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Pauline Marty, Sabrina Dermine-Brullot, Sophie Madelrieux, Julie Fleuet,
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1 **Transformation of socioeconomic metabolism due to development of the** 2 **bioeconomy: the case of northern Aube (France)**

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

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

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

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

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

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

9 **Abstract**

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

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

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

26 1-Introduction: current development of the bioeconomy and criticisms 27 of it

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

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

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

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

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

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

84 2- Theoretical and operational framework

85 2.1-A bioeconomic approach to the bioeconomy: socioeconomic metabolism and the 86 fund-flow model

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

89 European level (Pahun *et al.*, 2018). Originally, bioeconomics was a scientific paradigm used to study
90 physical and biological foundations of human societies (Georgescu-Roegen, 1971). Georgescu-Roegen
91 changed the understanding of economic processes by highlighting the unsustainability of economic
92 models based on linear production processes. The latter were defined as incompatible with natural-
93 resource renewal, the environment's carrying capacity for pollution and social issues. It replaces the
94 traditional cumulative accountability of stocks and flows with a "fund-flow" model. In this model,
95 "funds" are long-lasting agents that produce, transform and/or consume "flows" (of matter, energy or
96 information) within the metabolic system through production processes, without being destroyed
97 themselves by these processes (Couix, 2020). The goal is to ensure sustainable use of the funds,
98 especially the ecological ones, that support the many processes necessary to sustain human societies,
99 while considering their functioning and regeneration rhythms, and even to limit the range of the
100 economy to that allowed by the flows (Missemer, 2015). Georgescu-Roegen pleads for re-embedding
101 economic development within planetary limits and, without naming it specifically, for a metabolic
102 approach to economy. Georgescu-Roegen's scientific heritage extend in ecological economics,
103 especially in regards to socioeconomic metabolism. According to Pauliuk *et al.* (2015), "socioeconomic
104 metabolism constitutes the self-reproduction and evolution of the biophysical structures of human
105 society. It comprises those biophysical transformation processes, distribution processes, and flows
106 which are controlled by humans for their purposes". Based on and compatible with bioeconomics, the
107 metabolic approach appears relevant for analyzing the transformation that results from past, current
108 and potential future transitions in the agricultural system. This approach thus goes beyond a single-
109 sector and single-scale scientific approach. The fund-flow model developed in bioeconomics can be
110 applied in metabolic approaches, as they are used to connect the economy and ecology of human
111 activities (Madelrieux *et al.*, 2017) at multiple spatial scales and organization levels (Gabriel *et al.*,
112 2020). Different methods are applied, but all rely greatly on accounting for matter and energy flows
113 that support the socioeconomic system's existence and thus its material interactions with the
114 biophysical sphere. In this sense, they are compatible with and applicable within the bioeconomics
115 fund-flow model.

116 2.2-Operationalization of the metabolic approach

117 Based on the literature on agri-food systems, Gabriel *et al.* (2020) analysed how researchers describe
118 and represent socioeconomic metabolisms. They distinguished eight schools of thought related to
119 three types of representation: (1) space and compartment-based, (2) economic agent-based and (3)
120 multi-faceted and composite. In the first type, metabolism is usually analyzed using statistical
121 databases, at the scales at which they are commonly available (national, regional or, in France,
122 departmental (Courtonne *et al.*, 2016) or for large metropolitan areas (Barles, 2009; Kennedy *et al.*,

123 2015; Athanassiadis et al., 2016; Bahers et al., 2020). However, BAO is produced, allocated and has
124 impacts at smaller scales, which are more difficult to document and characterize. Moreover, this type
125 of representation considers actors as a “black box” and often excludes the drivers that explain their
126 decision-making. Nonetheless, most decisions about BAO metabolism are made at smaller scales, at
127 which immaterial aspects of the metabolism (i.e. values that drive decisions and actions, cultural and
128 social embeddedness, and governance) partially shape actors’ decisions and ability to act. Therefore,
129 we used economic agent-based representation (the second type) to apply this approach to territories
130 smaller than a French department, even though statistical databases at that scale are of uneven quality
131 or do not exist. Moreover, focusing on this scale allowed us to fill a knowledge gap. Indeed, the
132 literature on bioeconomy over the past several years has usually focused on national or international
133 scales, and ignoring the local complexities implied at the local scale except in a few research at the
134 regional scale (Low, Isserman, 2009 ; Horlings, Madsen, 2012 ; Bugge *et al*, 2016).

