INPUT_SEED_DIR(i,s,sc)
+INPUT_INORG_FE_DIR(i,s,sc)
                    +INPUT_MANURE(i,s,sc)+ INPUT_LP_DIR(i,s,sc)+ INPUT_HP_DIR(i,s,sc)+INPUT_ANIMAL_DIR(i,s,sc);
TOTAL_INPUT_INDIR(i,s,sc)= INPUT_EN_INDIR(i,s,sc)+
INPUT_SEED_INDIR(i,s,sc)+INPUT_INORG_FE_INDIR(i,s,sc)+INPUT_HP_INDIR(i,s,sc)+INPUT_LP_INDIR(i,s,sc)+INPUT_ANIMAL_IND
IR(i,s,sc);
TOTAL_OUTPUT(i,s,sc)= OUTPUT_LP_DIR(i,s,sc)+ OUTPUT_HP_DIR(i,s,sc)+ OUTPUT_milk(i,s,sc)+ OUTPUT_ANIMAL(i,s,sc);
SYNE(i,s,sc)= (TOTAL_OUTPUT(i,s,sc))/(TOTAL_INPUT_DIR(i,s,sc)+TOTAL_INPUT_INDIR(i,s,sc)-(stock_n_soil(i,s,sc)));
SYNB(i,s,sc)=(TOTAL_INPUT_DIR(i,s,sc)+TOTAL_INPUT_INDIR(i,s,sc)-(TOTAL_OUTPUT(i,s,sc))-(stock_n_soil(i,s,sc)))/sum((c,r,t),
X.l(c,r,t,i,s)$(X.l(c,r,t,i,s)<>0));
(...)
```

Appendix G.
Description of technical coefficients and data sources of the SYNERGY model

The SYNERGY model has 58 technical coefficients that belong to one or more modules that shaping this model. The table D1 presents all these technical coefficients. The references of their sources are available after this table. When several sources were used to generate one technical coefficient (e.g., annual data on prolificacy rate of sows for year 2013-2017), only the more recent source is indicated. Besides, for reasons of ease of reading, the sources of the same organization were gathered.

Table D1. Technical coefficients of the SYNERGY model and associated data sources

Name of technical coefficients	Description of technical coefficients	Unit	Source	Crop	Livestock	Feeding	Fertilization	SyNE	Number of elements
chop_a	production costs of animal	€/animal	IDELE-Inosys[a], IFIP-GTE[b]		X				33
chop_c	production costs (seeds and pesticides) of crops	€/ha	Extension services (ES)[c]	X					20
coeff_biomass_air	coefficient aerial biomass	-	SyNE calculator[d]					X	11
coeff_biomass_root	coefficient root biomass	-	SyNE calculator					X	11
content_dryM_c	content of dry matter in harvested crop	%	SyNE calculator, INRA[e]	X				X	11
content_dryM_co	content of dry matter in concentrate	%	SyNE calculator, INRA	X				X	4
content_dryM_seed	content of dry matter in seed crop	%	SyNE calculator, INRA					X	11
density_seed	density of seed	kgseed/ha	SyNE calculator, INRA					X	11
indloss_N_a	indirect loss of N in animals	kgN/Twl	SyNE calculator, ecoinvent[f]					X	2
indloss_N_c	indirect loss of N in crops	kgN/Tdm	SyNE calculator, ecoinvent					X	11
indloss_N_co	indirect loss of N in concentrates	kgN/Tdm	SyNE calculator, ecoinvent					X	4
indloss_N_seed	indirect loss of N in seeds	kgN/Tdm seed	SyNE calculator, ecoinvent					X	11
keq_ma	effective synthetic fertilizer equivalence coeff.	kg/T or Tdm	COMIFER[g]				X		354
mat_c	crude protein of crops	kg/T or Tdm	INRA			X			11
mat_co	crude protein of concentrate	kg/T or Tdm	INRA			X			4
mat_gr	crude protein of fodder	kg/Tdm	INRA-INRAtion[h]			X			5
max_ma	max % of fertilization by N from manure	%	Agreste[i]				X		11
mh	net mineralization of humus	kgNmin / ha	COMIFER				X		159
mhp	net mineralization by grassland overturn	kgNmin / ha	COMIFER				X		19
mr	mineralization of crop residues from previous one	kgNmin / ha	COMIFER				X		41
mrci	net mineralization of intermediate crop residues	kgNmin / ha	COMIFER				X		26
nb_rot	share of crop inside a crop rotation	-	authors' expertise	X					55
need_c	animals' need in crops	kgms/animal	INRAtion, IFIP-Porfal[j]			X			282
need_co	animals' need in concentrates	kgms/animal	INRAtion, IFIP-Porfal			X			116
need_gra	animals' need in fodder	kgms/animal	INRAtion, IFIP-Porfal			X			150
pwb_a	price of animal bought	€/animal	IFIP-GTE, ES		X				1
pwb_c	price of crops bought on the world market	€/T	IFIP[k]			X			9
pwb_co	price of concentrates bought on the world market	€/T	IFIP			X			4
pwb_fe	price of fertilizers bought on the world market	€/T	INSEE[l], La Dépêche[m]				X		1

Name of technical coefficients	Description of technical coefficients	Unit	Source	Crop	Livestock	Feeding	Fertilization	SyNE	Number of elements
pws_a	price of animal sold	€/kgwl	FranceAgriMer[n], IDELE[o]		X				5
pws_c	price of crops sold on the world market	€/T	FranceAgriMer, experts	X					9
pws_milk	price of milk sold	€/L	FranceAgriMer		X				25
