



Modelling biomass and nutrient flows in agro-food systems at the local scale : scenario simulation and assessment in a French case-study

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ÉCOLE DOCTORALE : SCIENCES ET ENVIRONNEMENT

Par : HUGO FERNANDEZ MENA

TITRE :

*« Modélisation des flux de biomasse et de nutriments dans les territoires agricoles.
Simulation et évaluation de scénarios appliqués à un cas d'étude en France. »*

*“Modelling biomass and nutrient flows in agro-food systems at the local scale.
Scenario simulation and assessment in a French case-study.”*

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“Todo lo que puedas imaginar es real”

Pablo Picasso

PhD Abstract

Feeding the growing global population in a context of global change raises new challenges for agriculture regarding its production efficiency and impacts on natural resources. Solutions for towards farming sustainability require to improve nutrient and biomass recycling in agro-food systems, i.e. to move from linear to more circular flows of fertilizers, crop products, feedstuff, by-products and organic wastes. Innovative tools exploring material exchanges between farms and their upstream and downstream partners in agro-food systems at the local scale are needed. In the present work, the state of the art about analysis methods, models and environmental tools addressing nutrient and biomass flows at different scales is reviewed. The FAN (“Flows in Agricultural Network”) model, an agent-based model that simulates a range of material flows among farms and their partners within agricultural districts is developed. FAN processes are explained in details and a sensitivity analysis to some key variables is performed. In addition, the FAN model is applied to a French case-study to assess the performances of contrasted scenarios aiming to enhance nutrient use efficiency, recycling strategies, biogas production and system redesign. The outcomes from the scenario simulation are analyzed and assessed in terms of food provisioning, nutrient cycling and greenhouse gas emissions. This work shows the usefulness of prospective, agent-based tools for greater farming and food-chain sustainability, to design and evaluate collective solutions for circular economy and to account for interactions among economic actors within complex agro-food systems.

Keywords: nutrient flows, agro-food systems, nitrogen, agent-based model, circular flows, agro-industrial ecology, local scale, organic waste recycling.

Résumé de la thèse

Nourrir une population mondiale croissante dans un contexte de changements globaux pose de nouveaux défis à l'agriculture en termes d'efficacité de production et d'impacts environnementaux. Rendre les systèmes agro-alimentaires plus soutenables nécessite de mieux recycler la biomasse et les nutriments, c'est-à-dire de tendre vers des flux de fertilisants, de produits végétaux, d'aliments du bétail, de coproduits et de déchets plus circulaires. À ce titre, il est nécessaire de développer de nouveaux outils pour mieux explorer et évaluer les échanges de matières entre les fermes et leurs partenaires économiques amont et aval dans les territoires. Dans le travail présent, l'état de l'art concernant les méthodes d'analyse, de modélisation et d'évaluation environnementale des flux de biomasse et d'éléments minéraux à différentes échelles est réalisé. Le modèle multi-agents FAN (« Flows in Agricultural Network») qui simule les flux des matières entre les fermes et leurs partenaires économiques dans les territoires agricoles a été développé. Les processus de FAN sont expliqués en détail et une analyse de sensibilité des variables clés est présentée. Par ailleurs, le modèle FAN a été appliqué à un cas d'études en France pour évaluer la performance des scénarios contrastés visant à améliorer l'efficacité d'utilisation des éléments minéraux, développer le recyclage de la matière, favoriser la production du biogaz ou reconcevoir les systèmes de production. Les sorties de simulations des scénarios sont analysées en termes de production alimentaire et énergétique, de flux de matières et de logistique, de cycle des nutriments et d'émissions de gaz à effet de serre. Ce travail montre l'utilité des outils de prospective et modèles multi-agents pour améliorer la durabilité des systèmes agricoles et des chaînes alimentaires, pour créer et évaluer des solutions collectives tendant vers l'économie circulaire et pour prendre en charge les interactions entre acteurs économiques au sein des chaînes et filières alimentaires complexes.

Mots clés : flux de nutriments, systèmes agro-alimentaires, azote, modèle multi-agents, flux circulaires, écologie agro-industrielle, échelle du territoire, recyclage des produits organiques.

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Introduction

What the current issues related to material flows in agro-food systems are and how the present work is going to address them.

Agriculture altered global biogeochemical cycles

Population growth and consumption are driving increasing demands on agriculture and natural resources (Godfray et al., 2010). In this context, it has become one of the greatest challenges of this century to meet society's growing food needs while simultaneously reducing agriculture's environmental burden (Cumming et al., 2014; Erb et al., 2016; Fedoroff et al., 2010; Le Mouél and Forslund, 2017). Studies on sustainability have pointed out agriculture to be one of the major natural resource user (Ellis et al., 2013), chiefly land and water, and, at the same time, to be one of the major causes of environmental pollution (Tilman et al., 2001). Increasing meat in human diets has fostered livestock population globally, despite the fact that the sustainability of animal production still remains under concern (Wirsenius et al., 2010). Overall, agriculture impact drives the planet beyond its safe operating space for several ecological processes such as land-use, climate change, biodiversity, and, especially, global biogeochemical cycles (Rockstrom et al., 2009; Steffen et al., 2015).

Indeed, one of the major issues of the global change is the alteration of the biogeochemical cycles due to nutrient management in agriculture, in particular linked to fertilizers use and livestock wastes management that severely impact the environment (Bouwman et al., 2009). In the case of fertilizers, intense production and extraction induced the democratization of mineral fertilizers in agriculture (Dawson and Hilton, 2011). Regarding nitrogen (N), since the Haber-Bosch process, i.e., industrial synthesis of ammonia, was invented, it has resulted in around half of humanity being depend on it to feed on (Erisman et al., 2008). Widespread mineral N over-fertilization practices in agriculture have resulted in an extremely low nitrogen use efficiency (Braun, 2007). Reactive nitrogen has affected the global nitrogen cycle in atmospheric, aquatic and terrestrial pools (Gruber and Galloway, 2008), by greatly increasing transfer and emissions since pre-industrial times (**Figure 1.**). Another key fertilizer is phosphorus, that is derived from phosphate rock, a non-renewable resource which current global reserves may be depleted (Bennett and Elser, 2011; Cordell et al., 2009). Similarly to nitrogen, its use remains inefficient in many agroecosystems (MacDonald et al., 2011). The massive use of fertilizers have triggered great losses to the atmosphere (Sutton et al., 2011), in particular as greenhouse gases (Carlson et al., 2016; Sanz-Cobena et al., 2016) and as nutrient leaching that triggers algae bloom and water eutrophication (Conley et al., 2009; Paerl et al., 2014).

Organic fertilization may play a crucial role as an alternative to non-renewable mineral fertilizers through manure recycling (Jensen, 2013; Rufino et al., 2007). Yet, management of livestock dejections has become a challenge in many parts of the world, where animal excreta accumulates in soils and water (Chen et al., 2010; Leip et al., 2015a). In addition, livestock production drives severe environmental problems, especially in terms of greenhouse gas emissions (Herrero et al., 2013).

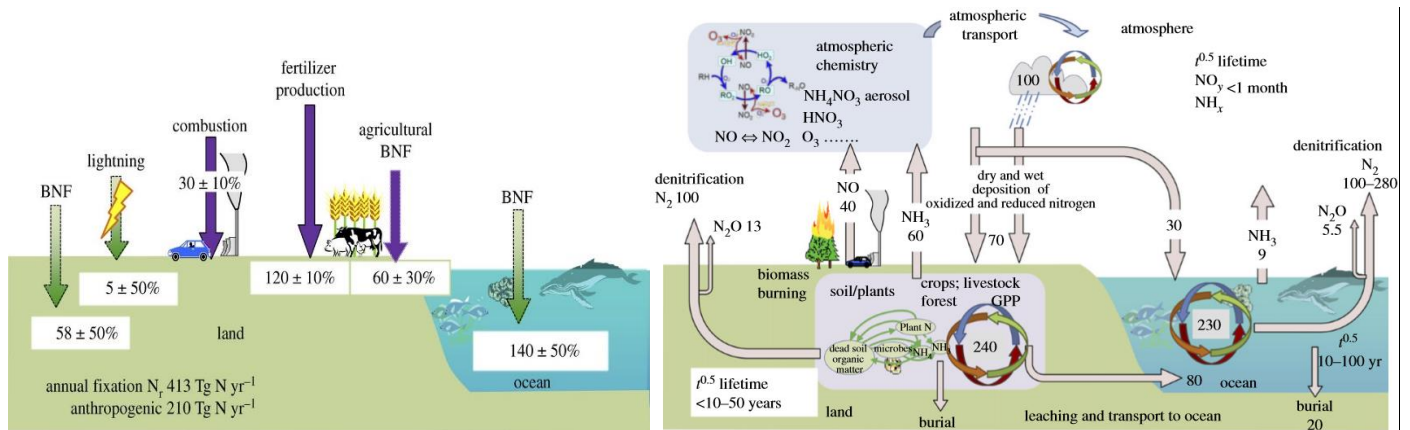


Figure 1. Natural and anthropogenic nitrogen inflows on the left, and flows of reactive Nitrogen on the right in terrestrial, oceanic and atmospheric ecosystems (units are in Teragrams of Nitrogen per year). On the left, green arrows represent natural sources and purple arrows represent anthropogenic sources. On the right, colors represent different forms of reactive N. Figure adapted from Fowler et al., (2013).

The reliance on massive nutrient and biomass material inflows are linked to environmental issues that need to be addressed (Vitousek et al., 2009). Therefore, solutions for more sustainable food systems should involve alternatives combining both the way farming activity is performed and the use and allocation of the agricultural materials produced (Foley et al., 2011a).

Agro-food system dependency on linear flows

Current farming productions have become dependent on numerous agro materials as inputs via national and international trade (Fader et al., 2013). This high dependency is quite recent in the history of agriculture and has evolved together with farming specialization at both the farm and the regional scales (Billen et al., 2009; Carmo et al., 2017). The reliance of agricultural management on external inputs is especially intense in the case of livestock systems, usually by sourcing animal feed from crops produced elsewhere (Lambin and Meyfroidt, 2011). Not only

material flows between the agents of the agro-food system are key drivers of the current challenges on food security, biogeochemical balances and systems stability (Ercsey-Ravasz et al., 2012). Many agro-food systems are ultimately relying on non-renewable sources of nutrients, usually fertilizers. The increasing connectivity created by these 'linear material flows' may support access to resources at lower prices, yet it does it at the cost of decreased local self-sufficiency and destabilization of biogeochemical cycles.

Circular flows in agro-food systems as a local solution

As seen before, the constant use of linear flows exacerbate the reliance of farming systems on external nutrient inputs, yet, it does it triggering great losses to the environment. In contrast to linear flows, the development of 'circular flows' that are based on the local production and consumption of resources while reducing losses, needs to be encouraged (Madelrieux et al., 2017). Enhancing material exchanges in 'circular flows' by closing material loops, limiting travel distances and associated energy costs and emissions can help to advance towards the sustainability of the agro-food systems (El-Chichakli et al., 2016) and renew governance of food chains (Brulot et al., 2014). Still, these flows need the cooperation of the actors within agro-food chains, e.g., through linking their material production and needs in local networks (Durand et al., 2015). Some examples of more 'circular flows' can be reached by promoting crop-livestock integration (Moraine et al., 2014; Regan et al., 2017), biogas energy production (Lorenz et al., 2013) and efficient waste recycling (Alvarenga et al., 2015; Bodirsky et al., 2014; Metson et al., 2016). Material reuse and recycling among economic actors seems a win-win solution to maintain food production while reducing pollution and preserving natural resources (Barles, 2014). It is necessary to apply those principles to agro-food systems, concerning food production, food processing, farming practices, interactions between crops and livestock, and wastes management (Pagotto and Halog, 2016).

However, most studies that addressed the analysis of circular flows have been restricted to input-output tables and static pictures of current flows, as done in substance flow analysis and industrial ecology studies (Brunner and Ma, 2009; Chertow, 2007). Additionally, sustainability of farm management practices have been traditionally studied and assessed at the farm scale in detail (Bockstaller et al.,

2009). Yet, we need new tools to estimate circular flows in agro-food systems, taking into account interactions among farms and their partners and prospective quantification of flows together with their associated environmental performances. In particular, models can be very useful to design and assess alternative scenarios of material flows and their consequences for the environment. However, there exist very few studies developing models able to estimate nutrient and material flows and to simulate alternative, circular flows among agents in the agro-food systems. This project aims to fill this gap by conceiving and testing a model simulating flows in agro-food systems that can also be useful to simulate scenarios.

System under study

In this Ph.D. thesis, we aimed to model material flows and cycles developed by human activities related to food production and consumption as well as their associated environmental effects. For this purpose, we were interested in methods analysing flows at different local scales. We defined the local scale as regions or districts in which economic partners are spatially close enough to be connected within biomass and waste exchange networks, while sharing the same natural environment. We excluded long upstream and downstream chains such as global food markets from the scale of analysis, even if their role is important for shifting from global to local flows.

Considering the high diversity of agents in rural agro-food systems, we wondered if some of the mechanics might be to interact with higher levels of actor's organizations, from the farm to the local scale. Our local agro-food systems encompass farms, feed dealers, food consumption, food processing industries, organic wastes managers and fertilizers suppliers (**Figure 3**). We considered all forms of materials containing nutrients: fertilizers, crop and livestock products, organic wastes, organic and mineral fertilization flows, animal feeding and bedding flows, food processing flows and energy flows of biomass and wastes as well as related nutrient losses and emissions to the environment.

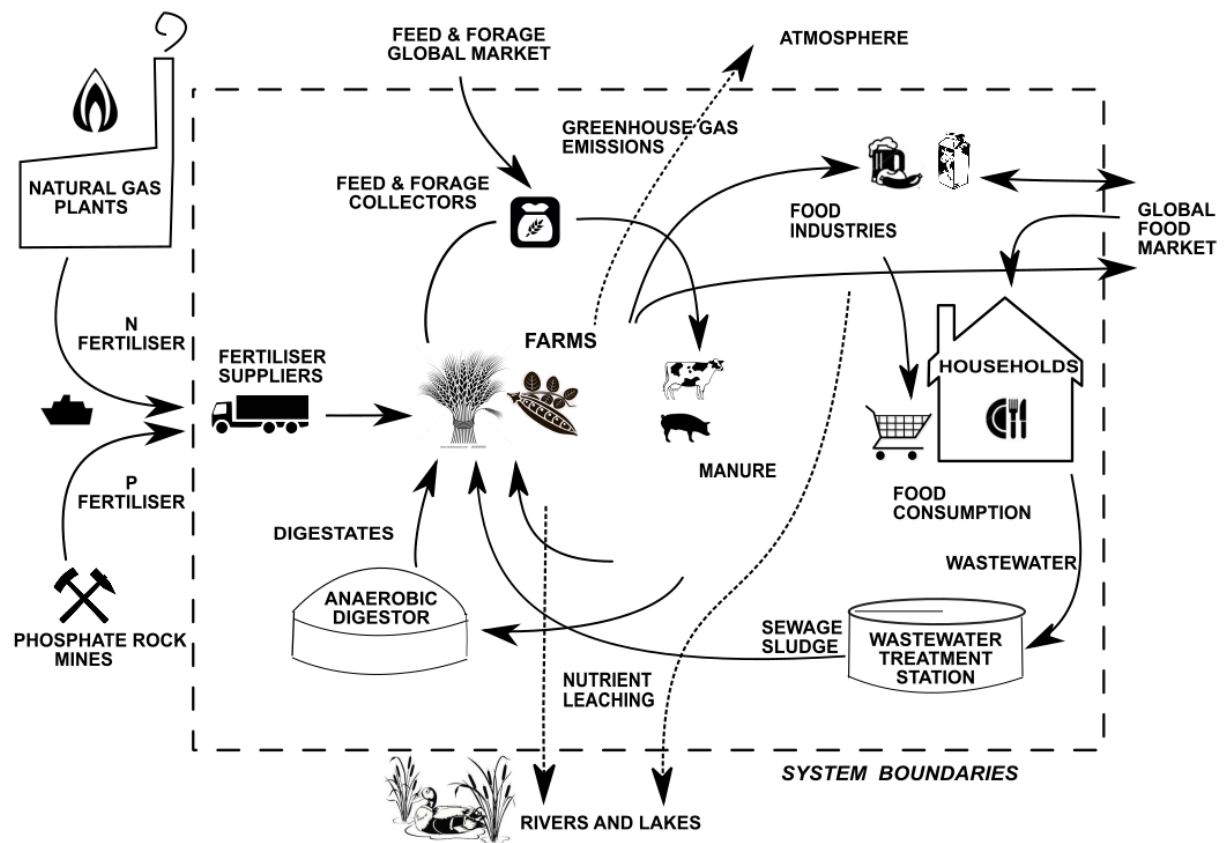


Figure 3. Conceptual framework of nutrient and material flows in agro-food system at the local scale. System boundaries are indicated by the dotted box. Arrows represent flows, solid lines represent material exchanges, and dotted lines represent losses to the environment. Adapted from Fernandez-Mena et al. (2016).

Research questions

With the objective of proposing a robust modelling tool, we formulated the three following questions:

1. Which approaches already exist in the scientific literature to study the exchange of biomass and nutrient flows in local agro-food systems?

Although going beyond the plot towards larger scales may be useful to better understand circular flows among actors of agro-food systems, studies and terms addressing nutrient flows and exchanges in the scientific literature are vast and sometimes confusing. A state-of-the-art exploration was performed to know if there was already an existing powerful tool for our goal, and if not, to identify the approaches to get inspiration from.

2. How can we simulate biomass and nutrient exchanges in local agro-food systems?

We wondered about the modelling approaches to estimate and simulate the socioeconomic and agroecological drivers behind material exchanges. This encouraged us to improve existing tools thanks to our literature exploration in order to design a new simulation model.

3. Can we assess scenarios of alternative material flows in agro-food systems with multiple indicators?

The ultimate goal of a simulation model is to estimate contrasted scenarios of circular flows. This is crucial in order to improve the sustainability of the system locally and to assess their production and environmental outcomes.

Thesis structure

We carried out an exploration of the scientific literature, by reviewing peer-reviewed articles dealing with nutrient and material flows, in different social-ecological and agro-food systems. We classified all the relevant approaches depending on the methods they use to understand, model and represent the conceptual framework of nutrients and biomaterials transfer in both ecological and socio-ecological systems, paying special attention to the latter. We published a review article with the different methods explained in detail, presented in Chapter 1. We found that there are three main approaches (i) those interested in measuring the impact of nutrients flows from human activities on the ecosystems; (ii) originated by the stock-flow systems related to agriculture and ecology and (iii) those simulating multi-agent populations to manage natural resources. We concluded by highlighting the need of a specific tool to simulate the exchanges between individual agents of the agro-food network.

In order to test the viability of an accurate simulation of alternative farming activities and material flows, we selected a case-study by paying special attention to areas affected by issues concerning nutrient management, and also where data was available. We decided to work on the Ribéracois district, where our research unit had previous experience. The Ribéracois is located in the Dordogne department, in the

southwest of France. This district exhibits several issues concerning local nutrient and biomass management such as nutrient losses to water sources, difficulties for feeding livestock locally and development of biogas production. Although the boundaries and size of the district were difficult to set, we found that the French local entity ‘Communauté de communes du pays de Ribéracois’ satisfies a compromise between enough diversity of agents and a reasonable amount data to process in the simulations. The total selected area was around 1000 km², with 635 km² of utilizable agricultural area. The district includes approximately 835 farms encompassing a diversity of farming activities, such as arable, dairy, beef production, pig, ovine and horticultural production, in both specialized and mixed crop-livestock farms. The Ribéracois characteristics are further explained in Chapters 2 and 3.

We present a new agent-based model, ‘*Flows in Agro-food Networks*’ (FAN) in Chapter 2, which simulates the processing and exchange of fertilizers, feed, food and wastes among farms and with their multiple upstream or downstream partners (feed and fertilizer suppliers, food industries, waste processors, and anaerobic digesters) at the local scale. We developed the FAN model in GAMA 1.7 platform, an open-sourced coding environment that supports the use of geographical information systems within the agent-based language GAML. FAN includes a series of environmental indicators that can be used to assess alternative scenarios in terms of ecosystem services, nutrient cycling, and resource autonomy. It also provides a powerful tool to assess opportunities for circular bioeconomy, including by simulating competitions between local and global sourcing of resources in agro-food networks. We used the Ribéracois as a case study in France to demonstrate FAN’s dynamics and to explore its sensitivity to key variables.

Finally, we applied FAN to the simulation of alternative scenarios of material exchanges in Ribéracois in Chapter 3. Eight scenarios were implemented following the ‘Efficiency, Substitution and Redesign’ framework. These scenarios ranged from the introduction of best agricultural management practices, collective solutions including recycling and biogas production, up to complete redesign of the agricultural systems including changes in land-use, livestock population and chemical fertilizer availability. The outcomes of simulating the scenarios were analyzed through an integrated assessment.

Chapter 1 –

“Towards an Agro-Industrial Ecology: a review of nutrient flow modelling and assessment tools in agro-food systems at the local scale”

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Abstract

Improvement in nutrient recycling in agriculture is essential to maintain food production while minimising nutrient pollution of the environment. For this purpose, understanding and modelling nutrient cycles in food and related agro-industrial systems is a crucial task. Although nutrient management has been addressed at the plot and farm scales for many years now in the agricultural sciences, there is a need to upscale these approaches to capture the additional drivers of nutrient cycles that may occur at the local, i.e. district, scale. Industrial ecology principles provide sound bases to analyze nutrient cycling in complex systems. However, since agro-food social-ecological systems have specific ecological and social dimensions, we argue that a new field, referred to as “Agro-Industrial Ecology”, is needed to study these systems. In this paper, we review the literature on nutrient cycling in complex social-ecological systems that can provide a basis for Agro-Industrial Ecology. We identify and describe three major approaches: Environmental Assessment tools, Stock and Flow Analysis methods and Agent-based models. We then discuss their advantages and drawbacks for assessing and modelling nutrient cycles in agro-food systems in terms of their purpose and scope, object representation and time-spatial dynamics. We finally argue that combining stock-flow methods with both agent-based models and environmental impact assessment tools is a promising way to analyze the role of economic agents on nutrient flows and losses and to explore scenarios that better close the nutrient cycles at the local scale.

1.1. Introduction

The demand for agricultural and natural resources is continually increasing due to global population growth and overall diet transition to higher meat consumption. Meeting society's growing food needs while simultaneously reducing the environmental impact of agriculture is, undoubtedly, one of the greatest challenges of the century (Foley et al., 2011a); Godfray et al., 2010; Makowski et al., 2014). Nutrients such as nitrogen and phosphorus play a critical role in food production and global food security (Erisman et al., 2008; Wetzel and Likens, 2000) and have been widely used as fertilizers to sustain high agricultural yields for decades (Tilman et al., 2002). However, the massive use of fertilizers during the last decades has resulted in dramatic changes in global nutrient cycles. In particular, large nutrient losses from agricultural soils to the environment have resulted in natural ecosystem pollution and the loss of services provided by these ecosystems. For example, the massive use of mineral nitrogen fertilizers has led to dramatic changes in the atmospheric, aquatic and terrestrial pools of the global nitrogen cycle as well as to increased transfers between compartments, compared to pre-industrial times (Gruber and Galloway, 2008). This has caused serious ecosystem disturbances, including water eutrophication, soil acidification and greenhouse gas emissions (Conley et al., 2009; Galloway et al., 2008; Sharpley et al., 1994). Similarly, the widespread use of mineral phosphorus fertilizers derived from phosphate rock in industrial agriculture is increasing the risk of depletion of this non-renewable and highly geopolitically-sensitive resource (Cordell et al., 2009). Phosphorus transfers from agricultural lands to water bodies are also known to trigger algae bloom and eutrophication in freshwater ecosystems (Conley et al., 2009). There is, therefore, an urgent need for a drastic increase in use efficiency and recycling of these nutrients, in particular, in areas where food production has been highly intensified.

Large efforts have been made to improve nutrient management in agriculture over the last decades (Gerber et al., 2014). In the past, this generally involved understanding and modelling nutrient dynamics in the soil-plant system and designing decision tools for fertilization at the field and farm scale (Gruhn et al., 2000; Havlin et al., 2005; Nesme et al., 2005). These tools helped to correct improper management of fertilizers and manure by farmers and to better adjust fertilizer supply to crop requirements at these small spatial scales. However, these approaches were inherently limited since they did not consider some key segments of the

nutrient cycles that occur at larger scales, such as material flows (e.g., grain, straw and manure) between farms and their upstream and downstream economic partners (e.g., feed and fertilizer suppliers, grain and livestock product collectors and processors, waste producers, etc.). Such upscaling is in fact needed to improve our understanding of how nutrients flow in and out of farms and, ultimately, into the environment, and to promote more efficient recycling loops in agriculture (Nowak et al., 2015).

Industrial ecology emerged during the last decades as a scientific field focused on the interactions between industrial societies and their environment, considering industrial societies as systems (Allenby and Graedel, 1993). Developing a circular economy that protects finite natural resources by the better closure of materials and energy cycles is at the core of its principles (Ayres and Ayres, 2002; Socolow, 1997). For that purpose, industrial ecology encompasses a range of approaches ranging from ecology and industrial management to economy and sociology (Andrews, 2000; Boons and Howard-Grenville, 2009; Seuring, 2004). Numerous approaches have been developed to design recycling loops and to explore circular economy options in industrial social-ecological systems. They include Substance Flow Analysis (Brunner and Ma, 2009), Industrial Symbiosis analysis (Chertow, 2007) and regional Life Cycle Assessment (Frischknecht, 2006). However, these approaches strongly differ in terms of purpose, scope and framework, making the assessment of their advantages and drawbacks to design recycling loops extremely difficult.

Our aim in this paper is to review the different approaches that were designed to analyze, assess and simulate nutrient flows and to explore nutrient recycling scenarios in complex social-ecological systems. We focused our analysis on agro-food systems at the local scale where economic agents may exchange agricultural inputs, products, by-products and waste. We defined the local scale as regions or districts in which economic partners are spatially close enough to be connected within exchange networks while sharing the same natural environment. We excluded long upstream and downstream chains such as global food markets from our analysis (**Figure 3**).

We argue that agro-food systems have several specificities compared to purely industrial social-ecological systems. These specificities are related to: (i) the strong interactions between farming production processes and the natural environment; (ii) the predominance of diffuse vs. point source pollution in farming operations; (iii) the

highly scattered nature of farming enterprises within landscapes; and (iv) the high diversity of farming practices and interactions over time and space. For these reasons, we paid specific attention to environmental assessment approaches that account for diffuse nutrient losses to the environment, and to agent-based models that account for social interactions within complex social systems. We consider this extended set of approaches to be better suited to the analysis of nutrient flows within agro-food chains and to the design of efficient recycling loops in agriculture. In that perspective, we propose to define Agro-Industrial Ecology as the specific application of industrial ecology to farming system analysis (**Figure 4**).

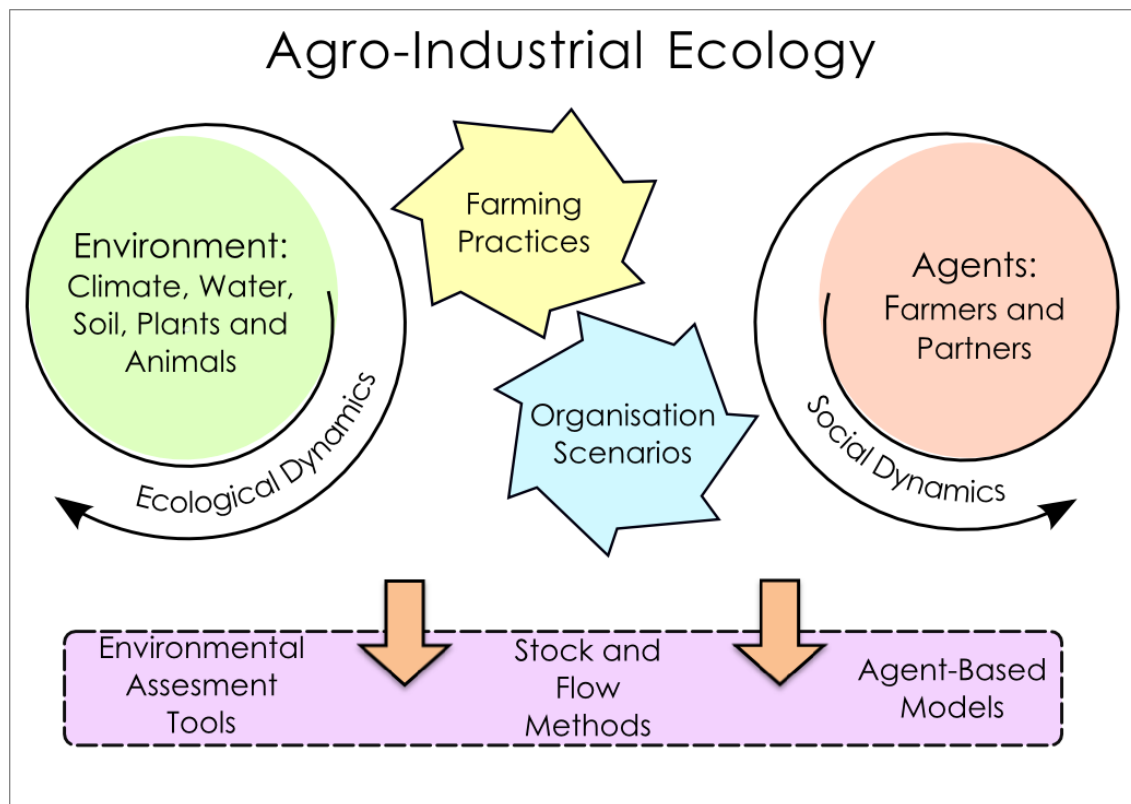


Figure 4. Agro-industrial Ecology conceptual Framework: factors, drivers and tools.

We explored the scientific literature in search of approaches that would help to assess, analyze or model nutrient flows (food, fertilizers, bio-products and waste) in social-ecological systems with different objectives, scales and complexity. The literature reviewed covered the period 2000-2015, including a few earlier pioneer papers when relevant. Although we primarily focused on agricultural systems, we did not totally exclude non-agricultural approaches. We limited our exploration to the local scale, encompassing farming regions and industrial or urban ecosystems.

We provide below a comparison of the major approaches that we identified based on their purpose, scope, application context, and environment and actor representation. According to these criteria, we found that these approaches could be classified into three major groups:

- (i) Environmental impact assessment tools (Section 2);
- (ii) Stock and flow Analysis methods (Section 3);
- (iii) Agent-based models (Section 4).

We develop each of these approaches in the following sections. In each section, we describe the major characteristics of each approach, giving examples of studies with a brief contextualisation, highlighting their relevance and their key features. Finally, we present a comparison of their potential for modelling nutrient flows and for designing recycling loops in agro-food systems (Section 5) and a conclusion (Section 6). Although classifying approaches may be debatable at some level, we distinguished between tools, methods and models. Depending on their final purpose, we considered tools to be usage-oriented, methods to be analysis-oriented, and models to be prediction-oriented. Even though the boundaries of these terms might be fuzzy, we decided to consider models only if they are based on complex numerical calculations to predict future events.

1.2. Environmental Impact Assessment Tools

The first group we identified is related to the environmental impact assessment of agro-food systems. These tools have a clear focus on nutrient losses from agricultural land to the natural environment. These approaches often use nutrient emission indicators that we classified into two categories, depending on the way they estimate impacts. These categories are “real nutrient flow indicators” when nutrient flows and production processes are co-located; and “virtual nutrient flow indicators” when nutrient flows and production processes are spatially disconnected.

