# Analysing and supporting territorial dynamics of agri-food systems: insights into the benefits and challenges of circular frameworks

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**Abstract**

The environmental crisis is forcing societies to rethink how they operate and manage resources. In this context, circularity frameworks have emerged, underpinned by intentions to close the loops of material and energy cycles in order to improve the environmental and socio-economic performance of anthropic systems. In this article, we combine five contrasting case studies focusing on material flows within different components of the agri-food system: assessment of livestock farming; material flow representations for a territorial development strategy; evaluation of food waste flow and loss; analysis of potential pollution of urban green space lands; and governance of methanization projects. The results illustrate the value of quantitative analyses of material flows and studies of the governance of these flows to support local territorial development strategies. They also highlight the limits of these analyses and the blind spots, especially the difficulty of reproducing the complexity of interactions, the limits of the analogy between natural biological cycles and recycling loops, in particular with respect to environmental and sanitary considerations, and the limited effective contribution of these analyses to the emergence of territorial innovations, beyond raising local actors' awareness of the material dimension and environmental impacts of their activities. The toolset offered by circularity frameworks is relevant by their multi-criteria and multidisciplinary characteristics, but it still largely remains to be integrated. The articulation between quantitative analyzes of material and energy flows and the governance mechanisms largely remains to be invented in order to think about and implement sustainable transition in the territories.

**Keywords**
Agri-food systems, Circular economy, multi-criteria, sustainability, Materials flows analysis, Territorial development

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## 1. Introduction

The ecological crisis is forcing societies to rethink how they function and how they manage resources. The question of the best allocation and use of resources, which is at the heart of regional economics, was intensified by the emergence in the 1960s of models that were critical of the impacts of industrial development on the environment and on social well-being (Boulding, 1966; Georgescu-Roegen, 1971). They led to the emergence of different coexisting conceptual frameworks and analytical approaches that seek to take greater account of the limits of the biosphere. In the late 1980s, the Brundtland Report highlighted the concept of sustainable development. This opened the way to new public policies and numerous field experiments, which quite significantly preceded the incorporation of sustainability issues into regional economics models (Archibugi and Nijkamp, 1990).

Today, new frameworks inspired by ecology are emerging and becoming institutionalised. In addition to the efficient use of resources, these frameworks share a common foundation in their attention to the entire life cycle of products and to the locally closed loops of material and energy cycles in the quest to improve the environmental and socio-economic performances of anthropic systems. While industrial activities were originally the principal field of application of these frameworks, we are witnessing their gradual extension to other economic sectors and to all territories. In this article, we mainly employ the frameworks of circular economics (CE) to cover these new frameworks inspired by ecology (social or territorial metabolism, industrial and territorial ecology, etc.). The CE is defined as an economic system of trade and production which, at every stage in the life-cycle of products, seeks to make more efficient use of resources and to reduce environmental impacts while contributing to the well-being of individuals. To this end, CE promotes sustainable supply systems, responsible consumption, eco-design, longer product life, and waste management that focuses on recycling. CE approaches notably draw on the quantitative and qualitative analysis of flows of materials and energy, as well as the spatial and territorial embeddedness and the governance of those flows (Barles, 2010; Bonaudo et al., 2017).

A fundamental aspect of territorial functioning is how actors exploit and transform territory in order to produce the means of subsistence within it, in particular food. Agri-food systems are therefore, once again, at the heart of many strategies for ecological transition and sustainable territorial development. Agri-food systems encompass all the activities and functions involved in the production, storage, processing and the consumption of food. The management of by-products, wastes and losses are included in the system. Agri-food systems are composed of sub-systems like the farming system, waste management system, input supply system, etc. and interact with other key systems like the energy system and trade system (FAO, 2018). They are complex systems, operating at multiple levels of scale. Often criticised for the pollution and damage to biodiversity that they cause, agri-food systems also bring numerous territorial innovations in the production of bioproducts, the valorisation of biowaste (energy, fertiliser) and the limitation of environmental impacts. Today, these ideas are reshaping practices and institutional frameworks, as well as the conceptual frameworks through which we think about territorial development. In particular, they have led to a rethink about the notion of resources, wastes and their valorisation, with an emphasis on their limitations and the gridlock of linear systems. Finally, they emphasise the possibilities inherent in innovative partnerships designed to reinforce the reterritorialisation of activities and circular approaches. Circularity is becoming a goal in its own right, challenging the location of and interactions between activities and hence regional economics models.

New public policies and field experiments are thus emerging through the debate over the transition and relocation and resilience of systems (Bhamra et al., 2011). There is, for example, the model of cities and territories in transition, based on community discussions that aim to promote local energy reductions and thereby diminish dependency on fossil energy sources (Hopkins, 2010). The debate is underpinned by a growing number of interdisciplinary academic studies, including joint research involving territorial players, in order to understand the processes involved in the creation of knowledge that encourages diversity in territorial transitions. However, the question of the spatial and territorial dimension of CE strategies has so far received little scholarly attention, despite the desire to see them implemented in regulatory provisions and public intervention strategies (Niang et al., 2020). We introduce our argument by showing how regional economics is converging through the CE approach and we will then present the objective of this article.

*Convergence between circular economics and regional economics*

Circular economics and regional economics have developed separately without the question of the connections between them being explicitly raised. However, the territorial grounding of activities is an important aspect of CE. Conversely, the question of methods of resource management is central in regional science models. Therefore, we are now seeing a gradual and reciprocal integration of approaches.

The initial regional science models (North, 1955), founded on the quest for competitive advantages through reduced transport costs and the efficient allocation of production resources, were characterised by their lack of interest in environmental matters. In the 1970s, attempts to rediscover the benefits of specialist clusters in the relations between firms by reactivating an interest in the industrial district model (Marshall, 1919; Becattini, 1990), retained the linear principles governing production models. A complex and dynamic combination of relations of competition and cooperation, functional complementarities and flexibility within networks of businesses belonging to a single sector then became the dominant approach to an effective solution (Piore and Sabel, 1984). This "territorial turn" (Pecqueur, 2006) emphasised the largely endogenous nature of regional development processes.

