Transformation of socioeconomic metabolism due to development of the bioeconomy: the case of northern Aube (France)

Pauline Marty, Sabrina Dermine-Brullot, Sophie Madelrieux, Julie Fleuet, Philippe Lescoat

Transformation of socioeconomic metabolism due to development of the bioeconomy: the case of northern Aube (France)

Pauline Marty*, CREIDD, InSyTe, Université de Technologie Troyes, France

Sabrina Dermine-Brullot, CREIDD, InSyTe, Université de Technologie Troyes, France

Sophie Madelrieux, Univ. Grenoble Alpes, INRAE, LESSEM, France

Julie Fleuet, CREIDD, InSyTe, Université de Technologie Troyes, France

Philippe Lescoat, AgroParisTech INRAE UMR SADAPT, Université Paris Saclay, France

*Corresponding author: Pauline Marty (pauline.marty@utt.fr)

Abstract

This article presents results of an ongoing research project on production and allocation of biomass of agricultural origin (BAO), a key resource in ecological and energy transitions. The production and allocation of BAO are changing under the current development of the bioeconomy, which is the narrative promoted for intensifying the use of BAO, that we question through the lens of the scientific paradigm of bioeconomics. We developed a metabolic approach to agriculture, that we applied to the case study of northern Aube (France), an area specialized in intensive crop farming, undergoing rapid development of agricultural biogas production. Our results indicate that the ongoing changes influence BAO production and allocation at several scales (farm, small collective of farms, value chain, territorial). Development of the bioeconomy strongly influences the socioeconomic metabolism of the territory's agriculture. Diversion of BAO flows due to biogas production are increasing structural imbalances and have some negative impacts on flows and ecological or economic funds strategic for sustainability, agronomic and economic balances of agricultural activities at multiple scales and as a whole. The changes described are especially disruptive since they strengthen competition and have blocking effects for the existing and potential agricultural metabolism.

Keywords: agricultural metabolism, socioeconomic metabolism, agricultural biogas, bioeconomy

Word count (incl. abstract and references): 8 679

1-Introduction: current development of the bioeconomy and criticisms of it

Biomass of agricultural origin (BAO) faces the triple challenge of providing food and energy while minimizing environmental impacts. Global demand for food and feed is estimated to increase by 70% from 2010 to 2050 (Garot, 2015), and concern is growing about impacts of food and feed quality, mostly on human and animal health. BAO is also expected to reduce dependence on fossil fuels. For the energy transition in France, for example, renewable energy sources are expected to provide 32% of total energy consumption by 2030, with half of it coming from biomass, but renewable sources provided only 10.7% in 2017 (CGED, 2019). In addition, agriculture must reduce its greenhouse gas emissions drastically (19% of French emissions in 2018; Haut Conseil pour le Climat, 2020), even though farming practices rely heavily on fossil fuels (Harchaoui, Chatzimpiros, 2018) and the energy density of BAO is debated (Smil, 2015). Finally, agricultural production has environmental impacts on biodiversity, water and soil quality, especially when it becomes specialized at the territorial scale (Carmona and al., 2020). Simultaneously, agriculture is expected to increase soil carbon capture (Pellerin *et al.*, 2019) and strengthen overall sustainability (by diversifying and connecting of several types of agricultural production at the territorial scale (Montoya *et al*., 2019; Gaba, Bretagnolle, 2020)). Moreover, the growing utility of biochemistry and biomaterials to BAO (Nieddu, Vivien, 2015) could increase the overall demand for BAO and thus change how it is allocated among uses.

This new focus on BAO as a resource that needs to be used more efficiently is a key feature of the institutional definition of the bioeconomy (Pahun *et al*., 2018). In this vision, public policies at the European level (European Commission, 2012) and national level in France (Ministère de l'Environnement et de l'Energie, 2018) perceive BAO as essential for the energy transition. The growing demand of several economic sectors for biomass raises challenges for this resource, and creates a plethora of public-policy programs, which leads to a complex landscape for collective decisions about allocation of BAO (CGAER, 2019). In France, BAO use is strategically organized at local scales through regional public projects that encourage public and private actors, especially energy production facilities, to increase the use of biomass (SNMB, 2018). Furthermore, biomass is perceived as a key element in circular economy strategies, which is another strong narrative in public incentives. At the European level, the bioeconomy, understood as the (circular) economic sector that relies on production and use of biomass, is claimed to be a new path for sustainability (EEA, 2018). In France, well-reasoned articulation of BAO uses is described as being essential for a relevant circular economy (SNMB, 2018).

The dominant narrative that supports development of the bioeconomy and the belief that the latter will contribute positively to the energy transition faces several criticisms (Giampietro *et al*., 2009). The rythms of renewal of resources cannot be accelerated and are inconsistent with intensification of production processes. Circularity implies dissipation of energy and concentration unwanted molecules due to multiple iterations of recycling. In addition, the bioeconomy cannot escape the Jevons paradox (i.e. rebound effect) (Alcott, 2005).

From an operational standpoint, developing the bioeconomy in territories implies tensions among individual strategies, common interest and benefits. Territorial-level transitions in production and allocation of BAO can be considered a result of (1) public incentives to develop the bioeconomy and (2) the search for new economic opportunities for farmers to strengthen their activity. However, these transitions imply changes in production and allocation of BAO that could jeopardize territorial agriculture as a whole. Uncertainties and potential weaknesses appear at individual and collective/territorial scales that aggravate both short- and long-term issues. They need to be examined because they are currently not well known or perceived collectively by agricultural actors, and the objectives of the bioeconomy seldom consider them.

Public policies and private strategies demand a significant increase in BAO production (and thus an increase in environmental impacts) and its use in a wide variety of economic sectors. However, there is no integrated vision at the regional/local scale for collective planning of BAO production and use. This leads to conflicting incentives and prevents thorough investigation of the true circularity of BAO flows and their dynamics at the territorial scale, which needs to consider interrelations between value chains and their local features.