rate_clay	rate of clay in soil	g/kg	GisSol[p]					X	9
rate_CN_fe	C/N rate in fertilizer	kgC/T	SyNE, IFIP					X	6
rate_Corg	rate of C organic in soil	g/kg	GisSol					X	9
rate_cull	cull rate	%	IDELE-Inosys / IFIP		X				33
rate_N_a	rate of N in animals	kgN/Twl	SyNE calculator					X	5
rate_N_c	rate of N in crops	kgN/T or Tdm	INRA					X	11
rate_N_co	rate of N in concentrates	kgN/T	INRA					X	4
rate_N_fe	rate of N in fertilizers	kgN/T	SyNE calculator, IFIP					X	6
rate_N_seed	rate of N in seeds	kgN/T or Tdm	SyNE calculator, INRA					X	11
rate_prolif	prolificacy rate of animals	%	IDELE-Inosys, ES		X				33
rate_purchase	purchase rate of animals	%	ES		X				1
rate_renew	renew rate of animals	%	IDELE-Inosys, IFIP		X				33
rate_sale	sale rate of animals	%	expert		X				5
rf	quantity of Nmin in soil at balance closing	kgN/ha	COMIFER, experts				X		9
ri	quantity of Nmin in soil at balance opening	kgN/ha	COMIFER, experts				X		54
su_c	coupled support for crops	€/ha	Ministère Agriculture[q]	X					3
symb_Nfix	N fixed by legumes	kgN/Tdm	SyNE calculator, Herridge et al (2008)[r]				X	X	3
tb_milk	fat rate of milk	g/kg	IDELE-Inosys					X	25
time_c	cultivation time	year	SyNE calculator					X	11
tmoy	mean Temperature of department	°C	Infoclimat[s]					X	9
tp_milk	protein rate of milk	g/hg	IDELE-Inosys					X	25
y_c	yield of crop	T or Tdm/ha	Agreste	X				X	99
y_milk	yield of milk produced per cow	L/cow	IDELE-Inosys		X			X	5
y_N	production of manure from animals	kgN/animal	Dourmard[t], Levasseur[tu], ES				X	X	207
weight_a	live weight of animals	l kg	SyNE calculator, IFIP		X			X	5
xxa	crops' needs in fertilization	kgN/ha	COMIFER				X		99

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Appendix H.
Executive summary of the TERUnic foresight

La prospective sur l'autonomie protéique dans les filières animales de l'Ouest

Projet TERUNIC : les scénarios

Le projet TERUNIC propose une méthode de prospective partagée et régionalisée sur l'autonomie protéique du secteur de l'élevage en Bretagne et Pays de la Loire.

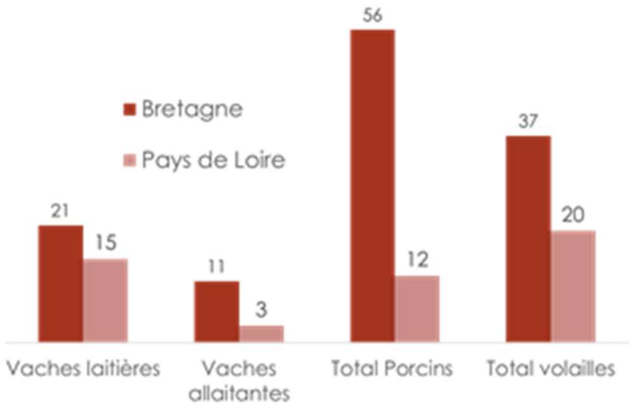
Ce fascicule présente la démarche de construction des scénarios et les hypothèses sur lesquelles elle s'appuie ainsi que les scénarios qui ont été construits.
Trois scénarios contrastés d'évolution de l'« Autonomie protéique » à l'horizon 2040 sont proposés.

Prospective
Elevage
Ouest
Autonomie protéique

Le territoire de l'Ouest (Bretagne et Pays de la Loire) est caractérisé par une forte concentration des trois filières animales : bovine, porcine et avicole. Ces filières requièrent de fortes ressources en protéines végétales pour la croissance des animaux. Les protéines d'origine territoriale sont insuffisantes pour répondre à cette demande et la majeure partie des matières premières riches en protéines, comme les tourteaux, souvent OGM, sont importées d'autres continents.

Le projet TERUNIC, au sein du programme SOS PROTEIN (PEI-PEADER), vise à évaluer à l'échelle du territoire différentes stratégies pour améliorer l'autonomie protéique en alimentation animale.

La mise en œuvre d'une approche de prospective a conduit à la production de trois scénarios contrastés d'évolution de l'autonomie protéique territoriale à horizon 2040.



Part des productions animales dans l'effectif national (en %)

La méthodologie de la prospective n'a pas pour objectif de prédire l'avenir mais d'anticiper différents états finaux ainsi que les cheminements que l'on pourrait rencontrer pour y parvenir, sans préjuger de leur caractère probable ou souhaitable. Dans la tradition française, la prospective est une approche participative et volontariste qui mobilise un groupe d'experts réunis afin de croiser leurs compétences diversifiées dans un contexte de liberté de parole et de compréhension.

Après avoir recueilli des états finaux, fixé l'horizon de l'étude et identifié les facteurs qui déterminent le futur, il s'agit de produire plusieurs scénarios décrivant les évolutions possibles. L'intérêt est d'éliminer la nécessité d'un consensus sur une seule vision du futur et d'ouvrir la pensée à de multiples possibilités. Elle aide à la construction de stratégies flexibles capables de s'adapter à des conditions changeantes.