These theoretical models provide a conceptual arsenal that considers the diversity of configurations in the territorialised organisational forms of production systems. In particular, they place an emphasis on relations of complementarity within cluster value chains (Porter, 1998), issues of quality and resource specification (Colletis and Pecqueur, 2005) and even the role of local environments (Aydalot, 1986) and relations of proximity (Rallet and Torre, 2005) in innovation processes. They would therefore provide a framework for understanding territorial approaches to CE. One way of considering the contribution of regional sciences to CE is to look at the dynamics of innovation and territorial development associated with the establishment of circular approaches (Bocken et al., 2014). Research on the governance of territorial innovation systems (Cooke et al., 2000) has shown that the drivers of territorial development combine dynamics both of production and governance. The interplay between the geographical proximity and the organisational proximity between businesses and other local actors, leads to specific governance processes that make possible the territorial innovations entailed in the sharing of know-how and knowledge and in collective learning (Torre and Wallet, 2016).

*A reflexive approach to the use of the CE framework to tackle the development of agri-food systems*

However, due to the complexity of agri-food systems, scientific research has often focused on the analysis of a sub-system (agricultural production or processing or waste management) by mobilising a specific method (material flow analysis, governance of the sector, ...). Despite these difficulties, it is essential to think of a programmatic approach to promote the emergence of holistic, multi-criteria and multidisciplinary analyses necessary for the sustainable transitions of agri-food systems and their territory. In order to contribute to this reflection, we have mobilised five case studies to develop a reflexive approach to the use of circularity framework to tackle agri-food systems at territorial scale. The different case studies employ different methods of analysis of flows and of the governance of those flows. The data acquisition and processing methods are detailed in the references given for each case study. Our approach is exploratory and we assume a certain heterogeneity of the case studies to cast a particular light on the production and use of bioresources, and on closed-loop cycles, and illustrate the diversity of fields in which circular economy can be applied. Our goal is therefore to show the strengths and practical and conceptual challenges of these frameworks from the perspective of sustainable territorial development. This will then lead into a discussion of three major dimensions to be considered in the perspective of circular agri-food systems: (i) advantages and limitations of territorial metabolism approach, (ii) unexpected effects of material circularization, (iii) the consideration of system complexity, diversity and resilience.

## 2. Presentation of case studies linked to agri-food systems

The circular economy (CE) is defined as an economic system of trade and production which, at every stage in the life-cycle of products, seeks to make more efficient use of resources and to reduce environmental impacts while contributing to the well-being of individuals. To this end, CE implies a net reduction of material flows through very low growth rate. It promotes sustainable supply systems, responsible consumption, eco-design, longer product life, and waste management that focuses on recycling. In this respect, the circular economy is not the equivalent of green growth (Arnsperger and Bourg, 2016). CE approaches notably draw on the quantitative and qualitative analysis of flows of materials and energy, as well as territorial embeddedness and the governance of those flows (Bonaudo et al., 2017). Agri-food systems encompass all the activities and functions involved in the production, storage, processing and the consumption of food (Figure 1). The management of by-products, wastes and losses are included in the system. Agri-food systems are composed of sub-systems like the farming system, waste management system, input supply system, etc. and interact with other key systems like the energy system and trade system (FAO, 2018). They are complex systems, operating at multiple levels of scale.

The proposed case studies analyse how new ways of managing resources are established at territorial scale. They relate to changes in agri-food systems, in the broad sense, from agri-supply to waste management. Each case study is focused on a specific subsystem of the agri-food system (Figure 1). These cases deal with (1) the interactions between livestock farming and territory, (2) evaluation of food loss and food waste, (3) potential land pollution in urban green spaces due to recycling loops, (4) the governance of methanisation projects, and (5) finally the application of material flow representations for territorial development in the Saclay Plateau territory.