On these grounds, our study aims to test the utility and operationalization of a metabolic approach at the territorial scale to examine and understand past transformation of the socioeconomic metabolism of the agri-food system of a territory, and current transformation related to development of the bioeconomy. We draw on contrasting characteristics of the bioeconomy framework and apply the approach to a French territory: northern Aube.

2- Theoretical and operational framework

2.1-A bioeconomic approach to the bioeconomy: socioeconomic metabolism and the fund-flow model

This article analyzes the agricultural socioeconomic metabolism of a territory through the scientific paradigm of bioeconomics. Bioeconomy was only recently used as an institutional watchword at the

European level (Pahun *et al*., 2018). Originally, bioeconomics was a scientific paradigm used to study physical and biological foundations of human societies (Gerogescu-Roegen, 1971). Georgescu-Roegen changed the understanding of economic processes by highlighting the unsustainability of economic models based on linear production processes. The latter were defined as incompatible with natural-resource renewal, the environment's carrying capacity for pollution and social issues. It replaces the traditional cumulative accountability of stocks and flows with a "fund-flow" model. In this model, "funds" are long-lasting agents that produce, transform and/or consume "flows" (of matter, energy or information) within the metabolic system through production processes, without being destroyed themselves by these processes (Couix, 2020). The goal is to ensure sustainable use of the funds, especially the ecological ones, that support the many processes necessary to sustain human societies, while considering their functioning and regeneration rhythms, and even to limit the range of the economy to that allowed by the flows (Missemer, 2015). Georgescu-Roegen pleads for re-embedding economic development within planetary limits and, without naming it specifically, for a metabolic approach to economy. Georgescu-Roegen's scientific heritage extend in ecological economics, especially in regards to socioeconomic metabolism. According to Pauliuk *et al*. (2015), "socioeconomic metabolism constitutes the self-reproduction and evolution of the biophysical structures of human society. It comprises those biophysical transformation processes, distribution processes, and flows which are controlled by humans for their purposes". Based on and compatible with bioeconomics, the metabolic approach appears relevant for analyzing the transformation that results from past, current and potential future transitions in the agricultural system. This approach thus goes beyond a single-sector and single-scale scientific approach. The fund-flow model developed in bioeconomics can be applied in metabolic approaches, as they are used to connect the economy and ecology of human activities (Madelrieux et al., 2017) at multiple spatial scales and organization levels (Gabriel et al., 2020). Different methods are applied, but all rely greatly on accounting for matter and energy flows that support the socioeconomic system's existence and thus its material interactions with the biophysical sphere. In this sense, they are compatible with and applicable within the bioeconomics fund-flow model.

2.2-Operationalization of the metabolic approach

Based on the literature on agri-food systems, Gabriel et al. (2020) analysed how researchers describe and represent socioeconomic metabolisms. They distinguished eight schools of thought related to three types of representation: (1) space and compartment-based, (2) economic agent-based and (3) multi-faceted and composite. In the first type, metabolism is usually analyzed using statistical databases, at the scales at which they are commonly available (national, regional or, in France, departmental (Courtonne et al., 2016) or for large metropolitan areas (Barles, 2009; Kennedy et al., 2015; Athanassiadis et al., 2016; Bahers et al., 2020). However, BAO is produced, allocated and has impacts at smaller scales, which are more difficult to document and characterize. Moreover, this type of representation considers actors as a "black box" and often excludes the drivers that explain their decision-making. Nonetheless, most decisions about BAO metabolism are made at smaller scales, at which immaterial aspects of the metabolism (i.e. values that drive decisions and actions, cultural and social embeddedness, and governance) partially shape actors' decisions and ability to act. Therefore, we used economic agent-based representation (the second type) to apply this approach to territories smaller than a French department, even though statistical databases at that scale are of uneven quality or do not exist. Moreover, focusing on this scale allowed us to fill a knowledge gap. Indeed, the literature on bioeconomy over the past several years has usually focused on national or international scales, and ignoring the local complexities implied at the local scale except in a few research at the regional scale (Low, Isserman, 2009 ; Horlings, Mardsen, 2012 ; Bugge *et al*, 2016).

The economic-agent based representation allows immaterial aspects to be considered to highlight the power structures in which actors are embedded (Nuhoff-Isakhanyan et al., 2017) and the proximities they rely upon (Dansero et Puttilli, 2014). In this research, we include only the immaterial issues that could illustrate an actor's decisions (e.g. about management of their farm or processing unit, or their production, allocation and exchanges of BAO).

This approach also represents the socioeconomic metabolism of agriculture in an intelligible manner based on the fund-flow model. We distinguish the ecological funds that produce (*e.g.* agricultural land), transform (*e.g.* cattle) or consume (*e.g.* plant growth) BAO from the economic funds that do the same (i.e. farms, agricultural supply chains, processing and storage units). Flows between these funds are material (e.g. BAO, energy, water) or immaterial (e.g. information, money, technical advice).