1.2.1 Real nutrient flow indicators

In this category, we aggregated different approaches aimed at quantifying nutrient losses from agricultural lands to the environment, e.g., to estimate nitrate leaching to water bodies or nitrous oxide (N₂O) emissions to the atmosphere. These

approaches have a strong biophysical background and are clearly focused on agro-ecosystem processes, whereas they do not generally take economic agents other than farms into account. Most of these indicators are based on simple statistical calculations - such as N₂O emissions as a linear or exponential function of nitrogen fertilizer supplied (Philibert et al., 2012) - but some of them are based on more sophisticated models that incorporate several natural and anthropogenic drivers such as soil, climate and farming practices (Brisson et al., 2003). Many of those indicators have been developed at the field scale, but some upscaling has in fact been attempted to address larger systems such as districts and regions. Among them, we highlighted two widespread approaches that appear to be relevant to assess nutrient flows: environmental risk mapping and integrated assessment of agricultural systems.

The environmental risk mapping approach aims to establish pollution risk maps, generally for one specific pollutant. It uses geographical information systems to superimpose several sets of spatial information underlying the environmental risk, e.g., soil, climate, elevation, land-use, farming practices, etc. (Lahr and Kooistra, 2010). Several cases exist in the literature concerning nutrients, including soil phosphorus fertility depletion (Brown et al., 2000), nitrogen flows within landscapes (Theobald et al., 2004) and nitrate leaching risk (Assimakopoulos et al., 2003). This approach is adapted when risk mapping can be accurately assessed by just superimposing information about biophysical context, land-use and management practices. However, it does not account for complex interactions in management practices, nor for the role of agents and their social organization in that pollution.

The integrated assessment of agricultural systems aims to estimate agricultural impacts on the environment within a multi-criteria perspective. While different impacts are considered, nutrient losses to the environment are almost always considered. In contrast with the previous approach, nutrient losses are often considered in a sophisticated way by accounting for multiple farming practices and their potential interactions. Although there is a wide variety of tools that could be used (Bockstaller et al., 2009), most of them bring together a set of agro-environmental indicators. The INDIGO® tool, for example, is a wide-ranging set of indicators capable of evaluating farm sustainability based on farming practices such as crop rotation, fertilization, irrigation and pesticide use (Bockstaller and Girardin, 2006). Ultimately, these indicators can serve as multi-criteria decision-making tools

that support farmers' groups and policy-makers (Sadok et al., 2009). Most of these tools have been designed at the field or farm scale, whereas very few have been designed at the district scale. In addition, this approach is usually based on local or multi-local data, but is rarely spatialised. Payraudeau and van der Werf (2005) provided one of the very few reviews of the application of those tools at different regional scales, including examples at the local scale. They concluded that different indicators of nutrient losses to the environment could be identified, but the clarification of their position in the cause-effect chain related to farming practices is strongly recommended (**Figure 5**).

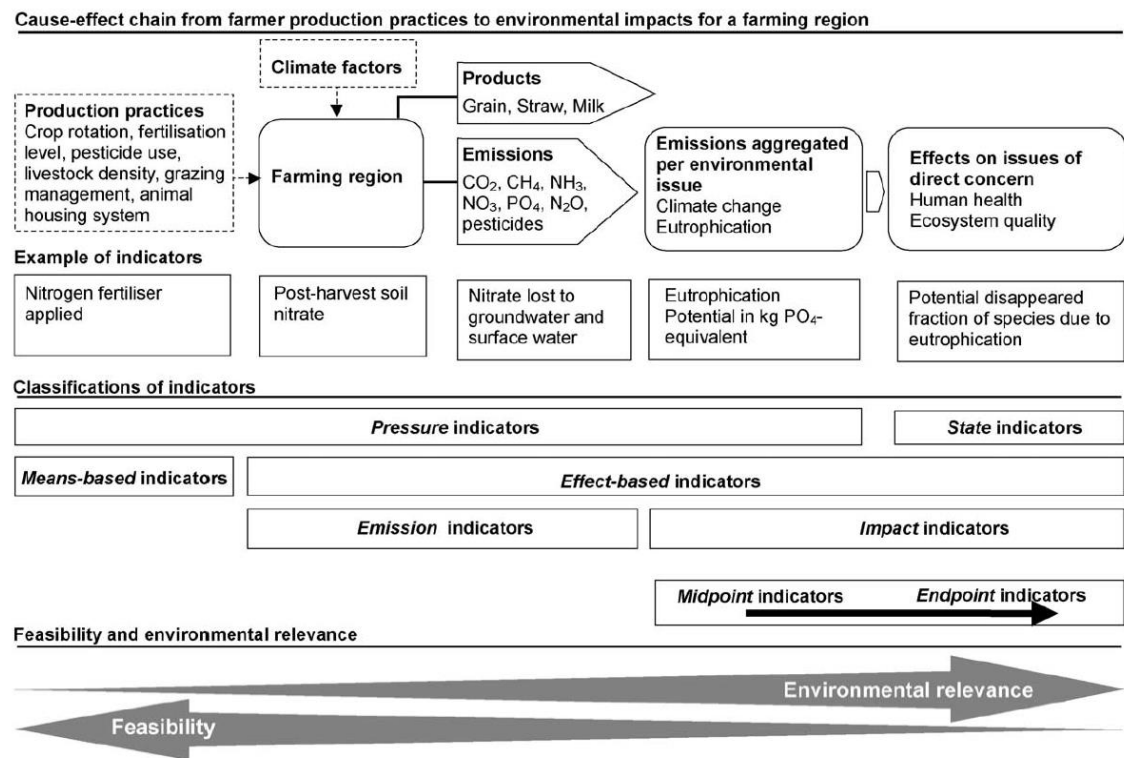


Figure 5. Example of nutrient loss indicators of a farming region according to their position in the cause-effect chain linking production practices to their impacts (from Payraudeau and van der Werf, 2005).

Overall, a key asset of real nutrient flow indicators is their ability to integrate both soil and climate conditions together with farming practices to accurately estimate diffuse nutrient losses from agriculture. Such indicators are therefore of critical importance to capture the complex interactions between farming systems and their natural environment and to accurately estimate nutrient losses in social-ecological systems. However, these indicators remain strongly focused on agro-ecosystems and do not consider economic agents other than farms: since they do not address nutrient

losses from other agents, in particular, from point sources, these indicators are therefore not appropriate to assess total nutrient losses within complete agro-food systems. In addition, their focus on the agricultural production segment of agro-food chains makes them inappropriate to explore opportunities for designing recycling loops among agents and their environment.

1.2.2 Virtual nutrient flow indicators

In this category, we aggregated indicators used to estimate nutrient flows related to product development, use and disposal. Here, nutrient flows and production processes can be spatially disconnected: in addition to direct (on-site and internal) emissions or resource use, these indicators also account for indirect (off-site, external, embodied, upstream and downstream) emissions or resource use. This category encompasses two major groups of indicators: nutrient footprints and Life Cycle Assessment (LCA). Although several definitions exist, footprint approaches usually encompass nutrient losses occurring upstream of a given product. In contrast, LCA encompasses all nutrient losses that may occur upstream and downstream along a product chain, i.e., through the whole life cycle of a product, including during product use and disposal.

Footprint indicators have been widely used to estimate single environmental impacts of a given product or activity. The carbon footprint remains the most widespread of these: it estimates the total amount of greenhouse gas emissions that are directly and indirectly caused by an activity or that are accumulated over the life stages of a good or a service, expressed in kg of CO₂-equivalent (Wiedmann and Minx, 2008). Some studies considered a spatial scale dimension in LCA assessments. In that case, all consumption activities within a defined area are taken into account and equated into a single element, such as estimating carbon footprints of regions and countries by input-output tables (Wiedmann, 2009). Similar footprint indicators have been developed concerning nutrients. Nitrogen footprint indicators (Andrews and Lea, 2013; Galloway et al., 2008) have already been applied to European food products (Leip et al., 2014). Similarly, phosphorus footprint indicators (MacDonald et al., 2012; Matsubae et al., 2011; Metson et al., 2012; Wang et al., 2011) follow

mineral phosphorus consumption paths in agro-food chains. They can be used to estimate the contribution of specific regions to the global depletion of non-renewable phosphate rock resources. When applied to nutrients, these indicators are able to estimate nutrient pollution along agro-food chains, and to aggregate local and remote impacts within a globally sensitive context.

Life Cycle Assessment (LCA) assesses all environmental impacts associated with a product or a process by accounting for and evaluating its resource consumption and pollutant emissions during its life stages (Guinée, 2002). When applied to nutrients, LCA uses nitrogen and phosphorus footprint indicators, in particular, to estimate the risks of water eutrophication. For food production systems, the analysis includes not only on-farm activities, but impacts related to the production of farm inputs such as fertilizers, seeds and imported feed as well. LCA has been widely used to study food production systems (Roy et al., 2009) where further research has been carried out to quantify fertilization impacts (Van Zeijts et al., 1999). Despite the fact that LCA is usually applied to a specific production process (Haas et al., 2000), it has recently been applied to landscapes and districts. In that case, LCA either focuses on a specific production process or accounts for any activities that take place in the area considered (Loiseau et al., 2013). Examples of the former include the comparison of the environmental performance of fossil fuels vs. local biomass and biofuel production in New York State (Heller et al., 2003), Spain (Butnar et al., 2010; Gasol et al., 2009) and China (Ou et al., 2009). Examples of the latter include territorial LCA applied to a university campus in Barcelona (Lopes Silva et al., 2014) and to a French Mediterranean region (Loiseau et al., 2014). Through these examples we can observe that LCA assesses multiple environmental impact categories and that it is powerful enough to account for a set of diverse activities within the same area.

Compared to real flow indicators, virtual flow indicators are able to consider nutrient losses to the environment related to inputs and outputs occurring on upstream or downstream farms. They, therefore, provide integrated assessment of resource use efficiency throughout complex production chains. However, estimations of nutrient losses to the environment are generally not site-specific or spatially explicit, which limits their accuracy. Finally, although these indicators have some potential to estimate nutrient losses and resource use along agro-food chains, they have rarely

been applied to complex social-ecological systems such as agent networks at the local scale.

1.3. Stock and Flow Analysis Methods

The second group of approaches we identified is related to the calculation of stocks and flows of substances, materials or energy through social-ecological systems within territories. In these methods, the system under study is described in terms of storage and transfer of conservative energy or matter flowing in, out and through the system. These stock and flow methods are widely used to represent and sometimes model nutrient cycles within complex social-ecological systems, with the specific objective of identifying losses and accumulations occurring within the systems. Such methods belong to the family of mathematical input-output models applied to system dynamics (Miller and Blair, 2009). They aim to integrate the socio-economic dimension into ecological system analysis (Folke, 2006), with a particular focus on resource and substance flows through human activities.

Basically, stock-flow methods break down the systems under study into compartments. Those compartments usually aggregate major physical or economic agents within the study area considered, whereas one or several compartments represent the environment. Major flows among compartments are then identified and represented by arrows in a specific graphical schematisation. Those flows are generally quantified by multiplying material flows by their specific nutrient content but they may sometimes be calculated by differences with other flows based on the mass conservation law (Chen and Graedel, 2012).

All the stock and flow methods refer to some substance flow analysis principles (Section 3.1). However, other related approaches exist with specific objectives and contexts. They yield different sub-groups and names such as: *urban metabolism*, when applied to cities; *industrial symbiosis*, when applied to clusters of industries with an optimisation objective; and *integrated crop-livestock system analyzes*, when applied to mixed farming systems. Although some overlap exists between these methods, we develop each of these sub-groups, along with some examples, in Sections 3.2, 3.3 and 3.4.

1.3.1 Substance Flow Analysis

Substance Flow Analysis (SFA) is a generic method to quantify substance or material flows and stocks in various contexts and scales (Van der Voet, 2002). Although SFA can be applied to very detailed systems, a classical characteristic of most SFAs is the aggregation of all physical or economic agents with similar properties into single compartments. For example, all industries with similar input use and output production are aggregated into the same compartment, whereas soils, crops and animals are aggregated into “soils”, “crops” and “animal” compartments, respectively, each of them having stocks where substances may accumulate or be depleted. This aggregation strategy makes SFA different from industrial symbiosis or crop-livestock systems analysis where each economic agent is represented individually. When modelling nutrients along social-ecological systems, such system analysis is used to reveal where nutrients may accumulate and be transferred to the environment.

To better illustrate the schematic representation of nutrient cycles in SFA, we selected the analysis of the phosphorus cycle at the national scale in France (Senthilkumar et al., 2014). In this study, all physical agents (agricultural soils, crops, animals, landfills and water bodies) and economic agents (food/feed industry, municipal waste and human populations) were aggregated depending on their characteristics and their input/output properties (**Figure 6**). In addition, recycling flows and losses were estimated, highlighting the efficiency properties of the system. In this case, agricultural soils, water bodies and landfills were clearly major phosphorus sinks at the country scale.

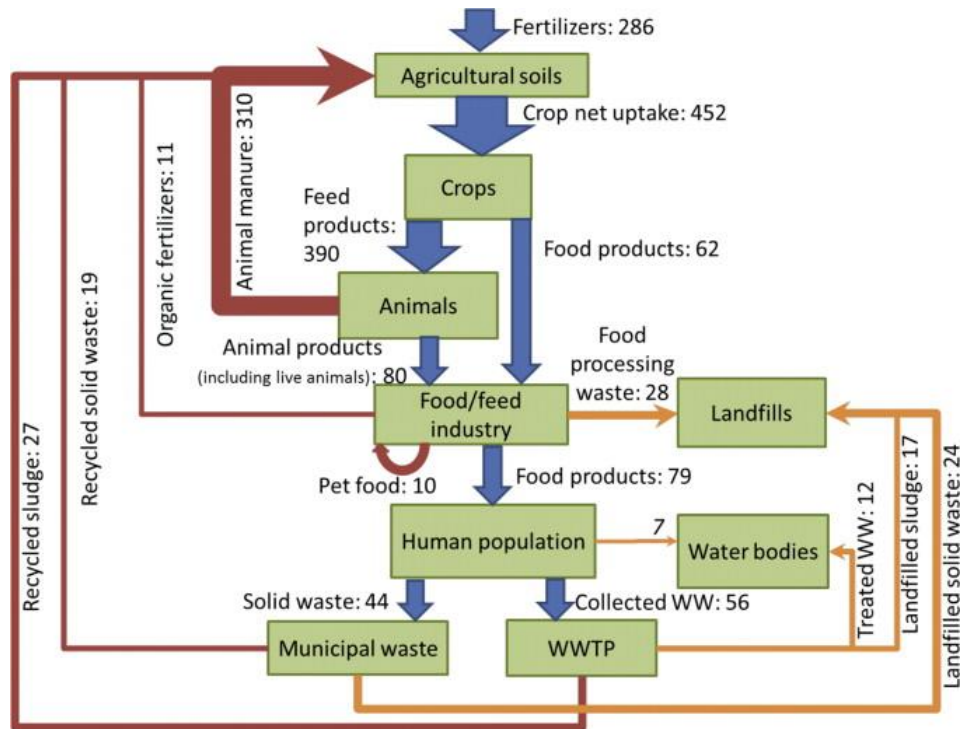


Figure 6. Substance Flow Analysis of phosphorus in France (from Senthilkumar et al., 2014). Values are phosphorus (P) flows in kt P y⁻¹ for the year 2006. Losses are indicated in orange and recycling routes are indicated in red. Only flows greater than 5 kt P y⁻¹ are represented.

SFA principles were applied to nutrient cycles at different spatial scales from districts to cities, basins, landscapes, regions and countries. Some examples include nutrient flows applied to specific economic sectors in different parts of the world, such as the steel industry (Jeong et al., 2009), municipal waste (Sokka et al., 2004) and the trout fish sector (Asmala and Saikku, 2010). Nutrient analysis using SFA methods has been applied to cities (Li et al., 2011; Ma et al., 2008; Schmid Neset et al., 2008; Yuan et al., 2011) and to landscapes (Liu and Chen, 2006). Finally, Substance Flow Analysis has been widely used for phosphorus analysis at the country scale, frequently considering agro-food systems (Antikainen et al., 2005; Chen et al., 2010; Cooper and Carliell-Marquet, 2013; Cordell et al., 2013; Matsubae-Yokoyama et al., 2009; Senthilkumar et al., 2012a, 2012b). These examples illustrate the broad spectrum of the SFA application contexts, from industrial chains and economic sectors, to cities, landscapes or countries.

By providing a robust framework for analysing nutrient flows and stocks under different material forms within social-ecological systems across different scales, SFA methods are a critical element for assessing and modelling nutrient cycles within agro-food systems. They provide the possibility to follow nutrient paths under

different material forms. This feature is essential to the study of mixed contexts where materials easily change their forms, as often happens in agro-food systems where farming, industrial and natural pools of nutrients are observed together. Their system representation also provides a sound basis for calculating nutrient budgets at the district scale and for deriving estimations of nutrient losses. However, the aggregation strategy, which is often a core principle of SFA approaches, is clearly a limitation to the simulation of detailed flows among different economic agents. In addition, their often static basis is a limitation to the dynamic simulation of nutrient flows within complex and interacting social-ecological systems.

1.3.2 Urban Metabolism

Considering cities as super-organisms, urban metabolism analysis aims to quantify material and energy flows in, out and through the area under study. Appearing between the 1960s and the 1970s (Duvigneaud, 1974; Wolman, 1965), urban metabolism analysis methods were originally limited to black-box models and input-output accounting (Kennedy et al., 2011). Nowadays, urban metabolism analysis are inspired by other complex approaches such as ecological networks, substance flow analysis and environmental assessment methods (Zhang, 2013). Urban metabolism usually considers flows and stocks from different materials, substances and energy among very different urban compartments (industries, households, infrastructures, environmental entities, etc.). In some occasions, system representation in urban metabolism might be very similar to those used for natural food webs by categorising the different urban sectors into “producers” (e.g., the environment as the supplier of natural resources), “consumers” (e.g., productive and domestic activities), and “reducers” (e.g., pollution clean-up activities): such system representation was adopted in urban metabolism studies of the water cycle in Beijing (Zhang et al., 2010).

Nutrient budgeting has been extensively considered in urban metabolism approaches. Nutrient budgets integrate inputs and outputs from and to different urban compartments that often include households, industries and environmental entities. For instance, nitrogen budgets were assessed in Toronto (Forkes, 2007), Phoenix (Baker et al., 2001) and Paris (Barles, 2007; Barles, 2009; Billen et al., 2009), and in Chinese urban food systems (Li et al., 2012). Carbon, nitrogen and

phosphorus flows have been assessed in Minnesota (Fissore et al., 2011). Moreover, landscape metabolism includes examples of nitrate flows and emissions in Central Europe (Haag and Kaupenjohann, 2001) and in Hungarian lowlands (Oláh and Oláh, 1996). These examples show that although urban metabolism studies focusing on nutrients can target the same objectives as the SFA methods applied to cities, they may not consider a whole mass balance since some flows are sometimes not quantified and do not always follow elements along their whole cycle.

Some urban metabolism studies may consider nutrient flows together with other material flows such as water, energy and greenhouse gas emissions. Although urban metabolism remains far from agro-food chain assessment, some key ideas such as the conceptualisation of urban actors as producers, consumers and reducers (or waste recyclers) are of primary importance to simulate nutrient flows within agro-food systems that include several trophic and product transformation levels. However, the poor mechanistic basis underlying urban metabolism may prevent their use for exploring and simulating options for more efficient recycling loops within social-ecological systems.

1.3.3 Industrial Symbiosis Analysis

Industrial symbiosis analysis aims to understand how economic agents can be integrated within clusters to better close material, nutrient and energy cycles. By looking for optimised exchanges and the use of raw materials, products, by-products and waste among agents, it searches for closed loops of materials and energy (Chertow, 2000). Industrial symbiosis analysis is therefore an essential method for the circular economy and geographic proximity.

A key asset of industrial symbiosis is the ability to consider different kinds of industries, i.e., not only farms but their upstream and downstream partners as well, and to make their specific input demands and supply capacities explicit. An additional asset of these methods is their ability to cover different types of materials, substances (e.g., water, nutrients and carbon) or energy (e.g., heat and electricity) flows that may be converted into each other. By analysing how, and with what degree of efficiency, these different resources are processed, produced and transformed within clusters of agents, efficient recycling loops can be designed at the local scale.

However, industrial symbiosis analyzes are merely descriptive since they represent static, actual flows among industries and activities, although they have the potential to design dynamic predictive models. In addition, this method strongly focuses on economic agents, but only provides rough estimations, if any, of nutrient losses to the environment.

One of the paradigmatic examples of industrial symbiosis is the Danish industrial park of Kalundborg (Ehrenfeld and Gertler, 1997). This case study includes several economic agents such as a refinery, a power plant, a gypsum plant and enzymatic industries, numerous local farms and a municipality. As indicated in **Figure 7**, numerous recycling loops are highlighted but nutrient losses to the environment are not explicitly estimated.

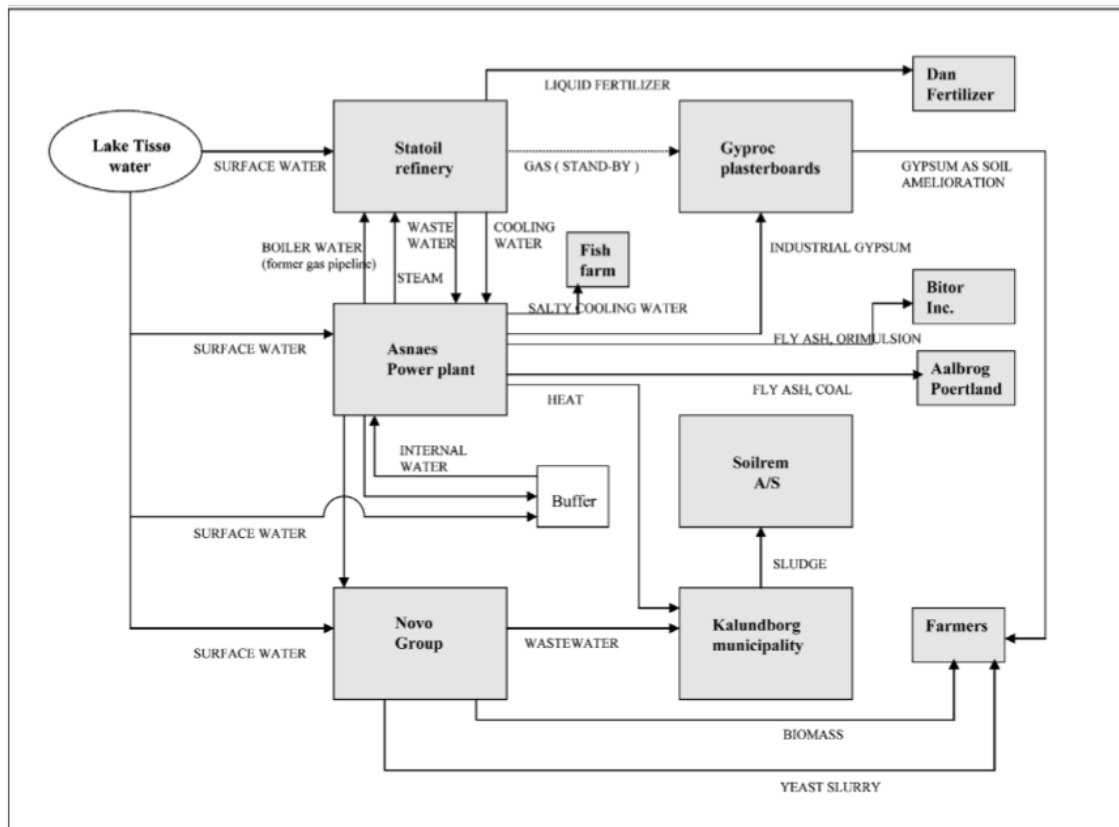


Figure 7. Industrial symbiosis of Kalundborg Industrial Park, Denmark (Jacobsen, 2006).

In classic examples of industrial symbiosis, organic compounds are rarely at the core of industrial symbiosis analysis. They are generally considered as by-products or waste from bio-refineries, agro-industries or organic-oriented chemical industries,

and they end up as fertilizers for local farmers (Beers et al., 2007; Ehrenfeld and Gertler, 1997). However, some studies have focused more specifically on nutrient flows related to organic compounds: examples of such studies are related to biofuels (Martin and Eklund, 2011; Ometto et al., 2007); to the forestry and paper industries (Korhonen, 2001; Sokka et al., 2011); to pharmaceutical, cogeneration and wastewater treatment (Chertow et al., 2008); to algae cultivation through wastewater treatment (Soratana and Landis, 2011); and to food processing industries such as sugar refineries (Zhu et al., 2007) and an agro-food cluster (Simboli et al., 2015). Industrial symbiosis approaches have been applied to farming systems, e.g., to couple aquaculture, crops and livestock (Dumont et al., 2013), and to smallholder farms in Liberia (Alfaro and Miller, 2014). There is thus a great potential to apply industrial symbiosis analysis to agro-food chains, in particular, when economic agents strongly interact within a given district (Nowak et al., 2015). The multi-resource and multi-agent approach of industrial symbiosis analysis can indeed serve as a guideline for designing recycling loops in agro-food chains, even though nutrient losses are hardly considered.

1.3.4 Integrated Crop-Livestock System Analysis

Integrated crop-livestock system analysis aims to represent and simulate nutrient flows through material exchanges among complementary farming enterprises. When applied to the district scale, they focus on flows between livestock and arable farms through feedstuff (e.g., cereals and straw) and organic fertilizers (e.g., animal manure and crop residues) (Thornton and Herrero, 2001). Although these approaches focus on organic materials in agricultural contexts, their system representation may be similar to Industrial symbiosis analysis since both represent detailed flows between partners at the local scale. Nevertheless, crop-livestock system analysis often uses more complex approaches such as mechanistic or dynamic models to derive flows among system components. For example, they may include crop models to simulate crop growth response to fertilizer application or livestock models to simulate manure production in response to livestock feed.

Crop-livestock system analyzes have been used, for example, to assess farming system sustainability (Bonaudo et al., 2014), farming diversification (Sulc and Tracy, 2007), and resource use efficiency (Cortez-Arriola et al., 2014). These methods have

been widely applied to improve African smallholder crop-livestock systems in terms of soil carbon, nitrogen and phosphorus management (Alvarez et al., 2014; Barrett et al., 2002; Bouwman et al., 2013; Giller et al., 2011; Manlay et al., 2004) and can also be spatialised (Bellassen et al., 2010). Major progress on nutrient analysis and modelling has been made within the NUANCES Project (Nutrient Use in Animal and Cropping systems - Efficiencies and Scales), where not only actual nutrient flows were analyzed, but also dynamically simulated under different scenarios (Rufino et al., 2011, 2007; Tittonell et al., 2010, 2009a; van Wijk et al., 2009). In these examples, complex crop-livestock models were applied to study nutrient flows among African smallholder farmers and the environment. Many crop-livestock models have been applied in developing countries where access to chemical fertilizers is limited and waste management is, instead, a key issue. In most cases, farm typologies are a prerequisite to identify and model the different agents and their material exchange strategies according to their farming systems (**Figure 8**).

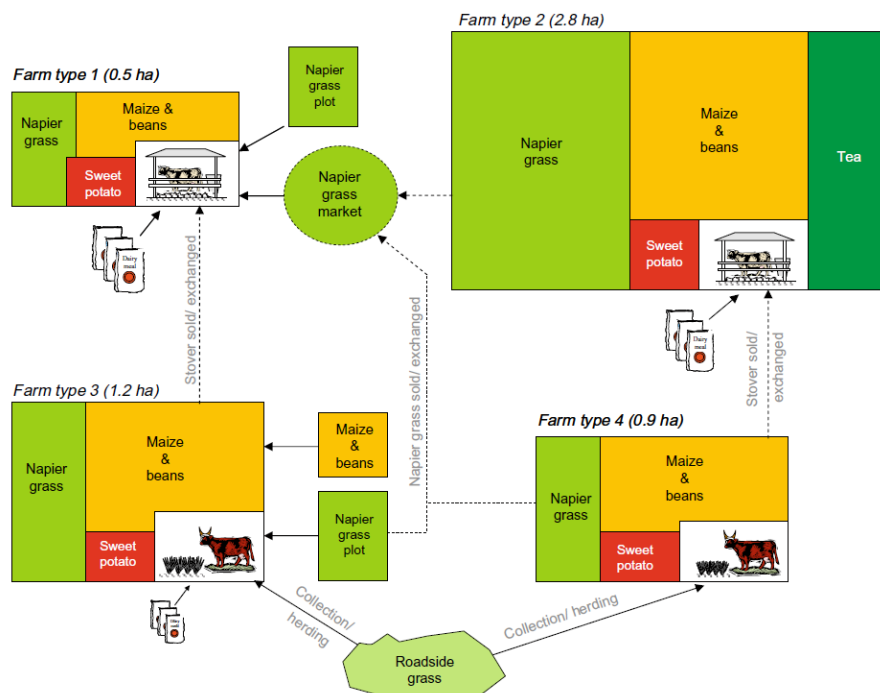


Figure 8. Example of a crop-livestock model in the Vihiga district, Kenya. The different material flows among farms are strongly related to the differences in farm types. Dotted lines stand for occasional flows (from Tittonell et al., 2009).

A definitive asset of crop-livestock analysis methods is their strong biophysical and biotechnical background: by incorporating mechanistic models that simulate crop and herd processes and management, they provide realistic representations of farming systems. They thus represent a critical element in the simulation of nutrient

flows within and between farming systems in a given territory. However, their strong focus on farms limits their possibility to simulate nutrient flows within complex agro-food systems that involve upstream and downstream economic partners.

1.4. Agent-Based Models

The third group of approaches we identified consists of a diverse research domain related to artificial intelligence based on the concept of “agents” (Niazi and Hussain, 2011). Agent-based models are computerised simulations of a number of stakeholders, decision-makers and institutions that are formally represented in the model and that interact through prescribed rules. Agent-based models were originally developed for the artificial intelligence field, which aimed to reproduce the knowledge and decision-making of several heterogeneous agents that are embedded in and that interact with a dynamic environment. When these agents need to coordinate to jointly solve planning problems, they generally have learning capacities that adapt in response to changes in the environment (Bonabeau, 2002). These models offer a better comprehension of the agents’ roles and the consequences of their actions within interconnected agent networks. They help to improve stakeholders' knowledge, to facilitate their dialogue and to negotiate from different viewpoints and conflicting objectives (Barnaud et al., 2008). They have been used in a wide range of disciplines, from social and economic behaviour to species networks. So far, agent-based models have been used for many kinds of resources, but not directly for nutrient cycle modelling. To remain consistent with our objective, which is to simulate nutrient flows through complex agro-food systems, we limited our analysis to two application contexts of agent-based models: those applied to natural resource management and those applied to industrial symbiosis.

Agent-based models have been applied to natural resource management to better understand the role of actors within a district on the conservation of these resources (Janssen, 2002). The interactions of the social agents with their dynamic environment are at the core of these models. According to Bousquet and Le Page (2004), multi-agent systems help researchers in the field of ecosystem management to go beyond the role of individual agents: they help to understand the role of agents’ interactions and organization (spatial, networks, hierarchies) in natural resource

conservation. Due to the scattered nature of farming operations in agro-food chains, such models are clearly helpful to improve resource management in farming systems. In addition, Delmotte et al., (2013) showed the high adaptability of the agent-based modelling approach to develop participatory assessment of scenarios. In such an approach, different interacting agents (such as farmers, water managers, policy makers or managers of protected areas) are asked to validate the conceptual model and to discuss the different model outputs. Here, agent-based models clearly serve as a means for supporting discussions between possibly conflicting actors.

Agent-based models have been extensively developed in relation to agricultural systems and resource management. Due to the scattered presence of farmers and agents among landscapes, these agent-based models are helpful to improve resource management, land-use and farming systems. In these models, the capacity to simulate actors' decision-making in a realistic way and natural processes at the same time remains challenging. Numerous examples exist in relation to water management in order to estimate or negotiate water demand for irrigation between farmers (Athanasiadis et al., 2005, Becu et al., 2003; Feuillette et al., 2003). Agent-based models have also been used to simulate farmers' assimilation of technological innovation, public policies or changes in resource availability (Mathevet et al., 2003). These models have also served as platforms in participatory analysis, such a role-playing game to simulate land-use (Castella et al., 2005) or water management (Gaudou et al., 2014). Concerning agro-food-systems, Schreinemachers and Berger (2011) showed how to couple farmers' decision-making simulations with biophysical models, thus accounting for strong interactions between farmers' investment decisions and crop dynamics (**Figure 9**). In this study, they developed an agent-based model to understand how agricultural technology, market dynamics, environmental change and policy intervention affect farm households and their agro-ecological resources.