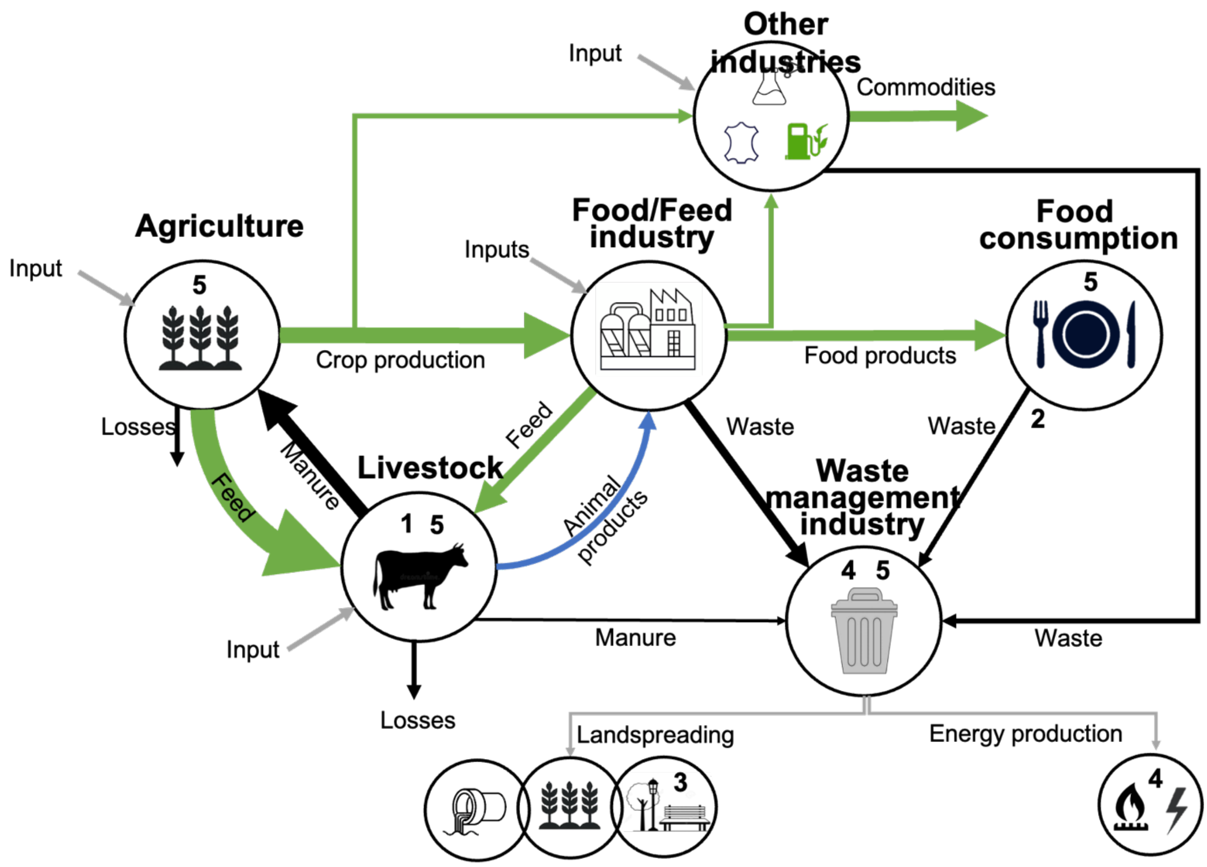


**Figure 1:** Specific positioning of our five case studies in an agri-food system
The number represents the sub-sectors analysed by the five case studies: 1/ Interactions between livestock farming and territories, 2/ Evaluation of food loss and waste, 3/ Analysis of soil flows in urban green spaces, 4/ Governance of methanisation projects, 5/ Material flow representations for territorial development. Studies 1, 2, 3 and 5 focus on the quantification and analysis of flows entering and leaving the sub-sectors concerned, while study 4 focuses on the analysis of the governance of flows in the methanisation sub-sector.

### *2.1. Interactions between livestock farming and territories*

Livestock farming is a major factor in the equilibrium or disruption of biogeochemical cycles and biodiversity (Bonaudo et al., 2014). It is also an indispensable socio-economic player, and the diversity of the bioresources consumed and produced gives it a central role in the emergence of a circular economy (Dourmad et al., 2019). The conceptual frameworks of circularity oblige us to rethink the linkage between livestock farming and land in terms of its consumption of resources, its dependency on inputs and its waste products. In this context, the analysis of the systems of material flows generated by livestock farming is a major issue for ecological transition. The studies focus on nitrogen flows in order to analyse together the biotechnical characteristics of livestock farming systems (species, density, consumption index…), their use of resources (land, feed, fertilisers…), their outputs (milk, meat, eggs), and also their waste products (manure).

### *2.2. Evaluation of food loss and waste*

The evaluation of food loss and waste has become a matter of concern to public authorities. In France, public initiatives have proliferated through several legislative provisions and action programmes designed to prevent such waste. However, there exist few quantitative data, let alone spatial data, about food loss and waste. The information relies largely on one-off measurements using various methods, which fail to reflect the diversity of situations. According to Ademe (2016), the amount of food wasted annually per inhabitant is 150 kg (from production to consumption). This represents some 19% of total food production. This research assessed food flows and the associated loss and waste for the Île-de-France region.

### *2.3. Analysis of soil flows in urban green spaces*

The lessons learned from the analysis of the development of green spaces on 49 sites in Paris since the 2000s show that the land is not cultivated in situ, but that gardening is developed on "buried off-soil" systems or off-soil trays created by introducing additional soil brought from the outskirts of Paris. The problem relates to the characterisation of these soil flows (past and present) into urban centres. For this, our research combines physio-chemical analyses of the quality of soil originating in former market garden areas and historical analyses of the systems of flows involved in the development of green spaces in Paris. This enables us to discuss the reality of these material loops.

### *2.4. Governance of methanisation projects*

Methanisation is an interesting territorial strategy for the application of circular economy principles (Bourdin et al., 2019). The project developed by the Syndicat Mixte du Point Fort (SMPF), using a sorting centre and a methanisation unit, is a typical example of the territorial dynamics of organic waste valorisation. Located in Cavigny, the methanisation unit processes household wastes from 125 villages organised into five Public Intermunicipal Cooperation Establishments (EPCI) that are members of the SMPF. In this process, the fine part of the organic waste is sent to the methaniser to produce heat, to be reused in situ, or in electricity for resale. The intermediate part of the organic waste and the digestate are converted into compost for farming.

### *2.5. Material flow representations for a territorial development project*

Since the 1990s, there has been a proliferation of public policy provisions for sustainable development and transition in the food, agricultural and energy sectors. These objectives are tackled at local scale by actors such as territorial authorities and civil society organisations that back endogenous development projects. Near Paris, the Saclay Plateau is an area characterised by the coexistence of big government ambitions around a science and technology cluster and local ambitions, embodied in local authorities and organisations. Since the early 2000s, a multi branch agri-urban civil society organisation has positioned itself as a federating and mediating structure between the various stakeholders of the territory. The goal of this organisation is to unite regional stakeholders around the challenge to enhance agricultural and natural areas. Among the flagship actions of the association is the organisation of territorial ecology workshops with local actors and researchers. The workshops made it possible to work on i) the characterisation of the territorial metabolism of the agri-food system and ii) the formulation of a possible contrasted future for the territory. Since then, these flow representations have been the basis of numerous discussions with local actors, questioning the scope of a metabolism analysis approach for territorial development.

## 3. Results

Based on these case studies, our results seek to illustrate the advantages and limitations of material flow analyses and the circularity framework for understanding and driving sustainable territorial dynamics.

### 3.1. *Characterising* the flows of materials in a territory for a multi-criteria analysis

The major advantage of metabolism studies is to quantify the material flows involved in activities and to represent them in relation to each other within a single formal framework. This is a didactic approach that characterises the nature, the scale, the trend and the organisation of the flows of different activities within a territory. These studies also make it possible to link material flow systems to production models (practices and techniques). These quantitative analyses are multi-criteria and holistic. Two of our examples illustrate this essential work of characterising material flows and objectifying the links between activities.