L'approche se veut transdisciplinaire, c'est-à-dire combinant les approches scientifiques disciplinaires et les savoirs d'acteurs de terrain. Au final, les résultats de la prospective résident autant dans les scénarios élaborés que dans le processus de construction partagée qui permet aux acteurs d'identifier et d'estimer les zones d'incertitude sur les enjeux de l'autonomie protéique dans leurs régions.

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Éléments de cadrage de la prospective

Echelle d'étude

On étudie l'autonomie protéique dans les filières bovines, porcines et avicoles en agriculture conventionnelle et en agriculture biologique dans les régions Bretagne et Pays de la Loire.

La production végétale est abordée en complément d'un atelier animal ou de façon indépendante, avec un focus sur les légumineuses.

Ouest
- Bretagne
- Pays de la Loire

Filières
- Bovines
- Porcines
- Avicoles
- Céréales Oléoprotéagineux

Exploitation
- Élevages spécialisés
- Polyculture élevage
- Grandes cultures

Déroulement de la prospective

La méthode de construction des scénarios a été condensée sur une période de 6 mois, alternant une phase de synthèse bibliographique avec des focus groupes et des entretiens individuels

Panel des acteurs

Les entretiens ont été menés avec trente acteurs de structures privées et publiques, représentant les différentes filières végétales et animales. Au total, sept catégories d'acteurs ont été identifiées.

La méthode de construction des scénarios a été condensée sur une période de 6 mois

A **Agriculteurs (3)**
Polyculture élevage *(lait et allaitant)*
Polyculture élevage AB *(lait et volailles)*
Polyculture élevage AB *(lait)*

B **Instituts techniques (5)**
IDELE *(bovin viande et économie)*
IFIP *(nutrition porcine)*
ITAVI *(nutrition volaille)*
Terres Inovia *(protéagineux, oléagineux, et économie)*

C **Organismes de développement (3)**
CIVAM Bretagne et Vendée
FRAB
GABB Anjou

D **Organismes consulaires (3)**
Chambres d'Agriculture Bretagne *(filière volaille)* Pays de la Loire *(filières porcine et laitière)*

E **Organismes de recherche et Administration (6)**
DRAAF Bretagne et Pays de la Loire *(SRISE / valorisation des données)*
FranceAgriMer *(Céréales et oléo protéagineux)*
INRA *(économistes)*

F **Coopératives et entreprises (10)**
AGRIAL
BEL
CAVAC
DESHYOUEST
TERRENA
TRISKALIA

G **Alimentation animale**
Elvor (SAVENCIA)
MixScience (AVRIL)
Nutrinoë
Valorex

Horizon

L'horizon 2040 a été choisi pour la prospective. Il s'agit d'un compromis qui permet d'avoir des anticipations suffisamment solides tout en s'affranchissant du futur proche, comme la réforme de la PAC ou les innovations déjà en place.

Tendances lourdes

Il s'agit de tendances supposées constantes et certaines, agissant sur tous les scénarios. Elles concernent les prévisions démographiques nationales, la prise en compte du changement climatique susceptible d'introduire un aléa croissant sur la production agricole, l'augmentation du prix de l'énergie fossile ainsi que l'annonce d'une réglementation environnementale de plus en plus stricte sur l'utilisation des produits phytosanitaires.

Une augmentation de la population mondiale de 9,8 milliards d'ici 2050, avec 66% de la population en zone urbaine selon l'ONU et une progression de +19% de la population de l'Ouest entre 2012 et 2040 selon l'Insee.

La prise en compte du changement climatique + 1 à 2,5 °C sur le territoire d'ici 2050 avec des conséquences sur les ressources en eau et les périodes de sécheresse.

L'augmentation du prix de l'énergie fossile et une réglementation stricte sur l'utilisation des produits phytosanitaires

Résultats de la prospective

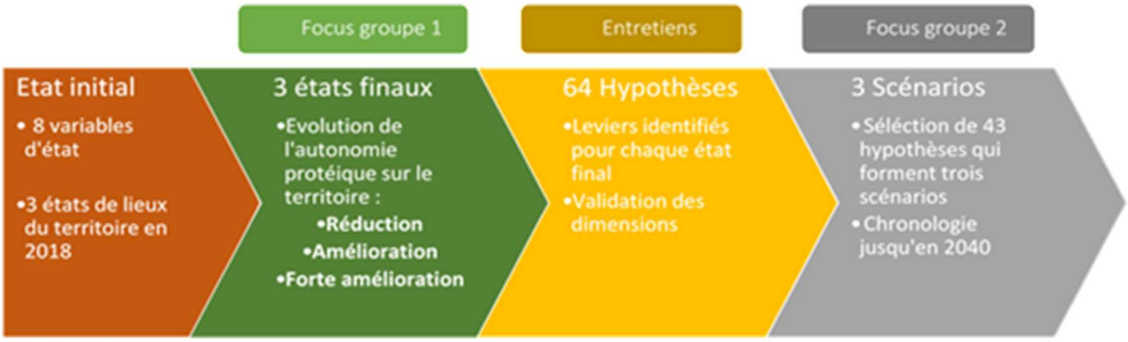
Le déroulement du travail participatif

Les résultats ont été construits en plusieurs temps ; après chaque étape une mise à plat des informations et des points de vue collectés était nécessaire pour garder une cohérence dans l'interprétation des résultats ; des retours en arrière ont parfois été réalisés.

Les états finaux n'ont été validés qu'à la fin du 2ème focus groupe comme point de départ des scénarios

L'état initial est devenu complet après la construction des états finaux et la validation des différentes variables d'états par les acteurs

Les hypothèses ont été retravaillées plusieurs fois entre l'identification des principales hypothèses au début de l'étude, celles décrites après les entretiens, et la synthèse des 43 hypothèses classées par nos soins et choisies par les acteurs pour construire les scénarios.