3-Materials and methods

3.1-Study area

This article highlights results of an ongoing interdisciplinary research project on BAO at the territorial scale (BOAT, "Biomasse d'Origine Agricole dans les Territoires"). The team (land planners, animal scientists, economists, agronomists) from four institutions formed in 2017 to develop a method to describe and analyze BAO metabolism in two contrasting agricultural territories in France – the north of the Aube department (intensive and specialized cereal agriculture) and the Drôme Valley (diversified agricultural production and smaller farms) – with a focus on reducing environmental impacts. We focus here on northern Aube, a part of the French Grand Est Region, which identified bioeconomy as a key sector of its "regional DNA" and aimed at developing renewable energy (with biogas as the front one) simultaneously with a very ambitious agricultural carbon capture program to mitigate the climate change. Therefore studying the socioeconomic metabolism of Northern Aube is a way to test the relevance of these challenges. Northern Aube contains 1 434 farms that are specialized mainly in cash crops or high-value industrial crops (i.e. wheat, sugar beets, potatoes and malt barley), with scattered residual livestock farms. Most agricultural practices are intensive, and the large mean farm size (143 ha in 2010[1] (RGA 2010)) continues to grow as the number of farmers decreases. Our data collection relied on interviews with 45 farmers and 15 key actors from processing industries, farmer cooperatives and institutions. The farmers interviewed were identified by representatives of the main value chains (i.e. cereals, beets, alfalfa, field vegetables, "Brie de Meaux" cheese, sheep, pigs, broilers, laying hens and beef cattle), with a diversity of cropping systems and livestock in the farm structure. The percentage of livestock or crop-livestock farmers interviewed (44%) was higher than that in the territory (12% in 2018 (SIRENE), on 7% of the utilized agricultural area in 2010 (RGA 2010)), since our study also focused on relations between livestock and crop value chains. The sample included farms specialized in cash or industrial crops, which represent 84% of farms in the territory (on 91% of the utilized agricultural area). At 234 ha in 2010 (RPG, 2014), these farms are much larger than average. Nonetheless, we carefully chose which farmers of cash and industrial crops to interview to ensure that the sample represented practices well. The 15 key actors we interviewed worked for the main agricultural cooperatives or private firms that manage the collection and marketing of these crops, as well as official representatives of agricultural or public local authorities. Overall, our sample covers the types of production and practices on nearly 98% of north Aube's utilized agricultural area due to its narrow agricultural diversity.

3.2- Survey to capture transformation of the metabolism due to introduction of the bioeconomy

We used a survey to understand the metabolism of BAO and its transformation due to development of the bioeconomy. The goal of the interviews with farmers was to identify, specify and characterize the connections of their agricultural activity, especially material flows, to the rest of the socioeconomic system. The first set of questions focused on farm organization (e.g. types of production, crop rotation, machines). Next, each material flows that entered or left the farm, or flowed from one activity to another on the farm, was described quantitatively (e.g. type of product, volume) and qualitatively (e.g. role in the farming system, quality, issuer or receiver of the flow, influence on the farm's organization of human and mechanical labor). Then, the immaterial aspects (i.e. embeddedness of these flows was

[1] The mean farm size including champagne viticulture was 125 hectares in 2010, but we excluded champagne viticulture farms from our study because their extreme specificity – small (*i.e.* 10-20 ha) and huge added value per ha – made it difficult to compare their results to other agricultural activities in the territory.

addressed: monetary dimension (if present), type of commercial relationship with the issuer or receiver of the flow, and perception of this relationship (chosen, necessary or tolerated). We then addressed all immaterial flows and links that had not been described previously, such as technical or agricultural advice, group meetings about agricultural activities and participation in agricultural organizations. By including the immaterial aspects, we consider that these connections contribute to shape the agricultural metabolism. Finally, we asked a set of more open questions about the farmer's perception of the farm's activity, past evolution, and future, individually and within the territory's current dynamics; his/her ability to help govern agricultural organizations; and his/her overall perception of the dependence or autonomy of his/her farm management decisions.

The goal of the interviews with key actors of agricultural organizations was to describe more accurately current dynamics of the main agricultural value chains of the territory: the material flows they managed, their functioning (technically, commercially or governance-wise), the main problems they faced, and the public support, regulations or incentives that may influence their current and future actions.

We represented the metabolism at multiple scales (individual farm, small collective of farmers, value chain, multiple value chains, and territory). Our goal was to analyze metabolic links between funds (economic and ecological) to identify (1) flows and funds coined as 'strategic', meaning they are crucial for renewing funds and (2) funds that play a pivotal role in the metabolism (i.e. that lie at the confluence of several flows, and whose disappearance would change the metabolism's shape greatly). We focused on these funds and flows because the interviewees considered them problematic (*e.g.* competition for access to a flow critical to a farm's existence), the research team considered them problematic for sustainability (*e.g.* decreasing soil fertility), or either group considered that they increased the sustainability of an agricultural activity or the territory (*e.g.* flows between farms that conserve soil fertility).

On this basis, we analyzed the stability of the circulation of flows and how variation in or the disappearance of flows or funds reconfigure it. This allowed us to analyze past and current changes in the socioeconomic metabolism of agriculture in northern Aube. We then extrapolated the impacts of the current transformation to contemplate possible future scenarios.

4-Results

The economic funds identified were common (e.g. sugar or starch refineries, alfalfa and sugar beet pulp dehydration units, biofuel production from rapeseed), but a strong emerging fund was highlighted: biogas plants fed mostly with BOA. Ecological funds were connected mostly to soil fertility and livestock herds. From the interactions with the farmers and actors interviewed, a important example of unbalanced dynamics of territorial metabolism is the expected growth in biogas production. Therefore, we focused on understanding the territorial metabolism in connection with this growth.

The actors interviewed manage fund such as industrial facilities for storage and the first processing stage. However, development of the territory's bioeconomy is characterized by the recent growth of a new fund, anaerobic digestion projects to produce agricultural biogas (individually or by collectives), while a fund previously developed, like biofuel production based on rapeseed, is currently jeopardized by public policy changes and agronomic issues. Regional public authorities strongly support these biogas projects through general incentives for green energy development and subsidies, encouraged by natural gas distributors (who offer contract prices for 10-15 years), and farmers and their unions see these projects as a way to diversify revenue and securing opportunity (Berthe *et al*., 2018). Anaerobic digestion is easy to develop in the territory since BAO, such as sugar beet pulp and intermediate crops, is widely produced there, although its availability is debatable, as discussed later. This new fund influences the current metabolism of BAO, first by changing production and agricultural practices, and then by reorganizing value chains and their exchanges of flows. It creates a new landscape of flow allocation, with new competition and synergies.