Recent work has shown the contribution of agriculture within the local food system in the Saclay Plateau area, by evaluating the different sectors in relation to consumption needs (Tedesco et al., 2017; Petit et al., 2018). These studies were used to characterise the agri-food system and the hydrological flow of nutrients (Verger et al., 2018). The quantification of material flows has shown that food production and consumption are mostly disconnected. The average share of local food consumption in total food production is 12.9% and the average share of local production in total local consumption is 7.8% (Tedesco et al., 2017). There are two different situations. For animal products, fruits and vegetables, local production and local consumption are strongly coupled (65% and 100% of local production is consumed locally), but local production is very low compared to consumption (respectively 4.4% and 4.8%). On the contrary, for cereal products, there is no coupling (0.2% of total production is consumed locally), while local production is very high and could potentially exceeds local needs. The agri-food metabolism patterns made visible the importance of the flows corresponding to imported fertilisers and to wastewater treatment and the marginal nature of flows corresponding to local short circuits. This objectification is essential for understanding the system and thinking about the potential of different actions to reconfigure the metabolism.

On the subject of food loss and waste, we quantified 792 kilotonnes of food waste present in household waste (Redlingshöfer, 2022). This quantity of waste consists of the inedible components of food (peelings, bones, etc.), but also of wasted food, though these could not be distinguished from each other. A rough analysis based on the work of Ademe (2019) allows to suggest a quantity of around 300 kilotonnes of wasted food, or less than 40% of household food waste, for the Île-de-France region. Household food waste is collected as mixed waste by the public service and essentially incinerated in the area. Other food waste is collected, also mixed, but comes exclusively from businesses (235 kt), and is generally put into landfill. In 2014, only 8% of solid food waste (including used cooking oil) was collected separately and recycled. This corresponds to 55 kilotonnes of food waste valorised through anaerobic digestion and composting in Île-de-France and additional 21 kilotonnes valorised outside of Île-de-France, and 28 kilotonnes of cooking oil recycled as fuel. The redistribution of unsold food from stores through food banks, a key element of the fight against waste, accounted for less than 2 kilotonnes. Although the anti-food waste campaign is intensifying, notably through food donations, such actions remain limited. All the quantities cited concern only solid food and used cooking oil, of large producers. Given the mismatch between the available data sources and the concept of food loss and waste, it is difficult to arrive at an accurate quantification of the flows. In fact, loss and waste flows are largely invisible. Nonetheless, the findings show that the great majority of food loss and waste is discharged as waste in a linear manner. While the priority should be reduction at source, most of these quantities are incinerated. Circular systems for returning organic matter from food waste to the soil are poorly developed. Because of the multiple outlets and actors responsible for them, it is difficult to measure food waste. Public statistics provide no information on the quantities of food loss and waste and the amount of wasted food that could be avoided. Moreover, the disparate and dispersed nature of this waste makes it very difficult to collect and recycle.

### *3.2. Identifying long-term transformations of production models*

The analysis of material flows also makes it possible to objectify the long-term transformation of production models at different scales. For example, Domingues et al. (2018, 2019) have shown that livestock farming in France has become increasingly intense over the period from 1938 to 2010. Production has doubled, rising from 0.139 Tg N/year to 0.279 Tg N/year. This increase is primarily attributable to monogastric animals (+200%) and dairy production (+180%). Greater intensity of production has been accompanied by a massive use of concentrates (cereals, cakes, co-products), which have risen from 29% to 58% of animal feed. Recent studies in animal feed have consolidated this conclusion (Cordier et al., 2020). Domingues et al. (2018) show an increase in feed imports, mainly soybean meal, and consequently a decline in self-sufficiency from 94% to 77%. Many other authors have calculated a similar order of magnitude in protein autonomy (Jouven et al., 2018; Cordier et al., 2020). This reflects the opening up of material cycles in livestock farming, which can be seen from municipal level to the national and regional scale (Bonaudo et al., 2017; Lassaletta et al., 2016; Gameiro et al., 2019). This average national trend hides very sharp regional disparities in the systems of flows associated with livestock production. Whereas in 1938, livestock were distributed across the whole of France, in 2010 they were concentrated in the West (50% of the national total) and in and around the Massif Central (30% of the national total) (Domingues et al., 2019). This dynamic has concentrated pollution. With regard to Small Agricultural Regions, Therond et al. (2017) estimated a disparity in livestock production of from 1.6 kg of protein/ha to more than 392 kg of protein/ha, with autonomies ranging from less than 25% to more than 100%. This method therefore makes it possible to objectify the trajectories of the agri-food system by quantifying productivity, efficiency, autonomy, losses to the environment.

### *3.3. Material flow analysis to identify soil contamination*

Finally, the study of material flows over time can be useful in identifying soil contamination. Lead concentration in soil is a recognised indicator of anthropic pressure on the environment. Urban land thus typically has lead concentrations that are significantly higher than found in farmland. The proximity of certain industrial sites or traffic arteries may have led to significant increases in lead concentrations. The same is true of certain agronomic practices such as the spreading of urban sewage waste or sludge. This urban sewage sludge, made up of sweepings from streets, buildings and markets, was extensively used by market gardens in Paris (Larbaletrier, 1898). An examination of lead concentrations in soil clearly shows that these depend on the period of development. Developments completed before 1950 are thus observed to have the highest concentrations of ground lead. For the period after 1990, these concentrations are lower. The intermediate period reveals more varied levels of contamination. This could be explained by the mixture of soils and contamination by older soils or external deposits. The results obtained in this exploratory study (Gitton et al., 2019) show that the sanitisation of the different areas of Paris in the 19th century entailed the evacuation of urban sewage and sludge containing pollutants, including heavy metals (Barles, 1999), in proportions that are difficult to quantify, to peripheral market gardening areas. Topsoil was then returned from these same areas to the Parisian districts from which the sludge originally came, thus generating circles of a certain viciousness. An historical analysis of the flows of waste and soil thus reveals potential and actual contamination with MTE (metallic trace elements). In other words, these contaminants are associated with the reintroduction of soil contaminated by urban waste that was previously discharged into the outskirts. However, contamination from atmospheric pollution (Foti, 2017) or indeed from urban compost produced using city waste cannot be ruled out. In an extension to this initial study, we are pursuing research on the question of composts produced by gardeners themselves (on allotments and in private gardens), a subject about which very little is known. Composts produced by gardeners themselves can include green waste originating from a very long way away: for example, the green waste of Versailles is used to make compost in an allotment in Montreuil, which raises questions about local supply chains. These composts may be contaminated or are sometimes overused, and can therefore lead to re-contamination of the soil. This undermines the supposedly always virtuous principle of "recycling the city on the city". This observation prompts us to a broader scrutiny of the principles of the circular economy, especially as issues of pollution receive little attention in studies on urban metabolism.