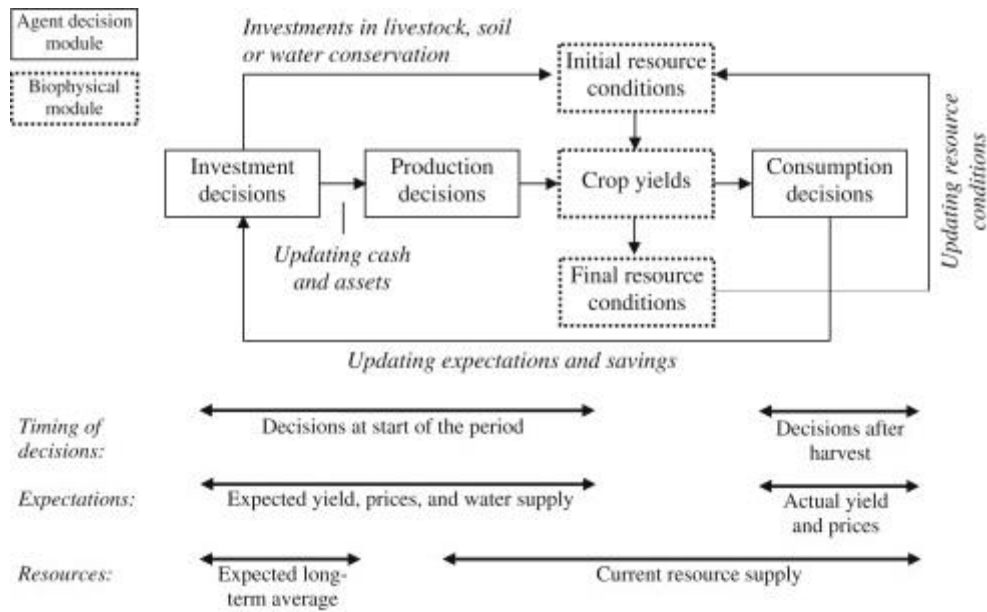


Figure 9. An agent decision module within an agent-based model (Schreinemachers and Berger, 2011a). Proceeding in annual time steps, the agent decision module goes through three phases (investment, production and consumption) and includes specific criteria, resources, periods and feedback.

Agent-based models can also be applied to industrial symbiosis aiming to simulate industrially transformed materials among network exchanges of industries (Axtell et al., 2001; Kraines and Wallace, 2006). This type of models goes beyond the static approach of industrial symbiosis analysis: it considers how agents adapt to different environmental, social and economic conditions. However, very little research exists on agent-based models applied to the symbiosis within agro-food production systems. A significant example is the study of pulp and paper industries and oilseed crops (Bichraoui et al., 2013) where driving forces that promoted industrial symbiosis under different scenarios were identified, although no ecological and farming dynamics were included. Another example is related to the BIOMAS Project (Guerrin and Paillat, 2002), which aimed to model organic matter exchange between horticultural farms, animal farms and wastewater treatment stations.

By accounting for interactions among a wide variety of economic actors, agent-based models are clearly essential in simulating material exchanges within complex social-ecological systems. Their ability to address different economical or environmental contexts is an additional asset to realistically simulate decision making of

interacting agents. However, their often limited biophysical background means that their ability to simulate nutrient flows within agro-food chains requires significant adaptation efforts.

1.5. Discussion

In the previous sections, we reviewed three main approaches that help to simulate nutrient flows in agro-food systems. In this section, we provide an overall comparison of those approaches in terms of purpose, scope and framework (**Table 1**Table 1.) and in terms of scale and agent modelling (**Figure 10**). We then discuss their interest for modelling nutrient flows in agro-food systems at the local scale.

Table 1. Comparison of the different approaches according to their purpose, scope and framework.

Purpose and Scope	What is the objective?	To assess farming system impacts on the environment	To quantify nutrient flows among agents, companies and physical compartments	To simulate agents' roles and behaviours
	What is the application context?	Agriculture	Agriculture and industrial related systems	Resource management in social systems
	How is the environment represented?	As a receptor or impacted compartment. Some of its features may be taken into account (soil, climate)	As one or several physical compartments (soil, water, air) that exchange substances with economic compartments	As a surrounding context with sensitive resources
	How are the agents represented?	Through their activities and practices	As aggregated compartments supplying or receiving flows	As autonomous, interacting decision-makers
	What is the spatial scale?	From plot to farm, sometimes extended to larger scales (Env. Risk Mapping) or to production chains (LCA, Footprints)	From local to global (districts or cities)	Mostly local (districts, cities or regions)
	What is the time scale?	From day to year	year	From day to year
	How is the system dynamics?	Generally static, based on empirical (e.g., footprints, LCA) or mechanistic data (e.g., as a function of climatic conditions or farming practices)	Generally static and sometimes dynamic	Dynamic through stochastic simulation of social and natural processes and decision-making
	Globally, they are	Tools (although sometimes based on encapsulated models)	Analysis methods, but sometimes models as well	Models

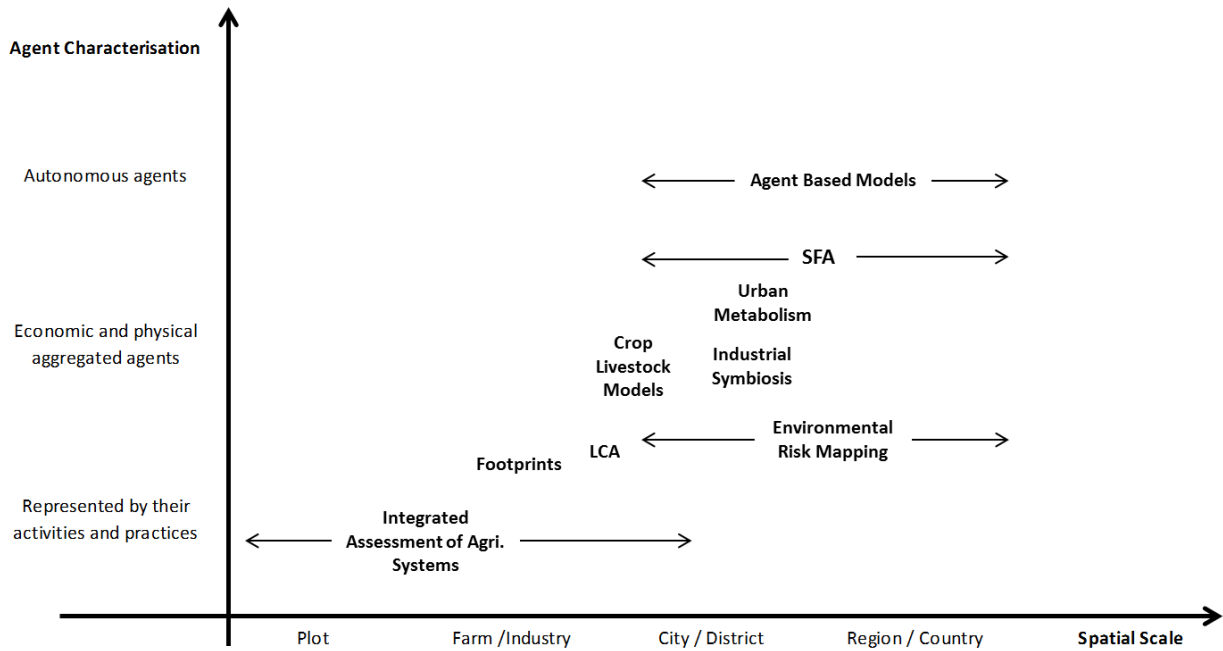


Figure 10. Classification of the different approaches based on how agents are represented (on the Y axis) and the spatial extent of the systems studied (on the X axis).

Our analysis revealed that each of the approaches that we considered in the previous sections has its pros and cons when simulating nitrogen or phosphorus cycles in complex agro-food systems. For instance, our analysis highlighted the fact that environmental assessment tools are indispensable to account for the critical segment of nutrient cycles that is related to losses to the environment. However, these tools remain clearly focused on a short segment of the agro-food chain, namely the agricultural production segment, making them inappropriate to link these losses to the complex functioning of the local agro-food chain or to design recycling loops among economic agents within districts.

In contrast, stock and flow analysis methods are more ubiquitous and can be applied to a vast range of spatial scales, from cities and districts to regions and countries (**Figure 10**). Moreover, these methods generally embed a large number of economic agents that are more or less aggregated. The degree of aggregation varies from no aggregation (e.g., in industrial symbiosis), to large aggregation based on input/output typology (e.g., in SFA and Crop-Livestock System Analysis). This makes stock and flow analysis methods capable of simulating material exchanges within longer segments of the agro-food chain (e.g., including farms and their

upstream and downstream partners) (**Figure 10**). However, our analysis also revealed that the interactions between economic agents and their environment are generally poorly considered in these methods, leading to rough estimations of nutrient losses from agro-food activities to the environment. In addition, stock and flow analysis methods are often static and rarely spatially explicit, thus providing limited opportunities to dynamically explore alternative scenarios of agro-food chains that could promote resource conservation and recycling.

Finally, although stock and flow methods represent a progress in conceptualising agents' practices compared to environmental impact assessment tools, our analysis showed that agent-based models provide unique opportunities to simulate dynamic interactions among economic agents within a district (**Figure 10**). Conceptualising autonomous and decision-making agents makes it possible to take the interactions among agents and with the environment into account (**Table 1**). However, our analysis highlighted the fact that nutrient losses to the environment are generally simulated on a simple basis. In addition, modelling the specific decision-making of the different agents remains a challenge.

Although the aim of all of these approaches is sustainability, it is not surprising that each of these ways to estimate nutrient flows has specific advantages and drawbacks when we consider the background of the research teams working on them. On the one hand, industrial ecology tools such as LCA or industrial symbiosis analyzes were originally developed by engineers, indicating a greater interest in technological innovations of industrial and manufactured products and less emphasis on environmental features and ecological processes. On the other hand, agronomists have been more likely to use integrated assessments of agricultural systems, as well as crop-livestock system analyzes, showing a clear focus on farming activities, with less attention to the behaviour of economic agents, product chains and technological innovations. In the case of agent-based models, a rich multidisciplinary of backgrounds exists, including computer scientists, economists, sociologists and other environmental modellers. Although some ecologists and environmental scientists are already working together within different teams, a big effort has to be made to encompass all of these different perspectives of sustainability. Hence, we encourage the contribution and cooperation of the different domains through Agro-Industrial Ecology to study agro-food systems sustainability and food chain cycles.

1.6. Conclusion and perspectives

Rural districts are characterised by a high number of individual and interacting agents, i.e., numerous individual, autonomous and scattered farms; input suppliers; agricultural product collectors and processors; waste managers; etc. By contributing to material exchanges, all of these agents control some segments of the global nitrogen and phosphorus cycle. Designing agro-food systems that efficiently recycle nutrient resources and limit their losses to the environment therefore requires the consideration of these different agents. This is even reinforced by the fact that agricultural production systems are increasingly specialised and embedded in long supply chains, leading to more extensive material exchanges within food chains. Actually, nutrient recycling opportunities at the farm scale might be limited in the future and there is the additional need to explore recycling loops at the local scale. While classical analysis methods provided by industrial ecology may be of great help to simulate material exchanges among economic agents, their inability to account for agricultural processes in terms of ecological dynamics and agent behaviour makes them poorly adapted for exploring realistic scenarios of agro-food system organization. The same holds true for agent-based models that often have a very limited capacity to accurately simulate diffuse nutrient losses to the environment and material exchanges among agents.

Indeed, coupling a consistently mechanistic natural environment with an unpredictable socio-economic system necessarily requires complex tools, analysis and models. For instance, coupling stock and flow and environmental assessment tools would help to link nutrient losses to the environment with material exchanges within food chains. Similarly, coupling stock-flow methods with agent-based models would help to link exchanges within food chains to agent decision-making and their corresponding driving forces. Due to their complete accounting of system functioning, stock-flow methods appear to be a critical element in nutrient modelling at the local scale. However, such couplings remain challenging in terms of system representation (e.g., to have a correspondence between decision-makers and stock-flow compartments) and in terms of system spatialisation (e.g., to have a correspondence between stock-flow compartments and accurate estimation of nutrient losses to the environment). The fact that each of the methods, tools and models presented above has its own limitations means that none alone is able to accurately simulate nutrient cycling in agro-food systems alone. In contrast, we

consider that linking stock and flow, environmental impact and stakeholders' decision-making approaches would be of great help to explore and assess innovative scenarios of agro-food systems. We believe that the development of an Agro-Industrial Ecology capable of linking complex environmental assessment, socio-economic agent interactions and farming decision-making would be an essential approach to address the global challenges concerning nutrient management today.

Chapter 2 -

“Flows in Agro-food Networks (FAN): An agent-based model to simulate material flows in agriculture at the local scale”

Submitted in 2017 to Environmental Modelling and Software, under review.

In the last chapter, we argued that combining stock-flow methods with both agent-based models and environmental impact assessment tools is a promising way to analyze the role of economic agents on nutrient flows and losses and to explore scenarios that better close the nutrient cycles at the local scale. Here, we present our attempt to build a model in that perspective. In particular, our aim was to design a model that took into account different nutrient-containing materials (such as food, feed, biomass, wastes, and fertilizers), that was able to simulate their flows between farms and their economic partners, and finally, that was able to assess different scenarios of flows among agents. The present chapter has been submitted to Environmental Modelling and Software and is currently under review.

Abstract

Agro-food networks are characterized by complex materials exchange among farms, processors, consumers, and waste managers. Better coordination of materials exchanges at the local scale could help to facilitate more closed-loop agro-food systems. Here, we present a new agent-based model, “Flows in Agro-food Networks” (FAN), which simulates the processing and exchange of fertilizers, feed, food and wastes among farms and multiple upstream or downstream partners (feed and fertilizer suppliers, food industries, waste processors, and anaerobic digesters) at a local scale. FAN includes a series of environmental indicators that can be used to assess alternative scenarios in terms of ecosystem services, nutrient cycling, and resource autonomy. We use a French case study to demonstrate FAN’s dynamics and to explore the sensitivity of key variables. FAN provides a powerful tool to quantitatively assess opportunities for a circular bioeconomy, including by simulating competition between local and global sourcing of resources in agro-food networks.

2.1. Introduction

Improving resource-use efficiency in agriculture is crucial to reducing pressures on natural resources while simultaneously enhancing agricultural productivity (Erb et al., 2016; Foley et al., 2011b). Food systems in many regions are increasingly comprised of highly specialised farms connected to global markets, which can create spatial disconnects between food consumers and agriculture's environmental impacts (Liu et al., 2013). Globalization has also resulted in massive exchanges of food, feed, forage, and fertilizers in agriculture (Lassaletta et al., 2014a; MacDonald et al., 2015), and such 'linear' flows among regions can exacerbate reliance of local farming systems on external inputs by decreasing the potential for local recycling (Schipanski and Bennett, 2012; Tittonell, 2013). The reliance of agricultural management on external inputs of fertilizers is especially pervasive in livestock farming systems (Herrero et al., 2013), and has been acknowledged as key drivers of water eutrophication (Leip et al., 2015b) and greenhouse gas emissions (Carlson et al., 2016). While the increasing connectivity created by global material flows via trade may support increased access to resources at lower prices, it does so potentially at the cost of decreased local self-sufficiency and import dependency (Fader et al., 2013; Le Noë et al., 2017). In contrast, greater reliance on local materials exchange ('circular' flows) can help to promote crop-livestock integration (Moraine et al., 2014; Regan et al., 2017), biogas energy production (Lorenz et al., 2013) and efficient waste recycling (Alvarenga et al., 2015; Bodirsky et al., 2014; Metson et al., 2016). Such 'closed-loop' approaches are key for more sustainable and autonomous bio-economy patterns in agro-food systems (El-Chichakli et al., 2016; Scarlat et al., 2015).

Designing and assessing alternative scenarios of material flows within local agro-food systems can help decision-makers to identify the feasibility and pathways to move towards a circular economy (Ingrao et al., 2016; Smith et al., 2016). However, assessment of alternative scenarios is challenged by the complex nature of *agro-food networks* (Fernandez-Mena et al., 2016), which involve flows and relationships among different economic agents in the food production sector (e.g., farms, fertilizer and feed suppliers, slaughterhouses, food processors, and waste managers). Modelling interactions by simulating material exchanges among economic agents in agro-food networks is an approach that helps to design, quantify and assess the potential socioeconomic and ecological benefits of social change towards circular economy patterns (Elsawah et al., 2015; Filatova et al., 2013; Le Page et al., 2013). Agent-based modelling is a particularly important as a tool that enables simulation of complex material flows among a range of economic agents and to assess the potential outcomes of different scenarios on multiple environmental indicators (Fernandez-Mena et al., 2016).

At present, only a relatively small number of studies have applied agent-based modelling to agro-food systems. These studies have typically focused on specific aspects of the agro-food systems, rather than integrating across multiple agro-food system sectors and activities. For example, past agent-based modelling has been applied to the study of environmental changes in farming systems (Acosta-Michlik and Espaldon, 2008; Murray-Rust et al., 2011; Schreinemachers and Berger, 2011b); agricultural markets and policies (Bert et al., 2015; Schouten et al., 2014); land-use change (Groeneveld et al., 2017; Le et al., 2010); agricultural water management (Becu et al., 2003; Gaudou et al., 2014); urban and agricultural waste management (Bichraoui et al., 2013; Courdier et al., 2002; Xu et al., 2016); and rural livelihoods and self-sufficiency (Iwamura et al., 2014; Magliocca et al., 2013; Villamor et al., 2014). To our knowledge, agent-based models have not yet been applied to simulate material flows across a broader range of components in agro-food networks, including multiple agents and a wide range of exchanged materials. This more holistic analysis is, however, key to assess alternative agricultural development strategies, waste recycling, and environmental impacts related to circular economy.

Here, we present an agent-based model, “Flows in Agro-food Networks” (FAN), which facilitates the simulation of multiple types of material exchanges across upstream and downstream agents in local scale agro-food networks. Multiple types of biomass materials containing nutrients are considered in FAN, i.e. fertilizers, forage, feed, food and wastes, in order to simulate the effect of contrasted scenarios of material exchanges. We developed the FAN model in GAMA 1.7 platform (Drogoul et al., 2013; Grignard et al., 2013; Taillandier et al., 2010), an open-sourced coding environment that supports the use of geographical information systems within the agent-based language GAML. In this paper, we present and illustrate FAN’s features, and how the model can be applied to assess outcomes arising from multi-agent interactions in terms of local food and bioenergy production, nutrient cycling, greenhouse gas emissions, and other indicators of environmental quality under user-defined scenarios. We also use a case study of a district in France to examine the model sensitivity for its key input variables.

2.2. FAN Model Overview

In this section, we use the Overview Design concepts and Details “ODD” protocol for agent-based model descriptions (Grimm et al. 2006; 2010) to outline the FAN model, including the model purpose, scope, and agents’ characteristics. We also introduce the mechanisms involved in the material exchanges through individual decision-making processes and social simulation. Each of the sub-sections further describes the modelling approach used in FAN, from the model

conception, to the submodel and processes simulated. The GAML code for FAN and its attached files are provided in the supplementary materials (**Supplementary Materials File 1**).

2.2.1 Purpose

We developed FAN in order to simulate material flows among economic agents in local agro-food networks. We define agro-food networks as encompassing various activities related to food production and consumption at local scales (**Figure 3**). They include farming activities and losses to the environment at the farm scale, interactions between farms and their partners through material exchanges, as well as waste and by-product recycling. In FAN, food, feed and wastes are processed and exchanged among farms, and their upstream and downstream partners that have direct connections to farms in the agro-food network. These partners include feed and fertilizer suppliers, food industries, waste processors, and anaerobic digesters. Their features are presented in the next section.

The key foundations for developing more closed-loop agro-food systems can be simulated by focusing on individual agent choices (e.g., for sourcing different materials) across the local network or via exchanges with global markets. The main variables driving these exchange processes in FAN are choices between organic versus chemical fertilizer use, use of crop products for human food, animal feeding or biomass-based energy production, and by-product and waste management strategies. In turn, the model can be parameterized in order to simulate alternative scenarios and their assessment in terms of various environmental indicators, including greenhouse gas emission, nutrient losses, and ecosystem service proxies that result from material exchanges among agents.

2.2.2 Entities, state variables and scales

FAN was developed for application to local or sub-regional case studies (e.g., $\approx 1,000 \text{ km}^2$). Although many agent-based models have been developed for applications to specific geographical contexts, FAN can be adapted for its use in a variety of rural and agricultural case studies where core input data is available. Key requirements include data on land use, livestock numbers and feed rations, as well as crop yields and fertilization rates. Here, we conduct sensitivity analysis by applying FAN to an agricultural case study for a sub-region of southwestern France with about 835 farms (Ribéracois district in the department of Dordogne, $\sim 1,000 \text{ km}^2$; see Section 3.1). Although we carried out surveys of major farm partners such as feed and food collectors and food industries in order to guide the development of FAN, the scale and number of farms is large enough to make unfeasible gather surveys of farmers individually. For this reason, FAN is able

to generate synthetic populations of agents based on general data collected in public statistics providing land-use and livestock in farms.

In FAN, points and vectors are used to represent agents and flows, rather than as raster grid cells that are common in agent-based models (e.g., Grimm et al., 2005; Rebaudo et al., 2011). As a result, agent attributes, such as the land use of each farm, are stored as attributes. The model is therefore able to take into account the geographic location of the agents (represented as points), flows between agents (represented as vectors), and to distribute these points according to specific addresses or randomly. Simulation of larger and smaller areas is also possible with FAN, as well as the use of different numbers of agents.

The agent population is composed of eight main types of agents, as represented by the agent class diagram in **Figure 11**. They include agricultural production (*farms, feed and forage collectors*), food industries (*milk & cheese industries, slaughterhouses, and fruits & vegetables industries*), waste managers (*anaerobic digesters, wastewater treatment plants*), and *fertilizer wholesalers*. We additionally use an intermediary conceptual agent ('Partner', white box in **Figure 11**) as a modelling tool to allow these agents to simultaneously demand and supply materials on each round of exchanges. Although farms are classified into eight different functional groups according to their characteristics (in terms of area, land-use and livestock numbers), all farm agents are capable of a set of defined actions while their annual production is based on their individual agent attributes. For instance, during a simulation, all farms conduct the action of animal feeding at the same time (regardless of the farm type), but farms that do not have animals remain unchanged by this action.

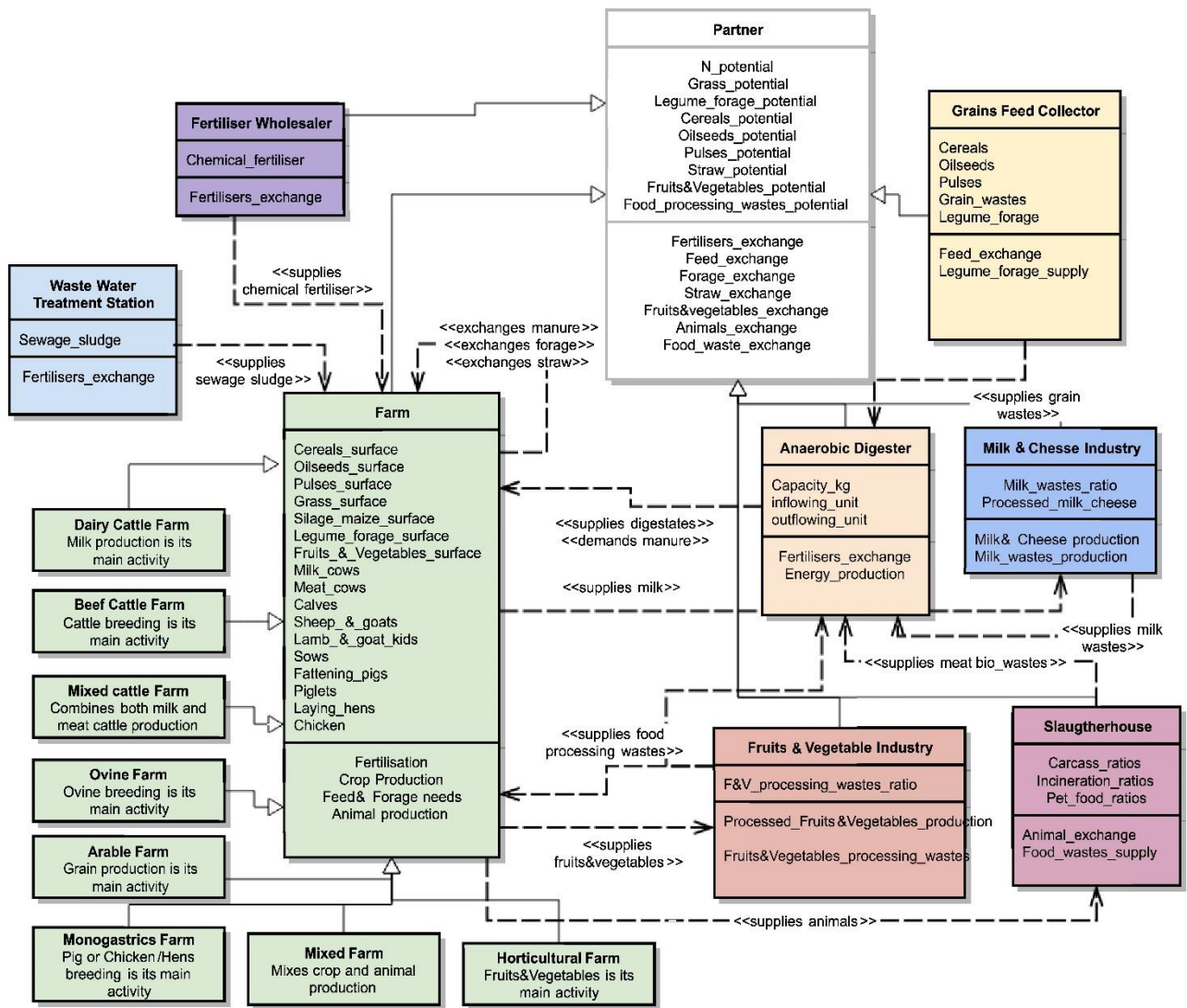


Figure 11. Class diagram in UML (Unified Modelling Language). Agents are represented in boxes with their attributes listed in the middle and their typical actions in the bottom. The eight farm agent functional groups are depicted in green. Solid arrows with hollow white ends represent belonging to a more general category (e.g., an ‘arable farm’ is an extension of the broader ‘farm’ class). Dashed arrows indicate actions as specified in angle quotation marks (<<>>).

Material flows represented in the FAN model include different groups of organic wastes and fertilizers, crop and animal products, and other biomass and feedstuff. In general, most of the material categories are flowing in and out of farms (**Figure 12**), and only some specific food processing wastes that are being digested for bioenergy do not come to farms until they are transformed in digestates for fertilizing soils. Materials include a range of subcategories such as (i) fertilizing materials (manure, sewage sludge, digestates from anaerobic digestion and chemical fertilizers); (ii) crop products (cereals, oilseeds, pulses, fruits & vegetables, grass, legume forage,

silage maize and energy crops); (iii) by-products from milk and fruits and vegetables; (iv) straw; and (v) bio-wastes from meat and grains processing.

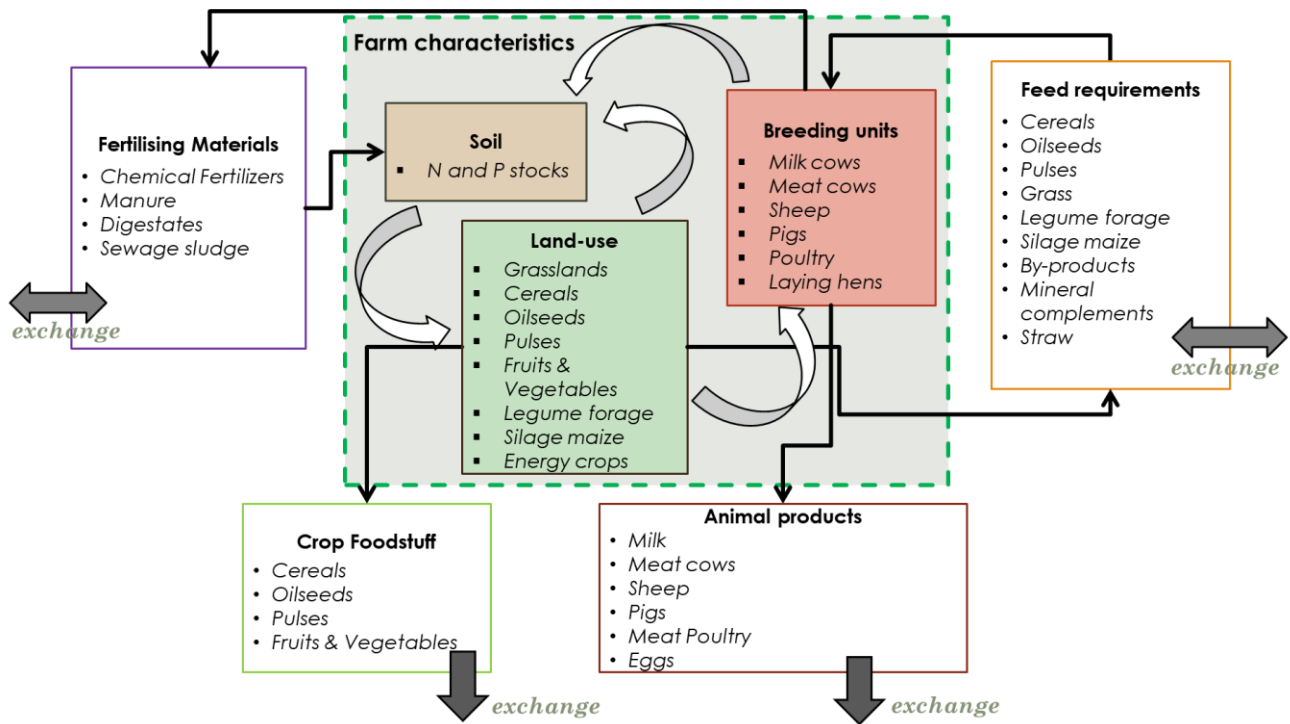


Figure 12. Farm agent entities in the model and their possible interactions and material exchanges with the local and global markets. Solid boxes represent the various types of farm features and white boxes represent the materials that farm agents (8 functional groups) can exchange within the local network. White arrows represent in-farm interactions, black thin arrows stand for interactions with the market (supply or demand of materials) and large black arrows stand for actual flows in and out the farm. Note that some exchanges are bidirectional (fertilizers and animal requirements) while some are unidirectional (foodstuff).

In FAN, the eight farm functional groups are created based on local farming typologies, each one having its own surface, land-use and livestock number of heads. Each farm agent may find partners to exchange with, depending on whether they are supplying or demanding specific materials (boxes in **Figure 12**) and if these materials are exchanged in the network or not. Although the model focusses on local-scale exchanges within the specified study area, agents can also exchange with global markets outside of the system boundaries. Global markets in FAN represent unidirectional supplies with (i) fertilizers, competing with local organic fertilizers; (ii) feed (cereals, oilseeds and pulses) and forage (such as dry alfalfa), compensating local deficit for feed requirements; and (iii) digestible biomass, compensating local deficit for anaerobic digestion. When local agents are connected to the global market, FAN assumes that they have access to an unlimited supply (e.g., fertilizer supply from the global markets is not constrained).

2.3. Process overview and scheduling

Since the core purpose of FAN is to simulate local-scale material flows in agro-food networks, here we present how the related processes are scheduled and what rules govern the types and magnitude of these flows. The steps of the model represent different production and exchange activities during a simulation cycle, equivalent to a year (**Figure 13**).