Focus groupe 1

Entretiens

Focus groupe 2

Etat initial
- 8 variables d'état
- 3 états de lieux du territoire en 2018

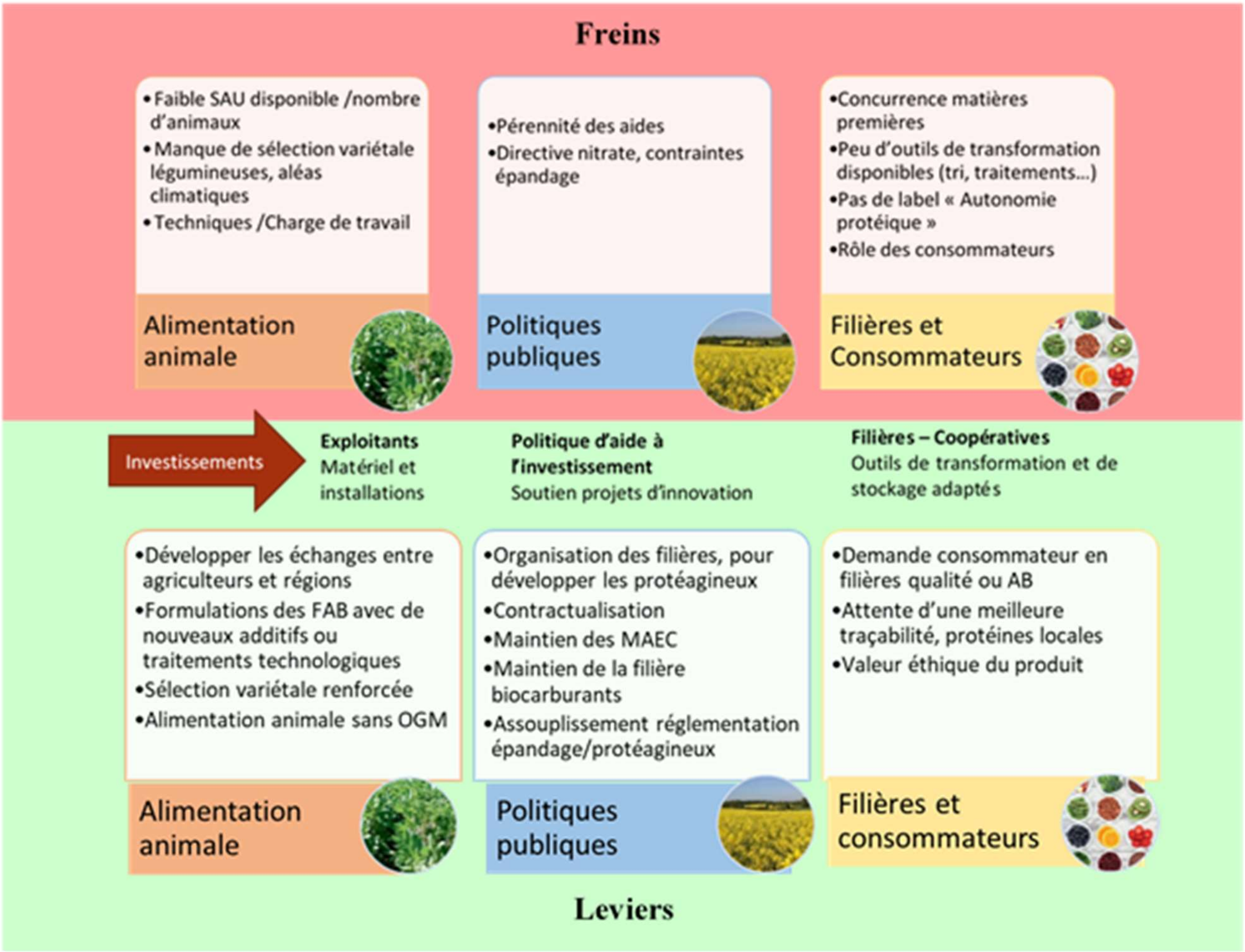
3 états finaux
- Evolution de l'autonomie protéique sur le territoire :
  - **Réduction**
  - **Amélioration**
  - **Forte amélioration**

64 Hypothèses
- Leviers identifiés pour chaque état final
- Validation des dimensions

3 Scénarios
- Séléction de 43 hypothèses qui forment trois scénarios
- Chronologie jusqu'en 2040

Les principaux freins et leviers identifiés par les acteurs

Les principaux freins évoqués par les acteurs balaient les trois dimensions d'analyse proposées : celle des innovations agronomiques et techniques, celles des marchés et de la régulation, celle des filières et des consommateurs, ceci à l'échelle de l'exploitation et du territoire.