### *3.4. Linking material flow analyse and participative territorial development scenarios*

On the Saclay Plateau, an interest in approaches to territorial metabolism emerged in 2014, which culminated in the organisation of participatory workshops in Saclay in 2016. The workshops led to the formalisation by the researchers of three contrasting scenarios for the future of the area, scenarios which – at the end of the workshop – were presented to a panel of local actors and collectively debated (Petit et al., 2019). In this dynamic, territorial metabolism is mobilised in its analytical and operational dimension: analytical in the systemic representation of the local flow of material, and operational in the exploration of possible futures for the territory. Metabolic analysis clearly corresponds to this system of action. Among the scenarios, the most debated focuses on the re-embedding of flows of food and organic materials via rural and urban synergies. This scenario greatly increases the food supply of local agricultural systems (without aiming for complete autonomy), by closing nutrient cycles. This implies an increase in the exchange of flows between crop and animal production systems, new cultivated spaces including urban agriculture, the implementation of composting sites and the reuse of some human excreta for agricultural use.

The agri-food metabolism patterns have quantified the flows of different activities and made visible the importance of the flows corresponding to imported fertilisers and to wastewater treatment; the marginal nature of flows corresponding to local short circuits. This objectification is essential for understanding the system and thinking about the future. This work has thus evaluated the potential of different actions to reconfigure the metabolism. Certain actions appear to be limited, such as strengthening the food self-sufficiency of the territory, intensifying exchanges between cultivation and breeding livestock, while others appear more promising, such as composting or the development of urine-based fertilizers. Metabolism graphs are rarely directly used by communities. The local players recognised the education value of graphics, on condition that they are supported to take ownership of the complexity of the flow systems. Representations of metabolism make it possible to embody the action of a sector of activity, or even individual action in the general system. We are close to a form of eco-marketing whose aim is to involve the user by explaining the links between wastewater management, agro-supply and environmental impacts. These graphics have played an intermediary role between researchers and practitioners to co-design new territorial resource management organisations.

The Saclay workshops helped bring out an objective of systemic transformation of the territory. Today, it is a question of going beyond the simple development of short local circuits, to move towards the valorisation of the territory's bioresources in a circular vision with the establishment of an action research project coordinated by the multi branch agri-urban civil society organisation.

### *3.5. A quantitative approach to reveal the network of actors involved in a CE project*

The implementation of methanisation strategies at the territorial scale requires that technological innovation be embedded in a dynamic of connection between multiple stakeholders with different interests. In the Cavigny case studied, the local authorities supply the waste, while various farmers and companies are involved in the valorisation of coproducts and the waste management. Central government departments are responsible for regulatory oversight of ICPE (classified environmental protection facilities). Finally, local people are involved with the framework consultation over the methanisation process. The coordination around issues associated with the use of inputs, the valorisation of coproducts, the management of risks, and social acceptability, require a form of innovation in organisation and governance to foster the smooth operation of facilities and generate positive outcomes for the territory. In order to understand the governance of this process, we are studying the relations between stakeholders, and the changes in those relations, over the periods of implementation of the project. Using an approach based on social networks of interactions between actors (Ferreiro and Sousa, 2018), we can study the relations of synergy and cooperation between stakeholders. Only recently applied to organisational approaches to territorial governance (Torre et al., 2019; Ferreiro and Sousa, 2018), this method enables us to identify and quantify the types of relations that exist between stakeholders, in order to characterise their influence and observe the evolution over time of the social networks they form.

Measurement of the densities of the links between them (number of links maintained relative to the number of possible links) shows that the interacting actors develop dense relational networks. This high density reveals the importance of social capital in the interactions, which is needed to create a framework of trust and consultation that is conducive to group cohesion and a source of success for territorial renewable energy projects (Walker et al., 2010). Measurement of the centrality of the interacting stakeholders reveals that the coordination of the methanisation processes is structured around the project initiator (SMPF), which plays the role of organiser of the networks. The project initiator undertakes the mediation functions, plays the role of middleman in facilitating the sharing of flows of knowledge and collective learning, with the local arms of central government departments, the coproduct professionals and authorities are not members of the materials and energy exchange network. Nonetheless, this network and the viability of the methanisation facilities remain deficient in the use and supply of inputs, because of the measures used to prevent and reduce waste at source.

While this quantitative approach to social networks enables us to identify, characterise and understand how the stakeholders in the methanisation project coordinate and govern this territorialised process, it is nevertheless difficult to apply it to spatial and territorial development issues. A theoretical framework that combines social network and proximity approaches, (Torre et al., 2019) would help to bring a better understanding.

## 4. Discussion

### *4.1. Advantages and practical limitations of studies of territorial metabolisms and their governance*

The metabolic approach has numerous advantages, the first being a systemic vision of agri-food systems, in which the flow of materials is identified for the different sectors of activity, from agricultural production through to processing and distribution, consumption and waste management. This approach reveals the flows – and the losses and waste – entailed in different activities, their causes and their scales. Metabolic analysis is therefore a way to formalise the link between technical systems, activities and systems of flows, with the positive and negative effects of circularity. The analysis makes it possible to situate activities and flows of materials in connection with a given territory but also the linear or circular dimensions of the metabolism. This encourages the analysis of processes internal or external to the territory, together with changes of scale. This approach also makes it possible to decipher the network of actors and the governance of these flows. Finally, this approach allows us to identify priorities for action or different scenarios. It can cast light on the tension between two objectives of territorial development to reconcile frugality and circularity (Ewijk and Stegemann, 2016).