The simulation cycle begins with the production of fertilizing materials such as manure, digestates and sewage by farms, anaerobic digesters and wastewater treatment plants. These fertilizing materials are then applied to agricultural soils according to each farm's nutrient demand. Chemical fertilizers can also be used by farms. Excess manure may be saved for bioenergy production by anaerobic digesters. Subsequently, each farm's crop production is calculated as a function of fertilizing material inputs to soils through a simple linear yield-response model. Animal feed requirements are estimated according to species-specific feed demand, and crop products are exchanged in order to meet these animal requirements. Once feed and forage requirements are satisfied, livestock production is calculated.

After total crop and animal production has been computed, fruits, vegetables, and animal products are exchanged with local food industries, where they are processed, generating processed food and food wastes. Finally, once food wastes have been exchanged with livestock farms and anaerobic digesters, the latter results in bioenergy production. Note that global markets can create competition with local materials (e.g., imported chemical fertilizers can compete with local manures for fertilizing soils) or can compensate local production deficits (e.g., in feedstuff and forage to meet animal requirements).

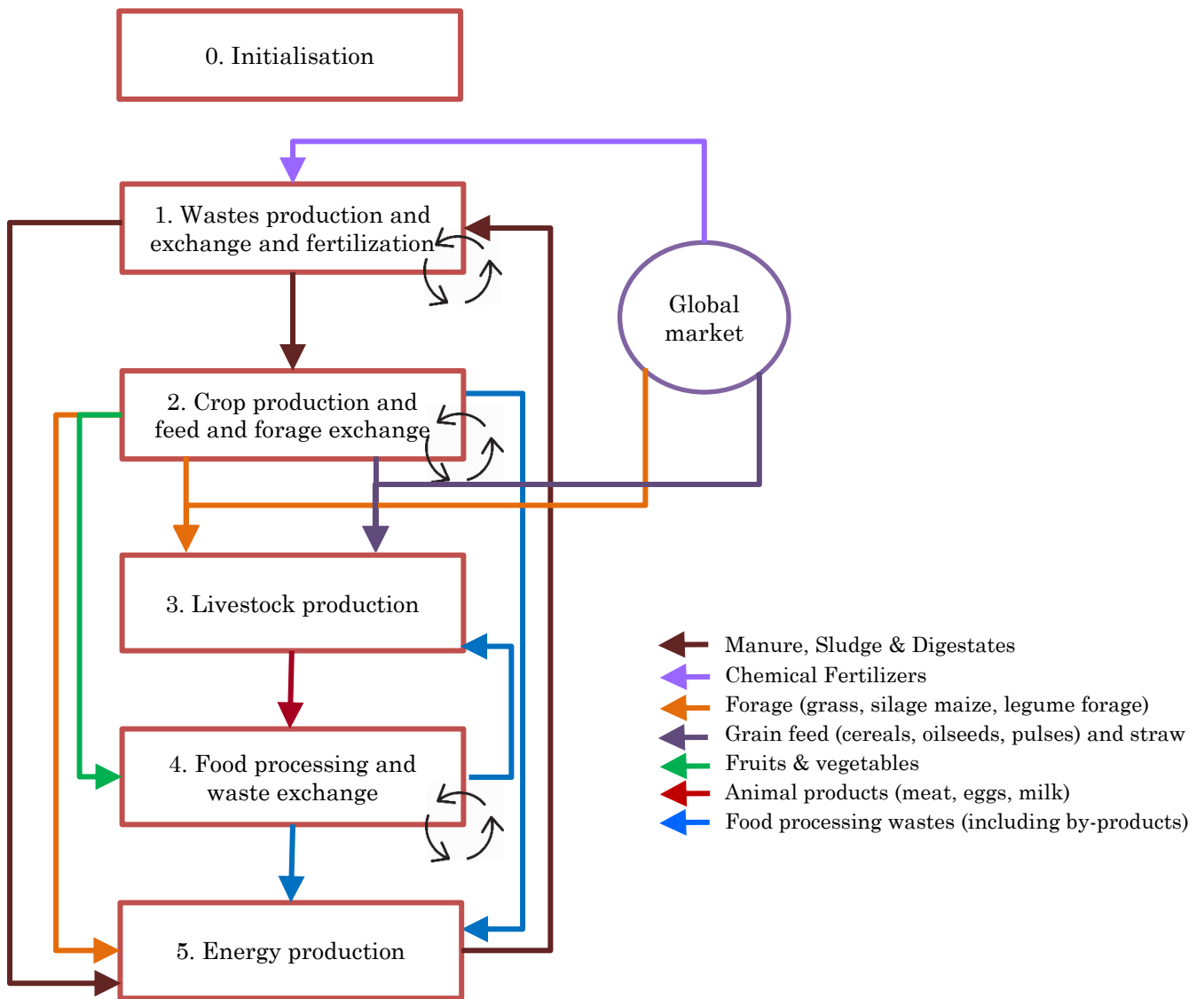


Figure 13. Process schedule along a cycle of one year. Linear arrows represent material flows interacting at different steps. Arrow loops at steps 1, 2, and 4 represent the materials exchange processes between agents within the network.

In FAN, each agent has a potential (Ψ) for any given material. Agents with a positive potential (internal production > internal requirements) are considered as ‘suppliers’ (Ψ_S) that can produce material outflows, whereas agents with negative potential (internal production < internal requirements) are considered as ‘demanders’ (Ψ_D) who may receive material inflows. Suppliers representing global supply chains (such as fertilizer or animal feed suppliers) have unlimited potential supply, whereas local industries and collectors have unlimited potential demand. On each round of exchanges, agents search for materials in the network until local resources are exhausted.

When exchanging each material, the choice of partners in the network is made based on the weight calculated according to **Equation 1**. Calculating this weight helps to rank each pair of agents combining a supplier (i) and a demander (j) willing to exchange.

$$\text{Weight}_{i,j} = \text{Proximity}_{i,j} * \text{Supply-Demand Ratio}_{i,j} * \text{Preference} \text{ (Equation 1)}$$

Where:

- Proximity = $(\frac{1}{\text{Distance}_{i,j}^a})$; with $\text{Distance}_{i,j}$ the distance in km between agents i and j ; a is a user-defined exponential of distance accounting for local transportation issues and a key factor when allocating biomass (Görgüner et al., 2015; Metson et al., 2016);
- Supply-Demand Ratio = $(\frac{\min[\Psi S_i, \Psi D_j]}{\max[\Psi S_i, \Psi D_j]})$ where $\Psi S_i, \Psi D_j$ are the potential supply and demand of the agents, respectively, in kg of materials. This ratio accounts for matching potentials among agents, which has been acknowledged to be significant driver of material exchanges (Zhao et al., 2017). This ratio is only applied to local biomass exchanges (i.e., it is not applied to commodities that are sourced from the global market);
- Preference coefficients [0-1] are simulation artefacts that we created to orient agents in a context where a specific material type or use is preferred, (e.g., because markets make it cheaper or regulation compulsory). These preference coefficients are used to represent agent behavior in a context where different material types can serve the same usage (e.g., both mineral fertilizers and animal manure can be used to fertilize soils) or a given material can serve different usages (e.g., animal manure can serve to fertilize soils and to be used as substrate by anaerobic digesters).

The factors that we have simulated (e.g., distance, supply-demand ratio, preference coefficients) drive the possibilities to initiate an exchange with one agent rather than with another one (**Figure 14**). While in theory Equation 1 applies to any potential supplier or demander, we added three additional variables to better mimic real-world processes and to limit the duration of calculations. First, a ‘Disposition to exchange’ variable helps to set the proportion of farms that are willing to exchange their biomass, including manure, forage and straw. This variable assumes the possibility that not all farmers are interested in exchanging products with no clear price in the economic market, i.e., biomass and wastes. Moreover, in order to consider temporal dimensions of agent relationships, after the first year, the number of agents keeping their previous year partner is proportional to the ‘Fidelity’ variable. ‘Fidelity’ accounts for the agents keeping the same partner as the previous year for each specific use, and it also includes the idea of the low variability of farmer partners in reality, and the low network exploration. Finally,

transportation distance is limited using a ‘radius of action’ that sets the maximum distance over which a given material can be transported. The radius of action is applied to bulky biomass materials including manure, sewage sludge, grass, silage maize, legume fodder. For a given supplier (or demander), this radius of action *de facto* excludes any potential demander (or supplier, respectively) that is located beyond its value (**Figure 14**). Another process used to govern exchanges is the adaptation of our local network market to either a buyers’ or a sellers’ market depending on the relative number of ‘suppliers’ (Ψ_S) versus ‘demanders’ (Ψ_D) present in the network. For instance, if forage demanders are more numerous than suppliers, FAN lets suppliers initiate the material exchange process, and vice versa.

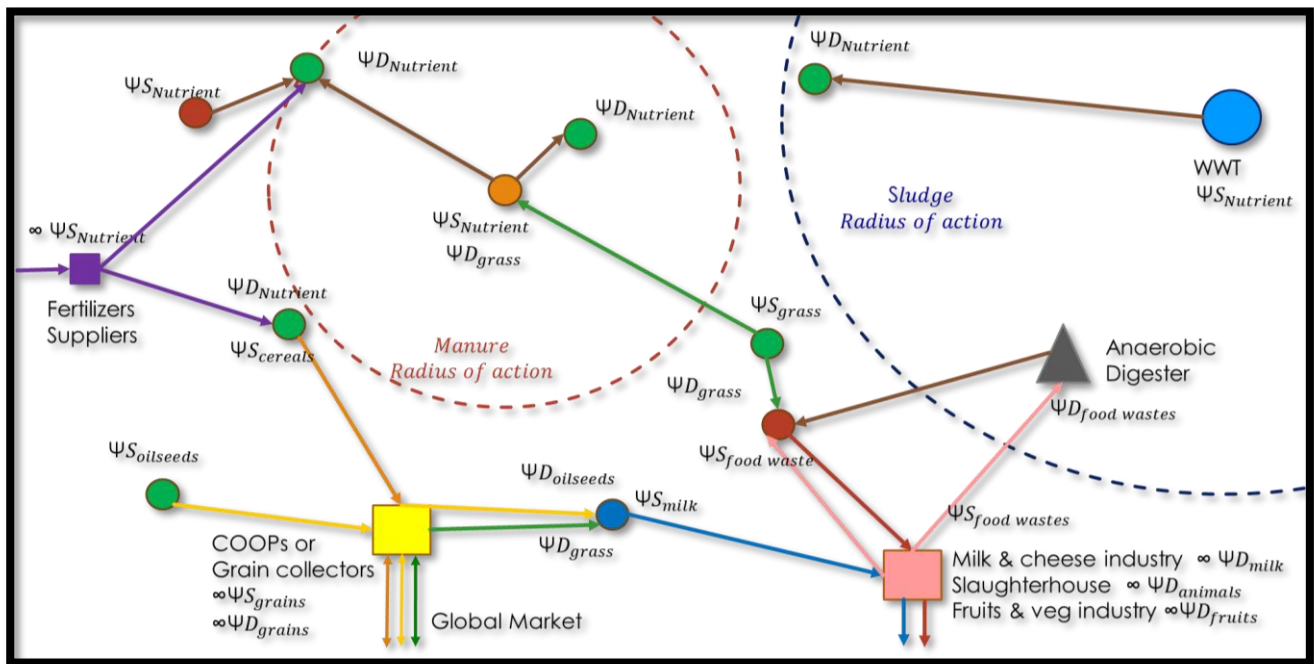


Figure 14. Representation of material flows in FAN. Farms are represented as small circles (green for arable, red for cattle, blue for dairy and orange for monogastrics). Arrows represent flows of materials: manure flows are in brown, chemical fertilizers in purple, grass flows in green, cereals flows in orange, oilseeds in yellow, milk in blue, meat in red and food processing wastes in pink. Flows crossing the system boundary represent exchanges with the Global Market. Examples of the radius of action for manure and sewage sludge are shown by the dotted circles. WWT stands for Wastewater Treatment plant.

The model calculates the weights according to Equation 1 for any potential pair of suppliers and demanders. Once all possible weights are calculated, pairs of agents are stochastically selected by the model following a probability distribution proportional to the series of weights obtained. Therefore, the corresponding material flows occur one by one, allowing to recalculate weights with the remaining of the agents in the network if they still need to exchange materials. FAN makes

use of this simple stochastic method to create partner couples as we understand that there is a high variability in partnership establishment in the real world that may not be fully captured by this model.

Note that FAN does not explicitly include prices or economic factors, since many biomass materials (e.g., forage, manure, food processing wastes) do not have a clear market value. Further consideration of economic modelling processes was considered beyond the scope of the model at this stage, and so our focus is on the biophysical and social factors that may drive materials flows at the local level. Instead, we include various simulation mechanisms and decision-making variables that can mimic market contexts when prices, costs, subsidies and farming strategies may interact. These mechanisms and variables include the radius of action, farm fidelity to their partners, their relative disposition to exchange and the set of preference coefficients for specific material uses. Note also that the exchange processes are organized to allow for different uses for a given material depending on agent preferences. This is simulated through the substitutability of interchangeable materials for the same use and, symmetrically, through the partition of a given material into different uses. Such substitutability was related in our model to chemical fertilizers and organic wastes; grains; forage; other crops and animal products and food wastes.

Table 2. User-defined variables and their default values in the model

Variable name	Units	Default value
Network features		
Exponential of the distance (a) in Proximity Equation 1	-	a=1
Fidelity	% farms	50
Disposition to exchange between farms	% farms	50
District capacity of anaerobic digestion	kg of materials	60000
Number of farms	-	850
Chemical and organic fertilizers		
Sludge for fertilization preference coefficient	[0-1] ratio	0.5
Manure for direct fertilization preference coef.	[0-1] ratio	0.5
Manure for anaerobic digestion preference coef.	[0-1] ratio	0.5
Chemical fertilizer pref. coef.	[0-1] ratio	0.5
Digestates pref. coef.	[0-1] ratio	0.5
Radius of action for manure	km	15
Radius of action for sewage sludge & digestates	km	80
Forage & feed		
Grass forage-digestion preference coef.	[0-1] ratio	100
Radius of action for grass	km	50
Radius of action for silage maize	km	20
Food wastes		
Fruits & vegetables wastes for digestion preference coef.	[0-1] ratio	0.5
Fruits & vegetables wastes for animal by products pref. coef.	[0-1] ratio	0.5

2.4. Design Concepts

Model presentations following the ODD protocol commonly include design concepts (Grimm et al., 2010), which we describe below with specific focus on those relevant to FAN.

Basic principles. The FAN model design follows an intermediate geographic scale in which farms and their partners are connected through a series of rules that govern decisions about materials exchange. The concept and theory behind FAN are related to the fact that agents exchange a series of materials based on their (negative or positive) potential, becoming suppliers or demanders. In FAN, we hypothesized that this potential results from both agronomic constraints (which are well represented) together with economic constraints (only considered through proxies).

Emergence The model provide emergent, poorly predictable results about competition among agents and among uses related to material flows. Other emergent results are related to deficits that may occur as a result of competition phenomena, or accumulation of wastes by specific agents (e.g., accumulation of animal manure within livestock farms that did not identify demanding partners). Such emergent results may also arise due to altering system attributes by the user, i.e., by modifying farm behavior or farm features.

Objectives. Basically, the objective of each agent is to achieve material exchange and production. That is, for suppliers to maximize the amount of materials that can be supplied, and, for demanders, to maximize the amount of material that can be collected. For instance, farms aim to both satisfy their fertilizing material, animal feed, forage and straw requirements by collecting appropriate materials from suppliers and to avoid animal manure accumulation on their land by exchanging their surplus. Regarding their partners, anaerobic digesters aim to complete their capacity, while food industries, grain collectors, wastewater treatment plants and slaughterhouses aim to get rid of their wastes and avoid their accumulation.

Sensing. Any agent in the model can sense any of the variables used in Equation 1. These variables relate to the potential supply and demand of all the agents and for all the considered materials, the geographic location of all the agents (calculated by Euclidian distance), their history of material exchanges and their preference related to substitutable products. The fact that each agent can sense these variables helps to identify the best partnership and to maximize material exchanges.

Interaction. Most interactions among agents are direct, through material exchanges among agents. However, some interactions can also be indirect through some specific resources for which

competition among agents occurs. Considering these two types of interaction is key to reveal unexpected processes and material exchanges.

Stochasticity. Although the model is clearly deterministic, we added a small stochastic effect in the process related to the selection of pairs of partners. A random choice of pair of partners is made by the model proportionally to the weights determined for the whole set of potential pairs of partners. While we considered that the set of variables used in Equation 1 is relevant to mimic the fact that two agents become partners, we acknowledge that this set may not capture all the socio-economic processes that determine such relationships. These un-captured processes –which we consider beyond the scope of FAN- are accounted for by adding stochasticity to the model.

Observation. At the end of each cycle (year), a set of outputs is generated by the model, including food and energy production on one side and greenhouse gas emissions, nutrient cycling and resources use on the other side. Outcomes for these environmental indicators are described in next section, and some of them are used in the Sensitivity Analysis, in Section 3.

2.5. Submodels

Initialization. In order to initialise FAN, a synthetic farm population was created based on the average features of different farm types. Farms were indeed classified according to their main agricultural productions into different farm types and, for each farm type, we calculated the mean and standard deviation of (i) the total farm area; (ii) the farm's land-use distribution and (iii) the farm's livestock number. Then, to create the synthetic population of farms, for each farm type, we first used a normal distribution of the farms' area centered on the mean observed value. We then distributed land-use and livestock numbers to the farms proportionally to their area. Other existing partners are placed using points (as a shapefile), and anaerobic digesters are distributed uniformly across the landscape. Each agent is supposed to have a null stock at the initialization.

Fertilizing material application to soils, crop production and nutrient losses. Although in some minor cases crop production could be phosphorus-limited, we considered that nitrogen (N) was clearly the most limiting factor of crop production in this area (Mueller et al., 2012). In simulations, crop yields thus vary with N applications to soils through organic and mineral fertilization, N fixation by legumes, atmospheric deposition and soil organic matter mineralization. Crop yield response to N application was considered to be linear up to a certain N application level, after which it reaches a plateau corresponding to the observed regional yields. This approach was justified by the fact that fertilization excess usually occurs in the considered region (Lassaletta et al., 2014b). Losses of N are estimated in the model through (i) leaching as

the surplus of N application relative to crop uptake, (ii) N volatilization from organic fertilizing material storage and application and (iii) N₂O emissions from soils to the atmosphere. Users can define the fertilization application rates by following a simple N budget based on crop nutrient uptake, by using observed fertilization doses, or by setting fertilization restriction policies.

Livestock feed, forage, bedding and production. Once crops are produced, animal requirements are estimated based on observed feed rations, forage use for ruminants, and straw for bedding that are applied in France (Agreste, 2011). These requirements are first supposed to be satisfied with inner farm production. However, if inner farm production fail to satisfy those animal requirements, the model simulates exchanges with others farms, feed suppliers or with the global market. In FAN, forage requirements per ruminant are linearly proportional to their production within a range of variation of $\pm 10\%$ around the average forage consumption reported in statistical data (Devun and Guinot, 2012). Finally, ruminant meat and milk production are proportional to the forage consumption.

Waste and by-product production. Waste and by-product production from food industries were determined by using food processing ratios (in %) both from local surveys and national data and by applying these ratios to the amount of raw products (e.g., live animals, raw milk, grains, fruits and vegetables) entering food industries. Although food processing wastes are demanded for energy production by the anaerobic digesters, non-animal food wastes such as fruits and vegetable wastes are also demanded by farms for animal feeding. In addition, animal manure production was determined by using excretion rates per animal type (in kg N per animal and per year) collected from national databases (Table 2) that were multiplied by the number of livestock of each farm. Fresh digestates from anaerobic digesters were estimated proportionally to the amount of materials entering anaerobic digesters.

Bioenergy production. In FAN, the number and capacity of anaerobic digesters can be defined by the user. Anaerobic digesters are supplied according to average composition of the feedstock observed in France. According to the French environmental and energy agency 'ADEME', in 2013, the average composition of feedstock was 68% manure, 17% green biomass (grass, energy and inter crops), and 15% food processing wastes. The energy produced by anaerobic digesters was modelled proportionally to the digestible potential of material inputs. We estimated a production of 42.02 m³ of biogas, with 34% of electric yield equivalent to 85.73 kWh of electricity per tonne of feedstock mix (ADEME, 2013; Pöschl et al., 2010).

Environmental extension. The outputs from FAN can be used not only to calculate food and energy production, but also to assess various environmental indicators, including greenhouse gas emissions from agricultural activities and material transportation, nutrient losses to water

bodies, and other ecosystem services (Table 3). Greenhouse gas (GHG) emissions from agricultural activities were estimated by using IPCC methods (IPCC Guidelines, 2006), including soil emissions and carbon storage, livestock enteric fermentation and emissions related to organic fertilizing material storage and application. GHG emissions from material transportation were estimated by emission factors from average truck and boat emissions per kg of material transported (IPCC, 2013) for local and global materials flows respectively. Additionally, potential GHG emissions avoided by biogas production emissions are estimated (European Environmental Agency, 2014). A soil organic matter dynamics model, inspired by Hénin and Dupuis, (1945), was used to estimate carbon storage in soils by accounting for soil organic matter stock, carbon humification following organic material inputs and organic matter mineralisation. Human and animal average food and feed consumption equivalents were used as a proxy to estimate food and feed autonomy indicators (FAO, 2010). The environmental outputs for all indicators are included in the code provided (**Supplementary Materials File 1**), but are not further detailed in this paper.

Table 3. Examples of the various environmental indicators that can be estimated by FAN’s submodels.

Activity or environmental component	Indicators calculated by the model	Estimation method
Crop production	Grains:	Land use and regional yields
	Cereals, Oilseeds, Pulses.	
	Other crops:	
	Fruits & Legumes	
	Forage:	
	Grass, Silage Maize and Legume forage.	
Livestock production	Beef meat	Number of heads and average national yields
	Sheep & Goat meat	
	Pork meat	
	Chicken meat	
	Cow milk	
	Goat milk	

	Eggs	
Renewable Energy production	m ³ of Biogas kWh of LHV kWh of electricity	Average digestates composition and energy potential
	CO ₂ direct emissions from: Truck local transportation Livestock Manure N Leaching	Direct and indirect emissions by emission factors (IPCC, 2016)
Greenhouse gas emissions	CO ₂ indirect emission from: Forage national supply Feed importation Chemical Fertilizers Avoided emissions: C storage in soils CO ₂ fossil fuel avoided by anaerobic digestion	Avoided emissions: Carbon sequestration in soils Bioenergy potential (ADEME)
Nutrient losses to water bodies	Nitrogen leaching	N applied in excess of crop needs Soil erosion rates
Soil C sequestration	C stored in soils	Humified carbon following C inputs to soils
Food and feed Autonomy	Feed and Forage autonomy Food and feed production equivalents	Total production in each district divided by average citizen consumption and average livestock requirements
Nutrient Cycles in Fertilization	Fertilization inputs and crop outputs Use of N from: chemical fertilizers; recycled sewage sludge	Potential local flows (fertilization, bioenergy, animal feeding). % N recycled N losses N use

2.6. Input Data and Initialization

For application of FAN, various input data are required to characterize the agents and to define the key processes that are considered. Characterizing the agents required specific data about their size (e.g., total area and livestock number for farms or energy production capacity for anaerobic digesters), their main activities (expressed in land use and livestock distribution per farm type for farms) and geographic location. Regarding the latter, the model allows for random spatial distribution of the agents or distribution according to a user-defined map. Defining the key processes considered in the model requires local, regional or national data concerning production rates (e.g., crop and animal potential yields); feed requirements for livestock and anaerobic digesters; waste and by-product production from production activities. We collected these data from French national, regional and local statistics (see Table 4 for some key examples). Nevertheless, it is recommended that users compile the best available data for application to case studies in other countries. This data gathering was obtained both from public data coming from farming extension programs as well as agricultural census.

Parameter	Value and units	Source
Land-use and livestock in farms	See model included files (ha of crops and livestock heads. farm ⁻¹)	Agreste (Ministry of Agriculture, France) 2010
Crop regional yields	See model included files (kg of crop. ha ⁻¹ . year ⁻¹)	Agreste (Ministry of Agriculture, France) 2010
N in animal excreta	See model included files (kg N. animal head ⁻¹)	COMIFER, 2013a
N content in crops	See model included files (kg N. kg harvested crop ⁻¹)	COMIFER, 2013b
Average N dose in arable crops	151 kg N. ha ⁻¹ . year ⁻¹	Agreste (Ministry of Agriculture, France) 2011
N in solid digestates, based on a national average	N = 5,7% (kg N. kg dM ⁻¹ . year ⁻¹)	Houot , 2014

Average forage consumption per milk cow, meat cow and ovine or caprine	4700, 4600 and 450 respectively (kg dry matter. animal ⁻¹ . year ⁻¹)	Devun and Guinot, 2012
	e.g., dairy cows:	
Feed requirements per animal and per year (milk cows, meat cows, ovine, caprine, pigs, laying hens and chicken)	344 kg cereals. animal ⁻¹ . year ⁻¹ 255 kg oilseeds. animal ⁻¹ . year ⁻¹ 272 kg pulses. animal ⁻¹ . year ⁻¹ 90 kg by-products. animal ⁻¹ . year ⁻¹	Devun and Guinot, 2012; Jousseins et al., 2014; Gaudré 2015; Dusard, 2015;
Straw requirements per animal and per year	e.g., dairy cows: 344 kg cereals animal ⁻¹ year ⁻¹	Agreste (Ministry of Agriculture, France) 2010
Waste and by-products ratio in food industries (dairy, fruits and vegetables), slaughterhouses and feed processers in France	See model included files (kg feed and wastes. kg of food process ⁻¹)	FAOSTAT, 2010
Average mix in anaerobic digesters (France)	68% manure; 17% green biomass; 15% food processing wastes	ADEME, 2013
Energy production in anaerobic digestion	42 m ³ of biogas. mix tonne ⁻¹ (eq. to 252.12 kW. LHV mix tonne ⁻¹ or 85.73 kWh electricity. mix tonne ⁻¹)	ADEME, 2011; France Agrimer, 2012

Table 4. Key input data and sources for main important processes in FAN submodels.

2.7. Comments on FAN processes

- *Exchanges mechanism*

As mentioned before, we aimed to simultaneously calculate the probability of all possible exchanges before starting allocating material flows. Yet, the exchanges carried out are not the always optimum ones, because although the occurrence of the exchanges is proportional to the probability of becoming partners (Eq. 1, Chapter 2), we introduced a stochastic element through the Mersenne Twister algorithm included in GAMA platform, the most popular pseudorandom number generator (Matsumoto and Nishimura, 1998). This stochasticity is a typical characteristic of agent based models, aiming to simulate social complex behavior (Bonabeau, 2002).

Economic factors such as prices of materials and transportation costs were not included explicitly in FAN. Indeed, further consideration of economic modelling processes was considered beyond the scope of the model at this stage. Instead, hypothetical market contexts were mimicked as a combination of prices, costs, subsidies and farming strategies. Thus, we included various simulation mechanisms and decision-making variables that are able to recreate these kind of contexts. The parameters and variables used in the exchanges are discussed as follows. They include: the radius of action, farm fidelity to their partners, their relative disposition to exchange and the set of preference coefficients for specific material uses.

- *Exchanges parameters*

Radius of action is the distance that a material can travel, they restrict farther exchanges that therefore implicitly more costly. To apply a value, we consulted both the local managers and scientific literature. In literature, although few papers addressed the question, values for manure ranged from 5 to 40 km, depending on the area under study and the humidity of the materials, being distances farther for dry products and shorter for wet ones (Dagnall et al., 2000; Nowak et al., 2013a; Riaño and García-González, 2014). Contrasting with local managers, larger distances were travelled by sludge and sometimes dry digestates, up to 80-100 km. In FAN, there are no different categories for wet and dry organic wastes, since their mass is accounted in dry matter and their volume converted in fresh mass for digestion. A radius of action of 15 km was set for manure and digestates (that in our simulations are being recycled more locally) and 80 km for sewage sludge. Forages were known to be transported to close locations (10-50 km), limiting local forage up to 50 km, except for dry legume forage such as alfalfa, that could come from more than 500 km away, and thus we considered it as a global market product. To progress into circular economy, more information about materials transportation for recycling and allocation is needed.

Fidelity was set as the percentage of farms keeping the same partner each year and therefore repeating the same exchange. This parameter aimed to account for the historical links between

real partners. No information about it was founded in the literature. A default value of 50 % of farms keeping the same partner each year was set for the scenarios simulations. Nevertheless, the sensitivity analysis showed a negligible effect of the fidelity factor on the exchanges.

Disposition to exchange wastes and biomass is the number of farms willing to locally exchange their forages, their manure and their straw. For instance, higher disposition to exchange wastes and biomass increases the number of farms that are offering and seeking for manure. This may be used to represent a context where organic fertilization is encouraged, or where manure recycling for energy or fertilization becomes an imperative, as applied in the scenarios.

Preference coefficients are parameters affecting the ranking result of a given material flow in the probability of becoming partners (Eq. 1, Chapter 2). They aim to represent the substitutability of interchangeable materials for the same use and, symmetrically, the partition of a given material into different uses. Such substitutability was related in our model to chemical and organic fertilizers and wastes; forages; other crops and animal products and food wastes for different uses including fertilization, bioenergy and animal feeding or bedding. We did not find similar coefficients in the literature. Although these coefficients can be considered as a modelling artefact, they were useful when imitating a context where some uses or materials are favored, as applied in the scenarios.

- *Simulating FAN production of crops, animal, wastes and energy*

Due to the complexity of agro-food systems, some simplifications were, however, necessary in the model. Those simplifications mostly concern production estimations, in particular crop yield response to fertilization and livestock yield response to animal feeding.

Since we are addressing nutrient materials reuse and recycling, we considered that nitrogen (N) was the of crop production driver in FAN. Even if in some minor cases phosphorus limitations may occur, most agronomists confer N the most important nutrient role in crop production (Mueller et al., 2012), especially in organic farming systems (Nowak et al., 2013a, 2013b). However, other well-known drivers of crop production have a great importance in crop production (Brisson et al., 2003), both biophysical (rainfall, temperature) and management practices (plant pests and diseases, weeds, tillage, crop rotations) are out of the scope of the present work. Thus, in FAN simulations, crop yields vary with N applications calculated as a function of fertilizing N inputs to soils through a simple linear yield-response model ending in a plateau. For the moment, we preferred to simplify this response linearly, despite the fact that a curve response is more accurate and should be applied in the future (Godard et al., 2008). In addition, once losses are accounted, all N applied to soils was considered to be available for crop growth. This simplification

avoids N mineralization dynamics across time, especially important in organic fertilization (Kaur et al., 2008).

Regarding livestock production, we considered a wide range of animal categories, helping to better estimate the meat production and animal requirements. They include calves, goat and sheep kids, sows, lambs and fattening pigs. Their feed requirements are estimated based on observed average feed rations that are applied in France per livestock category and year. However, each farm has its own specific rations depending on their own and their neighbors land use, therefore, more specific rations could be applied to the case studies. In our case study, farms locally exchanged cereals, oilseeds and by-products, and imported soybean, that was the only missing feed in the area. Straw local exchanges for bedding is also simulated in FAN, although we did not make any changes on this material in the scenarios. Contrary to feed, we observed that fixing forage rations to their average forage consumption reported in French statistical data forced too many forage exchanges between farms in Ribéracois. When farms were seeking for an exact quantity of forage, the number of exchanges was overestimated. In order to solve this issue, we set an internal range of variation of $\pm 10\%$ around the average forage rations, and therefore we linked in a linear proportion forage intake to ruminant meat and milk production (Vasta et al., 2008).

Waste and by-product production from food industries was determined by using food processing ratios (in %) both from local surveys and national data and by applying these ratios to the amount of raw products (e.g., live animals, raw milk, grains, fruits and vegetables) entering food industries. When simulating our case study, we got strong difficulties to gather waste generation, recycle and disposal data from local food industries. In consequence, we applied national statistics from the corresponding production sector. The collaboration of local food industries would have been crucial to obtain access to food processing wastes related data. Alternative sources and mix compositions of feedstock for bioenergy could also be applied in the future.

- *Simulating FAN environmental outputs*

FAN can assess various environmental indicators, including greenhouse gas emissions from agricultural activities and material transportation, nutrient losses to water bodies, and some other proxies to estimate ecosystem services.