4.1. Understanding the past transformation of the socioeconomic metabolism of agriculture at the territorial scale

4.1.1. An imbalance in flows produced that weakens the sustainability of agriculture

Most of the utilized agricultural area is devoted to grain and industrial crops, with relatively few farms that produce livestock, since their percentage decreased tremendously from 1988 (44%) to 2010 (11%) (RGA, 1988, 2010). This implies a strong dependence of the territory on external supplies of flows such as organic fertilizers, much of which is currently imported from other French territories or even abroad (especially poultry manure and sanitized compost from the Netherlands). This imbalance partially prevents circular exchanges of organic fertilizers from being established or maintained at the local scale, which appear critical for strengthening the territory's sustainability. From 1960-1990, integrated crop-livestock systems shifted to crop-only systems for two reasons. First, the poor rendzina and limestone soils of northern Aube, which previously supported only extensive sheep production, could be exploited easily by mechanical agriculture and a supply of external inputs (*e.g.* manure, clay), thus becoming a rich soil that allowed for regional specialization in grain and industrial crops. This transformation was accompanied by the emergence of large agricultural organizations that encouraged production of crops and the industries needed to collect, market and process them. At the same time, farms expanded in size (by a mean of 50 ha from 1988-2010 (RGA)) and mechanical equipment to adapt to this specialization. Second, from the farmer's viewpoint, abandoning livestock production was presented as a way to increase revenue and ease farm organization, since grain and industrial crops are less time consuming throughout the year than livestock production. Northern Aube now faces a path-dependence situation, with a dominant agricultural system composed of large, well-equipped farms, specialized in grain and industrial crops, dependent on imports and deeply integrated with processing industries that incidentally employ many people (600 in 2015 (INSEE)).

This evolution of agricultural activities in northern Aube provided an upside for farmers who abandoned livestock production, but led to certain weaknesses at the territorial scale (Lasseur *et al.*, 2019). First, it implied and increased a substantial lack of some flows – local organic nitrogen and organic matter production – and a strong dependence on external organic fertilizers, which need to be imported into the territory. Most BAO produced in the territory is exported as grain or industrial crops and their products. Second, this dominant path of high-yield crop farming progressively homogenized the agricultural landscape and decreased biodiversity. Third, population and employment density decreased in the territory. This has been reported as a current challenge for farmers' quality of life and adds to concerns about "young farmers willing to take over" farms in the territory, in a national context in which farm succession appears more challenging than ever (Coly, 2020).

4.1.2. Flows critical for circularity and competition for access to them

The increase in competition for access to certain BAO flows is not limited to the flows influenced by the development of biogas production. Instead, we observed that some flows critical for circular exchanges were experiencing strong competition, especially by more recent agricultural practices such as organic farming, which is not allowed to use synthetic fertilizers. This competition could have a "blocking" effect, especially for manure: since crop farmers need organic fertilizers, but livestock production in northern Aube is marginal, local manure is subject to strong competition between organic farmers and potentially with other high-value-added chains.

Ruminant manure is usually used directly on the farm that produced it, although we observed a few direct straw-manure exchanges between farms, but only at a local scale (mostly with neighbors or family members), through non-monetary exchanges. Other examples of circulation this flow observed highlight crop farmers' demand, which drives them to set up relationships or activities that are unusual in the current context of high-yield industrial farming. We highlight the example of a crop farmer who often scrapes out his neighbor's stalls and "gets paid in manure", or another who plows and sows the fields of a livestock farmer in exchange for manure. These labor-manure exchanges are non-monetary and embedded in long and often neighborly collaborative relationships between farmers.

Poultry manure circulates more widely outside of poultry farms because most of them produce more manure than they need for their crops. We observe monetary exchanges of straw-manure *via* corporate connections (agricultural service companies), due in part to farm diversification in northern Aube. Exchanges occurred particularly through the development of hired labor and equipment, when farmers started private companies to plow, sow, harvest or perform other cropping activities. These agricultural service companies generate profits using increasingly expensive equipment and enable other farms to grow in size by externalizing the workforce and equipment. They also often offer to scrape out and transport manure, since they have the appropriate equipment, which is sometimes too expensive for individual farmers to own. In this way, the companies collect manure and sometimes add field fertilization to their services as a strong differentiating strategy, which encourages them to collect even more manure.

The competition is especially strong for organic poultry manure. Although organic crops are expanding less in northern Aube than in other parts of France, organic manure is vital to their economic balance. Organic manure is so profitable that farmers who produce it but do not use all of it themselves would rather sell it than spread it on their non-organic fields. A national ban was even passed to prevent spreading of organic manure on non-organic fields, to protect the resource for the development of organic crops. When available on the local market, this flow is the subject of strong competition, as shown by the example of two organic crop farmers that secured their manure supply by setting up 10-year contracts (that fix quantities and prices) with all of the organic poultry farms in the territory. They do not know "what the other farmers who are going organic are going to do", because they "secured all the manure for 50 km around".

If this dominant regime of crop-livestock imbalance does not change, competition over manure as a flow critical for the soil fertility fund will remain strong. Thus, the lack of a strategic flow appears to be another weight on the structural weaknesses of the agricultural metabolism. In addition, it impedes development of agricultural practices such as organic farming and decreases the overall sustainability of the metabolism and its contribution to the ecological transition.

4.2. The metabolic approach to highlight funds and flows impacted by the bioeconomy development

The territory has approximately 20 agricultural biogas plants (using anaerobic digestion) in operation or planned, a number that increased greatly in the past two years due to strong public policies and the active involvement of energy companies. Some of these plants rely in part on manure, but most of them rely primarily on crops, with the addition of agro-industrial by- and co-products. The development of this new fund changes the allocation of BAO flows and their related land-use. These changes are occurring in a complex context, especially for the production of grain and industrial crops. Indeed, the future is uncertain for some of the territory's main crops, first due to effects of climate change. Northern Aube usually benefits from a sufficient amount and distribution of rainfall but has recently experienced drought and a changing rainfall distribution. Since 2010, which had especially high spring temperatures and summer rainfall events, yields of wheat and barley (which together cover more than 33% of the utilized agricultural area) have often decreased by 50%, when a bad harvest in previous years was a decrease of only 20-30%. Another high-value crop, potatoes, requires irrigation to reach a profitable yield in northern Aube and thus might compete for water. Second, farmers are facing a failure of the high-yield crop system, with increasing frequency of agronomic dead-ends, in which a crop can no longer be grown on some fields because pest resistance has developed or certain pesticides are prohibited. This is the case for rapeseed, whose production is declining, and soon could be the case for other crops. Third, sugar beet (13% of the utilized agricultural area) is facing significant turmoil in its market and industrial processing and value chains. Northern Aube has two sugar refineries, one owned by a local cooperative, the other by a cooperative corporation that now operates globally. This corporation's investment in sugar cane production and processing in Brazil – a competing market – over the last decade raised even more concerns when the European Union abandoned quotas and fixed prices for sugar beet in 2016. Sugar beet prices are no longer protected and, like wheat, face the turmoil of global markets and cannot compete against sugar cane. Agricultural biogas is developing in this uncertain context and adds to the ongoing changes in agricultural metabolism.

