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► To cite this version:

Julie Wohlfahrt, Fabien Ferchaud, Benoit Gabrielle, C. Godard, Bernard Kurek, et al.. Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review.. Journal of Cleaner Production, 2019, 232, pp.898-909. 10.1016/j.jclepro.2019.05.385 . hal-02154646

HAL Id: hal-02154646

<https://hal.science/hal-02154646>

Submitted on 25 Oct 2021

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Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review.

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Declaration of interest: none

Number of words:

10551 words (including: title, authors' affiliations, abstract, keywords, highlights, full text, figure captions and references)

7805 words (including: title, abstract, keywords, highlights, full text and figure captions)

1 **Abstract:**

2

3 The bioeconomy is expected to be a key solution to supply societies with food and non-food
4 products while replacing non-renewable resources and preserving natural ones. Sustainability
5 of bioeconomy systems is currently an issue that has to be addressed. Current research dealing
6 with the bioeconomy focuses primarily on technologies to improve biomass transformation
7 and, with regard to sustainability, on simple and unitary bio-based value chains such as
8 biofuel production from a single crop. In this paper, based on a literature review, we highlight
9 the complexity of bioeconomy systems and propose a framework to support their sustainable
10 development. We first review the key characteristics of bioeconomy systems: a wide variety
11 of stakeholders with a limited vision of bioeconomy systems, flexibility but also rigidity of
12 biomass feedstocks or transformation processes and a complex spatio-temporal layout.
13 Drawing on sustainability science, we show the relevance of the social-ecological concept to
14 approach territorial bioeconomy systems' sustainably and develop an analytical framework to
15 address sustainable development of territorial (local/regional) bioeconomy systems. This
16 framework is based on two complementary representations of territorial bioeconomy systems,
17 used to decipher their complexity. Finally, we outline an integrated assessment and modelling
18 approach designed to tackle specific bioeconomy sustainability issues. This participatory
19 approach has to take into account: i) the different sub-systems of territorial bioeconomy
20 systems, their high level of interactions, their heterogeneity in terms of entities and processes
21 involved and the circularity of matter and energy (production, transformation, use and
22 recycling) with particular emphasis on the transformation sub-system and the logistics ii) the
23 multiplicity and flexibility of stakeholders' nature, strategies and concerns, iii) the variety of
24 spatial and temporal scales at play; iv) the effects of exogenous drivers like supra-regional
25 policies and regulations, markets (e.g. prices of energies and biomass-based products) and
26 climate.

27 **Key-words:** social-ecological system; integrated assessment; territorial scale; landscape scale;
28 conceptual framework

29

30 **Highlights:**

- 31 - Territorial bioeconomy systems are complex social-ecological systems
- 32 - Bioeconomy systems are characterized by flexibility and complex spatio-temporal
33 layout
- 34 - Two complementary representations are proposed to decipher bioeconomy complexity
- 35 - A specific methodological framework to address bioeconomy sustainability issues

1. Introduction

Strategies to develop an economy based on renewable biological resources, the bioeconomy, are currently implemented in many countries around the world. In 2012, the European Union defined five objectives for the bioeconomy that remained valid for the reviewed bioeconomy strategy in 2018: ensuring food security; managing natural resources sustainably; reducing dependence on non-renewable resources; mitigating and adapting to climate change; creating jobs; and maintaining European competitiveness (European Commission, 2012 and 2018). Developing the bioeconomy appears as a key policy to simultaneously embrace major societal issues of climate change, food security, fossil fuel dependence, scarcity of natural resources, and territorial and economic development on all scales, from the small territory to the national-continental scale (Dubois and Gomez San Juan, 2016). Sustainable production and use of biomass are indeed inherent to the bioeconomy proposition.

A major challenge for any bioeconomy therefore lies in our ability to assess how its development will successfully achieve these different objectives in real world situations, from biomass feedstock production to the recycling of biomass-based products.

Research in the field of bioeconomy is currently carried out primarily in the natural sciences and engineering, with the objective of developing industrial processes that optimize the uses of biomass (Bugge et al, 2016; D'amato et al., 2017). As described by Bugge (2016), research focuses on bio-technological or bio-resource views of the bioeconomy, meaning that investigations are mostly driven by the quest for technical solutions related to the production and transformation of biomass feedstocks. Relatively little research has been done toward an integrated assessment of bioeconomy impacts (Golembiewski et al., 2015). The few studies that attempt to assess bioeconomy sustainability, taking into account biomass feedstock production's impacts on natural resources, mostly focus on dedicated agricultural biomass plantations, or on one biomass-based product (Gabrielle et al., 2018), or on a single project such as the Global Bioenergy Partnership (GBEP) sustainability indicators (Hayashi et al., 2014). In so doing, they disregard the complexity of the whole bioeconomy system (Robeldo-Abad et al., 2016). The lack of monitoring, standards and tools for a holistic sustainable assessment of bioeconomy projects is also highlighted by the FAO (Dubois and Gomez San Juan, 2016).

68 Our goal here is to provide a novel conceptual framework to address all bioeconomy systems'
69 sustainability, considering their specific characteristics (e.g. the flexibility of biomass
70 feedstocks and processes).

71

72 In this paper we consider bioeconomy systems as specific social-ecological systems which
73 aim at producing, using and recycling biomass to satisfy the food, energy, material and
74 chemical needs of a given population in a given geographical territory, while replacing
75 partially or entirely non-renewable resources with biomass and ensuring sustainable
76 management of natural resources. By analogy with a food system (Capone et al., 2014), a
77 bioeconomy system operates in and is influenced by a given social, political, economic and
78 environmental context. As proposed by the sustainability science community, using a social-
79 ecological framework allows for relationships between human and natural systems to be
80 deciphered, in order to understand the system's behavior, assess its sustainability, and
81 improve society's well-being (Haberl et al., 2011). Considering that a social-ecological
82 system at local/regional level is recognized as an appropriate level to deal with the
83 particularities of the social and ecological contexts of action (Wu, 2013; Therond et al., 2017;
84 Daher, 2018), we focus on bioeconomy systems in a given biophysical, social, technical and
85 economic context: the territorial context.

86 Our formal definition of a *territorial bioeconomy system* is a territory characterized by the
87 presence of one or several bio-based value chains (e.g. bioenergy plants, bio-refineries) aimed
88 at replacing non-renewable resources and partially dependent on local biomass feedstocks.
89 This territorial bioeconomy system is embedded in: i) a non-specific food and non-food
90 biomass production, use and recycling nexus, dependent on local and global networks; and ii)
91 a local system of activities related to natural resources management and socio-economic
92 development (see Figure 1). This operative concept is in line with the work of Moraine et al.
93 (2017a) on territorial crop-livestock systems. It allows us to operationalize the sustainability
94 assessment framework by focusing on bioeconomy systems' characteristics, while
95 considering their embeddedness into a wider landscape system (Pahl-Wostl, 2017).

96

106 **2. Particularities of bioeconomy systems**

107

108 **2.1. Review methodology**

109

110 In our research, the particularities of bioeconomy systems were identified based on an expert
111 literature review conducted by the different authors, each of whom is specialized in a specific
112 domain related to the bioeconomy. This method allowed us to cover a broad range of issues
113 currently spread across disciplinary or thematic publications. The main domains encompassed
114 by this review are green chemistry, bioenergy, cropping, farming and forestry systems, non-
115 food biomass chains and recycling, sustainability assessment, integrated assessment, and
116 modelling of social-ecological systems.