Freins

- Faible SAU disponible /nombre d'animaux
- Manque de sélection variétale légumineuses, aléas climatiques
- Techniques /Charge de travail

Alimentation animale

- Pérennité des aides
- Directive nitrate, contraintes épandage

Politiques publiques

- Concurrence matières premières
- Peu d'outils de transformation disponibles (tri, traitements…)
- Pas de label « Autonomie protéique »
- Rôle des consommateurs

Filières et Consommateurs

Investissements

Exploitants
Matériel et installations

Politique d'aide à l'investissement
Soutien projets d'innovation

Filières – Coopératives
Outils de transformation et de stockage adaptés

- Développer les échanges entre agriculteurs et régions
- Formulations des FAB avec de nouveaux additifs ou traitements technologiques
- Sélection variétale renforcée
- Alimentation animale sans OGM

Alimentation animale

- Organisation des filières, pour développer les protéagineux
- Contractualisation
- Maintien des MAEC
- Maintien de la filière biocarburants
- Assouplissement réglementation épandage/protéagineux

Politiques publiques

- Demande consommateur en filières qualité ou AB
- Attente d'une meilleure traçabilité, protéines locales
- Valeur éthique du produit

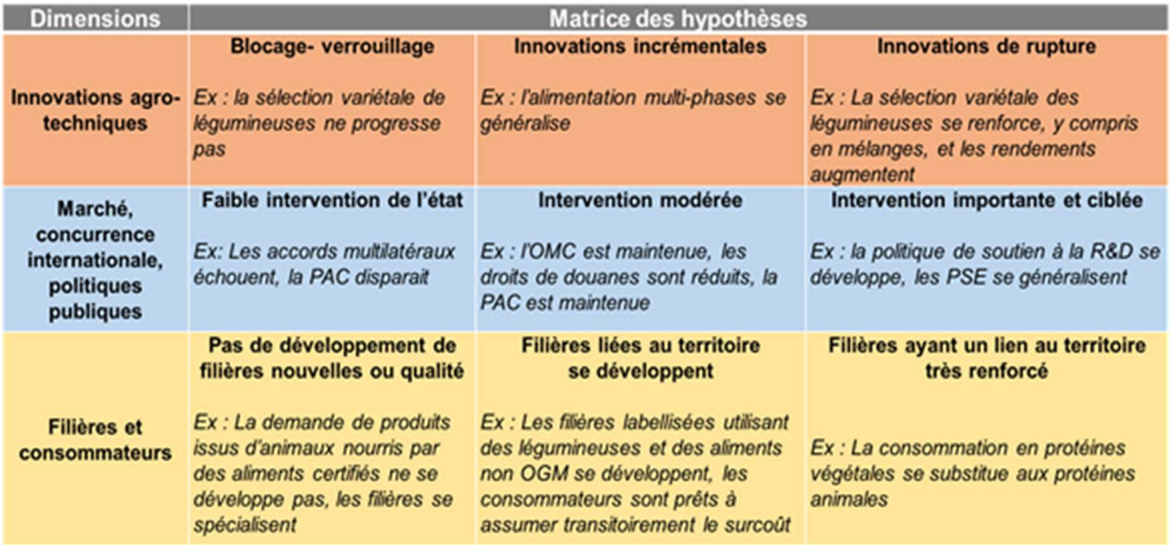
Filières et consommateurs

Leviers

Résultats de la prospective

Le classement des 64 hypothèses selon trois dimensions et plusieurs modalités

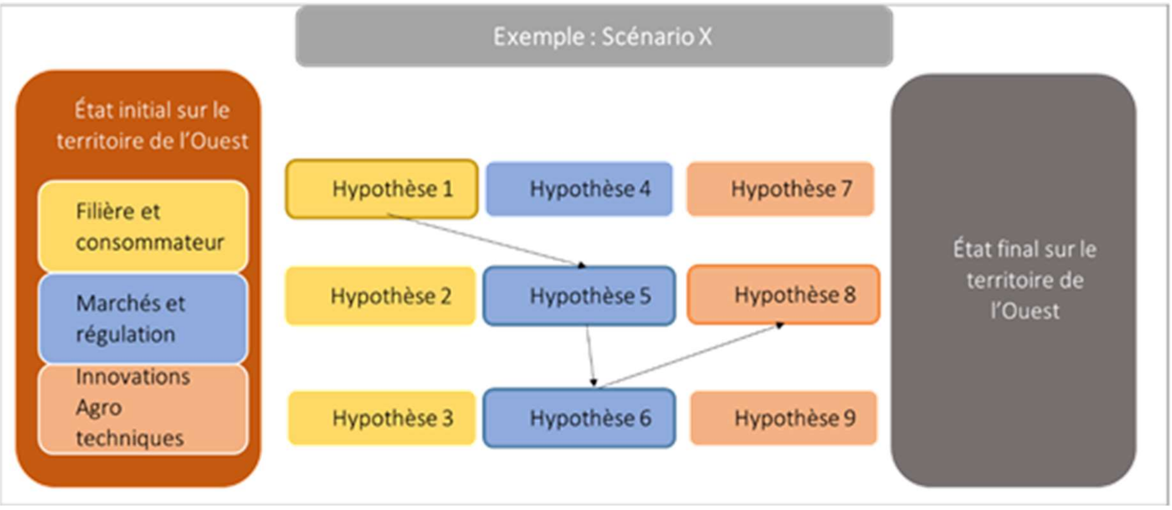
Les déterminants de l'autonomie protéique (freins et leviers) ont été classés selon trois dimensions : 1) celle des innovations agro-techniques ; 2) celle liée aux marchés et aux politiques publiques ; et 3) celle liée à l'organisation des filières et au comportement des consommateurs. Ainsi, à l'issue des entretiens, 64 freins et leviers, appelés **hypothèses** ont été collectés et classés dans ces trois dimensions.