4.2.1. Intermediate crops for digesters: flow diversion and changes in crop rotations

The recent development of agricultural biogas in northern Aube, and incentives for it to expand, whether from public authorities, agricultural actors or natural gas distributors, implies two types of diversions of existing flows that could strongly influence the agricultural metabolism and its sustainability over time. First, a large proportion of intermediate crops[2] is harvested to feed existing digesters, and relatively little is left on the soil. Second, after France established a regulatory limit of using no more than 15% of main crops in digesters in 2016, we observed a statistically significant increase in the growing time of intermediate crops at the expense of that of main crops. For example, wheat (9-10 months per field) is being replaced in rotations by malting barley (6 months per field). However, a current practice in northern Aube is to harvest an immature cereal, considered as the main culture, and then to sow maize, which qualifies as an intermediate crop, all of which can be harvested as silage and fed to digesters. As intermediate crops become more valuable than main crops, cropping

[2] To mitigate nitrate pollution, the most recent regulations encourage planting intermediate crops (sometimes nitrogen-fixing cover crops, in particular) or impose them in nitrate-vulnerable zones, as in northern Aube. These crops are planted to cover the soil between two main crops. They do not reach full maturity, are supposed to decrease nitrate leaching and/or fertilize the soil, and benefit biodiversity.

practices and crop rotations are changing, and flows of BAO that return to the soil are decreasing. Furthermore, the current development of maize in northern Aube could require more irrigation and thus induce water shortages never observed before.

At the individual scale, however, building digesters (individual or collective) is attractive. First financially, because each one ensures revenue for 10-15 years via a contract with a natural gas distributor that fixes an annual volume and purchase price. Each currently provides, in less than 10 years, revenue greater than the initial investment in the digester. Energy crops may also provide higher or at least more stable yield than grain or industrial crops, and the revenue generated is not influenced by instability in global market prices for at least 10 years. Thus, farmers seek out agricultural biogas production and set up collectives to build and feed digesters. Although the farmers were concerned about maintaining carbon in the soil (and the potential of digestate fertilization to do so), they were more interested in the increase in revenue, which they often mentioned as a way to set up new activities on the farm and strengthen its existence.

Second, the changes in crop rotations have complex effects on the workforce and quality of life, since they lead to changes in practices, pesticide use, and sometimes equipment, but energy crops and their associated (new) main crop also appear more secure than the previous ones. Operating a biogas plant requires new skills for the workforce, but farmers involve engineering firms that specialize in them. Furthermore, each digester in the territory relies on an employee workforce. The increase in quality of life compared to that with livestock production is clear for the farmers, even though “a digester is like a flock - when the alarm goes off at 2 a.m., one has to get out of bed”.

At this individual (or “small collective”) scale, benefits appear clearly in the short term, but raise awareness and concerns for the long term. Financially, even if the revenue from the 10-15-year price contract covers the initial investment, little is currently known about the cost of maintenance during this period. Moreover, now that digesters have reorganized metabolic links and shaped a meaningful portion of the crop production in the territory, the current trends of technical innovations in energy production suggest that they could rapidly become under-scaled and uncompetitive.

Other concerns appear at the value-chain scale. The development of agricultural biogas production will divert BAO flows and increase abandonment of crops on which most agro-industries of the territory rely heavily. First, it means that the flows collected and processed by these economic funds may decrease, thus decreasing their profitability. Second, it raises concerns about a potential decrease in soil fertility, an ecological fund which is a structural weakness of the agricultural metabolism of northern Aube. Admittedly, digestate is spread, which returns some carbon and nitrogen to productive land, but not always on the fields on which the input crop grew, since digestate can be transported only over short distances, unlike input crops for anaerobic digestion. The fertilizing potential of digestate in the middle or long term is also uncertain.

4.2.2. Allocating existing flows to digesters at the territorial scale: the issue of availability

This type of change in crop rotations implies reorganization of farmers' metabolic links and, at the territorial scale, changes the allocation of productive soil and the BAO produced. In particular, certain by- and co-products that were used before development of the bioeconomy but not in particularly high demand are currently essential to the agronomic and economic balance of some digesters. We observed two digesters that rely on inputs besides energy or intermediate crops. The first is a digester set up by a multi-product regional cooperative that uses waste from crop collection and storage. The second is a collective digester set up by a few pig farmers that uses pig manure as the main input, and whose digestate is used as fertilizer. These digesters require relatively few energy crops and use mostly by- and co-products from a nearby paper mill and a few vegetable processing industries. This cascading use of biomass is praised in the dominant narrative of the bioeconomy, and it does benefit all parties at the cooperative or small-collective scale and strengthen the existence of the associated production (pigs) or activity (industrial processing of crops and wood), both financially and from an environmental viewpoint. At the territorial scale, however, these developments imply that the digesters divert flows within the territory, which no longer remain available for other uses, including other digesters. No other industrial actor in the territory can provide the same flows; meanwhile, competition for anaerobic digestion inputs is intensifying, meaning that new digesters will rely more heavily on energy and intermediate crops, thus reinforcing the detrimental effects on the agricultural metabolism described previously. Finally, it should be noted that this evolution implies diverting flows from food to energy.