Nonetheless, the results emphasise the difficulty of quantifying and situating flows, in particular food flows, given the mismatch between the concepts and the available data sources. Developing a circular economy, i.e. managing flows of materials, demands a better characterisation of the diversity of bioresources, of their variation in time and space, but also attention to changes in scale and to levels of efficiency. These major advances require the application of tools and methods from geography, from economics, from sociology (GIS, territorial LCA, dynamic spatial modelling, network analysis, …).

### *4.2. Unexpected effects of circularity at the territorial level*

Just as the implementation of circularity principles at the micro level of a company or a sector can have negative effects at the macro-economic level (notably through "rebound" effects), the effect of the implementation of circularity at the territorial level can only have a weak impact at the global level, by not sufficiently questioning the system as a whole. Circularity in itself is not a guarantee of the sustainability and its implementation at local scales can have unforeseen perverse effects. If we want to drive an ecological transition, we must be able to reason about the consequences of changes from one scale to another, the direct and indirect effects, local, distant and global effects. This imposes to considering of the changes of scales and territorial impacts (Loiseau et al., 2018).

The valorisation of waste as a resource is a way to extract profit from it and to incorporate an initially undesirable flow into an economic process to create value. Encouraged by CE, this strategy can be a source of tension (Redlingshöfer et al., 2020). Numerous authors have noted how the narrative of "waste as a resource" suggests that there will be no more limits on the consumption of resources and on the production of waste (since this is recycled) (Bradshaw, 2018). This evades the main question of waste reduction at source, and hence the intensity of consumption. Yet the best strategy for handling waste is not to produce it in the first place, which can run counter to an economic choice if waste has a value, notably as a result of subsidies or public policies. Furthermore, food waste recycling practices have the potential to generate contamination (packaging residues, physical or chemical of recycling sewage sludge). This raises the question of risk assessment for the different recycling industries. There are only a few voices speaking up about the problem of contamination (Baxter et al., 2017) and about the need to remove dangerous waste from the loop.

### 4.3. *Complex system, diversity and resilience*

Closing loops presents numerous sociotechnical, organisational and economic obstacles, which are reflected in production and/or supply risks. Many bioresources are highly disparate, dispersed and non-standardised. The density of activities and flows poses problems in terms of the attainment of critical volume and viable distances of exchange. In these circumstances, the match between supply and demand is hard to achieve through the market or through contracts between actors (Dourmad et al., 2019). The procedures and forms of management must be adapted to different territorial contexts (small flows with a dispersed network versus mass flows with a centralised network). Other obstacles can be cited such as the limited resources of the actors (labour, time…), the lack of technical references and know-how, logistical and investment costs, regulatory constraints, social acceptability. All forms of coordination should be underpinned by the assessment of local potential for the production and recycling of bioresources and local demands. The territorial stakeholders will need to introduce adaptive management to deal with the variations and disparities in the flows. Trust between actor, long term engagement and the presence of a coordinating actor, which takes decisions but also assumes a large proportion of the risks, is an important factor for success (Ruth and Davidsdottir, 2009; Chopra and Khanna, 2014).

The analysis of resilience of the agri-food system is essential (Walker et al., 2004; Derissen et al., 2011). For instance, Fraccascia et al. (2017) suggest incorporating in the analysis two main vectors of resilience in industrial symbioses: diversity of enterprises and networks, and ubiquity of waste. This entails looking at the ubiquity of flows and the specialisation of functions (companies) in metabolisms. Thought must also be given to the (functional) redundancy of these flows and of the functions. Indeed, flows of materials must come from several sources (security of supply) and must potentially have several uses (security of outputs). In the same way, a stakeholder/company can perform several functions in the system of flows and functions must be fulfilled by several stakeholders/companies. This is about conceiving the system of flows and actors as an ecosystem with a base level of functional diversity and redundancy. Closing loops is often synonymous with diversifying production, creating new activities and managing waste. This means managing more and smaller flow exchanges. It is therefore a question of managing more complex systems, which implies higher learning, investment and even management costs.

## 5. Conclusion

The transformation of agri-food systems plays an essential role in the ecological transition. These systems drive a number of territorial innovations, both for the production of bioproducts and for waste management, including the limitation of environmental losses and impacts. Circular frameworks, such as social or territorial metabolism, industrial and territorial ecology, have led to a rethink about the notion of resources, wastes and their valorisation, with an emphasis on their limitations and the gridlock of linear systems. They emphasise the possibilities inherent in innovative partnerships designed to reinforce the reterritorialisation of activities and circular approaches. Based on contrasting case studies, we seek to identify the benefits and challenges of the circular economy for analysing and steering interaction between agri-food systems and territorial development. The advantages of material flow analyses are to objectify the importance of certain flows, to make them visible when information is non-existent and to highlight long-term transformations in agri-food systems. Our article also identifies numerous sociotechnical, organisational and economic challenges that need to be tackled in order to close the loops in the circular economy. The challenges concern in particular the definition of an appropriate territory of action, the design and management of these complex systems of flows, the resilience of these systems with the management of risks, and finally the main question of reducing the intensity of material flow.

**References**


Ademe, 2019. MODECOM TM 2017 Campagne nationale de caractérisation des déchets ménagers et assimilés.

Arnsperger, C., & Bourg, D., 2016. Vers une économie authentiquement circulaire. Revue de l'OFCE, 145(1), 91-125. https://doi.org/10.3917/reof.145.0091

Archibugi F., Nijkamp P. (Eds.), 1990. Economy and Ecology: Towards Sustainable Development, Kluwer, Dordrecht.

Aydalot Ph. (éd.), 1986. Milieux innovateurs en Europe, Paris, GREMI.

Barles S., 1999. La ville délétère. Medecins et ingénieurs dans l'espace urbain. XVIII-XIXèmes siècles,Seyssel, Collection Milieux. Champ Vallon, 370 p.

Barles S., 2009. "Urban Metabolism of Paris and its Region", Journal of Industrial Ecology, 13(6), 898-913.