Greenhouse gas emissions from some agricultural activities, including CH_4 from enteric fermentation, CH_4 from manure storage and N_2O from fertilizers application and indirect leaching emissions, were estimated by using emission factors from the 1st tier IPCC methods. However, improving their estimation by using the 2nd or the 3rd tier would be highly recommended. In addition, C stored in grasslands estimated by applying the C stored in grasslands from Soussana et al., (2010), was key factor of system emissions improvement, yet, it presented lower values

when other methods, such as the one presented in Chang et al., (2015), were applied. Scientific discussion concerning the estimation of C storage in grasslands are still running, so doing a FAN model update in consequence will be needed.

Concerning the Nitrogen budget estimation, soils were considered in steady state, neutralizing N inputs from crop residues, N immobilization and N soil mineralization. Still, accounting for these processes will demand gathering data by sampling N in soil organic matter for the case study simulated. N atmospheric deposition was neglected but could help to improve the N budget calculation. As previously mentioned, going further in the N dynamics will help to better estimate N availability for crop intake.

2.8. FAN Model Exploration

In this section, we provide an example of the application of FAN to a case study in France. We conducted a sensitivity analysis on the model in order to explore how FAN outcomes respond to changes in parameterization, as well as to evaluate the model's internal consistency. Sensitivity analysis is especially insightful for this study as FAN contains several variables that reflect behavioral characteristics, which were not empirically derived and therefore cannot be calibrated to fit known values.

2.6.1 Case-study presentation

We used a test case in the southwest of France in order to conduct the sensitivity analysis of FAN. This case study corresponds to the 'Ribéracois' sub-region (in Dordogne, France), which we refer to as a 'district' herein (

Figure 20). The Ribéracois has a total area of around 1000 km², an area slightly smaller than the average county in the US 1642 km² (US Census, 2010). There are approximately 835 farms that include a diversity of farming activities, such as arable, dairy, beef production, pig, ovine and horticultural production, in both specialised and mixed crop-livestock farms. There are a number of upstream and downstream partners of farms that operate across the district. These partners include three large companies that collect cereals and process feed, two milk industries, two slaughterhouses, several small fruits and vegetables industries, four wastewater treatment plants and some projects of anaerobic digestion. Data on average farm land-use and livestock units per farm type was collected from Agreste database and from interviews with the local extension services (e.g., Chamber of Agriculture, agricultural cooperatives). Exact location of farms was not available, but because the distribution of the different farm types inside within-district subzones was available, the farms were randomly located inside each subzone.

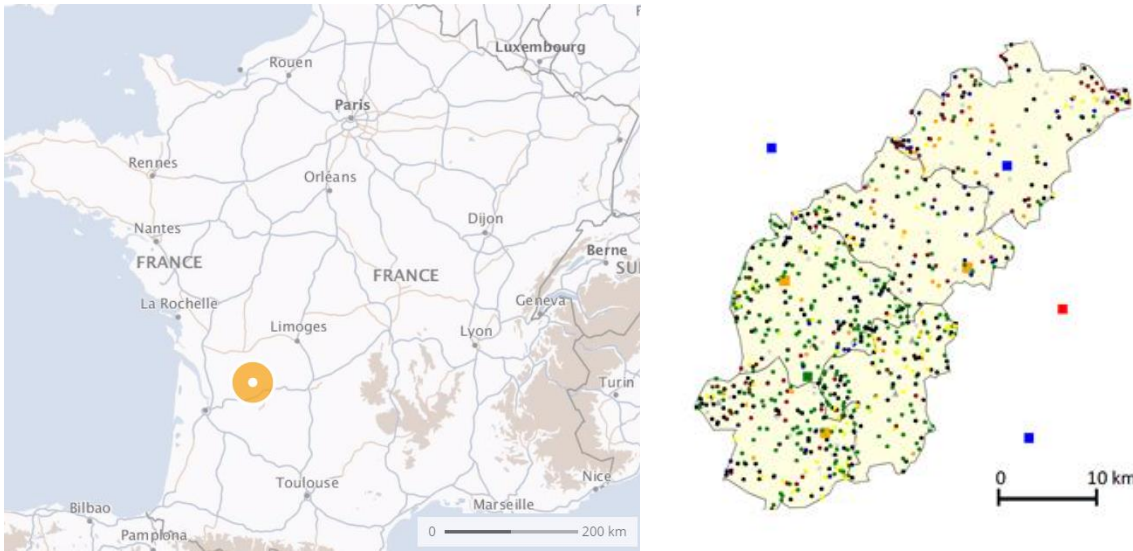


Figure 15. Representation of the ‘Ribéracois’ district. On the left, location of the district in France. On the right, graphical representation of the district in GAMA platform. Farms are represented by circles colored depending on their main production (green for arable; blue for dairy; red for beef cows; purple for mixed cattle; black for mixed crop-livestock; yellow for horticultural; orange for pig and grey for ovine and caprine). Squares represent food industries (yellow: feed collectors; blue: milk and cheese industries; green: fruits and vegetables industries; red: slaughterhouse).

2.6.2 Variables explored in Sensitivity Analysis

The sensitivity analysis was performed by selecting a set of key variables that we expect to have the greatest influence on the model outputs. These variables include: (see Table 2 for the full list of variables).

- The exponential of the distance in the proximity term of Equation 1 (parameter “a”) that sets the limitation related to material transportation.
- The fidelity coefficient, that represents the percentage of farms keeping the same partner each year.
- The disposition to exchange biomass between farms that represents the percentage of farms willing to exchange their biomass.
- The preference coefficients, accounting for the likeability of farms to select a material for a specific purpose. Here we tested those related to manure for both fertilization and digestion uses, as well as the coefficient related to chemical fertilizer use and to grass digestion.

We also tested other variables related to the model application to different case studies, such as the number of farms, the radius of action for materials exchanged between farms, or the capacity of anaerobic digestion. Since these variables had little influence, we decided not include them in the results shown in this section. The related results showed that changing the radius of action

of materials can help to simulate alternative recycling scenarios where agents can allocate their resources farther. Structural changes such as the number of farms can drastically change the number of flows without changing environmental performance or any other results.

For each variable, we explored a range of values that corresponded to 0.1; 0.5; 1; 1.5 and 2 times the default value (**Table 2**). The model was run over a period of five annual time steps (i.e., 5 years), and the data from the last year was retained. We then calculated the annual average of the 5 years for each output. In order to minimize randomness related to farm spatial distribution and farm size around average farm type size, we used 30 repetitions of these model runs to test each value. Additionally, the random seed was kept along the values tested to avoid the pseudorandomness of the initialisation. We focus our analysis on fertilizing materials (manure, digestates, mineral fertilizer) and livestock feeding (forage, by-products and straw) flows.

We selected output variables that were helpful to understand how the material flows were affected by the user-defined variables and to test their capacity to simulate contrasted situations. The output variables that we considered were as follows:

- The number of local flows within the district. Such variable aggregates all the material exchanged or used by the farms for fertilization, animal feeding or energy production within the area under study. We considered that a flow stops when the corresponding material is used to produce either food or energy. Exchanges inflowing or going to the global market were not included. We have classified these flows into (i) local fertilization flows (**Figure 7**) including manure, sewage sludge and digestates applied to soils; (ii) animal requirements flows including forage, by-products and straw for bedding; and (iii) energy flows including manure, grass and food processing wastes allocated to anaerobic digesters.
- The average distance in exchanges of manure and grass. This variable was calculated as the average distance travelled in km by a specific material when flowing from one agent to another.
- The CO₂ emissions from material transportation by trucks. This variable accounts for the distance travelled by a given material when flowing from one agent to another but also for the weight of the materials transported at each exchange.

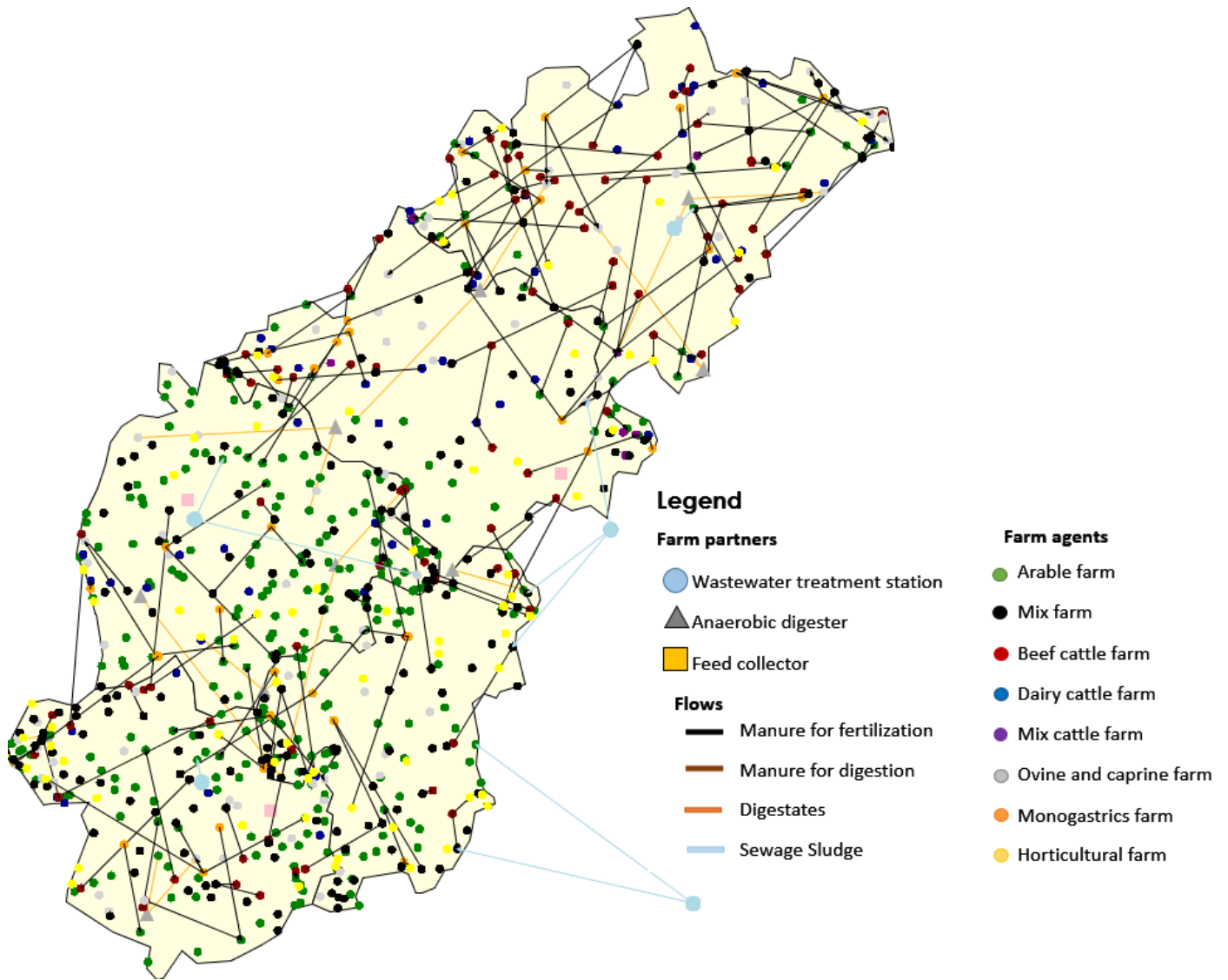


Figure 16. Example of simulation of local fertilization flows in Ribéracois.

2.6.3. Sensitivity Analysis Results

Regarding fertilizing materials (manure, digestates and mineral fertilizer) flows, the results showed that although the exponential of the distance (proxy for proximity) has an important role, the disposition to exchange biomass between farms clearly drives the amount of manure and consequently of digestates that were exchanged (**Figure 17**). The preference coefficients for manure and chemical fertilizers almost symmetrically induce and restrict the number of local fertilization flows: they respectively drive the fertilization by using either the manure from local exchanges to fertilize soils or favor chemical fertilizer use (**Figure 17**). Finally, the fidelity factor does not strongly affect the fertilization flows. When focussing on manure exchanges, we found that, as expected, manure travels greater distances when proximity between partners is not encouraged (low values for exponential of distance), suggesting greater tolerance for long transport

distances (**Figure 18**). We also found that manure travels greater distances when the farm disposition to exchange materials is low. This is probably explained by lower supply of manure when the disposition to exchange material is low, therefore inducing long distances to meet manure demand.

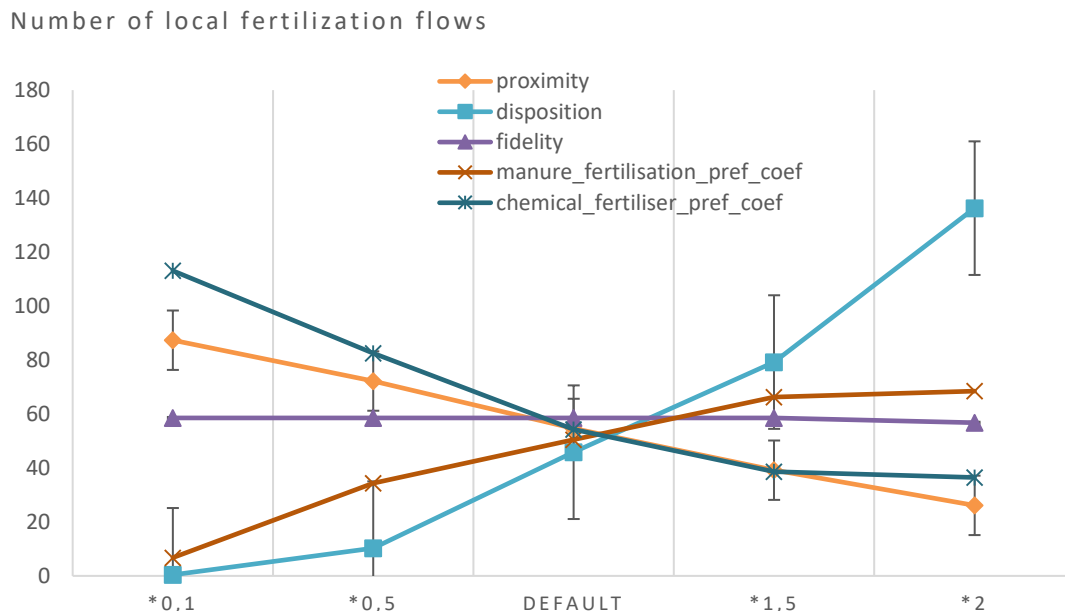


Figure 17. Variation in the number of local fertilization flows in relation to different values of exponential of distance (proxy for proximity), the disposition to exchange between farms, farms fidelity to the same partner and preference coefficients for chemical fertilizer and manure for fertilization use.

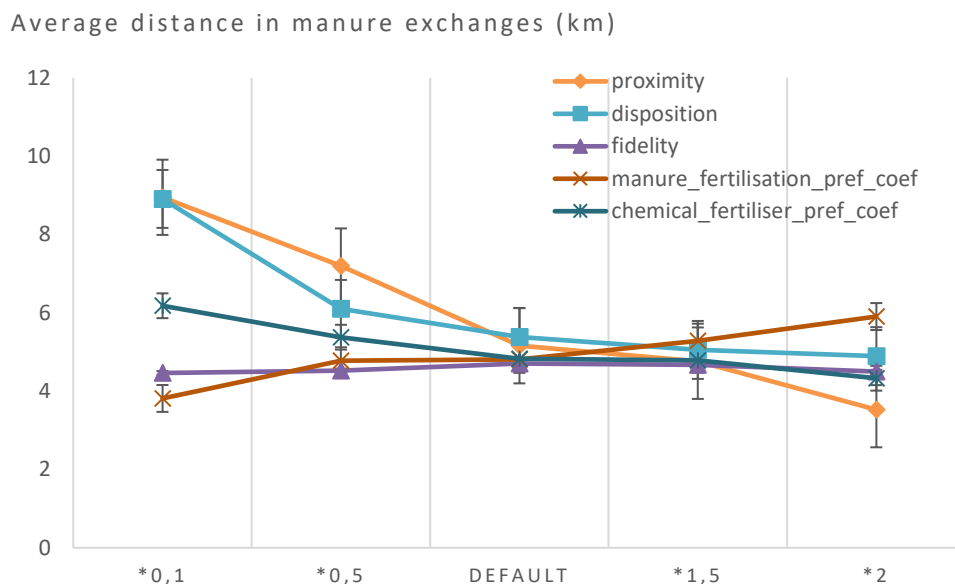


Figure 18. Variations in average distance (in km) when transporting manure. The variables explored are: exponential of distance (proxy for proximity), the disposition to exchange between farms, farms fidelity to the same partner and preference coefficients for chemical fertilizer and manure for fertilization use.

Regarding the biomass used for livestock feeding (i.e. forage, straw and by-products), we found that, in contrast, the number of flows of these materials are poorly affected by the considered input variables (proximity, disposition to exchange and fidelity, data not shown). This may be due to the fact that these materials are first exchanged locally among farms, followed by inflows from the global market only when local supply is exhausted. This modelling choice makes the number of local flows sensitive to the farm disposition to exchange materials, but less sensitive to the proximity between partners. This result is also due to the fact that there is no substitution of such materials with other ones or with other uses. Finally, we found that the distance travelled by these materials is clearly reduced when long distances between partners are penalized (high values for the exponential of the distance, Figure 19). However, the disposition to exchange between farms and the fidelity does not affect the distance travelled by these materials between local partners.

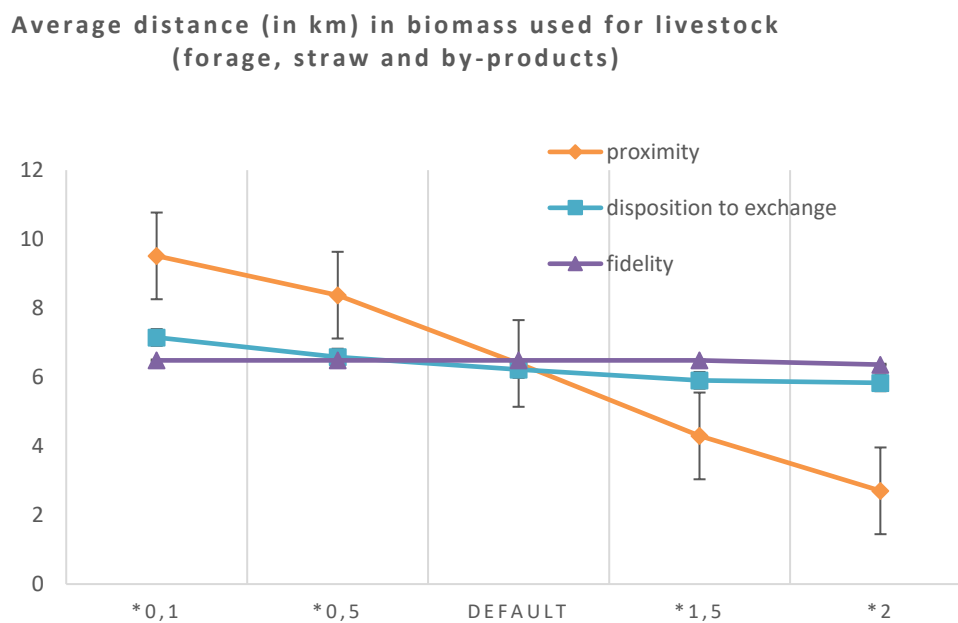


Figure 19. Average distance (in km) of local flows for forage, straw and by-products used by livestock. The explored variables are: the exponential of distance (proxy for proximity); the disposition to exchange biomass and the fidelity.

These results show a wide range of variation and enough to give an idea of how the user-defined variables included in FAN can be useful when simulating material exchanges among contrasting scenarios in local agro-food networks. The results also show indirect relationships among input and output variables (e.g., between the disposition to exchange and the distance travelled by materials), highlighting the relevance of using agent-based models to simulate complex decisions

made by agents. Comparing the different results shown here, we confirm that when a global market option exists as an alternative to local materials (e.g., as chemical fertilizers), farms can switch depending on their preference for one of the materials, forcing the chosen local materials to travel shorter distances. On the contrary, in the case of forage and by-products, even in a context of low disposition to exchange, the local materials are first exchanged locally before being substituted by external flows.

Sensitivity analysis using FAN shows that fertilization materials are relatively more sensitive in the model than feed materials, which are more dependent on parameters extracted from national and regional databases. Besides, there is a low effect of fidelity variable, which means that lower fidelity values are unlikely to influence the decision of the best agent to exchange with over time. This is probably because relationships initiated at the first cycle (year) are already close to 'optimal' in FAN.

2.9. Conclusion

Understanding how multi-agent behavior affects materials exchange is key to identify the drivers and dynamics of agro-food networks. Although agent-based models related to agricultural systems already exist (Iwamura et al., 2014; Schreinemachers and Berger, 2011b), to our knowledge FAN is the first model that combines social simulation with the environmental characteristics of farms across a wide range of materials in more complex agro-food networks. Therefore, one of the core innovations of FAN lies in its ability to simultaneously simulate multiple bio-sourced and biomass materials as a network of local potential exchanges. Another originality of the model lies in the considered system that encompasses a large range of agents. In total, eight types of agents were considered, which is beyond the agents modelled in other farming agent-based models, (e.g., two in Shastri et al., 2011 for famers and bio-refineries, and five farmer strategies in Valbuena et al., 2010). Considering both a large number of agent types and of material types helped to address an intermediate spatial scale between the farm and the country. Such a sub-regional level is critical because actors are uniquely identified and their potential role in a circular economy can be assessed. In addition, our model was developed by combining multiple approaches in order to address a set of environmental and economic issues to the sustainable development of agriculture in rural areas and the challenges they face in a global market offering manifold farm inputs.

Due to its capacity to account for a large range of economic agents and exchanged materials, FAN can help address several issues related agro-food systems and circular bioeconomy (El-Chichakli et al., 2016; Lainez et al., 2017; Sarkar et al., 2017). For example, FAN offers a promising

framework and the tools needed to assess alternative agricultural developments strategies, such as the development of localised food production and short supply chains (food autonomy and sovereignty), the better coordination between crop and livestock production at the local scale, the improved recycling, use and disposal of waste and by-products, the decreasing reliance on non-renewable fertilizer resources, as well as the dependency on international feed imports.

Due to the complexity of agro-food systems, some simplifications were, however, necessary in the model. Those simplifications mostly concern production estimations, in particular crop yield response to fertilization and livestock yield response to animal feeding—as well as, in some cases, waste production from industries (which were estimated from national sources when local were not available). In addition, although we excluded explicit economic variables in FAN, we can still approach contrasted contexts through the use of logistic variables and preferences coefficients for materials or for usages. Concerning the social simulation aspects, FAN does not yet include individual adaptation to dynamic processes (Berger and Troost, 2014), that are quite complex to simulate. Individual adaptation could potentially be included in FAN, for instance by allowing farmers to alter land use or livestock populations in response to material availability in the network or after the alteration of global supply chains.

Here, we presented the FAN model as a first attempt to simulate multiple interacting material flows at the local scale, including some global feedbacks. We gave an overview of the model framework, its processes, and an application to a case study in France where we have collected a considerable amount of data that is included in the model (**Supplementary Materials File 1**). We presented submodel mechanisms for crop fertilization, animal feeding, food wastes use and bioenergy production. Finally, we presented a sensitivity analysis of FAN, showing its strength when simulating soil fertilization and modulating alternative material uses, including the interactions between local and global markets in environmental policies. FAN features open promising avenues to simulate contrasted scenarios of agro-food networks at the local scale in other regions and case studies in a bioeconomy context.

Chapter 3 –

Can changes in material flow networks at the local scale reduce environmental impacts of agro-food systems while maintaining food and energy production?

FAN model exploration of different scenarios in the Ribéracois case study.

To be submitted to Agricultural Systems or to Regional Environmental Change.

In the last chapter we presented the FAN model and we explored its sensitivity to some key variables. We highlighted its novelty and its potential to simulate material flows among a large range of economic agents in agro-food chains. We also discussed its ability to be used to assess alternative situations of biomass exchanges among economic agents. In the current chapter we present an application of FAN to the simulation of contrasted scenarios related to material exchanges among economic actors at the local scale. In particular, we focus on the assessment of these scenarios through a large set of indicators related to agricultural production, local trade, nutrient cycling and greenhouse gas budget. In the close future, this chapter will be submitted to Agricultural Systems or to Regional Environmental Change.

Abstract

New strategies and regulations are needed to tackle agriculture's pressure on natural resources. In particular, agro-food chains have to move away from linear towards more close-looped systems by applying circular bioeconomy and agro-industrial ecology principles. Characterizing the agro-food network as agents interacting is key to explore alternative scenarios of biomass management at the local scale. Agent-based models can be efficient tools to simulate different agents' behaviors under alternative scenarios. In this study, we use the FAN ("*Flows in Agricultural Networks*") agent-based model to study alternative scenarios of materials management in agro-food systems at the local scale. FAN was applied to the Ribéracois, a case-study in the southwest of France, to simulate and assess a set of contrasted scenarios ranging from good management practices, organic waste recycling, bioenergy production, crop-livestock symbiosis to chemical fertilizers removal. The scenarios outcomes are assessed in terms of food and feed production, nutrient cycling and greenhouse gas budget. The environmental performance of the scenarios increased progressively through their application. However, several variables showed that this progression was not straightforward and sometimes food production could be drastically reduced. This information gave an insight on how different strategies can make agro-food systems change and adapt to local environmental issues.

3.1. Introduction

Current agricultural use of resources and impact on ecosystems is driving the planet beyond its safe operating space (Godfray et al., 2010; Tilman and Clark, 2014). In this context, new strategies and regulations are needed to tackle agriculture's pressure on natural resources including land, water, fertilizers and climate (Carlson et al., 2016; Foley et al., 2011c; Pretty et al., 2010). In a context where specialized farms rely on outsourced inputs –thus driving imbalances and dependencies globally (Lassaletta et al., 2014a)– some alternatives to the conventional food systems may be found at the local scales. In other words, food chains have to move away from linear towards more close-looped systems (Davis et al., 2016). Indeed, reducing agricultural pressure on natural resources can be achieved through a better use of local biomass materials (e.g., feed and forage for livestock as well as wastes for fertilization), by applying circular bioeconomy and agro-industrial ecology principles (El-Chichakli et al., 2016; Fernandez-Mena et al., 2016; Golembiewski et al., 2015). To apply these strategies, local material exchanges among farms to better use and recycle local resources need to be included.

Understanding the benefits and limitations of implementing alternative material flow strategies in local agro-food systems can be done by using simulation models together with material flow scenarios (Fernandez-Mena et al., 2016). To go further when applying scenarios assessment, we need to better estimate and quantify the both farming production and environmental performance linked to the associated material flows in the agro-food system locally. On one hand, some studies have attempt to do an assessment of alternative scenarios towards sustainable practices in a farming region, such as the scenario assessment of the Montérégie region in Canada (Mitchell et al., 2015) and the California Nitrogen Assessment (Tomich and Scow, 2016). Yet, they did not quantify the flows and the environmental outputs consequence of applying scenarios in these regions. On the other hand, some studies that quantified the outcomes by simulating flows and environmental indicators, such as the assessment of dairy farms in a French region (Acosta-Alba et al., 2012), and the biomass dynamics of crop-livestock systems in a region of Kenya (Tittonell et al., 2009a), only focused on a single specific sector of the food chain within the region studied. Although few studies have estimated this outputs from different sectors of the food, feed and wastes chains in a region, we need to better account for the interactions involving different farming activities and their upstream and downstream partners. Characterizing the agro-food network as agents interacting is key to represent alternative scenarios of biomass materials management. Agent-based models can be a useful tool to simulate different agents behaviors under alternative scenarios towards sustainability (Alonso-Betanzos et al., 2017). Although there is a large literature on agent-based models applied to land use systems (Matthews et al., 2007), very few studies have applied agent based simulations to study alternative scenarios of materials

management in agro-food systems at the local scale (Fernandez-Mena et al., 2016). In particular, to our knowledge, agent-based models have never been used to simulate alternative scenarios of material exchanges concerning crops, livestock, wastes and bioenergy all together.

In this study, we aimed to simulate alternative scenarios of material flows in a specific farming region. To do so, we applied the FAN (*“Flows in Agricultural Networks”*) agent-based model (Fernandez-Mena et al., submitted) to Ribéracois, a case-study in the southwest of France, described in section 3.2.1. The FAN model is a powerful tool to simulate different scenarios, to assess a range of environmental outputs, and to simultaneously simulate multiple bio-sourced and biomass materials as a network of local potential exchanges. Our scenarios, described in section 3.2.2, deal with good management practices, organic waste recycling, bioenergy production, crop-livestock symbiosis and chemical fertilizers removal. Thanks to FAN simulations, we obtained production and environmental indicators that are presented and discussed in section 3.3. Finally, our scenarios performances are evaluated through various environmental indicators.

3.2. Materials and Methods

3.2.1 The Ribéracois case-study

We used a case-study in the southwest of France in order to simulate alternative agro-food scenarios using FAN. This case-study corresponds to the ‘Ribéracois’ sub-region, which we refer to as a ‘district’ here. It is located in Dordogne département of the Nouvelle-Aquitaine administrative region, in the southwest of France (**Figure 20**). Ribéracois has a total area of around 1000 km², with approximately 500 km² of utilised agricultural area (UAA), a mean altitude of 80 m, an annual rainfall of around 800 mm, and an average annual temperature of 12.3 °C. In comparison, the surface of Ribéracois district is lightly smaller than the average county in the US (1610 km²).

In Ribéracois, the agricultural census registered 835 farms that include a diversity of farming activities, such as arable, dairy, beef, monogastrics, ovine, and horticultural production (**Table 5**). There are a number of upstream and downstream partners of farms that operate across the district. These partners include three large companies that collect cereals and process feed, two milk and cheese industries, two slaughterhouses, several small fruits and vegetables industries, four wastewater treatment plants and 2-3 projects of anaerobic digestion plants. Data on average agricultural land-use and livestock units per farm type was collected from Agreste’s database and from interviews with the local extension services (e.g., Chamber of Agriculture, agricultural

cooperatives). The exact location of farms was not available, but the number of farms in each farm type (n=8 farm types) and for each of the five subzones that composed the district was available.

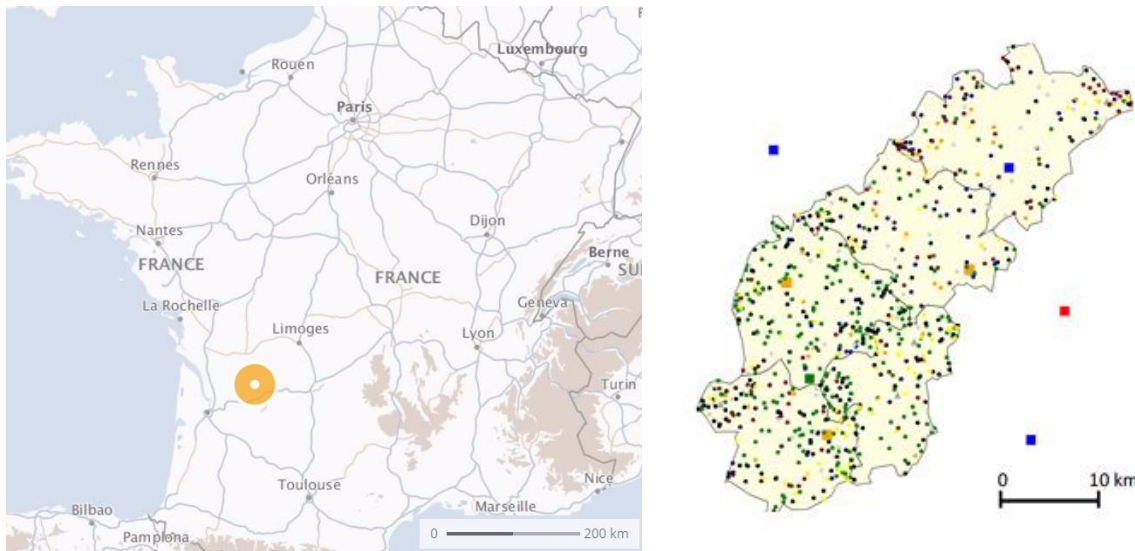


Figure 20. Representation of the ‘Ribéracois’ district. On the left, location of the district in Dordogne, France. On the right, graphical representation of the district in FAN. Farms are represented by circles coloured with their typology (green for arable; blue for dairy; red for beef cows; purple for mixed cattle; black for mixed crop-livestock; yellow for horticultural; orange for monogastrics and grey for ovine and caprine). Squares represent food industries (yellow: feed collectors; blue: milk industries; green: fruits and vegetables industry; red: slaughterhouse).