117

118 **2.2.The complexity of bioeconomy systems that scientists and decision makers struggle** 119 **to grasp**

120

121 **2.2.1. Bioeconomy systems: a new concept, studied by a scattered community**

122 Studies of bioeconomy systems mostly consider them through only one sectorial lens (e.g.
123 increasing biofuel production based on corn, or recycling agro-industrial wastes, or
124 diversifying crop uses), and focus in each case on a different sustainability issue, for instance
125 GHG emissions, carbon storage, land use impacts, energy provision and/or healthy food
126 production (Gabrielle et al., 2018). These studies are consequently scattered across the
127 literature. Scientific journals tend to specialize in one specific issue, such as energy, biomass
128 feedstock production or biodegradable polymers, and there are no leading journals dealing
129 explicitly with the bioeconomy concept as a fully integrated complex and multiscale system.
130 This increases the difficulty of identifying generic bioeconomy system studies and building a
131 scientific community around this subject.

132 Systems that can be considered as bioeconomy systems currently stand at the crossroads
133 between traditional sectors, mainly organized according to a single bio-based value chains, for
134 example agriculture, forestry, energy or process engineering for chemistry and materials
135 (Székács, 2017). The bioeconomy concept has moreover evolved over the years to comply

136 with sustainability requirements, thus progressively integrating circular economy paradigms.
137 While bioenergy and biomaterial production plants have been a growing feature of many
138 regions for a long time, only more recently have there been concerns about the
139 complementarity of biomass feedstock production systems (e.g. regarding ecosystems
140 services, see Therond et al. 2017, and Moraine et al. 2017a) or the optimization of resource
141 use in the transformation processes (e.g. through cascading uses, see Bezama, 2016; Olsson et
142 al., 2018). The territorial or landscape dimension of the bioeconomy, meaning the importance
143 of developing bioeconomy systems at the local level, is also emerging along with the
144 identification of this scale as the most relevant to grasp sustainability issues (Wu, 2013).
145 Hence, there is currently very little knowledge regarding the realistic and integrated
146 conditions of territorial bioeconomy systems development.

147

148 **2.2.2. Multiple stakeholders and partial visions**

149

150 Bioenergy projects' high rates of failure have been documented in the scientific literature
151 (Buchholtz et al., 2009; Han et al., 2008), and examples of such projects that were
152 discontinued or went bankrupt abound (Belfiore et al., 2009). The reasons for these failures
153 are not always well understood. In this respect, the complexity of a territorial bioeconomy
154 project that brings together diverse stakeholders, coupled with and the lack of involvement of
155 local players, seem more decisive than technical issues (Buchholtz et al., 2009). Lewandowski
156 (2015) highlights the fact that the bioeconomy requires a different, unfamiliar, business model
157 compared to the fossil fuel economy, as it is based on different geographical conditions and
158 many disconnected stakeholders. Indeed, the "in between" position of bioeconomy systems
159 induces the development of disconnected projects, in which different stakeholders are in
160 charge of parallel initiatives (e.g. municipal biogas projects supplied by local farmers;
161 biorefineries operated by oil companies) on a wide range of scales from the field/farm to the
162 international level (McCormick and Käberger, 2007; Cooper et al., 1998; Madlener, 2007).

163 Geels' proposition of a multi-level perspective is relevant here to describe the multi-
164 stakeholder layers of bioeconomy systems (Geels, 2002; Geels and Schot, 2007). Therefore,
165 besides the primary actors of the bioeconomy value-chains (regime – e.g.: producer,
166 transformers, users), the bioeconomy system depends on niche-innovation actors (e.g.:
167 scientists, research institutions) proposing new solutions to replace non-renewable resources
168 by biomass (e.g.: bioplastics, pyrogas from biomass) and improve biomass recycling (e.g.:
169 developing nitrifying-enriched activated sludge to improve wastewater recycling systems,

170 Sepehri and Sarrafzadeh, 2018). The bioeconomy system is also under the influence of a
171 sociotechnical landscape, composed of NGOs, political bodies, lobbyists, and influencing the
172 orientation of bioeconomy development. Each bioeconomy stakeholder might have a partial
173 vision of the bioeconomy system, as well as different goals and values (Daher, 2018).
174 The roles of bioeconomy stakeholders and organizations seem less specialized than in
175 traditional globalized food or timber systems (Borras et al., 2016; Therond et al., 2017). For
176 example, farmers are biomass feedstock producers but can also be biomass buyers,
177 transporters and energy producers (e.g.: on-farm biogas plant supplied by on- and off-farm
178 biomass), biomass-based product consumers (e.g. biofuels used for agricultural machinery)
179 and recycling actors (e.g. farmers using biomass transformation waste to fertilize their crops).
180 On the other hand, there is a wide diversity of stakeholders for each role within the
181 bioeconomy system. For example, biomass-based energy production can be produced on farm
182 (e.g. biogas plants), on large scales by companies (e.g. biofuel plants), but also on medium
183 scales by public stakeholders (e.g. municipality heating systems).
184 This complex stakeholder system represents a multi-level governance challenge (Juerges et
185 al., 2018 ; Pahl-Wostl 2017). The required multi-level governance structures and attempts to
186 build a common vision and sustainable management strategy between these stakeholders are
187 still lacking (Pahl-Wostl, 2017).

188

189 **2.3.Importance of policies in the development of bioeconomy systems**

190

191 Under current market conditions and the absence of a clear "peak oil", most bioeconomy
192 systems, especially the production of energy from biomass, do not appear to be price-
193 competitive. Non-food biomass is a low-density and currently low-value product. The
194 development of bioeconomy systems requires the articulation of biomass feedstock
195 production, transport, processing, and use, and is therefore not competitive compared to
196 energetically dense fossil fuels whose transformation processes have been developed over
197 decades and are perfectly controlled. Fossil fuels benefit from a historically built economy of
198 scale, due to mature processes initially developed without environmental constraints and
199 because of the law of diminishing returns (Priefer et al., 2017). The reason for this relative
200 non-profitability of bioeconomy systems on the current markets, especially compared to fossil
201 fuel systems, might lie in the fact that negative externalities, which are considerable for fossil
202 fuel systems, are not taken into account in such analyses (Székács, 2017; Olsson, 2018).
203 Furthermore, as bioeconomy systems must moreover meet sustainability expectations, it is

204 very difficult to assess their profitability only with orthodox market-related profitability tools
205 (net margins based on direct costs and prices).

206 Bioeconomy systems development furthermore relies on policies and public subsidies rather
207 than on completely private initiatives (Lewandowski, 2015). We can consider that one of the
208 most spectacular bioeconomy systems is the use of sugar cane ethanol as biofuel in Brazil,
209 initiated by the PROALCOOL programme in 1975. This initiative was first a political strategy
210 to improve Brazil's energy self-sufficiency. In the last decade, renewable energy policies such
211 as the European Renewable Energy Directive (2009/28/EC - European Parliament and
212 Council, 2009) have also been implemented elsewhere to improve the sustainability of the
213 energy supply (Priefer et al., 2017). The increase of biofuels incorporated into conventional
214 fuel or bio-based electricity is supported in such cases by preferential price regimes and
215 mandatory incorporation rates.