4.2.3. Impacts of agricultural biogas development on other flows and economic funds at the territorial scale: an example of entanglement

Since metabolic links are reorganized at a small scale, impacts on the overall sustainability of agriculture occur, particularly through entanglement with value chains and industrial facilities. The most salient examples of an associated detrimental impact of the increase in the number of digesters is its destabilizing impact first on alfalfa production and use and second on sugar beet pulp use (fig. 1), by a connection through the local feed market and industrial dehydrators.

[fig. 1 is to be inserted around here]

Figure 1. Flows (arrows) and economic funds (boxes) entanglement for biogas, sugar, animal feed and dehydration value chains at the territorial scale

Alfalfa has been produced in northern Aube since the 1970s, for two main reasons: it provides nitrogen to the soil (as a legume) and is a protein-rich animal feed. Alfalfa is thus part of crop rotations for livestock farmers, but also for crop-only farmers, and provides stable revenue. Indeed, the current program of the Common Agricultural Policy subsidizes alfalfa for its agronomic advantages. In addition, three long-established local dehydrator plants, owned by the local cooperative, helped to stock, market and export dried alfalfa. While livestock farmers mostly use their alfalfa on-farm, dehydration is critical to alfalfa's profitability for crop farmers. However, the economic stability of those dehydrators relies mainly on sugar beet pulp, which is an abundant by-product of sugar refineries within and near the territory. Pressed sugar beet pulp is sought for feed since it can replace maize in ruminant rations, and sugar beet farmers who have livestock recover nearly 30% of the pulp produced by the cooperative's sugar refinery. Since pressed sugar beet pulp is full of moisture and expensive to transport and store, the cooperative built the dehydrators in the 1970s to store and market dried sugar beet pulp for feed outside the territory. The dehydrators dried 227000 t of sugar beet pulp and 212000 t of local alfalfa in 2019, a dehydration capacity that is critical to their economic attractiveness for farmers. However, the recent development of biogas plants increases competition for access to sugar beet pulp, especially since digestion is particularly appealing to sugar beet farmers who had no other use for their pulp.

We observed an increase in the use of sugar beet pulp as a biogas input, which raises concerns about the potential of large amounts of it to be diverted from the dehydrator and thus endanger the latter's economic balance. The huge energy consumption of the dehydrators, powered by coal imported from South Africa, is another concern, but the decrease in input appears more critical to farmers and cooperative officers in the short term, because it could cause them to lose money and close. If this were to happen, alfalfa would disappear from crop farmers' rotations, which could increase risks to soil fertility, and the territory would lose approximately 100 jobs that the dehydrator currently provides. We also observed another effect of the ability of agricultural biogas to divert BAO: a rare but increasing use of alfalfa as a biogas input. In this case, alfalfa is diverted from the dehydrator and feed market but remains in crop rotations.

Another indirect effect of digesters in the territory revolves around the use of pressed sugar beet pulp as feed. Historically, sugar beet farmers had a legal "right to the pulp", meaning that the cooperative owned only the juices obtained from pressing the sugar beets it bought, while the farmers remained owners of the pulp. Legally and financially, this right disappeared in 2016 (the cooperative now buys the sugar beets whole, and the farmers lose ownership of them), but persists informally as a preferential commercial measure by which farmers can buy their share of pressed pulp at cost. Livestock farmers who produce sugar beets benefit from this measure, which ensures that they have easy access to good-quality and inexpensive feed. The increasing competition for sugar beet pulp caused by the development of anaerobic digestion could place this access in jeopardy, since it is no longer protected by law or cooperative bylaws.

Although development of anaerobic digestion is profitable at the individual scale, it raises issues at the value chain and territory scales, especially because it leads to diversion of flows and reorganization of metabolic links at the system scale by reallocating productive land and the use of BAO. These changes influence and increase already known risks for the current stability and balances of the agricultural metabolism, as well as for the existence of value chains and economic funds critical for maintaining them.

5-Discussion

The goal of this article is to test the utility and operationalization of a metabolic approach at the territorial scale to understand the transformation of the socioeconomic metabolism of the agri-food system of a territory in the past and its current transformation related to the development of the bioeconomy, especially biogas production. The increase in biogas production in northern Aube has reallocated BOA flows between existing ecological and economic funds. These shifts strengthen imbalances inherited from past evolutions of agriculture and raise concerns about the maintenance of crucial funds (e.g. soil fertility, processing machinery essential to local value chains) and the availability of strategic flows (e.g. organic fertilizers). The impacts occur through entanglement of flows in different value chains at the territorial scale.

The metabolic approach applied reveals that the current choices of BAO production and allocation at the territorial scale may deeply transform the socioeconomic metabolism of the territory's agricultural system. These choices can lead to conflicts and competition between flows and between funds, disrupting the current shape of the agricultural metabolism or, in contrast, strengthen the existing balance through synergies and circularities. These effects, disruptive or reinforcing, can be seen at the individual and collective (territorial) scales. This approach thus lays the groundwork for contemplating future scenarios of the socioeconomic metabolism of agriculture in northern Aube.

From an operational standpoint, using bioeconomics to illustrate development of the bioeconomy allowed us to show actors in the territory some effects of the entanglement of their BAO allocation choices and use of existing industrial facilities. We are currently presenting these results in workshops with farmers and agricultural officials, which will lead to a participative foresight study on the future of agriculture in northern Aube. The first workshop revealed that this integrated vision of effects of development of the bioeconomy has strengths and weaknesses that often elude actors, who seem eager to understand it.

From a scientific standpoint, impacts of these changes and choices are usually analyzed using tools that focus on one or more environmental criteria (e.g. carbon emissions, carbon storage, eutrophication) or economic criteria (*e.g.* economic growth, revenue). Moreover, most studies focus on a single scale (e.g. farm/individual, value chain, territory), thus excluding interactions between scales in which positive or negative impacts can influence one scale or another.