Dimensions	Matrice des hypothèses		
	Blocage- verrouillage	**Innovations incrémentales**	**Innovations de rupture**
Innovations agro-techniques	*Ex : la sélection variétale de légumineuses ne progresse pas*	*Ex : l'alimentation multi-phases se généralise*	*Ex : La sélection variétale des légumineuses se renforce, y compris en mélanges, et les rendements augmentent*
	Faible intervention de l'état	**Intervention modérée**	**Intervention importante et ciblée**
Marché, concurrence internationale, politiques publiques	*Ex: Les accords multilatéraux échouent, la PAC disparait*	*Ex : l'OMC est maintenue, les droits de douanes sont réduits, la PAC est maintenue*	*Ex : la politique de soutien à la R&D se développe, les PSE se généralisent*
	Pas de développement de filières nouvelles ou qualité	**Filières liées au territoire se développent**	**Filières ayant un lien au territoire très renforcé**
Filières et consommateurs	*Ex : La demande de produits issus d'animaux nourris par des aliments certifiés ne se développe pas, les filières se spécialisent*	*Ex : Les filières labellisées utilisant des légumineuses et des aliments non OGM se développent, les consommateurs sont prêts à assumer transitoirement le surcoût*	*Ex : La consommation en protéines végétales se substitue aux protéines animales*

Le chainage des hypothèses

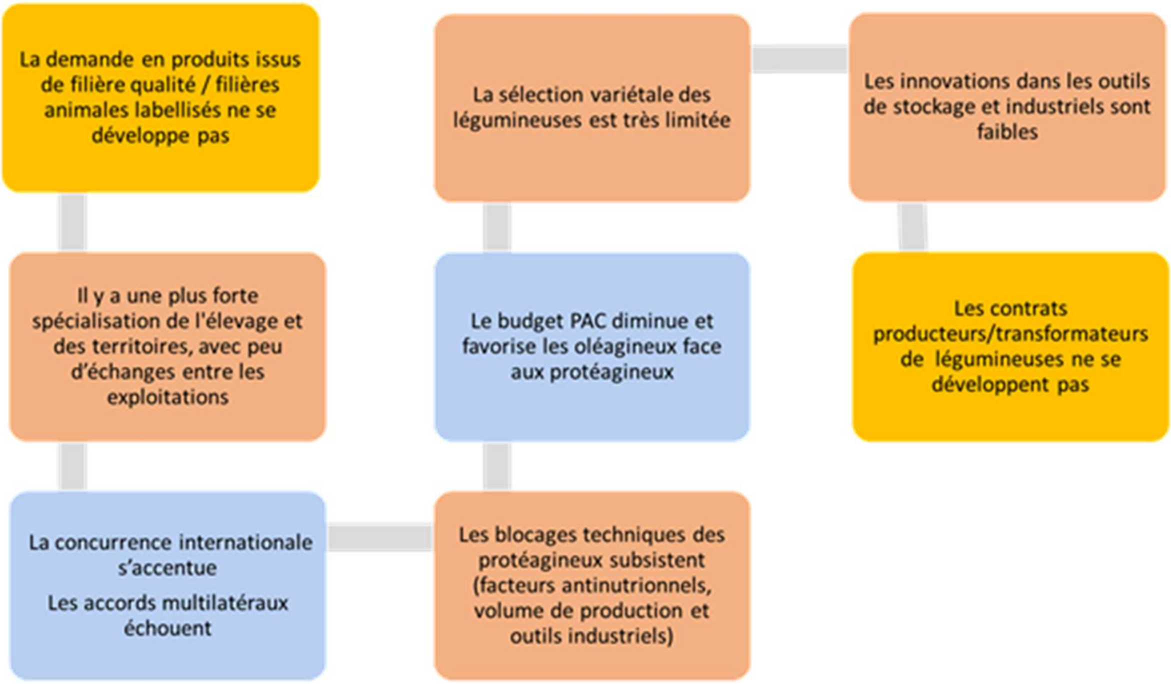
Chacun de ces scénarios a été construit comme une combinaison cohérente de 43 hypothèses différentes choisies par les acteurs lors du second focus groupe parmi les 64 hypothèses de départ. Le discours construit par chaque groupe d'acteurs autour de cette combinaison permet de décrire à la fois une image plausible du système considéré en 2040 et des éléments de trajectoire reliant l'état actuel du système à cette image future. Le groupe a retenu trois scénarios.



Les scénarios

Scénario 1 : « Spécialisation du territoire et économies d'échelle »

Les exploitations du territoire s'agrandissent et se spécialisent davantage dans l'élevage, le nombre d'animaux tend à augmenter dans toutes les filières, ce qui entraîne une disparition des petites structures d'élevage. La mondialisation impose une concurrence internationale élevée entre les régions productrices. La demande mondiale est dynamique en particulier pour les ressources céréalières et, a contrario, la situation des légumineuses se dégrade et les surfaces sont faibles dans la SAU. Le foncier agricole est réduit du fait de la forte demande d'espace liée à l'attractivité accrue du territoire. Enfin, la demande des consommateurs est tournée majoritairement vers des produits à bas prix, les filières-qualité et les labels subsistent, mais pour une faible part de la population. Du point de vue environnemental, La qualité de l'eau du territoire se retrouve dégradée par l'intensification des productions.