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

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

145 3-Materials and methods

146 3.1-Study area

147 This article highlights results of an ongoing interdisciplinary research project on BAO at the territorial
148 scale (BOAT, “Biomasse d’Origine Agricole dans les Territoires”). The team (land planners, animal
149 scientists, economists, agronomists) from four institutions formed in 2017 to develop a method to
150 describe and analyze BAO metabolism in two contrasting agricultural territories in France – the north
151 of the Aube department (intensive and specialized cereal agriculture) and the Drôme Valley (diversified
152 agricultural production and smaller farms) – with a focus on reducing environmental impacts. We focus
153 here on northern Aube, a part of the French Grand Est Region, which identified bioeconomy as a key
154 sector of its “regional DNA” and aimed at developing renewable energy (with biogas as the front one)

155 simultaneously with a very ambitious agricultural carbon capture program to mitigate the climate
156 change. Therefore studying the socioeconomic metabolism of Northern Aube is a way to test the
157 relevance of these challenges. Northern Aube contains 1 434 farms that are specialized mainly in cash
158 crops or high-value industrial crops (i.e. wheat, sugar beets, potatoes and malt barley), with scattered
159 residual livestock farms. Most agricultural practices are intensive, and the large mean farm size (143
160 ha in 2010¹ (RGA 2010)) continues to grow as the number of farmers decreases. Our data collection
161 relied on interviews with 45 farmers and 15 key actors from processing industries, farmer cooperatives
162 and institutions. The farmers interviewed were identified by representatives of the main value chains
163 (i.e. cereals, beets, alfalfa, field vegetables, “Brie de Meaux” cheese, sheep, pigs, broilers, laying hens
164 and beef cattle), with a diversity of cropping systems and livestock in the farm structure. The
165 percentage of livestock or crop-livestock farmers interviewed (44%) was higher than that in the
166 territory (12% in 2018 (SIRENE), on 7% of the utilized agricultural area in 2010 (RGA 2010)), since our
167 study also focused on relations between livestock and crop value chains. The sample included farms
168 specialized in cash or industrial crops, which represent 84% of farms in the territory (on 91% of the
169 utilized agricultural area). At 234 ha in 2010 (RPG, 2014), these farms are much larger than average.
170 Nonetheless, we carefully chose which farmers of cash and industrial crops to interview to ensure that
171 the sample represented practices well. The 15 key actors we interviewed worked for the main
172 agricultural cooperatives or private firms that manage the collection and marketing of these crops, as
173 well as official representatives of agricultural or public local authorities. Overall, our sample covers the
174 types of production and practices on nearly 98% of north Aube’s utilized agricultural area due to its
175 narrow agricultural diversity.

176 3.2- Survey to capture transformation of the metabolism due to introduction of the 177 bioeconomy

178 We used a survey to understand the metabolism of BAO and its transformation due to development
179 of the bioeconomy. The goal of the interviews with farmers was to identify, specify and characterize
180 the connections of their agricultural activity, especially material flows, to the rest of the socioeconomic
181 system. The first set of questions focused on farm organization (e.g. types of production, crop rotation,
182 machines). Next, each material flows that entered or left the farm, or flowed from one activity to
183 another on the farm, was described quantitatively (e.g. type of product, volume) and qualitatively (e.g.
184 role in the farming system, quality, issuer or receiver of the flow, influence on the farm’s organization
185 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.

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

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

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

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

214 4-Results

215 The economic funds identified were common (*e.g.* sugar or starch refineries, alfalfa and sugar beet
216 pulp dehydration units, biofuel production from rapeseed), but a strong emerging fund was
217 highlighted: biogas plants fed mostly with BOA. Ecological funds were connected mostly to soil fertility

218 and livestock herds. From the interactions with the farmers and actors interviewed, a important
219 example of unbalanced dynamics of territorial metabolism is the expected growth in biogas
220 production. Therefore, we focused on understanding the territorial metabolism in connection with this
221 growth.