Barles S., 2010. Écologies urbaine, industrielle et territoriale. In : Coutard O., Lévy J.P. (Eds). Écologies urbaines, Paris, Economica/Anthropos (collection Villes), 61-83.

Baxter W., Aurisicchio M., Childs P., 2017. Contaminated interaction: another barrier to circular material flows. Journal of Industrial Ecology, 21(3), 507-516.

Becattini G., 1990. "The Marshallian Industrial District as a Socio-Economic Concept", in: Industrial Districts and Inter-firm Cooperation in Italy, Pyke, F., Becattini, G. and Sengenberger, W. (eds), Geneva, IILS.

Bhamra R., Daniab S., Burnarda K., 2011. Resilience: the concept, a literature review and future directions International Journal of Production Research, 49(18), 5375–5393.

Billen G., Barles S., Chatzimpiros P., Garnier, J., 2012. Grain, meat and vegetables to feed paris: Where did and do they come from? Localising Paris food supply areas from the eighteenth to the twenty-first century. Regional Environmental Change, 12(2), 325–335. https://doi.org/10.1007/s10113-011-0244-7.

Bocken N.M.P., Short S.W., Rana P., Evans S., 2014. A literature and practice review to develop sustainable business model archetypes, Journal of Cleaner Production, 65, 42-56.

Bonaudo T., Bendahan A.B., Sabatier R., Ryschawy J., Magda D., Léger F., Bellon S., Tichit M., 2014. Agroecological principles for the redesign of integrated crop–livestock systems. European Journal of Agronomy, 57, 43-51.

Bonaudo T., Renard D., Berthelot V., 2018. Construction biotechnique et sociale de la qualité L'exemple du Comté, un élevage pour et par le territoire. In Alimentation des animaux et qualité de leurs produits (Berthelot V. coord.). Editions Tec et Doc - Lavoisier, Paris, 375-384.

Bonaudo T., Billen G., Garnier J., Barataud F., Bognon S., Dupré D., Marty P., 2017. Analyser une

transition agro-alimentaire par les flux d'azote : Aussois un cas d'étude du découplage progressif de la production et de la consommation. Revue d'économie régionale et urbaine, 5, 967-990.
Boulding K.E., 1966. The Economics of the Coming Spaceship Earth. In Environmental Quality Issues in a Growing Economy, edited by Henry Jarrett, 3–14. Baltimore, MD: Johns Hopkins Press.
Bourdin S., Colas M., Raulin F., 2019. Understanding the problems of biogas production deployment in different regions: territorial governance matters too." Journal of Environmental Planning and Management, 1-19.
Bradshaw C., 2018. Waste Law and the Value of Food. Journal of Environmental Law, July, 311–331. https://doi.org/10.1093/jel/eqy009.
Chopra S., Khanna V., 2014. Understanding resilience in industrial symbiosis networks: Insights from network analysis. J. Environ. Manag., 141, 86–94.
Colletis G., Pecqueur B., 2005. «Révélation de ressources spécifiques et coordination située», Économie et institutions, n° 6 et 7, 51-74.
Cooke P., Boekholt P., Tödtling F., 2000. The governance of innovation in Europe, London/New York: Pinter.
Cordier C., Sailley M., Courtonne J.Y., Duflot B., Cadudal F., Perrot C., Brion A., Lecadre P., Peyronnet C., Baumont R., 2020. Analyse des flux de matières premières en alimentation animale en France. Document édité par le GIS Avenir Elevages, 6p. https://www.gis-avenir-elevages.org/content/download/3692/36051/version/1/file/synthese_Avenir_Elevages_2020.pdf.
Derissen S., Quaas M.F., Baumgärtner S., 2011. The relationship between resilience and sustainability of ecological economic systems. Ecol Econ 70(6), 1121–1128.
Dermine-Brullot S., Junqua G., Zuindeau B., 2017. Écologie industrielle et territoriale à l'heure de la transition écologique et sociale de l'économie, Revue d'économie régionale et urbaine, n° 5, 771-795.
Domingues J.P., Ryschawy J., Bonaudo T., Gabrielle B., Tichit M., 2018. Unravelling the physical, tech- nological and economic factors driving the intensification trajectories of livestock systems. Animal, 12, 1652-1661.
Domingues J.P, Gameiro A.H., Bonaudo T., Tichit M., Gabrielle B., 2019. Exploring trade-offs among indicators of performance and environmental impact in livestock areas. Regional Environmental Change. 19 (7), 2089-2099. Doi: 10.1007/s10113-019-01538-z.
Dourmad J.Y., Guilbaud T., Tichit M., Bonaudo T., 2019. Les productions animales dans la bioéconomie. In : Numéro spécial. De grands défis et des solutions pour l'élevage. Baumont R. (Éd). INRA Prod. Anim., 32, 205-220. https://doi.org/10.20870/productions-animales.2019.32.2.2485.
Ewijk S. Van, Stegemann J.A., 2016. Limitations of the waste hierarchy for achieving absolute reductions in material throughput. Journal of Cleaner Production, 132, 122–128. https://doi.org/10.1016/j.jclepro.2014.11.051.
FAO, 2018. Sustainable food systems : Concept and framework. CA2079EN/1/10.18. Rome. http://www.fao.org/3/ca2079en/CA2079EN.pdf.

Ferreiro M., Sousa C., 2018. Governance, institutions and innovation in rural territories: The case of Coruche innovation network. Regional Science Policy and Practice, 11, 235-250.

Foti L., Dubs F., Gignouxa J., Lata J-C, Lercha T-Z., Mathieu J., Nold F., Nunana N., Raynauda X., Abbadie L., Barot S., 2017. Trace element concentrations along a gradient of urban pressure in forest and lawn soils of the Paris region (France) Science of the Total Environment, Volume 598, 15 novembre 2017, 938-948.

Fraccascia L., Giannoccaro I., Albin V., 2017. Rethinking Resilience in Industrial Symbiosis: Conceptualization and Measurements, Ecological Economics 137 (2017) 148–162.