216 Olsson et al. (2018) highlight the fact that, regarding bioeconomy systems, a difference
217 should be made between market value and inherent value in order to properly inform decision
218 makers and potential investors. The criterion of market profitability with respect to fossil
219 systems, excluding negative externalities, seems to be irrelevant to bioeconomy systems,
220 since these systems are developed under political impetus for environmental sustainability or
221 energy sovereignty. There is therefore a need for indicators that reflect more fundamental
222 properties than supply and demand.

223

224 **2.4.Variability, flexibility and rigidity inherent to bioeconomy systems**

225

226 Most of the scientific literature on bioeconomy systems or biomass feedstock production
227 focuses on a "one product" and/or "one resource" view of the bioeconomy (Gabrielle et al.,
228 2018), and research and development in industry is mostly value-chain driven; Yet alternative
229 resources and process flexibility are major characteristics of bioeconomy systems.

230

231 **2.4.1. Biomass feedstock diversity and variability**

232

233 Territorial bioeconomy systems can be based on a portfolio of alternative biomass feedstocks.
234 In the EU, biomass feedstock production is around 1.5 million tons per year, distributed
235 between agricultural biomass (economic and residue production; respectively 471,928 and
236 436,856 thousand tones DM in 2013), fisheries biomass (1,459 thousand tones FM in 2013),
237 algae biomass (143 thousand tones FM in 2013), forest biomass (511,544 thousand tones DM

238 in 2013) and waste biomass (91,435 thousand tones DM in 2012; European Commission,
239 2019). Non-food biomass feedstocks, representing around two thirds of the total biomass
240 produced in the EU, can be discriminated according to their origins and/or uses, for example
241 first-generation or recycled biomass feedstocks, dedicated or flexible biomass feedstocks,
242 main product or co-products, or agricultural, forest-based, or organic waste products. Some
243 biomass feedstocks can be dedicated to non-food purposes (e.g.: sludges, forest biomass,
244 dedicated energy crops) and others not (e.g.: cereals, oil bearing crops). Flex-crops are plants
245 cultivated for several purposes: not only food or non-food markets (Kline et al., 2017; Borrás
246 et al. 2016) but also different non-food markets. For example, triticale (*Triticosecale Wittm.*,
247 Poaceae) or oil palm (*Elaeis guineensis Jacq.*, Arecaceae) can have several uses, depending
248 on market opportunities. Triticale grains are mostly used for animal feed, whereas triticale
249 straw can be used for bedding, heat and/or power, biogas, or as construction material, or can
250 even be returned to the soil for carbon storage. Palm oil can be used for food purposes and
251 also as a first-generation biofuel, whereas fruit stalks can be used for second generation
252 bioethanol, heat and electricity production, or be returned to agricultural lands as organic
253 inputs (Bessou et al., 2011). On the other hand, dedicated crops have a limited range of uses.
254 For example, *Miscanthus x giganteus*, a perennial crop, remarkable for its productivity under
255 low-input (N fertilizer, pesticides) management (Lewandowski et al, 2000, 2003), is mostly
256 used for energy production and has no food use.

257

258 From a farmer's perspective, establishing a crop dedicated to either food or non-food
259 production commits land to one type of market (food or non-food), while flex-crops create the
260 opportunity of choosing the end-use of one crop, depending on market conditions in the short
261 term. The development of territorial bioeconomy systems should also increase the range of
262 potentially marketable crops with new bioeconomy-oriented crops (energy crops, fiber crops)
263 and will enable farmers to diversify their cropping systems. Increasing the diversity of plant
264 covers and the length of rotations enables them to provide ecosystem services such as
265 regulatory services associated with pest control (Krupinski et al, 2002) or crop production
266 (Bennett et al, 2012). Crop diversification can also help to improve the resilience of
267 agroecosystems to the vagaries of climate and prices (Lin, 2011).

268

269 From the transformation point of view, crops and all non-food biomass materials are
270 composed of the same building blocks (lignin, cellulose and hemicelluloses) constituting the
271 plant cell walls. This material is known by the generic term "lignocelluloses". Lignocellulosic

272 biomass feedstocks can therefore be classified according to their composition (Krasznai et al.,
273 2018; van der Weijde et al., 2017). For instance, woody biomass feedstocks issued from
274 forestry systems are composed of large amounts of lignin (20-28%), whereas biomass from
275 agricultural systems can have lower or more variable amounts of lignin, depending on the
276 crops and/or the crop part used: i.e. short rotation coppices (SRCs), stem or leaves from
277 perennial plants like *Miscanthus x giganteus*, or triticale show an amount of lignin ranging
278 from 20% to 5%. In addition to the gross chemical composition of the lignocellulosic biomass
279 (lignin, celluloses hemicelluloses, mineral content, etc.), the quality of the biomass feedstock
280 depends also on morphological and structural parameters, such as the integrity of the plant
281 stem/organs or the state of degradation after harvesting or storage stages. These quality
282 criteria can change the physical and chemical access to the polymers and molecules of interest
283 for applications, and will impact further transformation pathways into fiber, polymers or
284 molecules in biorefineries and for energy production routes (van der Weijde et al., 2017).

285 There is a trade-off between biomass quality and specific valuation processes that influence
286 the number of technical steps (extraction, purification, effluent treatments or valorization, etc)
287 hence the efficiency and the price of the transformation process (Lynd et al., 2017). For
288 example, heat and power production processes based on combustion can be engineered to use
289 different biomass products such as straw, whole plants (e.g. triticale or *Miscanthus x*
290 *giganteus*) or wood (Pang et al., 2018). Regarding biomass combustion, quality is generally
291 based on biomass chemical composition, particularly lignin content, moisture content and
292 physical characteristics like particle size.

293 For more integrated biorefinery systems, biomass quality management is more complex and
294 variable. Such biorefineries extract several separated compounds from the biomass in
295 cascades. Each compound requires specific characteristics for further use (molecules' purity;
296 specific molecular mass for polymers; presence of inhibitors for fermentescible sugars).
297 Transformation units then have to manage biomass feedstock quality trade-offs regarding
298 these different requirements.

299 Finally, using biomass feedstock of different nature and/or origin in the production process
300 can be an option to improve supply flexibility according to markets and availability, if the
301 industrial process is tailored to a wide range of feedstocks (Borras et al., 2016).
302 Transformation units have then to manage additional biomass quality variations linked to
303 production and transport conditions of each biomass feedstock type and origin (i.e. climate or
304 management variabilities) (see 2.5.1.).
305

306 In conclusion, biomass feedstock producers and transformers can then choose to produce and
307 use either only one specific type or several types of biomass feedstocks, depending on their
308 process constraints and objectives and for stability or flexibility purposes. The diversity and
309 variability of biomass value-chains and biomass feedstock flows are thus key characteristics
310 of a territorial bioeconomy system. The management of this diversity and variability in order
311 to achieve sustainability objectives and ensure economic viability is one of the great
312 challenges for territorial bioeconomy systems. However, it also provides managers with
313 flexibility opportunities to deal with the variability of endogenous and exogenous contexts,
314 and thus to increase the resilience of bioeconomy systems.