Farming activities in Ribéracois are quite diversified. Even so, they are challenged by inefficient nutrient and biomass management. Livestock production is concerned by the high volatility of input prizes due to overall deficit in soybean (imported from South America) and alfalfa (imported from the north of France) to meet livestock requirements. Green, renewable energy production through anaerobic digestion is strongly pushed by local authorities. Although there is no biogas plants in the district currently, a few of such plants are expected to develop in the next few years. Their capacity is estimated as the fourth of the biogas production potential in the area. Besides, the half south of Ribéracois area, where arable crops are predominant, is concerned by the Nitrate Vulnerable Directive since 2015 (DREAL, 2016). Still, high fertilization rates are applied overall the district, i.e., around 160 kg N/(ha.year) for arable crops, leading to high nutrient losses through various nitrogen pathways.

Farm Types	Number	Mean UAA (ha)	Stand. Dev of UAA (ha)	Cereals (ha)	Oilseeds (ha)	Pulses (ha)	Silage Maize (ha)	Other Forages (ha)	Grass (ha)	Fruits & Vegetables (ha)
Dairy cattle farms	53	96.52	74.32	25.08	3.23	0.2	17.13	10.18	41.31	1
Meat cattle farms	91	65.98	70.97	8.41	1.43	0	1.54	2.38	51.31	0.6
Mixed cattle farms	7	151.1	50.3	21.42	0	0	12.85	3.04	112.1	0
Ovine & Caprine farms	76	34.69	73.03	5.74	0.26	0	1.03	4.49	22.18	0
Monogastric farms	37	31.55	38.68	16.28	0	0	0	0.44	10.81	0.3
Arable farms	291	69.64	59.39	41.82	13.37	0.4	0.05	0.92	8.58	0
Mixed farms	208	62.06	74.1	25.6	6.67	0.16	1.42	2.01	23.77	0
Horticultural farms	72	6.6	11.0	1.1	1.6	0	0	0	0	3.7

Farm Types	Milk Cows	Adult Meat Cattle	Calves	Milk Sheep Goats	Meat Adult Sheep Goats	Lambs goat kids	Sows pigs	Piglets pigs	Fattening pigs	Laying Hens	Meat Poultry
Dairy cattle farms	52.28	33.43	21.58	0	0	0	0	0	0	4.31	3.97
Meat cattle farms	0	68.85	34.98	0	2.91	0.4	0	0	0	3.42	2.21
Mixed cattle farms	31.14	120.42	45.42	0	0	0	0	0	0	0	0
Ovine Caprine farms	1.42	12.89	3.42	78.56	28.85	52.06	0	0	0	2.55	1.64
Monogastric farms	0	9	4.13	0	4.35	0	49.5	29.73	56.89	5.94	1772.44
Arable farms	0.07	5.34	1.78	0	1	1	0	0	0	1.81	0.57
Mixed farms	2.62	29.39	11.45	1.01	4.5	4	0	0	0	3.56	6.01
Horticultural farms	0	0	0	0	0	0	0	0	0	0.5	0

Table 5. Farm types and their land-use and livestock characteristics in Ribéracois (Agreste, 2010).

3.2.2 Scenario design and description

In order to design our scenarios, we considered several alternative farming practices and farming network organization, to better couple material cycles and, ultimately, to improve system sustainability. The scenarios were built following the “ESR” framework, i.e., “Efficiency, Substitution and Redesign”, which has already been applied to agricultural systems transition towards sustainability (Lamine, 2011; Wezel et al., 2014). More precisely, the scenarios will be based on the following leverage factors: (i) reduction of fertilization losses by adjusting fertilization rates to crop requirements and by using catch crops (Valkama et al., 2015, 2016); (ii) adjustment of protein intake in cattle feed rations (Edouard et al., 2016; Pellerin et al., 2013); (iii) exchange organic fertilising materials among farms (Nowak et al., 2015); (iv) setting up biogas plants (Mao et al., 2015); (v) enhancing the production of local feed and forage (Bonaudo et al., 2014; Lemaire et al., 2014); (vi) reducing livestock population (Leip et al., 2015b) and (vii) removing chemical fertilizers (Bouwman et al., 2017). Although all these drivers can enhance system’s environmental performance, interconnected they have different expected effects that are represented in the **Figure 21**.

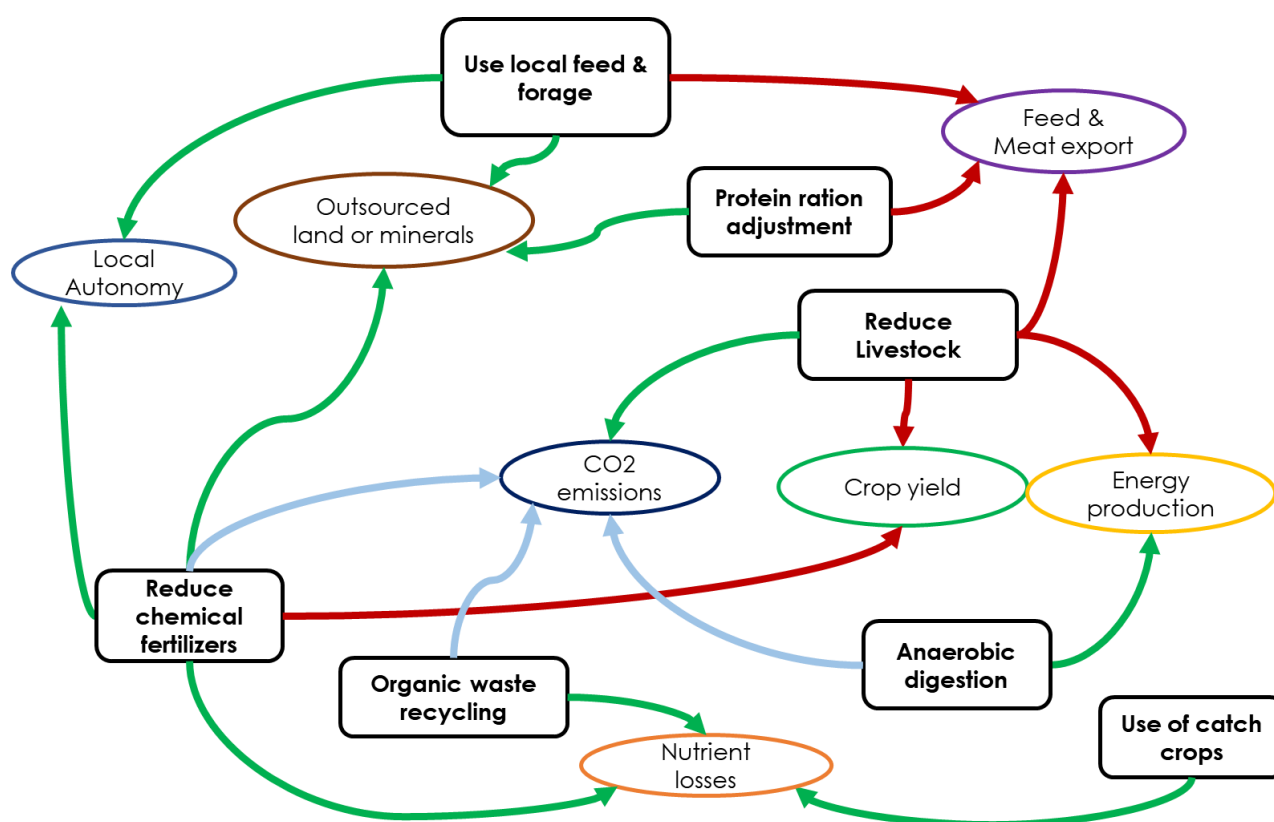


Figure 21. Expected effects of the leverage factors (boxes) on the system performances (circles). Arrows represent interactions between leverage factors

and system performances. Green arrows stand for positive effect, red arrows for negative effect and blue for unknown effect.

Based on the leverage factors mentioned above, we designed contrasted scenarios to be applied in the Ribéracois region. First, ‘Efficiency-like’ solutions were considered to design the ‘Best management practices’ scenario that implemented management recommendations to improve input fertilizer and animal feed use efficiency. Second, ‘Substitution-like’ solutions were used to design scenarios based on local collective solutions through exchanges within agro-food chains that promote the substitution of external flows (fertilizers, forage) for local flows, without modifying the farm structures. Third, in a complete ‘Redesign’ perspective, external supplies of feed and fertilizer were removed and farm structure (land-use and livestock population) was modified (

Figure 22).

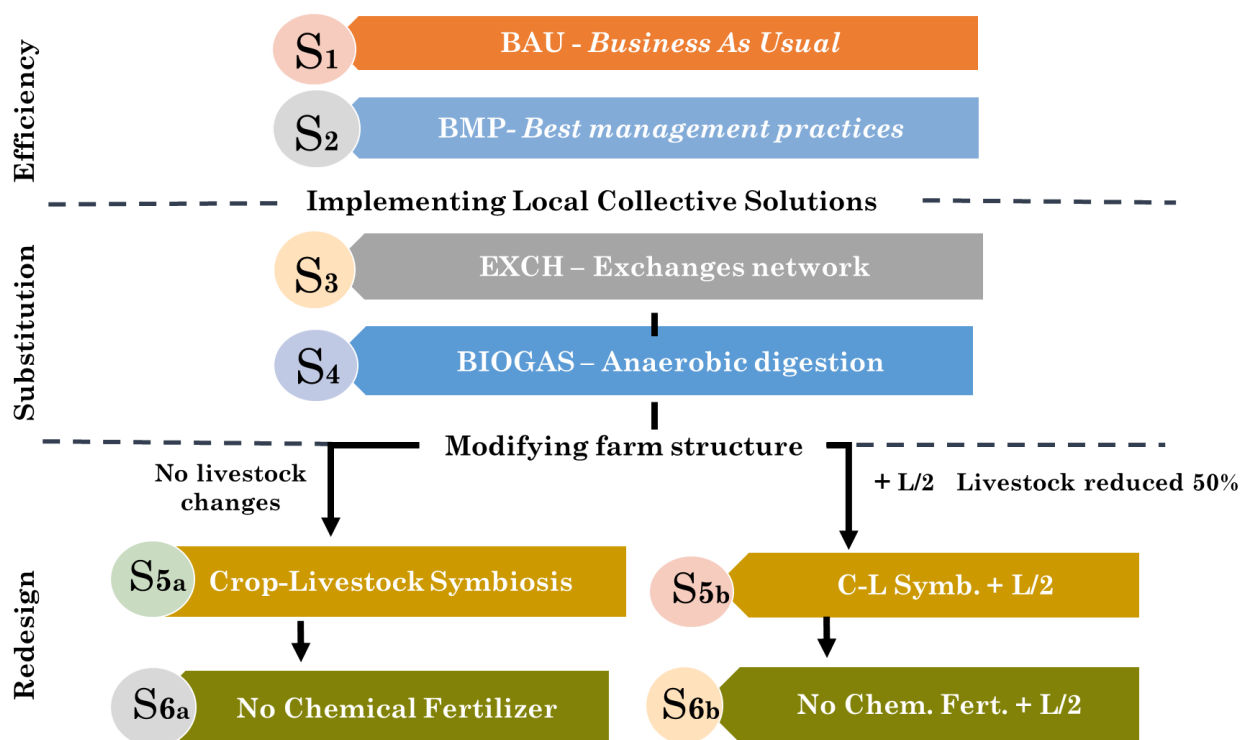


Figure 22. Scenarios explored in the Ribéracois case-study using the FAN model. The S5b scenario is Crop-Livestock Symbiosis and livestock is reduced to half of the initial population and the S6b Scenario is No Chemical Fertilizer and livestock is reduced to half too.

The scenarios were designed in an aggregative manner, i. e. each scenario applies the changes already implemented in the previous one. The scenario specific characteristics are the following:

S1. The “Business As Usual” (BAU) situation, represents the current farming practices, its production and impacts. It is considered as the baseline situation. Its parameters are set to their default values (**Table 6**).

S2. The adoption of “Best Management Practices” (BMP) by farms. In this scenario, farms aim to reduce their environmental pressure by applying some soft managing measurements that are commonly recommended in agrarian extension (Baumgart-Getz et al., 2012). In particular, the nitrogen fertilization application rate is adjusted to the crop nutrient requirements plus some unavoidable losses including N volatilisation and moderate N leaching. Farms are also asked to use catch crops in order to additionally reduce N losses through leaching. Animal diets are also adjusted by slightly reducing protein feed intake according to protein use efficiency recommendations.

S3. The fostering of exchanges among economic partners network (EXCH) including local forage and organic waste recycling for fertilization as a substitute of mineral fertilizers. Here, all farms are disposed to exchange materials with their partners. In addition, the preference coefficient for using manure and sewage sludge as organic fertilizers is increased to its maximum.

S4. The implementation of biogas (BIOGAS) production plants up to their maximum potential. In this scenario, ten anaerobic digester units are simulated to ferment biomass materials in order to produce electricity and heat from biogas ($\text{CH}_4 + \text{CO}_2$). Consequently, farms are assumed to give their manure to the digesters, getting back similar amounts of nitrogen as digestates to fertilize soils. Similarly to manure, farms will offer their digestates surplus to other farms in the network, also favoured to be chosen rather than the chemical fertilizers through preference coefficients. The digestion of other digestible materials –grass and food processing wastes– is also favoured by using preference coefficients.

S5a. A complete crop-livestock symbiosis (C-L Symb.) through local feed and forage production. In this scenario, arable production is adjusted to meet livestock demand in terms of crop and forage products. As a consequence, if forage deficit exists, some cereal area is converted to temporary grass production in order to compensate such deficit. Similarly, if any feed deficit exists –in particular in terms of pulses- cereal surfaces are

converted to pulses. Cereals were chosen because they are the most common crop in the area and because they exhibit a large surplus in the district.

S6a. The removal of chemical N fertilizers supply (No Chem. Fert.). In this scenario, chemical fertilizers are not available to fertilize soils. Because the remaining fertilizing sources (manure, digestates and sewage sludge) may not match crop demand, we introduced a simple yield response curve to soil N input in order to simulate yield limitation due to soil fertilization. In this response to N soil inputs, yields decrease linearly from their species-dependent upper value, which is equal to the current average yield.

S5b. Livestock is reduced to half of its initial population and principles of local feed and forage presented in S5a are also applied (C-L Symb. + L/2). In addition, unused silage maize for forage is reduced and replaced by cereals. Grasslands are not modified.

S6b. Livestock is reduced to half of its initial population and chemical fertilizers are removed (No Chem. Fert. + L/2). Changes applied in S5b and S6a are combined.

Variable	Default value
N fertilization dose	160 (kg N / ha)
Catch crops	No catch crops
Pulses protein reduction	0 %
Disposition to exchange	50 %
Capacity of anaerobic digestion	0
Number of anaerobic digesters	0
Chemical fertilizer preference coef	0,5
Manure and digestates fertilization preference coef	0,5
Grass digestion preference coef	0,5
Fruits & veg wastes digestion preference coef	0,5
Grass surface	Data from Agreste, 2010
Cereal surface	Agreste, 2010

Pulses surface	Agreste, 2010
Silage maize surface	Agreste, 2010
Livestock heads	Agreste, 2010
N chemical fertilizer availability	9999999999 kg N

Table 6. Parameters changed along the scenarios and their default values.

The scenarios were built in FAN by changing specific parameters of the model (**Table 7**). We hypothesised greater environmental benefits for scenarios that requested profound agro-food chain changes (i.e. for ‘Redesign-like’ scenarios). We performed 30 simulations of each scenarios by running each scenario until its 5th year.

Scenario	Changes in variables and agents attributes	Expected result
S1 BAU	No changes	No changes
S2 BMP	N fertilization dose = N crop needs * overdose coefficient (1.2) Pulses protein reduction to reach 14% of N in feed Catch crops reducing N leaching 50%	Slightly lower mineral and soybean resources Lower nutrient losses
S3 EXCH	S2 + manure (and digestates) fertilization preference coef = 0.9 chemical fertilizer preference coef = 0.2 disposition to exchange = 100	Lower imported mineral resources Increase local autonomy Higher CO2 emissions by truck transportation
S4 BIOGAS	S3 + number of anaerobic digesters = 10 and capacity of anaerobic digestion = all manure / 0.68 (% manure in mix) grass digestion preference coef = 0.9 fruits veg wastes digestion preference coef = 0.9	Bioenergy production Increase local autonomy Higher CO2 emissions by truck transportation
S5a C-L Symb	S4 + grass extra surface compensating forage deficit pulses extra surface compensating pulses deficit cereals surface reduced for grass and pulses	Lower GHG emissions Decrease external inflows Increase local autonomy
S6a No Chem Fert	S5a + No N chemical fertilizer	Lower yields Decrease external inflows Increase local autonomy
S5b C-L Symb + (L/2)	S6a + (Livestock /2) silage maize surface reduced to compensate forage surplus cereal extra compensating forage surplus	Same as S5a + Lower meat production Lower GHG emissions
S6b No Chem Fert + (L/2)	S6a + (Livestock /2) silage maize surface reduced to compensate forage surplus cereal extra compensating forage surplus	Same as S6a + Lower yields and meat production Lower GHG emissions

Table 7. Specifications of scenarios in the FAN model and their expected results.

3.2.3 FAN outcomes and indicators estimation

The production, environmental losses and environmental efficiency of the different scenarios were assessed through a set of environmental indicators provided by the FAN model. These indicators are necessary pieces for integrated assessment of the scenarios. They represent crop, livestock, and bioenergy production; feed and forage balance; N flows (inputs, outputs and losses); greenhouse gas emissions and carbon storage in soils; local flows and transportation amounts and distances. In this section, we present those indicators and we also give some clarifications about FAN mechanisms to simulate the related indicators.

Crop Production

Crop production (for food or feed) represents the ultimate goal of farming systems. While crop production is not expected to vary in several scenarios, some scenarios may have an impact on crop yields, in particular when chemical fertilizers are eliminated (S6) or livestock population is reduced (S5b and S6b).

In FAN, crop production is estimated as a result of areas under the different crop species multiplied by their regional yields adjusted by N input to soils. The crops included here were aggregated cereals, oilseeds, pulses, grass, fruits and vegetables, silage maize and legume fodder.

Feed and forage balance

Feed and forage balance indicators are important to see how the animal requirements are locally satisfied and to quantify external inflows (especially for soybean and alfalfa). Reducing farms dependency on external feed and forage is possible by better integrating crop and livestock production, by applying changes in the crop rotations to fulfil livestock requirements or eventually by reducing livestock population.

In FAN, once crop production is simulated, animal requirements are estimated based on species-based, average national livestock requirements (Agreste, 2011). These requirements are supposed to be satisfied, first, by inner farm production and, second, by exchanges with others farms, feed suppliers or with the global market. Forage is estimated in FAN as the addition of grass, silage maize and legume forage. Contrary to feed, forage requirements per ruminant are linearly proportional to their production within a small range of variation around the average forage consumption reported in statistical data (Devun and Guinot, 2012).

Livestock production

Similarly to crops, livestock is an important part of food production. In addition, although reducing livestock population may have positive impacts on the environment (e.g., in terms of greenhouse gas emissions), it may also generate indirect effects, such as lower crop and energy production due to reduced manure availability.

In FAN, livestock feeding inside the region is assumed, initially with local production and afterwards inflowing feed and forage from global markets. Livestock production is estimated according to French production rates for meat and milk. Therefore, when livestock numbers are not modified, animal production cannot vary, except in a range of $\pm 10\%$ of ruminants forage intake that affects meat and milk production.

Bioenergy production

In French conditions, the feedstock mix to be fermented is composed of, on average, 68% of manure; 17% of green biomass (considered as grass in FAN) and 15% of food processing wastes, including cereal, milk, fruit and vegetable wastes (ADEME, 2013). The energy produced by anaerobic digesters was modelled proportionally to the digestible potential of material inputs (Pöschl et al., 2010). The production, per ton of feedstock mix, was estimated to be 42 m³ of biogas, with 34% of electric yield equivalent to 85.73 kWh of electricity (ADEME, 2013). Anaerobic digesters total capacity was estimated as 225,210 tons of substrate for digestion and was calculated in the model according to total animal manure in the Ribéracois district.

Local flows and transportation

We proposed local flows as network indicators representing exchanges between two agents present within the Ribéracois district. We considered that a flow stops when the corresponding material is used and transformed to produce either food or energy, while exchanges inflowing from or outflowing to the global market were not included. Estimating the number of local flows is useful to give an insight of local synergies and cooperation.

In FAN model, there are numerous exchanges inside the district. Materials are assumed to be transported by truck from one farm to another, or between farms and their partners. Material flows were aggregated according to their final use into (i) local fertilization flows including manure, digestates and sewage sludge applied to soils; (ii) energy flows including manure, grass and food processing wastes allocated to anaerobic digesters; and

three flows allocated to animal requirements: (iii) feed flows; (iv) forage flows and (v) straw flows for bedding.

N flows

Nitrogen is the most limiting nutrient for crop production (Mueller et al., 2012, 2014), and at the same time has great impact when lost in large amounts to the environment (Bodirsky et al., 2014). Hence there is a need to use appropriate indicators to estimate its use efficiency (Godinot et al., 2015; Leip et al., 2015b). Because our scenarios were oriented toward maximizing organic fertilization, two indicators were proposed:

$$N_{org\ applied} \% = \frac{N_{org\ applied}}{N_{total\ applied}} = \frac{N_{manure} + N_{digestates} + N_{sewage\ sludge} + N_{fixation}}{N_{mineral\ fertiliser} + N_{manure} + N_{digestates} + N_{sewage\ sludge} + N_{fixation}} ; \quad \text{Eq. 2}$$

$$N_{org\ exchanged} \% = \frac{N_{org\ exchanged\ applied}}{N_{total\ applied}} ; \quad \text{Eq. 3}$$

“ $N_{org\ applied} \%$ ” accounts for all non-mineral sources in the total N added to soils, whereas “ $N_{org\ exchanged} \%$ ”, takes into account only the part of organic N that was exchanged between two agents before being used for fertilization. Note that, in FAN, there is no soil mineralization accounted for since the organic carbon soil dynamics is considered to be at steady state. In addition, all N applied is considered to be available for crop intake at an annual time scale.

Greenhouse Gas Emissions

Greenhouse gas (GHG) emissions and carbon sequestration indicators are necessary to estimate mitigation of agriculture’s impact on climate change (Lipper et al., 2014). Two GHG balances were estimated: (i) one including only in site emissions, and (ii) one also including induced and avoided emissions. In the C balance estimates, emissions were considered to be positive, whereas C stored and CO₂ avoided were considered to be negative. Indirect emissions were only considered if they were linked to materials inflowed to the area under study and were in our case those related to fertilizers production and feed importation. Additionally, is important to notice that emissions induced by producing the same amount of food or feed elsewhere to compensate for lower production in the study area were not considered.

In FAN, GHG emissions (expressed in CO₂ equivalent) from livestock enteric fermentation, manure management and soil fertilizers applications were calculated from emissions factor of first and second tier of IPCC, (2006). The CH₄ emissions when

anaerobic digestion is implemented are considered to be reduced as 10% of the initial emissions (Zeeman and Gerbens, 2002). CO₂ emissions from truck transportation and induced emissions from fertilizers and imported feed were estimated using emissions factors from ADEME, (2016). CO₂ avoided emissions from biogas produced were estimated according to the average CO₂ emissions per kWh in France and Europe (European Environmental Agency, 2014). A soil organic matter dynamics model, inspired by the Hénin and Dupuis model (1945), was used to estimate carbon storage in soils by accounting for soil organic matter stock, C humification following organic material inputs and CO₂ from organic matter mineralisation. Finally, carbon stored in grasslands has been calculated considering data from Soussana et al., (2010). Animal respiration is not considered in this C balance.

3.3. Results

Here we discuss the FAN simulation results estimated through the various indicators presented above. These indicators cover food and energy production, environmental performance and district autonomy. We show annual results as the average of the 5th year simulation (n=30 repetitions).

Crop Production

Simulation results showed that crop production is not affected in the first four scenarios, because no changes were applied to land-use or fertilizers availability (**Figure 23**). Crops demanding high N inputs (cereals, oilseeds, fruits and vegetables...) decreased their production to half their initial values in scenarios with no chemical fertilizer (No Chem. Fert.), especially when reducing livestock (+ L/2). Yet, pulses and grass are not affected since they are not fertilized with chemical sources in FAN and because they are assumed to get enough N through biological fixation. Cereal production decreased in Crop-Livestock Symbiosis scenarios (C-L Symb) when incorporating more pulses in crop rotations at the expense of cereals, but they increased in the scenario reducing livestock (C-L Symb. + L/2) due to the replacement of silage maize by cereals. Although pulse production increased when integrating crops and livestock (*C-L Symb*), there were no changes in grass and legume forage areas as there was enough of these products to meet animal forage requirements in the district.

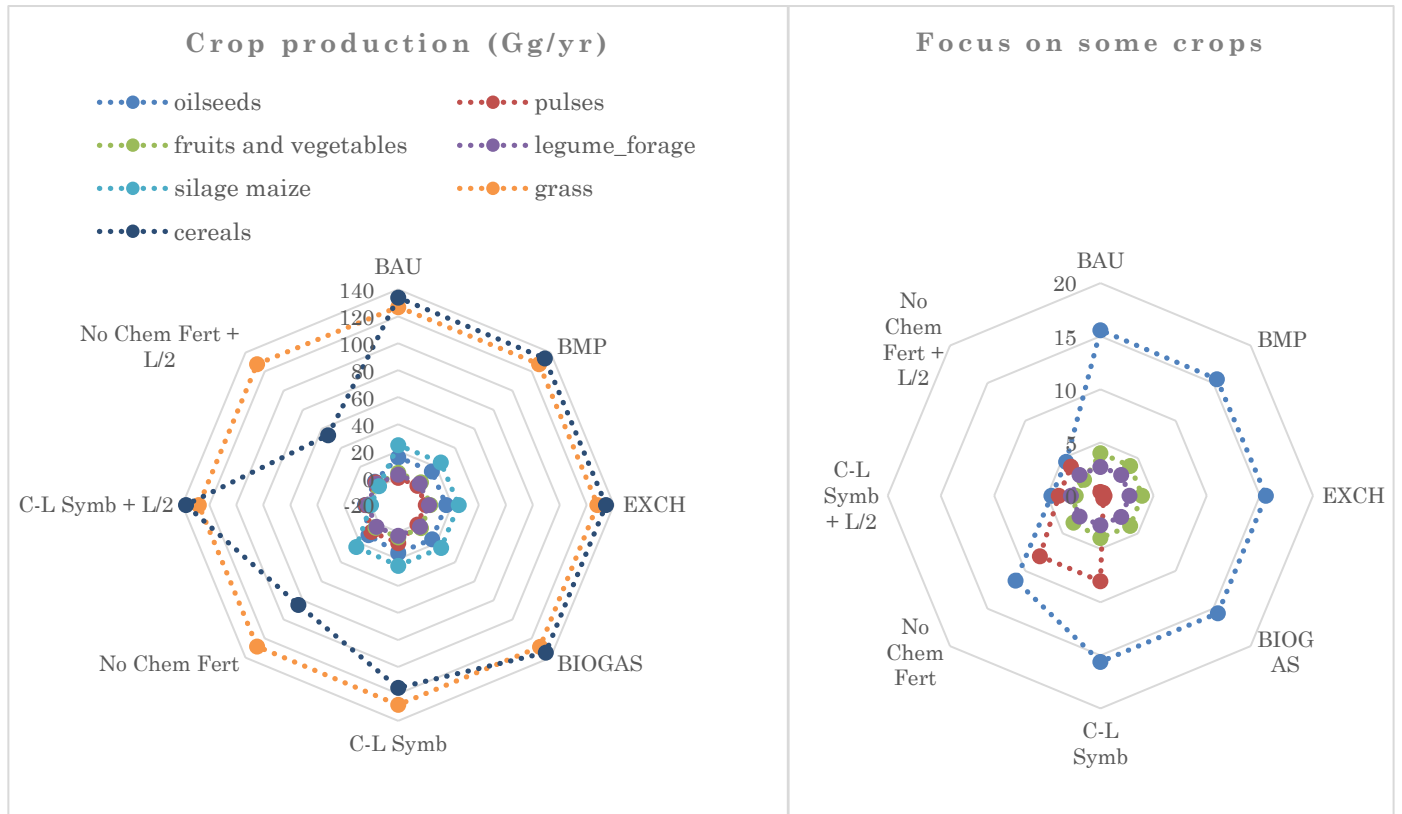


Figure 23. FAN scenarios outputs for crop production in the Ribéracois, in gigagrams (or kilotons) of crop products per year. Scenarios names are presented in Figure 3 and Table 3.

Livestock production

Results showed that livestock production remains constant until scenarios where livestock is halved (C-L Symb. + L/2; No Chem. Fert. + L/2). In these last two scenarios, pig and poultry production is reduced to half of the value observed in the baseline scenarios (**Figure 24**). However, livestock reduction did not affect ruminant meat production in the same way, because these animals can benefit from the higher forage availability that, in turn, increases productivity per animal. Those two effects compensate each other, as it is remarkable for beef meat production. Besides, even if crop production is lower in scenario without chemical fertilizers, livestock in FAN are fed in priority including by importing feed and forage to reach animal minimum requirements.

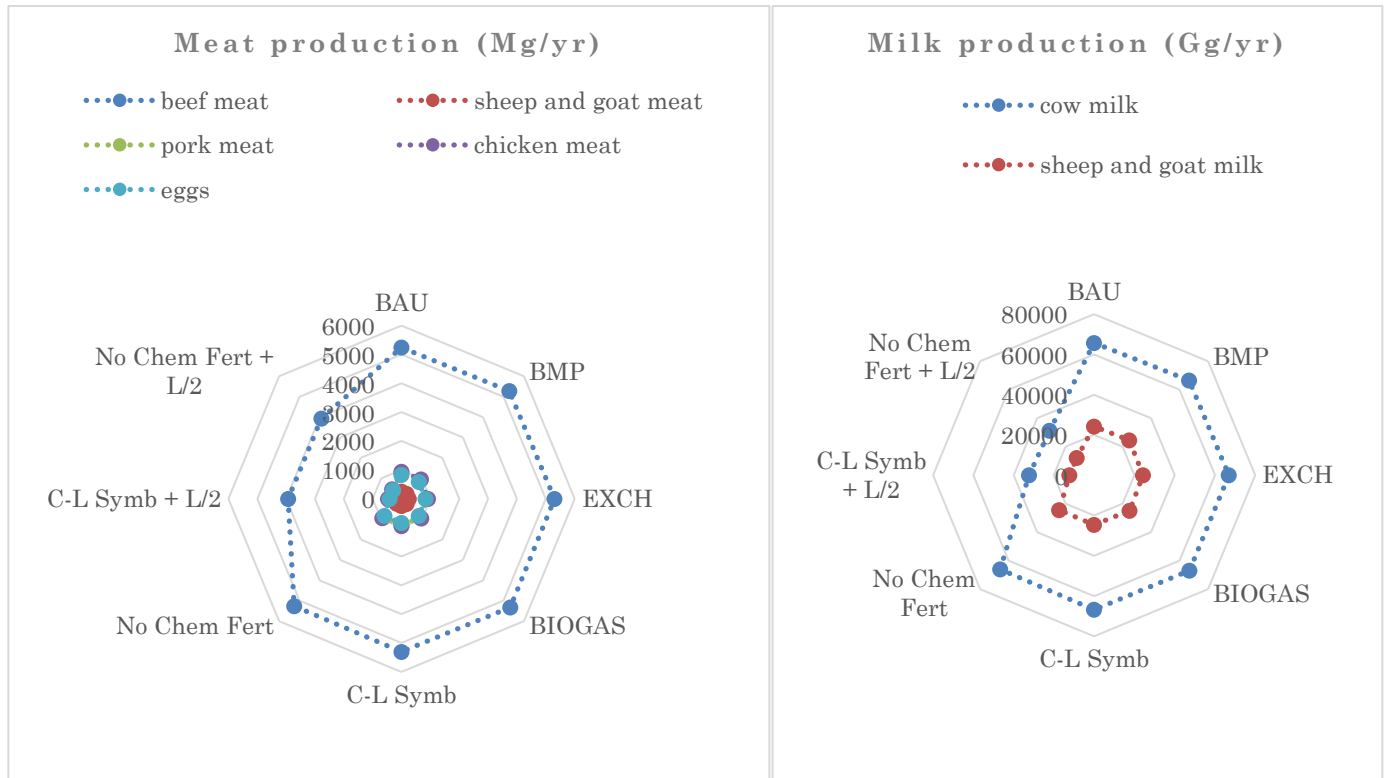


Figure 24. FAN scenario outputs for animal production in the Ribéracois, in megagrams (or tons) of meat and gigagrams (or kilotons) of milk per year.