La demande en produits issus de filière qualité / filières animales labellisés ne se développe pas

Il y a une plus forte spécialisation de l'élevage et des territoires, avec peu d'échanges entre les exploitations

La concurrence internationale s'accentue

Les accords multilatéraux échouent

Les blocages techniques des protéagineux subsistent (facteurs antinutrionnels, volume de production et outils industriels)

Le budget PAC diminue et favorise les oléagineux face aux protéagineux

La sélection variétale des légumineuses est très limitée

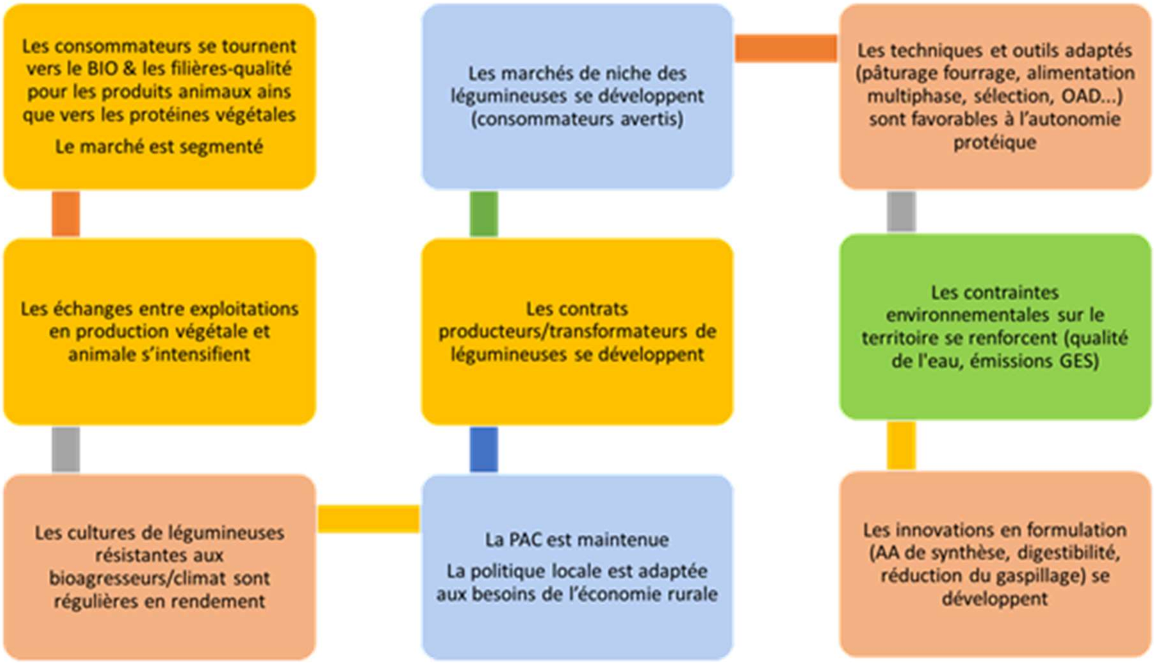
Les innovations dans les outils de stockage et industriels sont faibles

Les contrats producteurs/transformateurs de légumineuses ne se développent pas

Les scénarios

Scénario 2 : « Développement de filières locales »

Le nombre d'animaux est stable dans toutes les filières, avec une augmentation de la production grâce au développement de l'élevage de précision. Les exploitations s'agrandissent lentement et leur taille se stabilise par rapport à la tendance actuelle. Les légumineuses occupent une part importante dans la SAU du territoire, grâce à une politique de soutien qui taxe les engrais minéraux et les rejets azotés. Les collectivités locales favorisent le foncier agricole face à l'artificialisation des terres et maîtrisent l'étalement urbain. De plus, les consommateurs sont plus sensibles aux produits animaux nourris sans OGM, au bien-être animal, à la qualité des produits et à la rémunération du producteur. Dans ce contexte, les labels qualité se développent, avec une bonne reconnaissance par les consommateurs. Les normes environnementales sont strictes et la qualité de l'eau s'améliore sur le territoire grâce aux efforts engagés. L'autonomie protéique se renforce sur le territoire, en particulier dans la filière des ruminants.



Les consommateurs se tournent vers le BIO & les filières-qualité pour les produits animaux ains que vers les protéines végétales

Le marché est segmenté

Les échanges entre exploitations en production végétale et animale s'intensifient

Les cultures de légumineuses résistantes aux bioagresseurs/climat sont régulières en rendement

La PAC est maintenue

La politique locale est adaptée aux besoins de l'économie rurale

Les contrats producteurs/transformateurs de légumineuses se développent

Les marchés de niche des légumineuses se développent (consommateurs avertis)

Les techniques et outils adaptés (pâturage fourrage, alimentation multiphase, sélection, OAD...) sont favorables à l'autonomie protéique

Les contraintes environnementales sur le territoire se renforcent (qualité de l'eau, émissions GES)

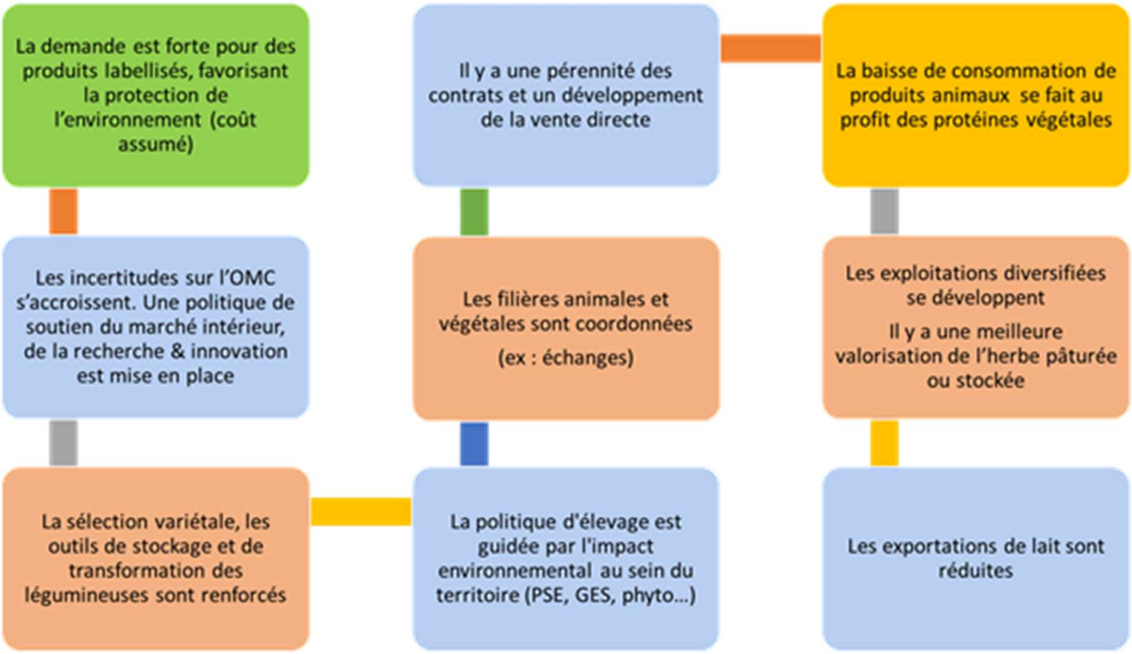
Les innovations en formulation (AA de synthèse, digestibilité, réduction du gaspillage) se développent

Les scénarios

Scénario 3 : « Environnement, complémentarité et économies de gamme »

La production baisse dans tous les élevages, le nombre d'animaux diminue, en particulier dans la filière porcine. Les fermes s'agrandissent peu, mais les terres agricoles sont maintenues grâce à l'aménagement parcellaire. La politique environnementale et les directives sur le bien-être animal se renforcent. Les légumineuses, elles, occupent une forte part dans la SAU du territoire, grâce au soutien public à ces productions et à la mise en place d'une taxe sur les produits OGM.