315

316 **2.4.2. Rigidity and co-dependencies**

317

318 Aside from diversity and variability, there are also dependencies that are entailed by specific
319 biomass value-chains and that generate rigidity. For example, cascading uses of forest
320 biomass theoretically places the priority on timber production (Vis et al., 2016). Once timber
321 is extracted, the rest of the forest biomass is considered as residue (e.g. products of early
322 thinning, small branches and leaves) that can be used for energy or chemistry purposes. The
323 type of wood available for uses other than building material is then limited and can constrain
324 the applicable transformation processes and therefore possible uses. Moreover, the quantity of
325 timber exploited will determine the quantity of residues available for other uses. As decision-
326 making on forest biomass harvesting is quite flexible compared to agricultural crops, which
327 have to be harvested every year (Sourdril et al., 2012), co-dependency of forest residues and
328 timber production can increase uncertainty on biomass feedstock availability.

329 More generally, there is a co-dependency between territorial bioeconomy systems, food
330 systems and traditional biomass-based systems that might be managed according to their own
331 objectives and constraints. These systems can share biomass feedstocks, biomass harvest and
332 transport logistics, and transformation plants (e.g. sugar cane transformation plants' energy
333 can be supplied by sugar cane residues; storage facilities can be shared between various
334 biomass feedstocks), as well as recycling logistics, processes and end-uses (e.g. digesting
335 food processing waste in a biogas unit).

336

337

338 **2.5. Spatio-temporal organization of bioeconomy systems**

339

340 The multiplicity characterizing bioeconomy systems implies a consideration of the
341 dependence between biomass feedstocks, processes and uses, given the temporal dynamics
342 and spatial patterns of each of its components.

343

344 **2.5.1. Bioeconomy spatial patterns**

345

346 Many studies dealing with the spatial distribution of land-based biomass feedstock production
347 assume that it follows biophysical land production potentials (Rizzo et al., 2014). Forest or
348 perennial non-food biomass crops are often supposed to be grown in low production potential
349 soils (i.e. marginal soils) while fertile soils are preferentially dedicated to food crops, either
350 according to the “food first” principle or based on economic assumptions that non-food
351 feedstocks are less profitable than food crops (Dauber and Miyake, 2016; Bogdanski et al,
352 2010). Although this kind of assumption is useful for understanding global tendencies (Heck
353 et al., 2018), at the territorial scale biomass feedstocks’ spatial distribution actually stems
354 from the interaction of biophysical factors influencing productivity with producers’
355 characteristics (e.g.: size of the estate), strategies regarding crops or biomass feedstocks
356 spatial allocation, territorial scale logistical issues such as the location of water supplies or
357 roads (Poggi et al., 2018, Martin et al., 2012) and historical legacy (Genin et al., 2013). This
358 complexity leads to a large variety of biomass feedstock spatial patterns in specific territories.
359 Even when limited to one type of biomass feedstock, for example forest biomass, the diversity
360 of landscape patterns is wide, as forests range from small-scale parcels to much larger
361 expanses. According to a survey in nine European countries, forest parcels less than 1ha in
362 size accounted for 61% of private forest parcels in 2006-2007, and forest parcels more than
363 100ha in size for 30% (UNECE, 2010). These parcels can also be spatially aggregated or
364 scattered across the landscape following a more or less regular pattern.

365 Regarding biomass uses and transformation, non-food biomass can be used at different spatial
366 scales, from the farm (e.g. biogas unit) to an international scale (e.g. large-scale biofuel
367 production units based on imported resources). In between, several individual, collective or
368 industrial initiatives for non-food biomass uses exist, such as collective heating systems based
369 on local forest production (McCormick and Käberger, 2005), or regional co-generation plants
370 based on local and imported biomass feedstocks (Thrän et al., 2017). Every biomass
371 transformation plant defines its own strategy according to its goals (collective heating, oil

372 market, etc.). In a given territory, these different transformation units may share parts of the
373 biomass feedstock resources, markets and biomass residue recycling opportunities.

374
375 At global scale, biomass flows between world regions are significant. For example, wood
376 pellets imported for EU consumption, mostly from North America, accounted for almost 30%
377 of the total pellets consumed in the EU in 2014 (World Energy Council, 2016; Thrän et al.,
378 2017). Biomass feedstocks' growth conditions vary around the world, and especially between
379 temperate and tropical regions. Biomass transformers are tempted to import biomass
380 feedstocks to limit the costs and to ensure a steady supply of a certain type and quality of
381 biomass feedstocks. On the other hand, high rates of biomass feedstocks exports could locally
382 limit the development of territorial bioeconomy systems. It is important to examine the global
383 bioeconomy spatial patterns, that is, the spatial distribution of biomass feedstock production,
384 transformation and uses around the world, if we are to understand territorial bioeconomy
385 systems' functioning. In other words, it is important to take on board indirect land-use
386 changes (Searchinger et al., 08) and, more generally, telecoupling effects (Liu et al., 2015)
387 between world regions via physical or economic processes.

388 389 **2.5.2. Time-scale discrepancies**

390
391 Biomass feedstock production is dependent on climate and ecosystem services such as
392 nutrients, water and biological regulation. The time scales of biomass feedstock production
393 and natural cycles can be very different. As several authors have pointed out, trade-offs have
394 to be acknowledged between provisioning (i.e. increasing biomass production) and supporting
395 (i.e. nutrient cycles, water cycle) ecosystem services (Juerges et al., 2018). Addressing this
396 time-scale discrepancy between production and natural cycles is particularly important with
397 regard to bioeconomy systems because the increase of biomass production needed to meet
398 bioeconomy goals increases the tensions between these short- and long-term processes.

399
400 Regarding primary land-based biomass feedstock production, agricultural biomass production
401 cycles range between less than a year (e.g. intercrop cycles, such as sorghum sown in
402 summer, are around three to four months in France) and a decade (e.g.: *Miscanthus x*
403 *giganteus* can be grown for fifteen to twenty years). By contrast, forest biomass production is
404 managed in a time frame of between ten and a hundred years, due to the slow growth rate of
405 trees. Considering a diversified territorial bioeconomy system, biomass feedstock harvest and

406 production can vary from intra-annual to pluri-annual cycles. Biomass feedstock producers'
407 strategies regarding the choice of the feedstock produced and the scheduling of technical
408 operations (e.g. forest thinning, type of harvest) can then be short-term for annual crop
409 production or very long-term in the case of forests.

410 These time-scale discrepancies regarding biomass feedstock availability also depend on
411 producers' behaviors when it comes to planting and harvesting biomass feedstocks. Biomass
412 producers show a range of behaviors, ranging from risky to conservative, depending on the
413 type of biomass feedstock produced, their own strategic profile, and the type of growers
414 (Bocqueho et al., 2014). For example, as the window for harvesting forest biomass is wide
415 (several years), forest managers' willingness to harvest forest biomass is a key factor to
416 understanding biomass feedstock availability dynamics (Erickson et al., 2002; Nordström et
417 al., 2010).

418

419 From a biomass transformer's point of view, ensuring the stability and regularity of the
420 biomass feedstock supply for a biomass transformation plant requires one to take this
421 diversity of production cycles into account. The duration for which harvested biomass
422 feedstock can be stored, depending on the storage system and biomass feedstock quality - for
423 example between fresh or dry feedstock -, should be factored into supply strategies. In
424 addition to inherent characteristics of biomass feedstocks (see 2.4.1.), external hazards can
425 also impact their availability dynamics, as can climatic events or market opportunities.