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

235 4.1. Understanding the past transformation of the socioeconomic metabolism of 236 agriculture at the territorial scale

237 4.1.1. An imbalance in flows produced that weakens the sustainability of agriculture

238 Most of the utilized agricultural area is devoted to grain and industrial crops, with relatively few farms
239 that produce livestock, since their percentage decreased tremendously from 1988 (44%) to 2010 (11%)
240 (RGA, 1988, 2010). This implies a strong dependence of the territory on external supplies of flows such
241 as organic fertilizers, much of which is currently imported from other French territories or even abroad
242 (especially poultry manure and sanitized compost from the Netherlands). This imbalance partially
243 prevents circular exchanges of organic fertilizers from being established or maintained at the local
244 scale, which appear critical for strengthening the territory's sustainability. From 1960-1990, integrated
245 crop-livestock systems shifted to crop-only systems for two reasons. First, the poor rendzina and
246 limestone soils of northern Aube, which previously supported only extensive sheep production, could
247 be exploited easily by mechanical agriculture and a supply of external inputs (*e.g.* manure, clay), thus
248 becoming a rich soil that allowed for regional specialization in grain and industrial crops. This
249 transformation was accompanied by the emergence of large agricultural organizations that
250 encouraged production of crops and the industries needed to collect, market and process them. At the

251 same time, farms expanded in size (by a mean of 50 ha from 1988-2010 (RGA)) and mechanical
252 equipment to adapt to this specialization. Second, from the farmer's viewpoint, abandoning livestock
253 production was presented as a way to increase revenue and ease farm organization, since grain and
254 industrial crops are less time consuming throughout the year than livestock production. Northern Aube
255 now faces a path-dependence situation, with a dominant agricultural system composed of large, well-
256 equipped farms, specialized in grain and industrial crops, dependent on imports and deeply integrated
257 with processing industries that incidentally employ many people (600 in 2015 (INSEE)).

258 This evolution of agricultural activities in northern Aube provided an upside for farmers who
259 abandoned livestock production, but led to certain weaknesses at the territorial scale (Lasseur *et al.*,
260 2019). First, it implied and increased a substantial lack of some flows – local organic nitrogen and
261 organic matter production – and a strong dependence on external organic fertilizers, which need to be
262 imported into the territory. Most BAO produced in the territory is exported as grain or industrial crops
263 and their products. Second, this dominant path of high-yield crop farming progressively homogenized
264 the agricultural landscape and decreased biodiversity. Third, population and employment density
265 decreased in the territory. This has been reported as a current challenge for farmers' quality of life and
266 adds to concerns about “young farmers willing to take over” farms in the territory, in a national context
267 in which farm succession appears more challenging than ever (Coly, 2020).

268 4.1.2. Flows critical for circularity and competition for access to them

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

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

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

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

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

310 4.2. The metabolic approach to highlight funds and flows impacted by the bioeconomy 311 development

312 The territory has approximately 20 agricultural biogas plants (using anaerobic digestion) in operation
313 or planned, a number that increased greatly in the past two years due to strong public policies and the
314 active involvement of energy companies. Some of these plants rely in part on manure, but most of
315 them rely primarily on crops, with the addition of agro-industrial by- and co-products. The
316 development of this new fund changes the allocation of BAO flows and their related land-use. These

317 changes are occurring in a complex context, especially for the production of grain and industrial crops.
318 Indeed, the future is uncertain for some of the territory's main crops, first due to effects of climate
319 change. Northern Aube usually benefits from a sufficient amount and distribution of rainfall but has
320 recently experienced drought and a changing rainfall distribution. Since 2010, which had especially
321 high spring temperatures and summer rainfall events, yields of wheat and barley (which together cover
322 more than 33% of the utilized agricultural area) have often decreased by 50%, when a bad harvest in
323 previous years was a decrease of only 20-30%. Another high-value crop, potatoes, requires irrigation
324 to reach a profitable yield in northern Aube and thus might compete for water. Second, farmers are
325 facing a failure of the high-yield crop system, with increasing frequency of agronomic dead-ends, in
326 which a crop can no longer be grown on some fields because pest resistance has developed or certain
327 pesticides are prohibited. This is the case for rapeseed, whose production is declining, and soon could
328 be the case for other crops. Third, sugar beet (13% of the utilized agricultural area) is facing significant
329 turmoil in its market and industrial processing and value chains. Northern Aube has two sugar
330 refineries, one owned by a local cooperative, the other by a cooperative corporation that now operates
331 globally. This corporation's investment in sugar cane production and processing in Brazil – a competing
332 market – over the last decade raised even more concerns when the European Union abandoned quotas
333 and fixed prices for sugar beet in 2016. Sugar beet prices are no longer protected and, like wheat, face
334 the turmoil of global markets and cannot compete against sugar cane. Agricultural biogas is developing
335 in this uncertain context and adds to the ongoing changes in agricultural metabolism.