Du côté de la demande, les consommateurs amplifient leur consommation de protéines végétales dans leur alimentation, ils consomment moins de produits animaux et leur comportements d'achat sont tournés vers des produits de qualité. La région est moins spécialisée en élevage et retrouve une forte autonomie protéique, par la réduction globale des besoins en protéines et une augmentation simultanée des ressources protéiques sur le territoire.



La demande est forte pour des produits labellisés, favorisant la protection de l'environnement (coût assumé)

Il y a une pérennité des contrats et un développement de la vente directe

La baisse de consommation de produits animaux se fait au profit des protéines végétales

Les incertitudes sur l'OMC s'accroissent. Une politique de soutien du marché intérieur, de la recherche & innovation est mise en place

Les filières animales et végétales sont coordonnées

(ex : échanges)

Les exploitations diversifiées se développent

Il y a une meilleure valorisation de l'herbe pâturée ou stockée

La sélection variétale, les outils de stockage et de transformation des légumineuses sont renforcés

La politique d'élevage est guidée par l'impact environnemental au sein du territoire (PSE, GES, phyto...)

Les exportations de lait sont réduites

DOCTORAT
BRETAGNE ECONOMIE
LOIRE ET GESTION

AGRO
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OUEST

Titre : Valorisation économique et environnementale des complémentarités culture-élevage à travers la production locale de légumineuses : approche par modélisation de l'Ouest de la France

Mots clés : légumineuses, complémentarités techniques, production jointe, modèle bioéconomique, programmation mathématique, sans-OGM

Résumé :

Cette thèse de doctorat porte sur les complémentarités culture-élevage permises par les légumineuses, dans la région de l'Ouest de la France. Une évaluation économique et environnementale de ces complémentarités est réalisée depuis l'échelle de l'exploitation agricole jusqu'à celle de la région.

Le principal apport de cette thèse est l'élaboration d'un modèle bioéconomique SYNERGY qui modélise les échanges locaux de cultures (dont les légumineuses) et d'effluents entre des exploitations de grandes cultures et des exploitations d'élevage. Ce modèle prend en compte l'effet précédent des légumineuses et comprend des rations alternatives avec ces cultures riches en protéines. Les principaux résultats de simulation montrent que les aides couplées aux légumineuses accroissent leur production mais n'engendrent pas une meilleure valorisation des complémentarités techniques. Un moyen d'accroître l'utilisation de légumineuses en alimentation animale est de labelliser les produits animaux sans OGM. Cependant, les échanges locaux simulés restant faibles, les légumineuses sont en grande partie importées de l'extérieur de la région. Ainsi, les résultats économiques et environnementaux ne sont pas améliorés à l'échelle régionale et l'autonomie en protéines diminue.

Enfin, à l'échelle des filières, nous montrons que les échanges de légumineuses engendrent des coûts de transaction élevés, peu réduits par les contrats existants. Le développement de marchés valorisant les ressources locales pourrait encourager la culture de légumineuses.

Title: Economic and environmental benefits from crop-livestock complementarities through local legume production: a modelling approach for western France

Keywords: legumes, technical complementarities, joint production, bio-economic model, mathematical programming

Abstract :

This Ph.D. thesis studies crop-livestock complementarities enabled by legumes in the region of western France. Economic and environmental assessment of these complementarities is performed from the farm scale to the regional scale.

The main contribution of this research is the development of the bio-economic model SYNERGY, which represents local exchanges of crops (including legumes) and manure between crop-oriented farms and livestock-oriented farms. This model represents the pre-crop effect of legumes and includes alternative rations with these high-protein crops. The main simulation results show that coupled subsidies to legumes increase their production but do not lead to better valuation of technical complementarities. One way to increase the use of legumes in animal feed is to label GMO-free animal products. However, since the simulated local exchanges of legumes remain low, these crops are largely imported from outside the region. Thus, the economic and environmental results do not improve at the regional scale, and protein self-sufficiency decreases.

Finally, at the scale of the agro-food chain, exchanges of legumes lead to high transaction costs, which current contracts reduce only slightly. Developing markets that value local resources could foster legume production.