Feed and forage balance

Results showed that cereals and oilseeds are always in surplus after feeding animals in the district (**Figure 25**, left panel). However, their production decreased in scenarios of crop-livestock symbiosis, due to the competition for land with pulses, and also in scenarios without chemical fertilizers due to yields depression by limited N input to soils. On the contrary, cereal balance increased in scenarios with reduced livestock population due to reduced feed demand and silage maize being replaced by cereals. Pulse deficit is reduced through the crop-livestock integration by adding more pulses to the rotations. Feed by-products exhibit slight deficit when anaerobic digestion is implemented thanks to competition with biogas plants for these materials. Concerning forage, results showed that after local exchanges, farms in Ribéracois can always satisfy the minimum livestock requirements (**Figure 25**, right panel). In addition, forage is much more available (even without silage maize) in scenarios with reduced livestock population, potentially explaining higher beef cattle productivity mentioned before.

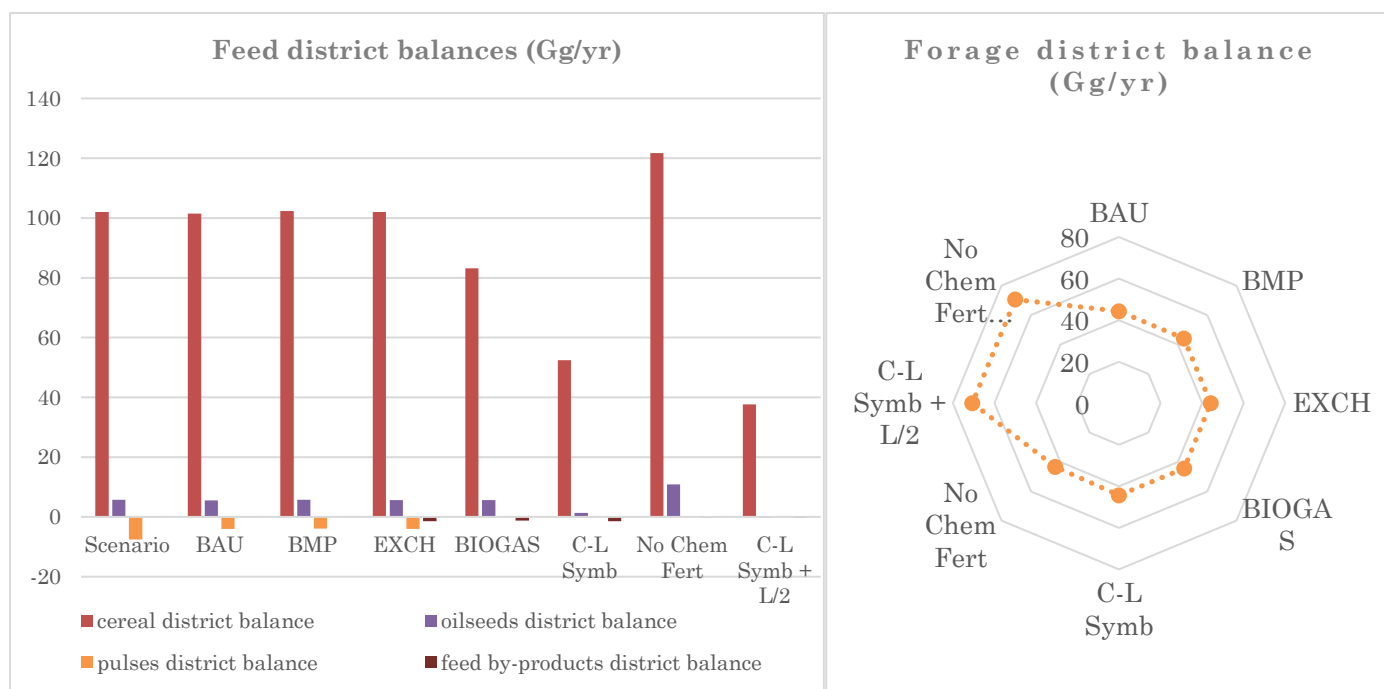


Figure 25. Feed district balance from FAN scenario outputs, calculated as the difference between feed produced and consumed by animals in the Ribéracois district, in Gigagrams per year. Forage district balance (on the right) is the difference between the forage produced (as grass, silage maize and legume forage), and the forage consumed in the district.

Bioenergy production

FAN estimated the anaerobic digesters total capacity to amount to 225,210 tons of substrate for digestion in the BIOGAS scenario (**Figure 26**). This capacity dropped to half when livestock population is reduced due to lower manure availability, which is the limiting factor of digestible biomass in our model. Results showed that biogas production was over 9,042,148 m³ in BIOGAS scenario, decreasing to half of that value when reducing livestock population. The biogas produced in the BIOGAS scenario was estimated as 18.4 GWh of electricity, without taking into account the associated heat production. Considering an annual electricity consumption of 4679 kWh per household in France, bioenergy production in the Ribéracois could satisfy the demand of 3942 households, which represents almost one third of the Ribéracois total population.

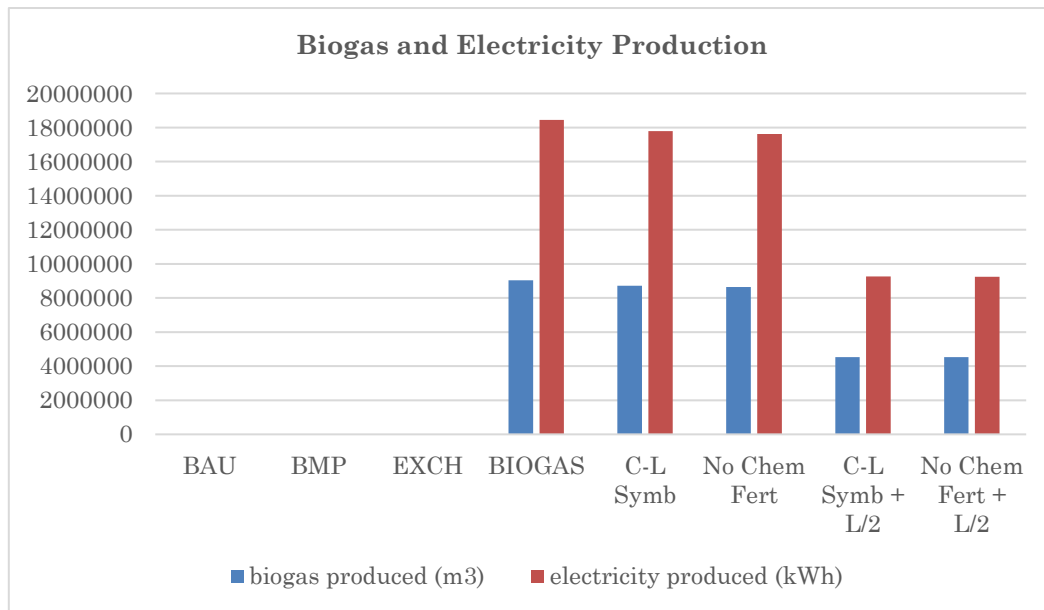


Figure 26. Bioenergy production and indicators from FAN scenario outputs. District anaerobic digestion capacity is the sum of all digesters capacity in terms of substrate digested. Biogas produced after digestion is expressed in m3 and the electricity recovered is expressed in kWh.

Local flows and transportation

FAN simulations showed that changes in scenarios for material reuse and recycling only slightly increased transportation distances in the district (**Figure 27**, left panel), especially when implementing anaerobic digesters. However, both the mass of material transported and the distance travelled by trucks decreased when reducing livestock. Overall, neither the mass of materials transported, nor the distances of truck moving those materials, increased significantly over the different scenarios. This information was useful to conclude that solutions related to material exchanges applied at local the scale would not need great logistic interventions in the case of Ribéracois.

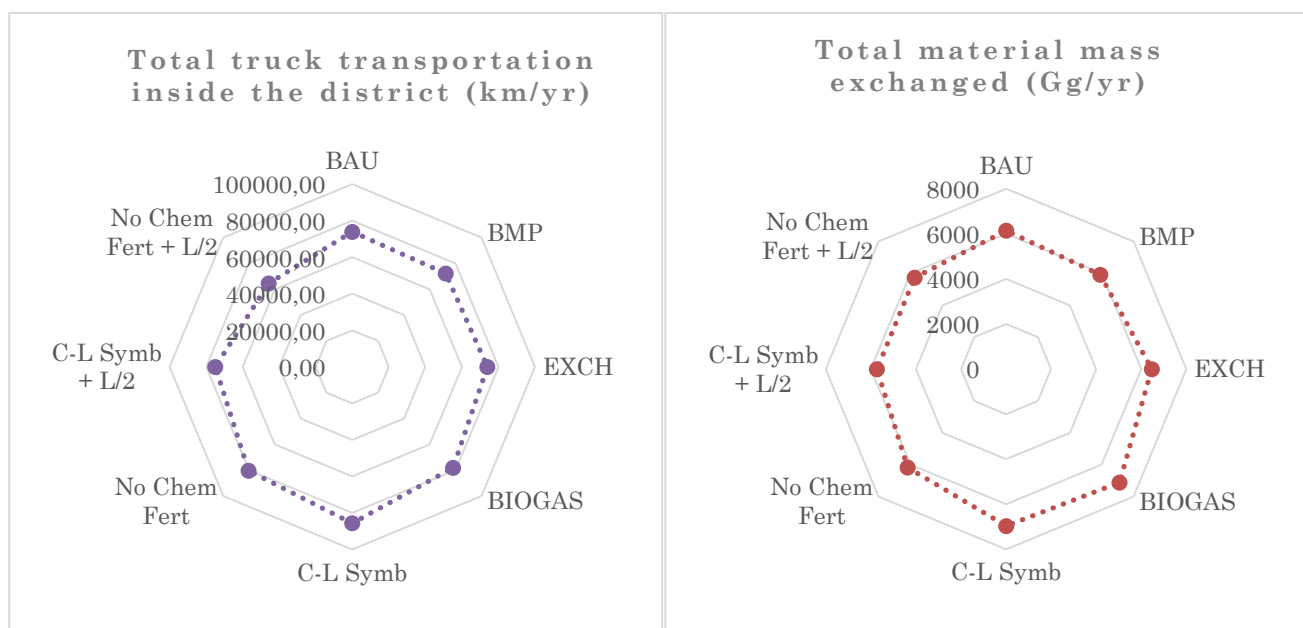


Figure 27. Distance of truck transportation inside the district (km) and material mass exchanged through these trucks, in gigagrams per year, from FAN scenario outputs.

Overall, the number of total local flows increased from the baseline to the last scenario, especially when implementing anaerobic digestion and crop livestock symbiosis (**Figure 28**). The number of total flow was reduced when decreasing livestock, since animal requirements flows are the most numerous ones. Local fertilization flows (corresponding to both manure and sewage sludge) increased considerably in the exchange network scenario (EXCH), up to 450 in No Chem. Fert. scenario, when organic manure is the only option for fertilizing soils. However, the number of fertilization flows is reduced when livestock population was reduced (L/2). Local food waste flows (corresponding to both energy and animal requirements) slightly increased when implementing digestion. The number of feed grain flows decreased when crop and livestock integration is applied (C-L Symb.) because this integration occurs mainly at the farm scale, therefore reducing the need for feed exchanges within the district. Although straw flows increased with crop livestock integration, local forage did not since there were enough forage surfaces. Finally, when reducing livestock population, because there is enough forage within each farm, forage exchanges are no longer needed.

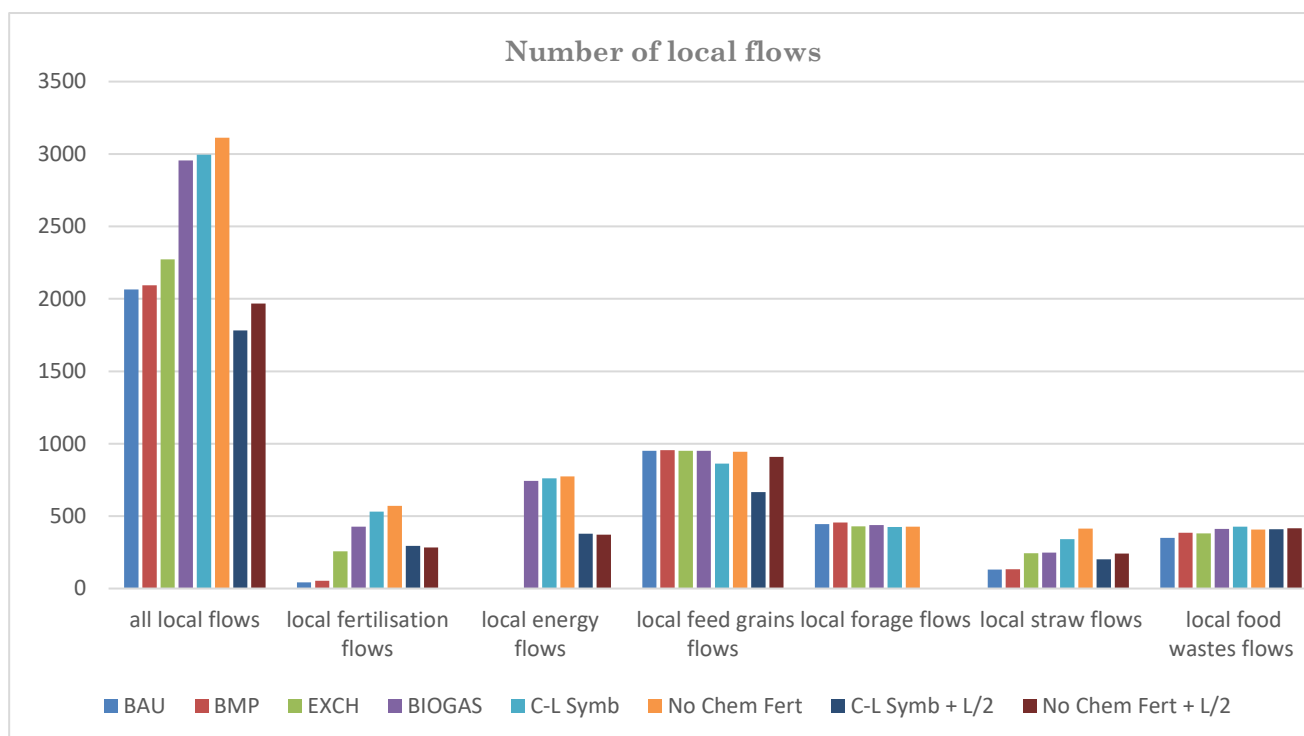


Figure 28. Number of local flows from FAN scenarios outputs.

N cycle

Concerning N inputs to soil, results showed the highest mineral fertilizer use in the BAU scenario, whereas fertilizer use exhibited a strong decrease when adjusting fertilization to crop needs in BMP scenario, as well as in the remaining scenarios (**Figure 29**). After EXCH scenario, N mineral remain low, since organic fertilization is privileged through preference coefficients. However, N mineral increases when reducing livestock in C-L Symb. + L/2 since the area under crops with strong N demand such as cereals increases. The N from animal excreta (collected in barns) allocated to crop fertilization only satisfies half of crop requirements, however, it is initially reduced with protein intake, and finally proportionally reduced to livestock heads in C-L Symb. + L/2 and No Chem. Fert. + L/2 scenarios. The N fixed by legumes is particularly remarkable when crop-livestock symbiosis is applied, that fostered pulses production. In addition, when implementing digesters in BIOGAS scenario, the N added by digested green biomass and food processing wastes behaves as a new input of nitrogen to the system under study. This source of N comes from the fermentation of wastes not mobilized in the previous scenarios, where grass and food processing wastes did not have any fertilization role. Finally, sewage sludge inflows play a small role in the overall N inputs.

Concerning N outputs, crop N demand varies only when changing land-use. Since legume crops are not fertilized in FAN, crop N demand decreases when replacing cereals with pulses in C-L Symb., which are less demanding. Still, when reducing livestock, cereals increased and pulses are lesser. Notice that crop N demand is not necessarily N harvested by crops but the necessary N seek for crop maximum yields. As shown in Crop production results, N inputs in scenarios without chemical fertilizers were not enough to satisfy N crop demand for maximum yields.

Regarding N losses, N leaching is very high in the BAU scenario, but applying BMP works as a great option to reduce N losses. In fact, best management practices have a double effect on N losses: on one hand, N fertilization rates are adjusted to crop needs; on the other hand, they introduce catch crops that reduce on average 50% of the N leached. Besides, N volatilization (as NH_3 and NO_x gases produced during manure storage and fertilizers application) losses are directly linked to N inputs. Volatilization losses increased considerably when anaerobic digestion is applied, due to higher ammonia emissions, approaching one third of total N applied to soils (Ni et al., 2012). Finally, although N_2O direct and indirect emissions remain a small proportion of N in any scenario, they have a great impact on greenhouse gas emissions.

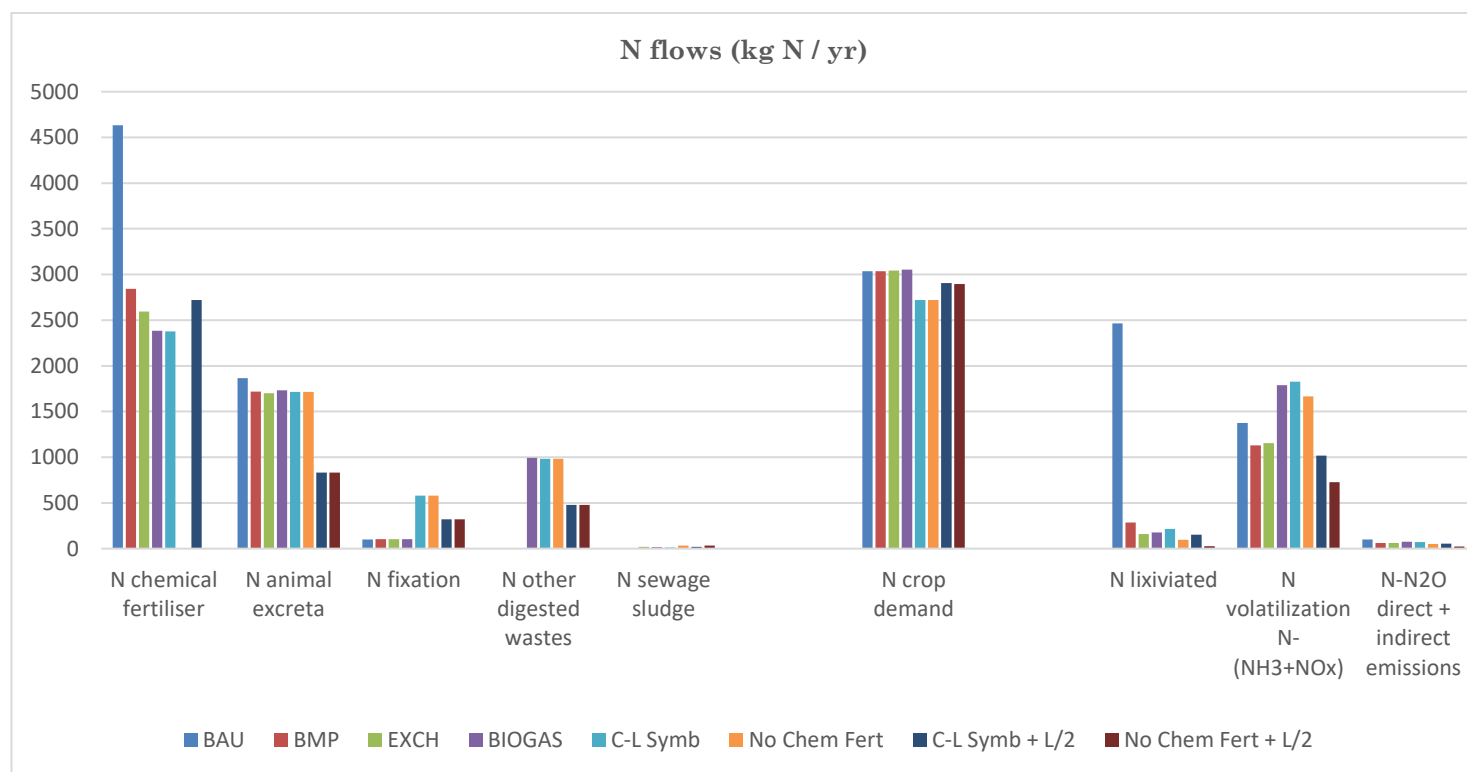


Figure 29. N flows from FAN scenarios output, in kg of N per year. N inputs to the system are on the left, and N outputs and losses on the right.

Along the scenarios, the relative importance of organic N in total inputs to soils increased (**Figure 30**). The fact of adding more N to the system through the digestion of green biomass and food processing wastes after the BIGOAS scenario, and the addition of pulses fixing N in C-L Symb., was important in this process. Still, when mineral fertilizers were an option for farms, its use reached, at least, half of the total N inputs to soils. In scenarios where N organic fertilization was the only option, (i.e. No Chem. Fert.), the total N available in the district was not enough to satisfy total crop N demand plus losses to the environment, therefore limiting crop yields.

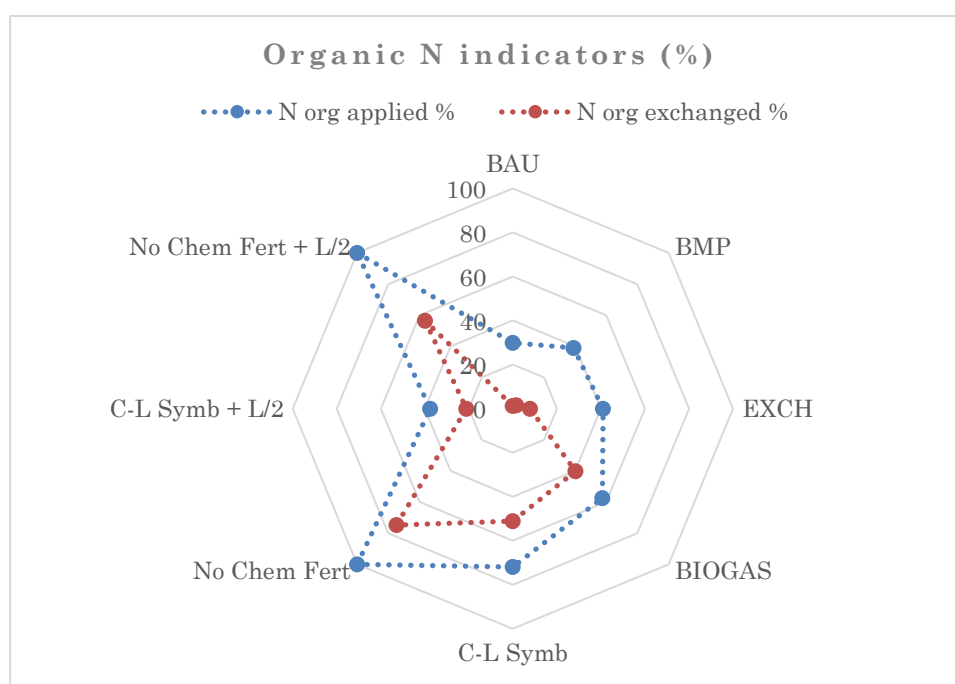


Figure 30. N indicators from FAN scenario outputs, expressed in percentage of N. “N org applied %” accounts for all organic sources in the N added to soils, whereas “N org exchanged %”, takes into account only the part of organic N that was exchanged between two agents before used for fertilization, see 2 and 3.

Greenhouse Gas Emissions

Results of FAN simulations showed that greenhouse gas in site emissions (in CO₂ eq.) decreased from the BAU to the last scenario (**Figure 31**). Most of CO₂ eq. was emitted from livestock and fertilizer management, including through CH₄ from both enteric fermentation and manure storage and through N₂O from fertilizer management and application. These emissions were substantially reduced when reducing livestock or removing chemical fertilizers. In addition, anaerobic digesters help to reduce most of CH₄

emissions from manure storage, significantly improving the balance. Enhancing materials exchanged inside the district only slightly increases CO₂ emission from truck transportation. Finally, C storage by grasslands plays an important mitigation role in CO₂ balance, by compensating enteric fermentation emissions.

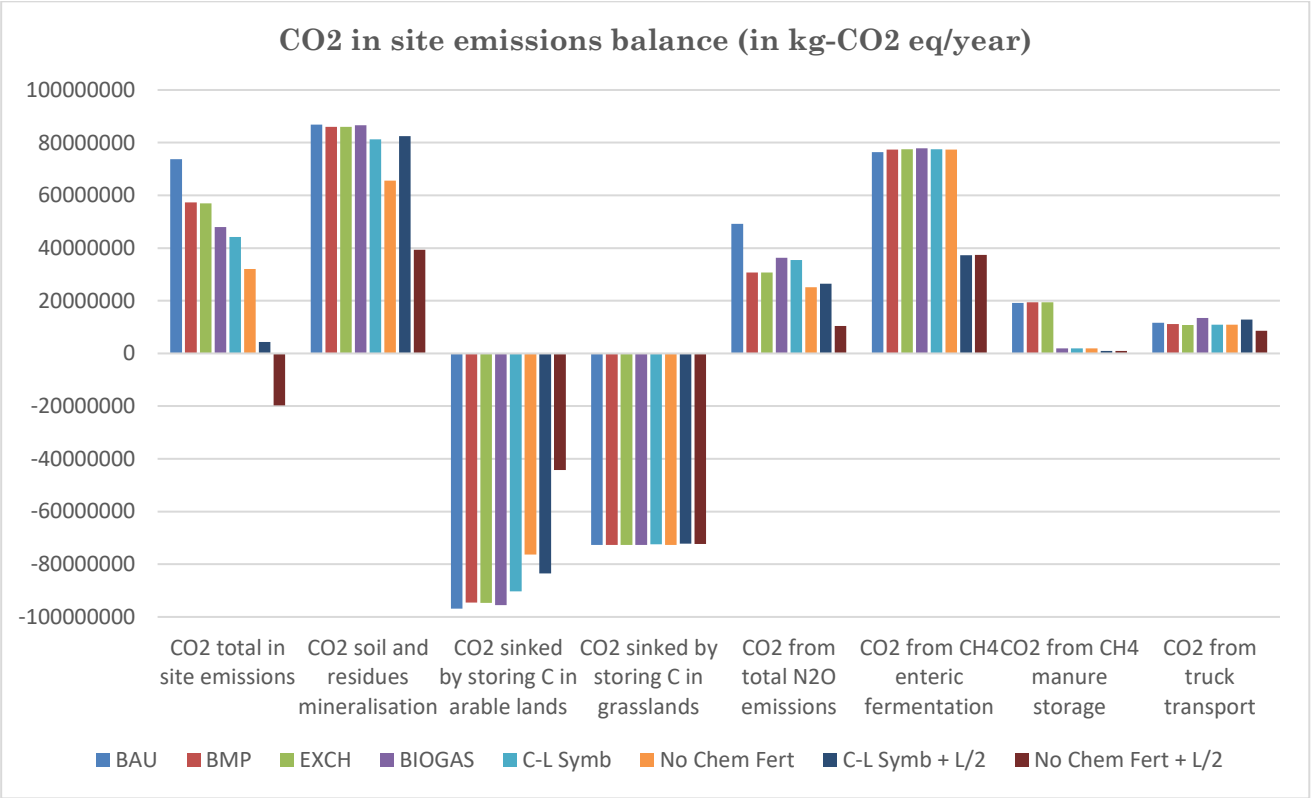


Figure 31. CO₂ eq. emissions (positive) and C stored or CO₂ avoided (negative), from FAN scenarios output in kg of CO₂ equivalents per year.

Results including both in and off site emissions showed higher emissions for all the scenarios, except the No Chem. Fert. scenarios that avoided chemical fertilizers synthesis emissions (**Figure 32**). CO₂ avoided emissions by biogas production in France are quite low. This is explained by the low CO₂ emissions of nuclear power that is the main source of electricity in the country. The amount of avoided CO₂ thanks to anaerobic digestion would be around four times higher if emissions per kWh of electricity produced in Europe were considered instead.

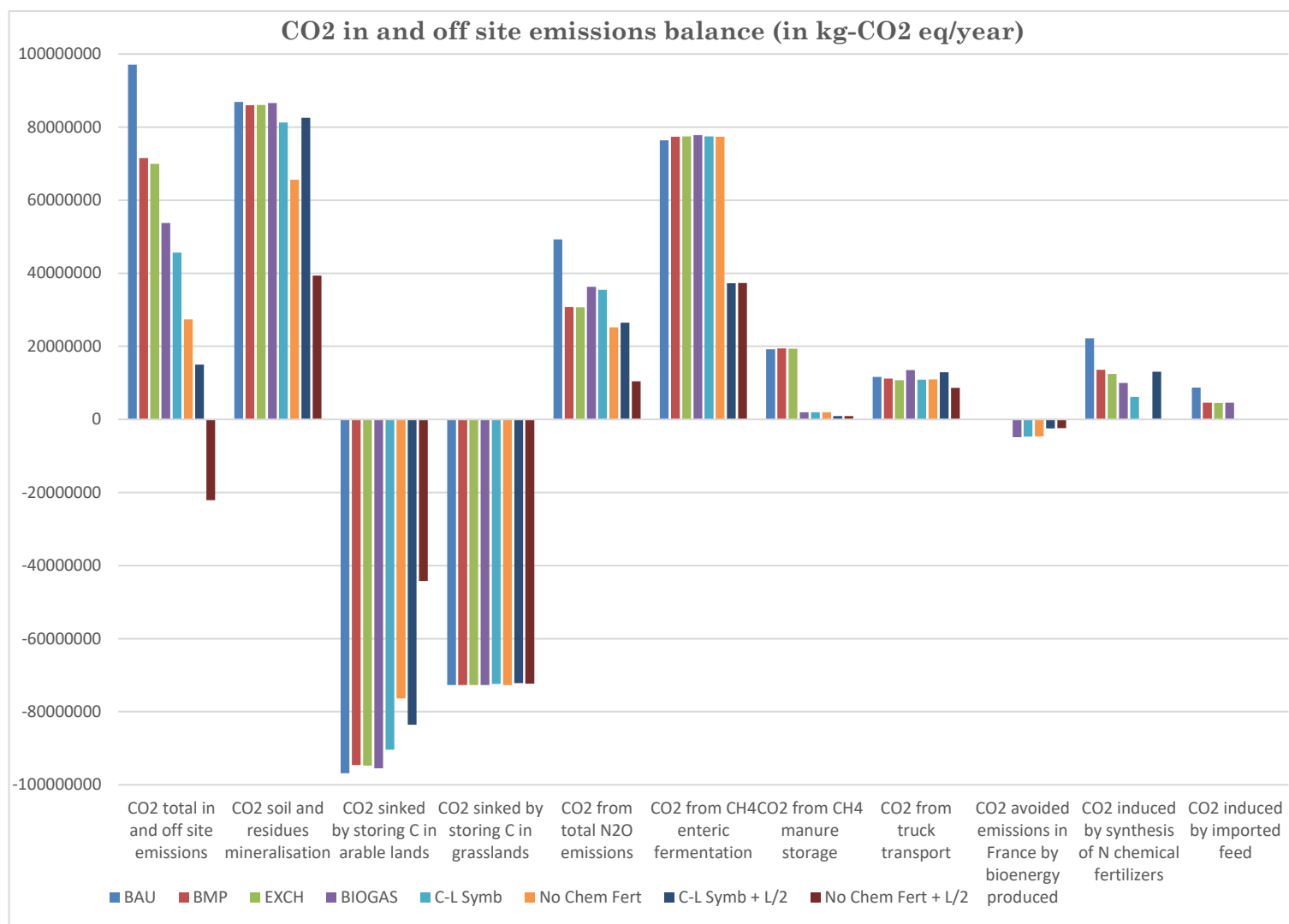


Figure 32. CO₂ eq. in and off site emissions (positive) and C stored expressed as CO₂ avoided (negative), from FAN scenario outputs (in kg of CO₂ equivalents per year).