336 4.2.1. Intermediate crops for digesters: flow diversion and changes in crop rotations

337 The recent development of agricultural biogas in northern Aube, and incentives for it to expand,
338 whether from public authorities, agricultural actors or natural gas distributors, implies two types of
339 diversions of existing flows that could strongly influence the agricultural metabolism and its
340 sustainability over time. First, a large proportion of intermediate crops² is harvested to feed existing
341 digesters, and relatively little is left on the soil. Second, after France established a regulatory limit of
342 using no more than 15% of main crops in digesters in 2016, we observed a statistically significant
343 increase in the growing time of intermediate crops at the expense of that of main crops. For example,
344 wheat (9-10 months per field) is being replaced in rotations by malting barley (6 months per field).
345 However, a current practice in northern Aube is to harvest an immature cereal, considered as the main
346 culture, and then to sow maize, which qualifies as an intermediate crop, all of which can be harvested
347 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.

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

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

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

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

374 Other concerns appear at the value-chain scale. The development of agricultural biogas production
375 will divert BAO flows and increase abandonment of crops on which most agro-industries of the
376 territory rely heavily. First, it means that the flows collected and processed by these economic funds
377 may decrease, thus decreasing their profitability. Second, it raises concerns about a potential decrease
378 in soil fertility, an ecological fund which is a structural weakness of the agricultural metabolism of
379 northern Aube. Admittedly, digestate is spread, which returns some carbon and nitrogen to productive
380 land, but not always on the fields on which the input crop grew, since digestate can be transported

381 only over short distances, unlike input crops for anaerobic digestion. The fertilizing potential of
382 digestate in the middle or long term is also uncertain.

383 4.2.2. Allocating existing flows to digesters at the territorial scale: the issue of availability

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

403 4.2.3. Impacts of agricultural biogas development on other flows and economic funds at the 404 territorial scale: an example of entanglement

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

410 [fig. 1 is to be inserted around here]

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

413

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

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

441 Another indirect effect of digesters in the territory revolves around the use of pressed sugar beet pulp
442 as feed. Historically, sugar beet farmers had a legal "right to the pulp", meaning that the cooperative
443 owned only the juices obtained from pressing the sugar beets it bought, while the farmers remained
444 owners of the pulp. Legally and financially, this right disappeared in 2016 (the cooperative now buys
445 the sugar beets whole, and the farmers lose ownership of them), but persists informally as a
446 preferential commercial measure by which farmers can buy their share of pressed pulp at cost.
447 Livestock farmers who produce sugar beets benefit from this measure, which ensures that they have

448 easy access to good-quality and inexpensive feed. The increasing competition for sugar beet pulp
449 caused by the development of anaerobic digestion could place this access in jeopardy, since it is no
450 longer protected by law or cooperative bylaws.

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

457 5-Discussion

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

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

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

479 development of the bioeconomy has strengths and weaknesses that often elude actors, who seem
480 eager to understand it.

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

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

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

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

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

541 By examining the socioeconomic metabolism of agriculture through the funds and flows that shape it,
542 we highlight that individual choices, analyzed from a transversal viewpoint and at the value-chain or
543 territorial scale, can disturb the agricultural metabolism through competition or conflict, or strengthen
544 its balance with synergies and circularity. It allows for analysis that focuses on strategic flows and

545 funds, which often excludes actors, but could help them collectively shape a more sustainable future
546 for their activities and the territory.

547

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