From our point of view, traditional approaches raise two problems. First, the inherent complexity of agricultural systems, which are socio-technical systems, calls for a systemic analysis that can integrate this complexity rather than a mono-criterion (or a few criteria) and mono-scale analysis. Our current research lays the foundation for a systemic analysis framework that can assess the sustainability of agricultural metabolism and integrate a variety of environmental, social and economic footprints, such as the agriculture environmental footprint (Courtonne et al., 2016) or energy and nutrient footprint (Fernandez-Mena et al, 2016; Harchaoui, Chatzimpiros, 2018). Our ongoing work will enable us to include the energy and nutrient footprint in the description of the socioeconomic metabolism of agriculture and will be the subject of a future article. Second, decisions that result from these approaches, which may enhance or address a transition, do not consider actors' abilities to act or change. On this latter point, our results raise the pressing issues of territorial governance and territorial capability (i.e. the capacity of territorial actors to decide their own future), especially given the current embeddedness of their activities and value chains in local and global economic power structures. This raises questions about the links of financial and economic decision power that connect the territory's agricultural metabolism and its evolution to the global scale.

Finally, as mentioned, databases of material flows at this local scale do not exist or are of uneven quality; thus, our research could not include all material flows or immaterial aspects of the metabolism. We could examine only the parts of the socioeconomic metabolism that we accessed through field investigation, which is why we emphasize that this research is not an exhaustive description of a territory's agricultural metabolism *per se*, but a metabolic *approach* to it. In our view, the main limits of our approach come from the sample of actors interviewed. First, the overrepresentation of livestock farmers could be a bias, but it allowed us to focus on the strategic flow of organic fertilizers and potential circularities in BAO flows; nonetheless, the crop farmers in the sample represent the overall diversity of crop farms and their practices in the territory. Second, we excluded vineyards, even though the more diversity of agricultural products a territory contains, the more potential the latter has for synergies and circularities of flows.

Nonetheless, this metabolic approach appears adequate to try to illustrate possible scenarios for the future of the agricultural metabolism of northern Aube. Two scenarios can be envisioned. The first is built on weak signals of development of sheep farmers who organize their flocks' grazing of other farmers' intermediate crops and rapeseed at a stage of growth that allows the crops to regrow afterwards. This circularity of matter has positive impacts for both parties, mainly fertilization of crops by animal waste *in situ*, which saves time and labor, in exchange for a free supply of forage for the flock in spring. It also weeds the crop, mitigates some pests and can decrease pesticide use. Even though this circular exchange is anecdotal (five cases are known in the territory), it is useful for the sustainability of these farms and the funds they rely upon, and moreover is seen as such by other farmers. Such circularities could be developed further by increasing sheep production in the territory.

The second scenario is negative. Based on the most negative effects and the entanglement of value chains, this scenario shows that the increasing use of sugar beet pulp in digesters could cause dehydrators to close. Alfalfa production would remain the same or even increase as an energy crop (to feed digesters), partly reducing the dependence on imported fertilizers. With climate change and its strong impact on yield variability, the emergence of new agronomic dead-ends would impoverish crop rotations, and land allocation would shift to a few high-value-added crops that need large amounts of water, thus jeopardizing agricultural revenue, and increase negative effects of intensive crop agriculture on funds such as biodiversity and water. If beet sugar prices were also to decrease due to competition of with cane sugar, sugar refineries in the territory could close as well. Sugar beets would be used directly in digesters and thus not be processed. Like the agricultural features, the agro-industrial landscape of northern Aube would change, experiencing crop specialization that would provide energy instead of food, with probable areas of marginal diversification (whether chosen or imposed). Furthermore, to maintain biogas production in the territory directly (by local inputs) or indirectly (by importing inputs), local actors would have to import BAO from other territories (whether fertilizers or crops), thus exporting the local imbalance to other territories and potentially adding to their own weaknesses and threats. This dangerous scenario highlights the change in allocation of BAO from food and feed to energy, and the little control that farmers collectively have over the future of their agricultural production, market share and the economic and ecological funds their activity relies on.

By examining the socioeconomic metabolism of agriculture through the funds and flows that shape it, we highlight that individual choices, analyzed from a transversal viewpoint and at the value-chain or territorial scale, can disturb the agricultural metabolism through competition or conflict, or strengthen its balance with synergies and circularity. It allows for analysis that focuses on strategic flows and funds, which often excludes actors, but could help them collectively shape a more sustainable future for their activities and the territory.

Acknowledgments

This study was supported by ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie), the French agency for ecological transition, in its GRAINE program, under grant no. 17-03-C0004.

References

Alcott B., 2005, "Jevons' paradox", *Ecological Economics*, 54(1): 9–21.

Athanassiadis A., Bouillard P., Crawford R.H., Khan A.Z., 2016, "Towards a Dynamic Approach to Urban Metabolism: Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010", *Journal of Industrial Ecology*, 21(2): 307-319.

Bahers J.-B., Tanguy A., Pincetl S., 2020, "Metabolic relationships between cities and hinterland: a political-industrial ecology of energy metabolism of Saint-Nazaire metropolitan and port area (France)", *Ecological Economics*, 167: 106447

Barles, S. 2009. "Urban metabolism of Paris and its region", *Journal of Industrial Ecology* 13 (6): 898–913.

Berthe A., Grouiez P., Dupuy L., "Les "upgradings stratégiques" des firmes subordonnées dans les CGV : le cas des éleveurs investissant dans la méthanisation", *Revue d'économie industrielle*, 163(3) : 187-227.

Bugge M.M., Hansen T., Klitkou A., 2016, "What is the bioeconomy? A review of the literature", *Sustainability*, 8-691:1-22.

Carmona C. P., Guerrero I., Peco B., Morales M. B., Onate J. J., Pärt T., Tscharntke T., Liira J., Aavik T., Emmerson M., Berendse F., Ceryngier P., Bretagnolle V., Weisser W. W., Bengtsson J., 2020, "Agricultural intensification reduces plant taxonomic and functional diversity across European arable systems", *Functional Ecology*, 34(7): 1448-1460.

CGAAER, 2019, *Place des régions dans le développement de la bioéconomie*. Rapport CGAAER n° 18109, 110 p.

CGED, 2019, *Chiffres clés des énergies renouvelables*, Commissariat Général au Développement Durable, 92 p.