Total CO₂ eq. emissions are the addition of all in and off site emissions of CO₂ eq. in FAN and the subtractions of the CO₂ eq. avoided or stored as C in soils. Results showed that globally the scenarios have improved total CO₂ eq. emissions progressively (**Figure 33**). The CO₂ emissions in BAU were estimated as 93,938 tons of CO₂ eq. per year. Thanks to the application of progressive solutions, CO₂ emissions were reduced in the further scenarios, for example down to half the initial emissions in the BIOGAS scenario. Finally, removing livestock and chemical fertilizers, in No Chem. Fert. + L/2, has a potential net storage of 19,256 tons of CO₂ eq. per year.

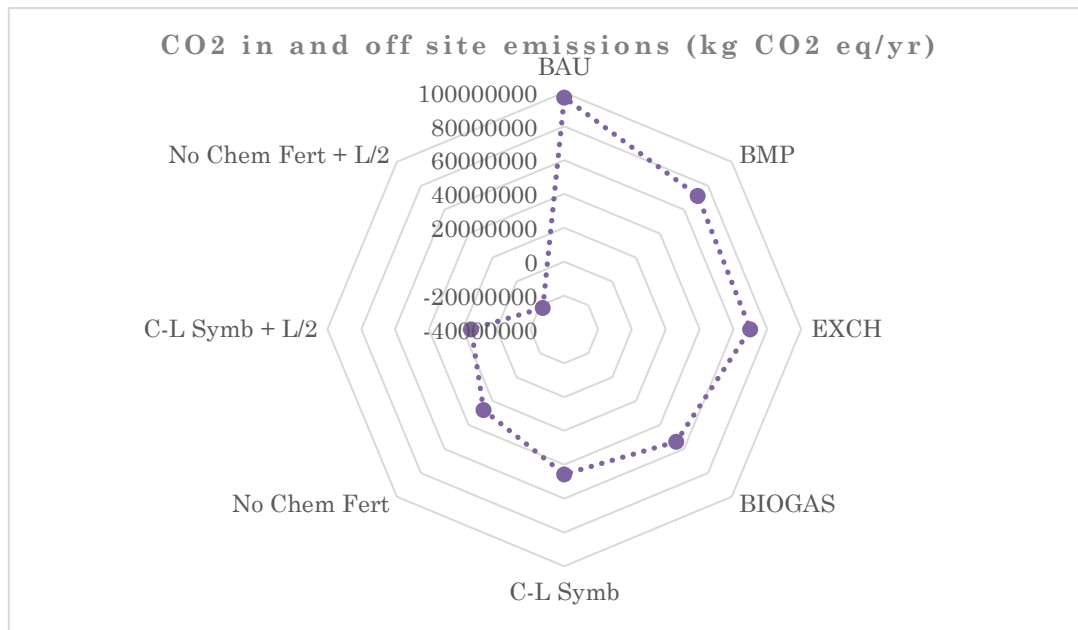


Figure 33. Total CO2 Emissions from FAN scenario outputs, in kg of CO2 equivalents per year.

When comparing CO₂ emissions to food produced in terms of calories and energy, the progressive pattern of improvement across the scenarios is maintained (**Figure 34**). Initially, emissions are reduced in BMP by reducing N losses and some feed imports. Then, anaerobic digestion implementation in BIOGAS scenario also presents a difference with previous scenarios in terms of efficiency. Surprisingly, when comparing No Chem. Fert. and C-L Symb + L/2, we observe that removing fertilizers or reducing livestock alone presents the same effect. Finally, the No Chem. Fert. + L/2 scenario exhibited a negative GHG budget, i.e., net avoided emissions while producing food.

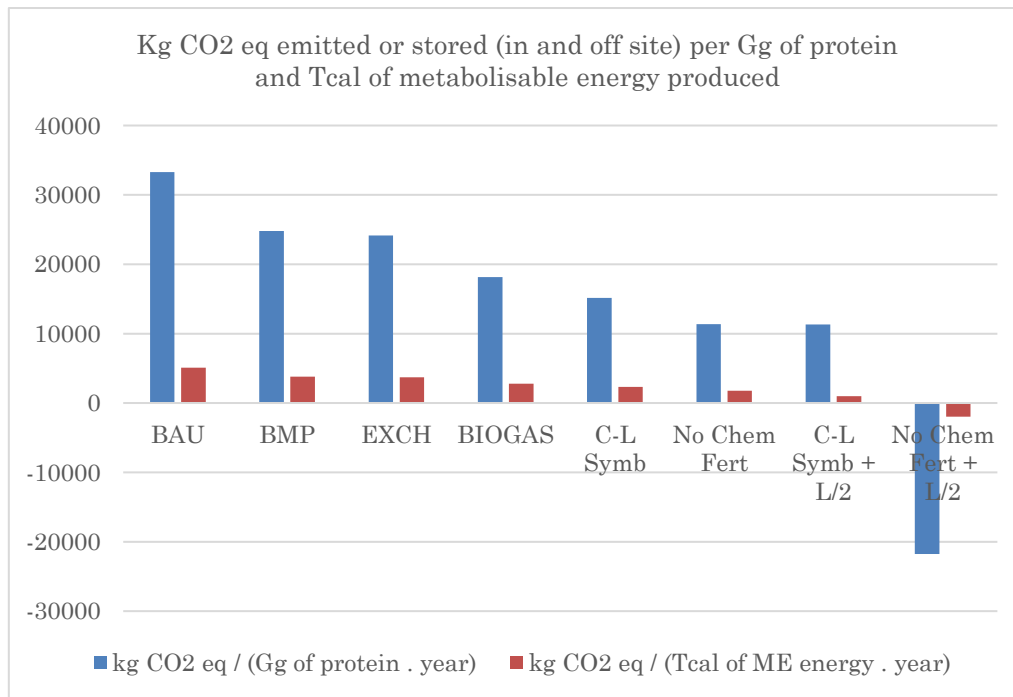


Figure 34. Kg CO2 eq. emitted or stored (in and off site) from FAN scenario outputs, in kg of CO2 equivalents emitted per Gigagram of protein and Tera-calorie of Metabolisable Energy (ME) in food produced per year.

3.4. Discussion and Conclusion

In this work we showed how FAN, a model combining an agent-based model with an agroecological model, was helpful for obtaining unexpected outcomes under different constraints. The agent-based core helped to simulate exchanges, quantifying them and especially locating them (Drogoul et al., 2013). These exchanges were especially important to simulate animal feeding and other requirements, as well as local collective solutions including recycling and biogas. On the other hand, the agroecological core of the model was useful to both estimate food and a set of environmental indicators (Bonaudo et al., 2014; Wezel et al., 2014). However, some FAN limitations lay on the non-consideration of socioeconomic and ecological barriers related to some alternative scenarios. The former include farmers' willingness to implement the solutions proposed in the various scenarios and their transition cost. The latter would require to better explore how the solutions proposed in the various scenarios are applied more precisely. For instance, we assumed that the adjustment of the N fertilization, or the substitution of chemical for organic fertilizers are straightforward. However, adjusting fertilizer rates is not easy without

technical assistance and incentives and that direct substitution of chemical fertilizers is difficult in terms of availability and soil dynamics (Carmo et al., 2017; Černý et al., 2010).

After applying the scenarios with FAN, we showed that, strictly applied as in BMP scenario, best management practices are very effective to reduce nutrient losses and GHG emissions. Although low progress was shown by the organic wastes exchanges EXCH scenario on GHG, because of higher truck transportation, the efficiency of nutrient use increased. The implementation of anaerobic digesters in BIOGAS scenario significantly decreased GHG emissions, even if more truck transportation was necessary, but this balance was compensated by the production of renewable energy collaborated. The symbiosis of crops and livestock in C-L Symb through, not only manure recycling for fertilization, but also local feeding, exhibited less greenhouse gas emissions than previous scenarios even if greater truck transportation was needed, thanks to the elimination of long protein feed chains. Livestock division scenarios C-L Symb. + L/2 and drastic reduction in GHG emissions, generate some strong costs and drawbacks. In particular, it compromises organic fertilizer availability, biomass inputs for anaerobic digestion and grassland role in carbon sequestration in soils. Finally, despite its low food production, the No Chem. Fert. + L/2 scenario, seems to be minimizing environmental impacts.

In this study, we applied an integrated assessment approach using FAN outputs to better study the cross-sectional outcomes of the scenarios. Globally, we observed that the environmental performances improved along with the application of the scenarios. This verifies our hypothesis on the progressive order of measures and solutions implemented in the scenarios. We showed that the scenarios performing more exchanges, i.e., EXCH, BIOGAS and C-L Symb., proved to be a good compromise for increasing environmental performance with agents' coordination without radically modifying farming systems. Actually, only some small land-use changes were applied to pulses along with recycling and anaerobic digesters. Recycling for fertilization, energy and animal feeding is possible and has still a large potential, even if the investment costs are quite high especially for anaerobic digestion equipment. Autonomy also showed a potential to increase in the area by better integrating crops and livestock, both for feeding and for soil fertilization. The system redesign in the last scenarios evidenced the need to rethink our agro-food systems to minimize our environmental impact. Nevertheless, some of these scenarios are less productive in terms of food, from both crop and livestock production. Indeed, the removal of chemical fertilizers and reduction of livestock population are significantly drastic

measures. These measures can eventually be considered in a context where environmental pressure overtakes food demand.

Overall, more sustainable food and renewable bioenergy production seem possible in Ribéracois district without compromising environmental impact. Thanks to the FAN model, we were able to account for complex interactions between the leverage factors applied resulting in different food production and environmental performance. This work gives an insight of how different solutions seeking sustainability in agro-food systems may bring to very different outputs. Future agricultural and environmental policies may be able to take into account simulations from predictive tools like FAN.

Discussion and Conclusion

To come back to the reasons that stimulated this Ph.D., we discuss here the initial methodological that we made in this original research project and we outline its contributions. This overall discussion will first situate our research approach within the scientific literature and the current terminology. We will then justify the choice of the specific case-study and system's scale. We will argue about the originality carried out by the FAN model, its assumptions, limitations and related modelling decisions. We will comment the application of FAN to the simulation of scenarios and to their integrated assessment. Finally, we will discuss FAN future applications and perspectives, in particular by providing recommendations for its improvement.

Our approach in reference to the state of the art

We are in a stage where human trace on the planet becomes more and more important, the so-called “Anthropocene” (Smith and Zeder, 2013). In this context, the traditional empirical approaches in science have lead into more integrated ways of observing natural and human activities, and their links through the study of environmental management (Mitchell, 2013), ecosystem services (Braat and de Groot, 2012), social-ecological systems (Binder et al., 2013) and resilience (Olsson et al., 2015). We acknowledged the need to work in this direction through the study of the links between agriculture, environment and society. We believe that our work comes to reinforce this framework, by proposing a social-ecological model that assesses development alternatives in local agro-food system.

In fact, our work appears in a context where more and more studies are showing the issues of agro-food systems and their links with resources management, economic activities, and the global environmental change (Carlson et al., 2016; Fader et al., 2013; Foley et al., 2011a; Steffen et al., 2015). Although many publications address this question at the global scale (Erb et al., 2016; Le Mouél and Forslund, 2017), considering regional food chains and local agro-food systems remains of great importance. This local scale is especially important because it provides specific guidance and solutions (Mascarenhas et al., 2010). Indeed, there is an imperative need to investigate not only the causes and the magnitude of the impacts, but also pathways for new solutions, by exploring and assessing the different alternatives that we locally have to make agro-food systems evolve. Undoubtedly, the scientific community plays a crucial role on our knowledge about these issues, by warning about the impact of agricultural activities and proposing innovative solutions to seek for food security and sustainability (FAO, 2016; Hedger et al., 2015).

Scientific fields and terminologies

To start our research work, we decided to explore the vast scientific literature about nutrient and material flows with a focus on local agro-food systems. Because we found several terms addressing similar things, we decided to gather them under the same umbrella that we called “*Agro-Industrial Ecology*”. We presented this concept as an essential approach to address the local biomass and nutrient management issues, capable of linking complex environmental assessment, socio-economic agent interactions and farming decision-making. This concept was inspired from different fields studying material flows. In particular, we grounded our thinking into the “*Industrial Ecology*” scientific discipline (Allenby and Graedel, 1993) that was framed by engineers to study how to couple material flows between stakeholders in the so-called “*Industrial Symbiosis*” (Chertow, 2007). We also got inspiration from the “*Urban and Landscape Metabolism*” (Zhang, 2013), the “*Crop-Livestock Models*” (Tittonell et al., 2009c) and from the “*Substance Flow Analysis*” that focusses on single element flows present in different materials and economic sectors. The Agro-Industrial Ecology field encompasses a local scale together with actors’ explicit representation and modelling and agro-ecological methodologies, as presented in Chapter 2. These methodologies include both ecological tools and social models in a deeper way that Industrial Ecology studies have done so far. This new approach was proposed in response to the need of sharing a common framework between agronomists and ecologists working with nutrient and material flows in sustainable agro-food systems. This concept is challenged by the emergence of two new popular terms closer to economy: “*Bioeconomy*” (El-Chichakli et al., 2016) and “*Circular Economy*” (Ghisellini et al., 2016; Murray et al., 2017). The former embraces all initiatives related to bio-sourced material efficient use and recycling, while the latter expands the idea of circular material flows to all sort of material types and production sectors. These two terms are even sometimes combined as “*Circular Bioeconomy*” (Mohan et al., 2016). Still, their definition is not clarified yet properly (Sauvé et al., 2016) and probably a reciprocal integration of these terms will be needed (D’Amato et al., 2017). In the future, we bet that Agro-Industrial Ecology can remain a specific field of agricultural application for closing material loops between partners of the agro-food systems, being at the same time compatible with both the Bioeconomy and the Circular Economy terms that target larger applications.

Case study issues, scale and data collection

In this PhD, we have decided to develop a model of material flows at the local scale, with a special focus on the areas with major environmental and agronomic issues. In fact, most agricultural areas in the European Union present modern agro-food systems with major issues related to nutrient and material management, especially high nutrient losses from fertilization and livestock excretions (Stoate et al., 2009; Tuominen et al., 2014; Velthof et al., 2009; Vitousek et al., 1997). In parallel to FAN conception and testing, we explored several case studies of local agro-food systems with strong issues related to nutrient and material management. Among them, the Ribéracois was chosen as being the closest case study to our institution, an area where we already had some experience (e.g., in Nowak et al., 2015). In the Ribéracois district, there are, in addition, farming issues related to the preservation of high quality livestock production, and grassland conservation. Livestock farmers face some great economic difficulties due to milk quota liberalization, high volatility of input price and encouragement to intensify farming systems. There is therefore a will to explore options to diversify the farming systems of the district, to cut into their input and material costs and to derive new income from alternative sources such as renewable energy production. The development of local feed and forage production and of biogas plants are options that are already considered and discussed by breeders and local extension services.

However, we faced several challenges to define what a local scale is and what its boundaries are. In Chapter 1, we defined the local scale as regions or districts in which economic partners are spatially close enough to be connected within exchange networks, while sharing the same natural environment. This definition resulted in including direct upstream and downstream partners of farms that operate across the district. We therefore excluded external agents connected to the global markets and long distance national markets. Only agents present within the area were considered as local partners. Exchanges with partners outside from the area were considered as exchanges with the global markets. In terms of spatial scale, our goal was to delimit an area that could be easily represented in the FAN model, with an administrative status, a project and where data was available. A French département, (e.g., Dordogne) could have been a good scale since the administrative delimitation is quite clear and extension services work at this scale. However, because the area and the number of agents were too large to be implemented in FAN (the Dordogne presents 9060 km² of total area and more than 5000 farms), we decided to consider smaller scales. In that perspective, we paid some interest

to the ‘small, historical farming regions’ (“petite région agricole”) that were originally defined based on homogeneous farming systems and land-use but without administrative unity. We also paid attention to the “communautés de communes” that correspond to local development projects lead by aggregation of municipalities. We therefore decided to limit our case studies to 1000 km², a surface in between both entities, where 835 farms and several partners were operating. At the scale we considered, farms land-use and livestock data were available from surveys carried out every 10 years by the statistical service of the French Ministry of Agriculture, Agreste. Since very few data were available regarding flows between farms and with their partners, we decided to directly inquire the actors concerned. Our experience was that local agronomists, more used to work at the total Dordogne area, had difficulties to provide accurate data at the scale we were working. In addition, private food and feed companies, fertilizer suppliers and other partners were not willing to share their materials and wastes flows data, or they did not have account for this data.

In our work, we dared to create boundaries in inlands farming areas to define a local scale, setting an example for future studies. Nevertheless, the size of what we called “local scale” remains quite ambiguous and should be defined according to each project needs. Moreover, collaboration between researchers, local managers, and private companies, seems fundamental for accurately study local agro-food systems.

Building a material flows agent-based model

After having reviewed the mechanisms used in the different approaches that study material and nutrient flows, we confirmed that stock-flow methods are crucial to analyze substance flows, due to their complete accounting of whole system functioning. However, stock-flow methods have commonly been applied at large scales, where agents’ characterization is merely an aggregation of individuals and the impact on the environment is roughly measured. Indeed, coupling a mechanistic natural environment with an unpredictable socio-economic system necessarily requires complex tools, analysis and models (An, 2012; Chen and Liu, 2014). We therefore hypothesized that coupling stock and flow with environmental assessment tools would help to link nutrient losses to the environment coming from the agro-food system and that coupling them with agent-based models would help to better account for agent decisions in flows and their corresponding driving forces. Therefore, we concluded Chapter 1 stating that linking stock and flow with

environmental impact and agents-decision models approaches would be of great help to simulate and assess alternative nutrient and biomass material flows in agro-food systems. This objective was materialized in the conception and application of the FAN model that couples these three approaches. Nonetheless, such coupling was challenging for four reasons: the agent representation, their decision making, the environmental dynamics and the system spatialization.

In terms of agent representation, contrary to stock-flow methods that aggregate agents driving material flows, agent based models represent individual agents. In other words, they simulate a so called “artificial population” that represents the actual one. In the case of FAN, the model is able to build an artificial population of farms and their partners based on the characteristics provided in the data gathered. Yet, a small level of aggregation was somehow applied when characterizing farm agents around a typology. This conceptualization is similar as the one used in crop-livestock models, a useful way to qualitatively understand a large diversity of farm features. Upstream and downstream farm partners were however represented individually.

In terms of decision making, stock-flow methods describe static situations defined in a specific context and constrain, i.e., they mostly represent material flows as they actually occur. In contrast, in agent based models interactions between agents to decide where to allocate material flows in sequenced steps is a must have. This is the case in FAN, where most flows are set by a ranking that each agent does. They calculate the appropriate agent to exchange with according to favorable conditions (historical, supply-demand ratio, disposition to exchange, location, etc.), as explained in Chapter 2.

In terms of environmental dynamics, whereas most environmental assessment indicators try to integrate empirical data from losses in dynamic systems, stock-flow methods estimates the flows released to the ecosystems thanks to historical data or emission factors. In the present work, the gathering of empirical data from material wastes, nutrient losses and emissions was out of the project scope. Hence, FAN was parametrized based on statistical data for waste production, such as sewage sludge and food waste production at the national scale, and based on emission factors for loses, such as those provided by IPCC or ADEME. Yet, a vast range of nutrient losses and greenhouse gas emissions was taken into account. This diversity in the elements considered, goes further than the single element flows commonly studied in stock-flow methods.

In terms of system spatialization, all stock-flow systems and most environmental assessment tools do not account for agent location or geographical characteristics of the environment. In contrast, agent based models can locate agents accurately if data is available, especially for small numbers. In FAN, this approach was partially implemented: artificial agents were located by scattering farms with their corresponding land-use and livestock in specific sub-zones of the district. This approach was key to consider major logistic and environmental constraints.

The FAN model discussion

As shown in our review of the literature, only a relatively small number of studies have applied agent-based modelling to agro-food systems (Schreinemachers and Berger, 2011b). They have typically focused on specific aspects of the agro-food systems, rather than integrating across multiple agro-food system activities and sectors (Acosta-Michlik and Espaldon, 2008; Bert et al., 2015; Bichraoui et al., 2013; Courdier et al., 2002; Groeneveld et al., 2017; Iwamura et al., 2014; Murray-Rust et al., 2011; Schouten et al., 2014). However, to our knowledge, agent-based models have not been applied to simulate material flows across a broader range of components in agro-food networks, including multiple agents and a wide range of exchanged materials. This more holistic analysis is important to assess alternative agricultural development strategies, such as waste recycling, and environmental impacts related to agro-industrial ecology and circular economy. So far, FAN is the first model that combines social simulation with the environmental characteristics of farms across a wide range of materials in complex agro-food networks.

One of FAN's most important strengths lies in its utility to simulate what we called the "local scale", by addressing an intermediate spatial scale between the farm and the sub-national region or the country. Such a sub-regional level is critical because actors are uniquely identified and their potential role in a circular economy can be assessed. In addition, the FAN model was developed by combining multiple approaches in order to address a set of environmental and agronomic issues to the sustainable development of agriculture in rural areas and the challenges they face in global markets offering manifold farm inputs. This allows FAN to be used to assess scenarios of circular economy by simulating material flows in local agro-food systems.

Indeed, to address the local scale, FAN encompasses a wide range of agents and material types. In total, eight types of agents were considered, which is beyond the number of agents modelled in other farming agent-based models, (e.g., two in Shastri et al., 2011 for famers and bio-refineries, and five farmer strategies in Valbuena et al., 2010). In addition, the difficulty of acquiring individual data for numerous farm agents (>800 in our case-study) make agent typologies useful to create artificial agent populations. In FAN, farm typologies help to build a farm population distributed around the average characteristics of each farm type. However, each farm was defined as belonging to a generic agent called “farm” in the model. This conception strategy differs from that commonly used in agent-based models, where agent classes are set with specific characteristics, making, for instance, dairy farms having a defined number of dairy cows, and restricting to no beef cattle or pig in the farm. In our case, typologies help to integrate a vast flexibility of farm features, in a way that, even if arable farms can have some dairy cows, only farms having dairy cows can produce milk. In addition, FAN can simulate multiple bio-sourced and biomass materials, including wastes and fertilizers, crops and feed, livestock and meat, straw and crop residues. These materials correspond to those usually found in western livestock and arable farming systems. In the future, FAN should be able to integrate more specific categories of crop and materials, such as different fruits and vegetables, depending on the case study applications. Similarly, more waste characteristics could be included in cases with specific food industries.

Another core innovation of FAN lies in its ability to simultaneously simulate farms’ interaction as a local network of potential exchanges. In numerous agent based models, individual actions are carried out one by one, starting by a random agent. Yet, we know that, in reality, several actions can be carried out simultaneously by different agents. For instance, two farms can negotiate their exchange of grains while two other farms can negotiate the same thing at the same time. To approach this complex phenomena, we developed a way in which the calculation of all the exchange possibilities was done first. Then, the actual exchanges were selected through a stochastic choice based on several parameters.

Explicit economic factors such as material prices and transportation costs were not directly used to determine the exchanges in FAN. Despite the fact that innovative, sustainable systems enhance circular waste flows to avoid material losses, energy consumption, and waste disposal, the prices of wastes and the cost of recycling have been poorly studied (Higashida and Managi, 2014; Iacovidou et al., 2017). In the case of agro-

food systems, most biomass materials (e.g., forage, manure, food processing wastes) do not always have a defined value in the market, and their costs and prices may vary depending on subsidies and local farming strategies (Dietrich et al., 2016). In our case-study, the difficulty in obtaining farmers disposition to assume recycling costs and the lack of waste prices data was confirmed by interviewing local agronomists and extension services. For all these reasons, economic factors such as prices of materials and transportation costs were not included explicitly in FAN. Instead, we included some innovative simulation mechanisms that were able to indirectly recreate these processes, namely the radius of action, the fidelity, the disposition to exchange and the preference coefficients. Although these coefficients can be considered as modelling artefacts, they were useful to imitate a context where some uses or materials are favored, as applied in the scenarios.

FAN was shown to be useful to estimate food production and waste recycling. Nonetheless, as mentioned in FAN discussion of Chapter 2, there is room for progress in this field. Concerning crops, some improvements can be applied to the simulation of crop response to N fertilization. Similarly, there are also further steps to make to better simulate how feeding rations determine livestock productivity. In the case of bioenergy production, although anaerobic digester supply is modelled based on the average composition of feedstock observed in France, it would be of especial interest to test different compositions of feedstock as digester inputs.

Finally, FAN proved to be used not only to calculate food and energy production, but also to assess various environmental indicators, including greenhouse gas emissions from agricultural activities and material transportation, nutrient losses to water bodies, and some other proxies to estimate ecosystem services. By considering them all at the same time, FAN provides guidance for an integrated environmental assessment. Yet, since we assumed important simplifications, there is also margin for improvement. In particular, by approaching national emission factors for greenhouse gases and by going further in the N dynamics will help to better estimate N availability for crop intake. Additionally, more indicators could potentially be added, inside farms, such as machinery combustion, energy use for heating and pesticides use; and outside farms, such as specific food processing emissions and losses, integration of trees and forest areas in the landscape, etc.

Scenarios simulation and assessment

The design and simulation of contrasted Agro-Industrial Ecology scenarios is a key target when progressing towards circular economy. These scenarios aimed to mimic contexts that may be encouraged by agrarian policies and regional management. Concerning the scenarios conceptualization, we inspired from the framework efficiency, substitution and redesign to apply measures and technologies towards more sustainable farming. After observing the results of the simulations, we confirmed that agro-food systems improved performance progressively along with the scenarios. Indeed, some of the changes applied in the system are win-win solutions. For instance, increasing efficiency and local recycling help to reduce input costs and to produce additional income by reusing wastes or producing renewable energy. On the contrary, chances concerning system redesign are not easily applicable without a compensation.

By implementing the simulations, we showed how FAN was helpful for obtaining unexpected outcomes under different constraints. On one hand, the agent-based core helped to simulate exchanges, quantifying them and especially locating them. These exchanges were especially important to simulate animal feeding and other requirements, as well as local collective solutions including recycling and biogas. On the other hand, the agroecological core was useful to both estimate food and environmental indicators.

The integrated assessment of FAN outputs helped to better study the cross-sectional outcomes of the scenarios. Results showed that best management practices, when strictly applied, can be very efficient for reduce losses and improve nutrient use efficiency. We also showed that local collective solutions through network coordination were effective, and could improve waste recycling for both fertilization and bioenergy production. In addition, these solutions presented less greenhouse gas emissions than previous scenarios even if truck transportation was higher to support them. Finally, we showed that the most environmental performant scenario implied the reduction of livestock heads, and therefore meat and milk production, plus the reduction of crop and bioenergy production due to lower livestock manure availability.

In the scenarios, we included at the same time policy measurements, food chain reorganization and farm structure modification. Under a policy perspective, the strict application of best management practices concerning fertilizer doses, nitrate catch crops and protein feed are urgently needed to preserve fragile natural ecosystems and watersheds. Moreover, local collective solutions seems to be a good option for farms to

improve their sustainability and to obtain alternative sources of energy and income. Finally, drastic changes in farms structure and production seem to be necessary in order to counteract climate change, and improve environmental sustainability. This reason can make society wonder about how to compensate farms for their restructuration. One way may be through monetary compensation from agrarian policies, or introducing sustainable labels in the goods produced (e.g., a circular economy region, climate positive food).

FAN application and improvement perspectives

Undoubtedly, the FAN model features opened promising avenues to simulate contrasted scenarios of agro-food networks at the local scale in other regions and case studies in a circular economy perspective. FAN can be directly applied to other French regions providing land-use and livestock from farms, food processing wastes, sewage sludge and regional yields data. It can also be applied to other contexts in Europe and western farming areas, by providing, on top of the latter, average livestock feed and forage requirements, fertilization rates, bioenergy feedstock composition and perhaps also livestock excreta. Very different contexts such as southern countries will require additional update of some production parameters, in particular for livestock meat and milk production.

FAN could be applied to other specific crop productions apart arable crops, such as horticulture, tubers, fiber or energetic crops. This goal is still possible by adjusting crop categories and providing their corresponding land-use, fertilization and yield data. Nonetheless, FAN application remains especially interesting when these productions are related to livestock, since animals are both consuming crop products and providing fertilizing materials for these crops at the same time, with the associated complex materials flows.

Without any doubt, FAN simulations can be improved in the way the model calculates food production and waste recycling. In particular by gathering more accurate data on farms, including individual farm exact structure and location, animal feeding rations, and fertilization practices. Additional information from the private sector concerning actual material flows may help to verify model simulations. Our experience on this issue was deceiving, as very low interest was shown by farming extension services to collaborate on providing their material flows information. More transparency should be demanded by public institutions concerning the companies' activities, including their exchanges, their byproducts and waste production and their emissions.

FAN could be potentially used to simulate alternative scenarios of waste recycling for fertilization and bioenergy production. Concerning fertilization, many improvements in FAN can be done to better account for temporality and nutrient availability, including waste production dates and timing of mineralization. In addition, the diversity of organic fertilizers should be targeted, including different forms of wet and dry products, as well as different mixes with crop materials and compost. Concerning bioenergy production, the role of local food industries may be key to improve wastes recycling in some specific areas. Although food processing wastes are demanded for energy production by the anaerobic digesters, fats and non-animal food wastes such as milk wastes, fruits and vegetable wastes are also demanded by farms for animal feeding. Besides, by modifying the composition of the anaerobic digester inflows, alternative sources of biomass such as crop residues may be used to obtain bioenergy. Competition for these kinds of waste materials and their use for energy or animal by-products may be an interesting application of FAN simulations.

Concerning the social simulation aspects, FAN does not yet include individual adaptation to dynamic social and ecological processes that are quite complex to simulate (Berger and Troost, 2014). Individual adaptation could potentially be included in FAN, for example by allowing farmers to alter land use or livestock populations in response to material availability in the network or in response to global supply chains. A more complex type of individual adaptation would be the adoption by farms of the changes implemented in the scenarios simulation. In this sense, some farms can be penalized by their pollution, or in difficulty to find specific partners to exchange materials. For instance, the progression to livestock reduction and organic fertilization may pass through a stage of dependency of some farms on others to obtain fertilizers or feed products.

Conclusion

In this Ph.D., we analyzed the scientific literature estimating, simulating and assessing biomass and nutrient flows across several sectors. We highlighted the need of a new tool for simulating circular biomass and nutrient material flows in the Agro-Industrial Ecology. We presented the FAN agent-based model in GAMA platform 1.7, as a first attempt to simulate multiple, interacting material flows at the local scale. We gave an overview of the model framework, its processes, and a sensitivity analysis of some key parameters. We explored different scenarios applying FAN to a case study in France where a considerable amount of data was collected. Finally, we assessed scenarios performance through an integrated assessment of FAN output, including production, network interaction and environmental indicators. In conclusion, the FAN model is proven to be an innovative, prospective tool for the simulation of sustainable agro-food networks at the local scale, confirming the progress that Agro-Industrial Ecology can make to propose more circular flows and other solutions towards agro-food systems' sustainability.

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