Gameiro A.H., Bonaudo T., Tichit M., 2019. Nitrogen, phosphorus and potassium accounts in the Brazilian livestock agro-industrial system. Reg. Environ. Change 19(3), 893–905. https://doi.org/10.1007/s10113-018-1451-2.

Georgescu-Roegen N., 1971. The Entropy Law and the Economic Process. Cambridge, MA: Harvard University Press.

Gitton G., Verger Y., Brondeau F., Charvet R., Nold F., Branchu P., Douay F., Lamy I., Mougin C., Petit C., Rémy E., 2019. « L'économie circulaire : cercle vertueux ou cercle vicieux ? Le cas de l'utilisation de terres maraîchères pour aménager des espaces verts urbains », Géocarrefour [En ligne], 92/2.

Hopkins R., 2010. Manuel de transition : de la dépendance au pétrole à la résilience locale, Montréal: Écosociété.

Jouven M., Puillet L., Perrot C., Poméon T., Domingues J.P., Bonaudo T., Tichit M., 2018. Quels équilibres végé tal/animal en France métropolitaine, aux échelles nationale et petite région agricole ? INRA Prod. Anim., 31, 353-364. https://doi.org/10.20870/ productions-animales.2018.31.4.2374

Larbaletrier, 1898. Manuel d'essais pratiques de chimie horticole.

Lassaletta L., Billen G., Garnier J., Bouwman L., Velazquez E., Mueller N.D., Gerber J.S., 2016. Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand. Environmental Research letters 11 (9), 1-14. doi:10.1088/1748-9326/11/9/095007.

Lasseur J., Bonaudo T., Choisis J.P., Houdart M., Napoléone M., Tichit M., Dedieu B., 2019. Élevage et territoires : quelles interactions et quelles questions ? In : Numéro spécial. De grands défis et des solutions pour l'élevage. Baumont R. (Éd). INRA Prod. Anim., 32, 189-204. https://doi.org/10.20870/productions-animales.2019.32.2.2504.

Loiseau E., Aissani L., Le Féon S., Laurent F., Cerceau J., Sala S., Roux P., 2018. Territorial Life Cycle Assessment (LCA): what exactly is it about? A proposal towards using a common terminology and a research agenda. Journal of Cleaner Production, Elsevier, 176, 474-485.

Marshall A., 1919, Industry and Trade, London, Macmillan.

Meerow S., Newell J.P., 2015. Resilience and complexity: A bibliometric review and prospects for industrial ecology. Journal of Industrial Ecology, 19(2), 236–251.

Niang A., Bourdin S., Torre A., 2020. L'économie circulaire : quels enjeux de développement pour les territoires ?, Développement Durable et Territoires, 11(1).
North D., 1955. Location Theory and Regional Economic Growth, Journal of Political Economy, 63, issue.
Petit C., Gimat C., Vettoretti A., 2019. Les Ateliers de Saclay, Réflexion en écologie territoriale sur le cas du plateau de Saclay: Synthèse.
Petit C., Levavasseur F., Verger Y., 2018. Reconnecter villes et campagnes: vers des symbioses agricoles et agri-urbaines? Une exploration sur le Plateau de Saclay. VertigO-la revue électronique en sciences de l'environnement, (Hors-série 31).
Piore M.J., Sabel C.F., 1984. The Second Industrial Divide. New York: Basic books, 354 p.
Porter M.E., 1998. Clusters and the new economics of competition. Vol. 76. No. 6. Boston: Harvard Business Review.
Redlingshöfer, B., 2022. Food waste in cities: an urban metabolism approach applied to Paris and Île-de-France. Humboldt-Universität zu Berlin. https://doi.org/10.18452/24362
Redlingshöfer B., Barles S., Weisz H., 2020. Are waste hierarchies effective in reducing environmental impacts from food waste? A systematic review for OECD countries. Resources, Conservation and Recycling, 156 (November 2018), 104723. https://doi.org/10.1016/j.resconrec.2020.104723.
Ruth M., Davidsdottir B. (Eds.), 2009. The dynamics of regions and networks in industrial ecosystems. Cheltenham, UK: Edward Elgar.
Ryschawy J., Disenhaus C., Bertrand S., Allaire G., Aznar O., Plantureux S., Josien E., Guinot C., Lasseur J., Perrot C., Tchakerian E., Aubert C., Tichit M., 2017. Assessing multiple goods and services derived from livestock farming on a nation-wide gradient. Animal, 11, 1861-1872.
Tedesco C., Petit C., Billen G., Garnier J., Personne E., 2017. Potential for recoupling production and consumption in peri-urban territories: The case-study of the Saclay plateau near Paris, France. Food Policy, 69, 35-45.
Therond O. (coord.), Tichit M. (coord.), Tibi A. (coord.), 2017. Biens produits par l'écosystème. In EFESE, services écosystémiques rendus par les écosystèmes agricoles, 693-894.
Torre A., Rallet A., 2005. Proximity and localization, Regional Studies, 39, 47- 59.
Torre A., Dermine-Brullot S., 2019. L'économie territoriale circulaire : Un pas vers la soutenabilité des territoires ? Systèmes Alimentaires / Food Systems, 27-47.
Torre A., Wallet F., 2016. Regional Development in Rural Areas. Analytical tools and Public policies, Springer Briefs in Regional Science, Springer.
Torre A., Polge E., Wallet F., 2019. Proximities and the role of relational networks in innovation: The case of the dairy industry in two villages of the "green municipality" of Paragominas in the Eastern Amazon. Regional Science Policy & Practice. 11, 279-294.
Verger Y., Petit C., Barles S., Billen G., Garnier J., Esculier F., Maugis P., 2018. AN, P, C, and water flows metabolism study in a peri-urban territory in France: The case-study of the Saclay plateau.

Resources, Conservation and Recycling, 137, 200-213.
Walker B., Holling C.S., Carpenter S.R., Kinzig A., 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society 9(2): 5.
Walker G., Hunter S., High H., Evans B., 2010. Trust and community: Exploring the meanings, contexts and dynamics of community renewable energy. Energy Policy, 38(6), 2655-2663.