426 Concomitantly, the transformation activities in a bioeconomy have to comply with various
427 time frames: short-term, for the competitiveness of the industries involved in the
428 implementation of the bioeconomy; mid-term, for their capacity to adapt to new political,
429 technological and societal constraints (i.e. food safety, zero petroleum-based plastics); and
430 long-term, for the application of innovation processes in industrial integrated systems (e.g.
431 reusable and recyclable biomass-based products). Biomass-based products have to be
432 considered as the result of dynamic innovation processes where technical progress will open
433 up new opportunities to better exploit the biomass potential for food and non-food goods, as
434 well as new services. The dominant solutions proposed today in all subsystems may be
435 discontinued or adjusted, according to innovations, and at different time scales.

436

437

438 **2.5.3. Importance of logistics in bioeconomy systems**

439

440 Managing biomass flows in a bioeconomy system implies the development and adaptation of
441 logistical infrastructures able to regulate different production and consumption times and
442 spatial frames. Logistics is considered to be a bottleneck when dealing with multiple, spatially
443 scattered biomass feedstock resources (Perrin et al., 2017; Lewandowski; 2015). The low
444 density of biomass feedstocks compared to fossil fuels, for example, implies the improvement
445 of logistical solutions in order to manage associated costs (e.g. spatial configuration of
446 biomass feedstock processing / densification units). Biomass feedstock storage is usually a
447 critical issue in the economics of bio-based value chains, in that it is supposed to buffer
448 differences between seasonality of harvesting periods and of the demand for biomass-based
449 products (Kaut et al., 2015).

450 By adapting biomass transformation processes so that they can accommodate a flexible mix of
451 biomass feedstocks with different cycle lengths, harvesting time windows, market
452 opportunities or conservation dynamics, could allow biomass transformers to adjust their
453 operation to fluctuating conditions, rather than relying on a single biomass feedstock or
454 importing biomass from overseas. Moreover, organizing territorial bioeconomy systems based
455 on the industry 4.0 principles, especially interconnection and decentralized decisions and
456 partial reliance on artificial intelligence to solve these complex logistical problems could
457 improve the overall optimization of biomass uses (Salminen et al., 17).

458

459

460 **3. Conceptual framework to assess bioeconomy systems' sustainability**

461

462 **3.1 Sustainability issues inherent to bioeconomy systems**

463

464 Since the 2008 food crisis, environmental impacts and displacement effects from food to non-
465 food biomass production, inducing direct and indirect land use changes, have been under
466 scrutiny (Cherubini et al., 2009; Searchinger et al. 2008). The magnitude of these effects has
467 been widely debated in the scientific community and policy arenas over the last decade, and
468 led the EU, for example, to cap its production of first-generation biofuels in 2015 after having
469 promoted it with the 2009/28/EC directive (European Parliament and Council, 2009). This
470 decision, which was based on the precautionary principle in the absence of an objective

471 framework capable of assessing this kind of impact, sent conflicting messages to bioeconomy
472 developers and society.

473

474 A holistic sustainability assessment framework for the bioeconomy therefore seems to be
475 critical to stabilize policies regarding it, and to ensure its sustainable development. As
476 highlighted in the introduction, aside from replacing non-renewable by bio-based products,
477 sustainable bioeconomy systems seek to reach objectives regarding food security (quantity,
478 quality and availability), restoration or conservation of natural resources (including ecosystem
479 services and biological diversity), economic competitiveness and, more generally, well-being.
480 The notion of bioeconomy encourages reflection on trade-offs between objectives at a much
481 higher level of complexity than in a single bio-based value chain view (energy production,
482 food production) or even in the Water-Energy-Food nexus (Daher, 2018; Pahl-Wostl, 2017).