Coly B., 2020, *Entre transmettre et s'installer, l'avenir de l'agriculture*, Avis pour le the Conseil Economique Social et Environnemental, 99 p.

Couix Q., 2020, “Georgescu-Roegen’s Flow-Fund Theory of Production in Retrospect”, *Ecological Economics*, 176: 106749

Courtonne, J-Y., Alapetite, J., Longaretti, P-Y., Dupré, D., Prados, E., 2015, “Downscaling material flow analysis: the case of the cereal supply chain in France”, *Ecological Economics*, 118: 67-80.

Dansero E, Puttilli M, 2014, “Multiple territorialities of alternative food networks: six cases from Piedmont, Italy”, *Local Environment* 19: 626–643

EEA, European Environment Agency, 2018, *The circular economy and the bioeconomy: Partners in sustainability*, 60 p.

European Commission, 2012, *Innovating for Sustainable Growth - A Bioeconomy for Europe*, Publications Office of the European Union, 60 p.

Fernandez-Mena H., Nesme T., Pellerin S., 2016, “Towards an Agro-Industrial Ecology: A review of nutrient flow modelling and assessment tools in agro-food systems at the local scale”, *Science of The Total Environment*, 543: 467–479

Gaba S., Bretagnolle V., 2020, “Social–ecological experiments to foster agroecological transition”, *People and Nature*, 2:317–327

Gabriel A., Madelrieux S., Lescoat P., in press, “A review of socio-economic metabolism representations and their links to action: cases in agri-food studies”, Ecological Economics.

Garot G., 2015, *Lutte contre le gaspillage alimentaire: proposition pour une politique publique*, Rapport au Premier Ministre, 51 p.

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

Giampietro M., Mayumi K., Ramos-Martin J., 2009, “Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale”, *Energy* 34 (3): 313▯22.

Harchaoui S., Chatzimpiros P., 2018, “Energy Nitrogen and Farm Surplus Transitions in Agriculture from Historical Data Modeling France, 1882-2013”, *Journal of Industrial Ecology*, 23(2): 412-425.

Haut Conseil pour le Climat, 2020, *Redresser le cap, relancer la transition*, Rapport annuel, 160 p.

Horlings L.G., Mardsen T.K., 2012, “Exploring the ‘New Rural Paradigm’ in Europe : eco-economic strategies as a counterforce to the global competitiveness agenda”, *European Urban and Regional Studies*, 21(1): 4-20.

INSEE, Institut National de la Statistique et des Etudes Economiques.

Kennedy C. A., Stewart I., Facchini A., Cersosimo I., Mele R., Chen B., Uda M., Kansal A., Chiu A., Kim K., Dubeux C., Rovere E. L. L., Cunha B., Pincetl S., Keirstead J., Barles S., Pusaka S., Gunawan J., Adegbile M., Nazariha M., Hoque S., Marcotullio P.J., Otharán F. G., Genena T., Ibrahim N., Farooqui R., Cervantes G., Sahin A. D., 2015, “Energy and material flows of megacities”, PNAS, 112, p. 5985-5990.

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 Baumont R. (E d) “De grands défis et des solutions pour l’élevage“. INRA Prod. Anim., 32: 189-204

Low S.A., Isserman A.M., 2009, “Ethanol and the Local Economy: Industry Trends, Location Factors, Economic Impacts, and Risks”, *Economic Development Quarterly*, 23(1) : 71-88.

Madelrieux S., Buclet N., Lescoat P., Moraine M., 2017 “Écologie et économie des interactions entre filières agricoles et territoire : quels concepts et cadre d’analyse ?” *Cahiers Agricultures* 26: 24001

Magrini M-B., Béfort N., Nieddu M., 2019. “Technological Lock-In and Pathways for Crop Diversification in the Bio-Economy”, in Lemaire G., De Faccio Carvalho P.S., Kronberg S., Recous S., *Agroecosystem Diversity*: 375⍰388, Academic Press.

Missemer A., 2015, *Nicholas Georgescu-Roegen, pour une révolution bioéconomique*, Feuillets : économie politique moderne, ENS Éditions.

Montoya D., Haegeman B., Gaba S., de Mazancourt C., Bretagnolle V., Loreau M., 2019, “Trade-offs in the provisioning and stability of ecosystem services in agroecosystems”, *Ecological Applications*, 29(2):e01853.

Nieddu M., Vivien F.D., 2015, “La bioraffinerie comme objet transitionnel de la bioéconomie”, *Économie rurale*, 4710: 349-350

Nuhoff-Isakhanyan G., Wubben E.F.M., Omta O.S.W.F., Pascucci S., 2017, “Network structure in sustainable agro-industrial parks”, *Journal of Cleaner Production*, 141: 1209–1220.

Pahun J., Fouilleux È., Daviron B., 2018, “De quoi la bioéconomie est-elle le nom ? Genèse d’un nouveau référentiel d’action publique”, *Natures Sciences Sociétés* 26: 3–16

Pauliuk S., Herwitch E.G., 2015, “Socioeconomic metabolism as paradigm for studying the biophysical basis of human society”, *Ecological Economics*, 199:83-93

Pellerin S., Bamière L., Launay C., Martin R., Schiavo M., et al., 2019, “Stocker du carbone dans les sols français, quel potentiel au regard de l’objectif 4 pour 1000 et à quel coût? ”, Synthèse du rapport d’étude pour l’Agence de l’Environnement et de la Maîtrise de l’Energie, Paris, 114 p.

RGA, Recensement Général de l’Agriculture, 1988, 2010, 2000, Ministère de l’Agriculture, Service Statistique Public.

RPG, Registre Parcellaire Graphique, 2014, Institut National de l’Information Géographique et Forestière.

SIRENE, Système national d’identification et du répertoire des entreprises et de leurs établissement, 2018, Institut National de la Statistique et des Études Économiques

Smil V., 2015, *Power Density: A Key to Understanding Energy Sources and Uses*, The MIT Press, 320 p.

SNMB, Stratégie Nationale de Mobilisation de la Biomasse, 2018, Ministère de l'Environnement et de l'Énergie, Paris, 131 p.