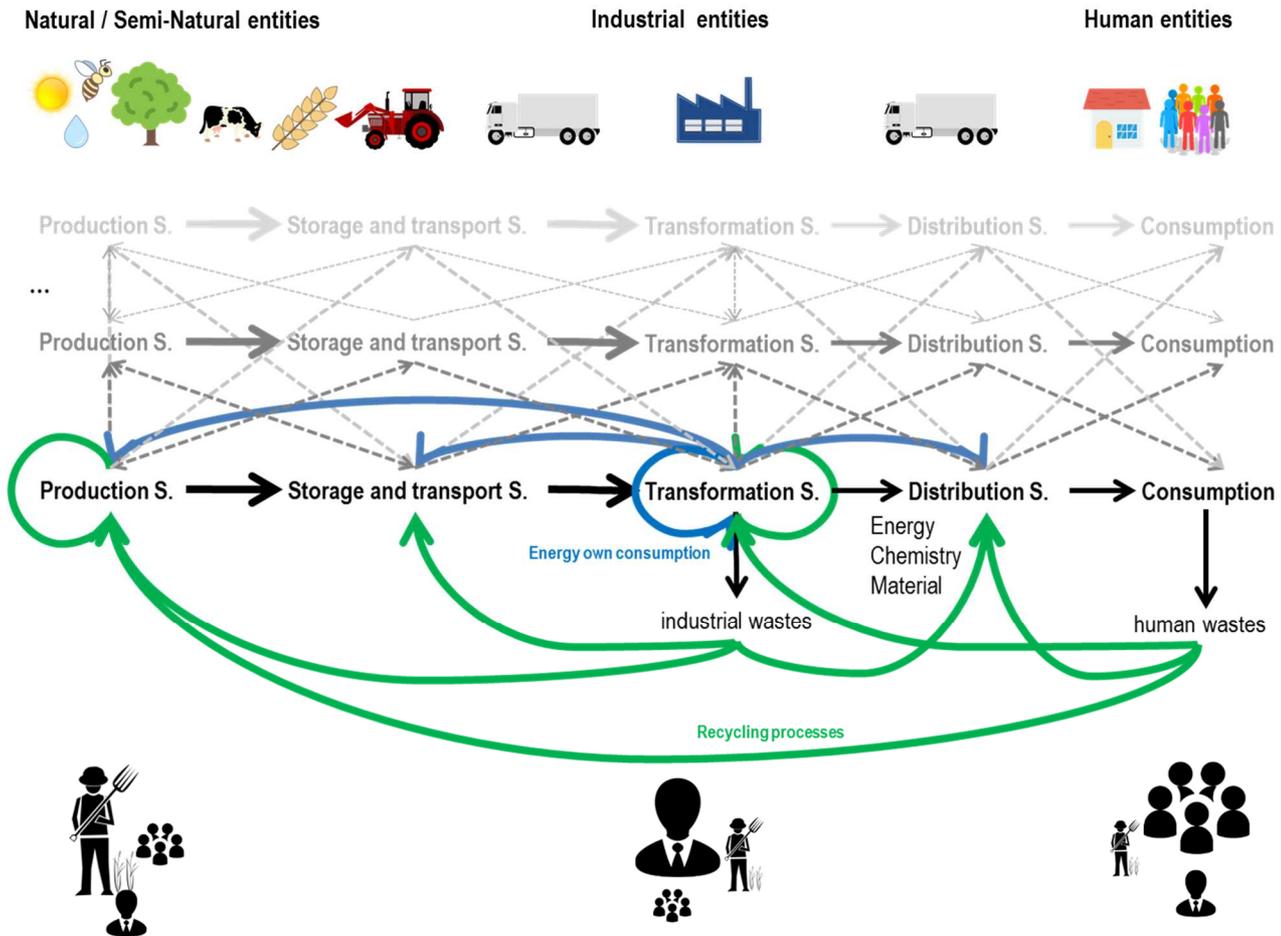
483

484 **3.2. Analytical framework of bioeconomy systems' sustainability issues**

485

486 As seen above, the entanglement of resource uses, and of the production, uses and recycling
487 of biomass-based products, along with stakeholders' roles and scales of action in a
488 bioeconomy system creates a high level of complexity. To assess and ensure bioeconomy
489 systems' sustainability, it is necessary first to develop an analytical framework to foster a
490 sharable understanding of the way territorial bioeconomy systems function (Berndes et al.,
491 2008; McGinnis and Ostrom, 2014). Like Jones et al. (2016), we think that such a
492 representation may help clarify where efforts are needed to improve system sustainability. In
493 the following section, we present two complementary representations (non-equivalent
494 models) of territorial bioeconomy systems, each providing key insights to decipher their key
495 characteristics regarding sustainability.

496

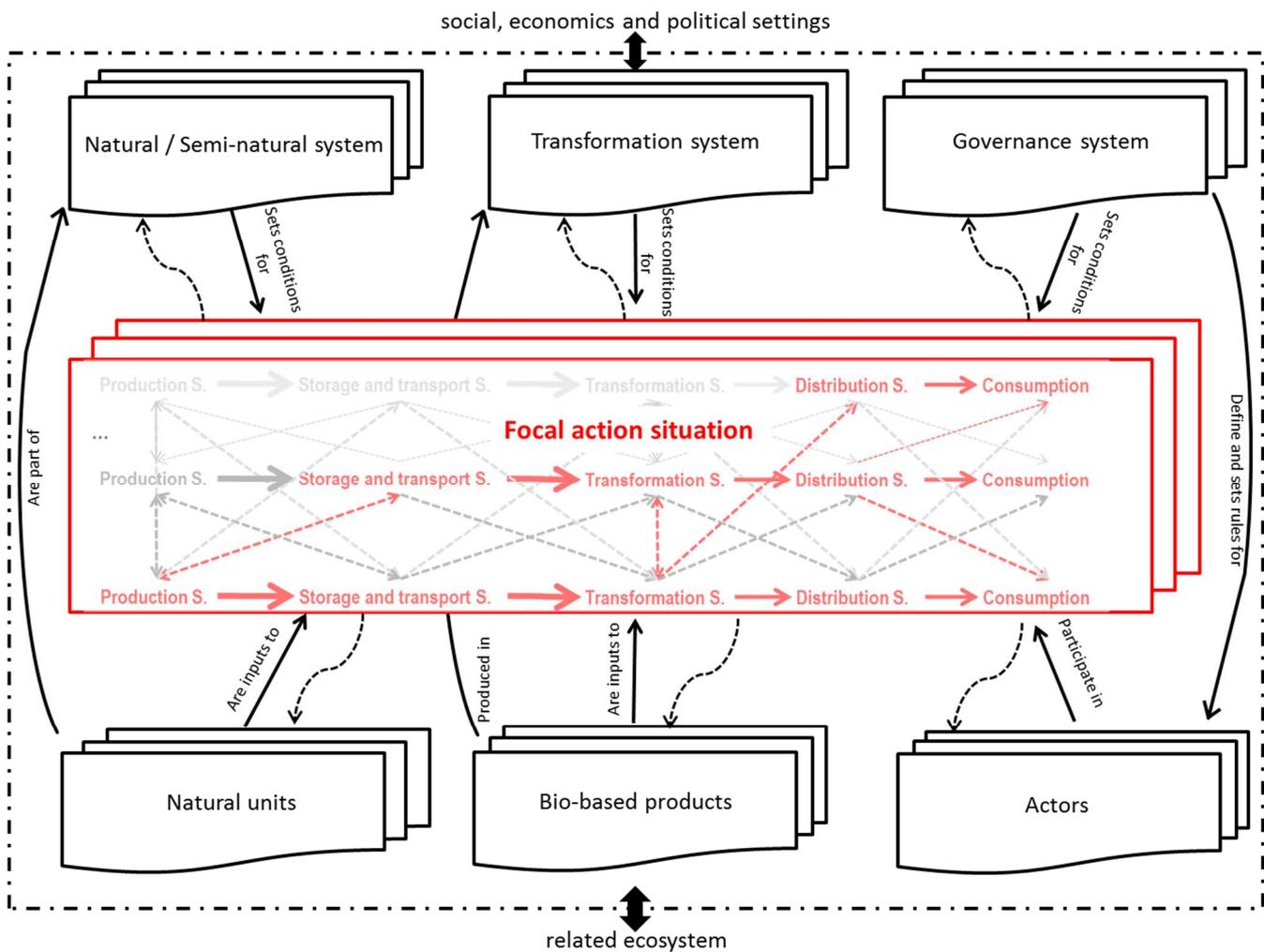


497

498 **Figure 2:** Bioeconomy system functioning and organization

499 *Sub-systems, biomass flows, stakeholders and main entities of a territorial bioeconomy system. S. stands for*
500 *System. Arrows represent solid biomass flows. Green arrows represent biomass flows linked to the recycling*
501 *process, and blue arrows represent biomass flows for energy own consumption options. Dotted arrows represent*
502 *potential biomass transfers between bio-based value chains. The bioeconomy system encompasses entities of a*
503 *different nature (human, industrial, natural, semi-natural). Examples illustrating the diversity of bioeconomy*
504 *entities are given by the icons at the top of the figure. Stakeholders directly involved in the bioeconomy value*
505 *chain are diverse and their relative participation varies regarding the subsystem considered. Icons at the bottom*
506 *of the figure represent the three main categories of bioeconomy stakeholders: biomass feedstocks*
507 *producer/farmers* , *companies* , *local communities* . *The size of each icon represents the relative*
508 *importance of each type of stakeholders in the different bioeconomy subsystems. The biggest icon represents the*
509 *fact that this type of stakeholder plays an important role (farmers for the biomass production step, companies for*
510 *the transformation step and local communities / society for the consumption step), the fact that the three*
511 *categories of stakeholders are represented for each step illustrate the diversity of roles each stakeholder can*
512 *play in the bioeconomy system.*

513



515

516 **Figure 3:** Bioeconomy system as a social-ecological system

517 *This figure is adapted from Marshall (2015) and McGinnis and Ostrom (2014). Each specific bioeconomy*
 518 *system (i.e. focal action situation) is determined by natural, transformation and governance systems and entities*
 519 *(natural units, biomass-based products, bioeconomy stakeholders). Feedbacks (dotted arrows) account for*
 520 *transformation/influences from the focal action situation to first-tier components of the social-ecological system.*
 521

522 Figure 2 is an attempt to represent a bioeconomy system structure composed of several
523 interacting bio-based value chains. Here we consider that a bioeconomy system is composed
524 of several bio-based value chains, each composed of several subsystems inter-related through
525 biomass flows: production system, storage and transport system, transformation system,
526 distribution system, consumption. As highlighted above, these subsystems are articulated in a
527 complex way (i.e.: a wide range of subsystem interactions are possible, yielding unexpected
528 emerging properties), and their sustainable interactions with natural resources are at stake.

529 Bioeconomy systems encompass different type of entities and processes: natural or semi-
530 natural entities such as soil-plant systems allowing biomass feedstock production; industrial
531 entities such as biomass transformation plants and logistical systems; or social entities such as
532 energy consumption networks.

533 The circularity of biomass flows is central, due to the need to preserve or restore natural
534 resources (including ecosystem services). Recycling processes as well as energy own
535 consumption along and across bio-based value chains are key elements to ensure sustainable
536 bioeconomy systems. Accordingly, the development of territorial bioeconomy systems is
537 convergent with the objectives of the circular economy. Industrial ecology is therefore a key
538 to downscale bioeconomy general principles to the biomass transformation system, as the
539 optimal transformation processes' organization to limit waste. (Belletante et al., 2016; Borrás
540 et al., 2016; D'Amato et al., 2017).

541 The multiplicity of stakeholders involved in bioeconomy systems is partially shown in figure
542 2 but the representation of the diversity and overlapping roles of these stakeholders remains
543 challenging. Moreover, this figure represents only the primary actors of bioeconomy systems.
544 Niche-innovation or sociotechnical landscape-related actors (e.g.: NGOs, research
545 institutions) are not represented, for the sake of clarity, even though their impact on
546 bioeconomy systems is crucial.

547

548 Figure 3 shows the structure of a bioeconomy system according to a now classical
549 representation of first-tier components (or attributes) and focal situation actions of social-
550 ecological systems (McGinnis and Ostrom, 2014 ; Marshall, 2015). Complementary to Figure
551 2, Figure 3 highlights the key components that determine bio-based value-chain
552 configurations and interactions, including the different governance systems. Embracing the
553 extended vision of social-ecological systems proposed by Marshall (2015), we explicitly
554 consider biomass transformation systems and biomass-based products as first-tier attributes of
555 the bioeconomy system. Considering all territorial bioeconomy systems' first-tier attributes as

556 either semi-natural or governance-related does not seem precise enough, as industrial
557 processes or biomass feedstocks and biomass-based products distribution logistics are
558 important for addressing sustainability and bioeconomy development issues. Therefore,
559 considering transformation systems as part of the social-ecological system allows us to
560 propose a more accurate solution for market-integrated systems such as bioeconomy systems,
561 by eliciting the transformation-dependent situations in relation to natural and governance
562 systems.

563

564 In conclusion, these two representations point out that, the interconnections between biomass
565 value-chains, the circularity of biomass and energy flows, the heterogeneity of processes and
566 entities of the system, the diversity of stakeholders, and the importance of the biomass
567 transformation sub-system and the logistics are key issues to approach bioeconomy systems'
568 sustainability.

569

570 **4. Scientific and methodological proposal for investigating the sustainability of** 571 **bioeconomy systems**

572

573 As very significant growth of the bioeconomy is expected in the future, we have to be able to
574 anticipate territorial bioeconomy systems' behavior, impacts and developments. Therefore, in
575 addition to the analytical framework of bioeconomy systems' structure and functioning
576 proposed above, managing and designing sustainable bioeconomy systems calls for adapted
577 methodologies to understand and capture the dynamics involved.

578

579 **4.1.Necessity of an integrated assessment and modeling approach**

580

581 Embracing the complexity of the Food-Non-Food-Natural Resources nexus in territorial
582 bioeconomy systems requires the development of multi-criteria, multi-level, ex-ante
583 assessment approaches that identify tradeoffs and synergies intra- or inter-nexus as well as
584 between sustainability domains (Therond et al. 2017). An integrated assessment and
585 modelling (IAM) approach seems to be the appropriate methodology to address bioeconomy
586 systems' sustainability (Hamilton et al. 2015; Ewert et al. 2011). It corresponds to a structured

587 modelling-based way to integrate knowledge and to investigate ex-ante environmental, social
588 and economic impacts of scenarios of the possible futures of social-ecological systems.

589

590 Regarding the characteristics of territorial bioeconomy systems highlighted in Parts 2 and 3,
591 the integrated modelling approach should explicitly take into account: i) the different sub-
592 systems of territorial bioeconomy systems, their high level of interactions, their heterogeneity
593 in terms of entities and processes involved, and the circularity of matter and energy
594 (production, transformation, use and recycling), with particular emphasis on the
595 transformation sub-system and the logistics; ii) the multiplicity and flexibility of stakeholders'
596 nature, strategies and concerns; iii) the variety of spatial organization and temporal scales
597 involved; and iv) the effects of exogenous drivers like supra-regional policies and regulations,
598 markets (e.g. prices of energies and biomass-based products) and climate.

599

600 **4.1.1. Modelling frameworks to assess bioeconomy systems' sustainability**

601

602 Being able to model a territorial bioeconomy system to assess and anticipate its sustainability
603 requires the combination of several modelling frameworks in the IAM approach.

604 First, spatially explicit modelling seems especially well-suited as bioeconomy systems are
605 strongly linked to and dependent on the landscape composition and configuration (e.g. soil-
606 vegetal cover-climate interactions; impacts on natural resources; ecosystem services; logistic
607 aspects see 2.5) (Parrott et al., 2012; Wu, 2013). Spatially explicit modelling will be a central
608 tool to manage the spatial organization of productions, bio-based value chains and, more
609 generally, territories, and will help manage the optimization of uses and the alignment of the
610 objectives of food and non-food production and natural resource conservation.

611 Second, different dynamic models have to be used to model the variety of dynamics and the
612 associated temporal scales involved in bioeconomy systems, such as the seasonality of
613 biomass feedstock productions, harvesting, markets for biomass-based products, or the
614 logistics of biomass supply (see 2.5.2).

615 Third, agent-based models are used to simulate the dynamics of social-ecological systems
616 (Rounsevell and Arneth, 2011) as they can simulate the strategies of various types of
617 stakeholders in relation to their own action situation (Parrott et al., 2012), the evolutionary
618 learning and out-of equilibrium dynamics (Filatova et al., 2013), and reveal emergent
619 properties and processes at different levels (Grimm et al., 2006) Agent-based models are then
620 central tools to consider modelling territorial bioeconomy dynamics.

621 Forth, considering the importance of logistics in bioeconomy systems sustainability (see
622 2.5.3), the modelling of the logistics - usually based on the minimization of operating costs
623 (Gold and Seuring, 2011)-, should feature in other criteria that are relevant to assess
624 bioeconomy systems' sustainability, such as environmental impacts (e.g. fossil energy
625 consumption, greenhouse gases emissions), or social criteria (e.g. employment, operators'
626 welfare) (Perrin et al., 2017; Poggi et al, 2018).

627 Fifth, indirect effects of bioenergy systems occurring beyond the region where they operate,
628 through telecoupling, should also be taken on board (see 2.5.1., Liu et al., 2015; Verburg et
629 al., 2016).

630 Sixth, the IAM approach will require the development of specific multi-criteria assessment
631 (MCA) methods that allow for systematic comparison and ranking of alternative scenarios
632 according to environmental, social and/or economic indicators for improving stakeholders'
633 decision making processes (see 2.2.2.). The wide range of spatial and temporal scales and
634 dimensions encompassed by territorial bioeconomy systems challenges MCA methods, as it
635 requires them to integrate both multiple criteria, multiple organizational levels, and the spatial
636 dimension (Allain et al. 2017).

637

638 **4.1.2. Improving bioeconomy system monitoring**

639

640 To be effective, the IAM approach has to be supported by high quality data from detailed
641 monitoring of bioeconomy systems at local and global scales. Due to the wide variety of
642 domains using non-food biomass feedstocks (biofuels, biomaterial, chemistry), and the
643 relatively recent interest in bioeconomy systems as such, detailed data on real biomass
644 feedstocks, flows and uses in bioeconomy systems are still scant. Efforts are needed to
645 provide reliable data on the wide range of current and prospective uses and co-uses of these
646 resources (e.g. location and supply plans of current biomass feedstocks users, potential of
647 biomass transformation processes) and on the various biomass recycling processes. Dedicated
648 local and global bioeconomy data monitoring and databases have to be developed.

649 On-going international initiatives currently pursue the goal of harmonizing models and
650 methodologies to factor into land-use change effects (Lotze-Campen et al., 2014), and may
651 provide data to better approach trade-offs between local and global bioeconomy systems.
652 Increasing digitalization in biomass production, transformation, uses and recycling processes
653 should improve the monitoring of the whole bioeconomy system. The IAM approach could
654 then be integrated in a "smart industry"-like organization of territorial bioeconomy systems,

655 allowing more decentralized, automated and intelligent solutions for a sustainable
656 bioeconomy.

657

658 **4.2. Involving stakeholders in the IAM approach**

659

660 **4.2.1. Sharing visions on bioeconomy systems**

661

662 Assessing sustainability of bioeconomy systems, being able to anticipate the future, i.e. the
663 IAM approach, and operating transitions towards a more sustainable bioeconomy system have
664 to rely on stakeholders' vision and expectations. Stakeholders have to share a common vision
665 of the current and future system to coordinate their actions and to manage cascading effects
666 (Duru et al., 2015).

667 In the case of territorial bioeconomy systems, this issue is especially critical as the transition
668 to a more sustainable bioeconomy relies on a massive reorganization - from linear to circular,
669 from sectorial to cross-sectorial - and must include a wide range of stakeholders, from
670 producers to consumers. In this shared-vision development process, stakeholders and
671 scientists will have to define common and quantifiable objectives and performances that will
672 ensure territorial bioeconomy sustainability (Caron et al, 2014) and underpin the sustainability
673 assessment of the IAM approach. Reaching this shared vision of the bioeconomy system
674 requires that stakeholders i) understand the functioning of the system as a whole and ii)
675 transcend their individual interests.

676 Compared to other natural resource management issues (e.g.: water catchment protection,
677 biodiversity conservation), the entanglement of biomass value-chains, and the diversity of
678 entities and processes (see Part 3.) of bioeconomy systems require further efforts for
679 stakeholders to reach this common understanding. The heterogeneity and multiple roles of
680 stakeholders in the bioeconomy system (see 2.2.2.) may emphasize the importance of
681 cognitive dissonance generally observed when individuals have to make choices regarding
682 collective issues (Duraiappah et al., 2014). This mis-match of values and interests might lead
683 to inconsistent or conflicting decisions when collective organization is needed.

684

685 **4.2.2. Methodological proposals**

686

687 To trigger a shared vision of the bioeconomy system in the IAM approach, we call for
688 participatory processes. Stakeholders' participation throughout conceptualization, modelling

689 and assessment of the territorial bioeconomy system and future scenarios ensures: (i) that the
690 multiplicity of interests and issues of the whole territorial bioeconomy system are considered;
691 (ii) that the required generic and local knowledge is integrated into a consistent representation
692 of the system; and (iii) that participant stakeholders are helped to grasp the underlying
693 assumptions, limitations and capabilities of the integrated model (Voinov and Bousquet,
694 2010; Voinov et al. 2016). More operationally, participatory processes will have to be
695 employed at least at three crucial steps of the IAM implementation process, for the co-
696 development of: (i) a shared and integrated representation model of the current situation (e.g.
697 Murgue et al. 2016; Moraine et al. 2017b); (ii) scenarios of endogenous and/or exogenous
698 changes (Leenhardt et al. 2012; Therond et al. 2009); and (iii) the integrated assessment of
699 scenarios (Moraine et al. 2017b; Allain et al. 2018).

700

701 Moreover, increasing shared knowledge on how each bioeconomy stakeholder makes
702 decisions regarding their own and collective issues regarding bioeconomy systems (e.g.: self-
703 profit and a collective biomass resource management) is an important step to capture
704 cognitive dissonance and try to resolve it. For example, the importance of cross-sector
705 collaboration regarding the forest products industry has been highlighted in several studies, as
706 forest-based resources' optimal valuing can require processes of different natures (e.g.
707 physical, chemical, biological), and therefore collaboration between existing sectors
708 (Guerrero and Hansen, 2018).

709

710 **5. Conclusion**

711

712 Bioeconomy systems' current sustainability assessment studies tend to be based on a limited
713 view of the bioeconomy, focused on single bio-based value chains. They fail to offer an
714 integrated approach to the territorial system under review. This narrow perspective produces a
715 partial consideration of bioeconomy system's functioning, and of alternatives and
716 sustainability issues which can generate controversies that discredit the potential of the
717 bioeconomy for society as a whole. A specific sustainability assessment framework that takes
718 into account bioeconomy systems' complexity is therefore needed to help decision and policy
719 makers. We have highlighted key characteristics of territorial bioeconomy systems, such as
720 the lack of knowledge surrounding the bioeconomy itself, the importance of policies for
721 bioeconomy development, the variability and flexibility characterizing bioeconomy systems,
722 and, more precisely, the multiplicity of resources and transformation processes, the co-

723 dependencies between bio-based value chains, and the specific spatial and temporal patterns
724 of bioeconomy systems. Based on this description, we have proposed an analytical framework
725 informed by two representations of territorial bioeconomy systems that are useful to describe
726 and decipher their organization and functioning, and to identify critical levers for
727 sustainability. Finally, we have outlined a specific IAM approach to explicitly account for the
728 diversity of stakeholders involved in bioeconomy systems, the range of options available to
729 produce and transform biomass, and the interface of the human and technological components
730 of these systems.

731 The next step will be to implement this IAM approach in territories, which will require: i)
732 pluridisciplinary collaboration, especially regarding the coupling of models (biomass
733 feedstock growth models, logistics optimization models, economic models, etc.), and ii) the
734 involvement of all bioeconomy-related stakeholders.

735 While the IAM approach should help local and relatively short-term decision making
736 regarding bioeconomy sustainability, some more fundamental issues have to be further
737 investigated. The development of a sustainable bioeconomy able to replace non-renewable
738 resources while supplying food to societies and preserving natural resources will depend not
739 only on innovations in biomass transformation processes, but also on the organization of
740 biomass feedstock production or biomass-based product consumption. Understanding the
741 emergence of innovations and their interactions with existing bioeconomy systems to improve
742 their sustainability seems important to anticipate the future of rural territories.

743

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