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Julie Wohlfahrt, Fabien Ferchaud, Benoit Gabrielle, C. Godard, Bernard Kurek, Chantal Loyce, Olivier Therond

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Authors:

J Wohlfahrt (corresponding author)

UR SAD ASTER, INRA, 88500 Mirecourt, France
julie.wohlfahrt@inra.fr
+33 389224920

F. Frechaud

UR 1158 AgroImpact, INRA, Site de Laon, 02000 Barenton-Bugny, France
fabien.ferchaud@inra.fr

B. Gabrielle

UMR ECOSYS, INRA, AgroParisTech, Université Paris-Saclay, 78850, Thiverval-Grignon, France
benoit.gabrielle@agroparistech.fr

C. Godard

Chambre d'Agriculture de l'Indre, 24 Rue des Ingrains, 36022 Chateauroux cedex, France
c-godard@orange.fr

B. Kurek

UMR614 Fonctionnement des AgroRessources et Environnement, INRA, 51100 Reims, France
bernard.kurek@inra.fr

C. Loyce

UMR Agronomie, INRA, AgroParisTech, Université Paris-Saclay, 78850, Thiverval-Grignon, France
chantal.loyce@agroparistech.fr

O. Therond

UMR LAE, INRA, 68000 Colmar, France
olivier.therond@inra.fr

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Abstract:

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

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

Highlights:

- Territorial bioeconomy systems are complex social-ecological systems
- Bioeconomy systems are characterized by flexibility and complex spatio-temporal layout
- Two complementary representations are proposed to decipher bioeconomy complexity
- 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).

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

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

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



Figure 1: Representation of a territorial bioeconomy system

In the following sections, we first highlight the specific characteristics of bioeconomy systems that need to be addressed in order to improve their sustainability, based on a literature review. We then develop our novel conceptual framework to assess the sustainability of territorial bioeconomy systems, identifying key scientific challenges in improving it.

2. Particularities of bioeconomy systems

2.1. Review methodology

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

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

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

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

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

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

2.2.2. Multiple stakeholders and partial visions

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

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

Sepehri and Sarrafzadeh, 2018). The bioeconomy system is also under the influence of a sociotechnical landscape, composed of NGOs, political bodies, lobbyists, and influencing the orientation of bioeconomy development. Each bioeconomy stakeholder might have a partial vision of the bioeconomy system, as well as different goals and values (Daher, 2018).

The roles of bioeconomy stakeholders and organizations seem less specialized than in traditional globalized food or timber systems (Borras et al., 2016; Therond et al., 2017). For example, farmers are biomass feedstock producers but can also be biomass buyers, transporters and energy producers (e.g.: on-farm biogas plant supplied by on- and off-farm biomass), biomass-based product consumers (e.g. biofuels used for agricultural machinery) and recycling actors (e.g. farmers using biomass transformation waste to fertilize their crops). On the other hand, there is a wide diversity of stakeholders for each role within the bioeconomy system. For example, biomass-based energy production can be produced on farm (e.g. biogas plants), on large scales by companies (e.g. biofuel plants), but also on medium scales by public stakeholders (e.g. municipality heating systems).

This complex stakeholder system represents a multi-level governance challenge (Juerges et al., 2018 ; Pahl-Wostl 2017). The required multi-level governance structures and attempts to build a common vision and sustainable management strategy between these stakeholders are still lacking (Pahl-Wostl, 2017).

2.3.Importance of policies in the development of bioeconomy systems

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

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

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

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

2.4.Variability, flexibility and rigidity inherent to bioeconomy systems

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

2.4.1. Biomass feedstock diversity and variability

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

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

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

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

biomass feedstocks can therefore be classified according to their composition (Krasznai et al., 2018; van der Weijde et al., 2017). For instance, woody biomass feedstocks issued from forestry systems are composed of large amounts of lignin (20-28%), whereas biomass from agricultural systems can have lower or more variable amounts of lignin, depending on the crops and/or the crop part used: i.e. short rotation coppices (SRCs), stem or leaves from perennial plants like *Miscanthus x giganteus*, or triticale show an amount of lignin ranging from 20% to 5%. In addition to the gross chemical composition of the lignocellulosic biomass (lignin, celluloses hemicelluloses, mineral content, etc.), the quality of the biomass feedstock depends also on morphological and structural parameters, such as the integrity of the plant stem/organs or the state of degradation after harvesting or storage stages. These quality criteria can change the physical and chemical access to the polymers and molecules of interest for applications, and will impact further transformation pathways into fiber, polymers or molecules in biorefineries and for energy production routes (van der Weijde et al., 2017). There is a trade-off between biomass quality and specific valuation processes that influence the number of technical steps (extraction, purification, effluent treatments or valorization, etc) hence the efficiency and the price of the transformation process (Lynd et al., 2017). For example, heat and power production processes based on combustion can be engineered to use different biomass products such as straw, whole plants (e.g. triticale or *Miscanthus x giganteus*) or wood (Pang et al., 2018). Regarding biomass combustion, quality is generally based on biomass chemical composition, particularly lignin content, moisture content and physical characteristics like particle size. For more integrated biorefinery systems, biomass quality management is more complex and variable. Such biorefineries extract several separated compounds from the biomass in cascades. Each compound requires specific characteristics for further use (molecules' purity; specific molecular mass for polymers; presence of inhibitors for fermentescible sugars). Transformation units then have to manage biomass feedstock quality trade-offs regarding these different requirements. Finally, using biomass feedstock of different nature and/or origin in the production process can be an option to improve supply flexibility according to markets and availability, if the industrial process is tailored to a wide range of feedstocks (Borras et al., 2016). Transformation units have then to manage additional biomass quality variations linked to production and transport conditions of each biomass feedstock type and origin (i.e. climate or management variabilities) (see 2.5.1.).

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

2.4.2. Rigidity and co-dependencies

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

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

2.5. Spatio-temporal organization of bioeconomy systems

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

2.5.1. Bioeconomy spatial patterns

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

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

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

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

2.5.2. Time-scale discrepancies

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

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

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

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

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

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

2.5.3. Importance of logistics in bioeconomy systems

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

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

3. Conceptual framework to assess bioeconomy systems' sustainability

3.1 Sustainability issues inherent to bioeconomy systems

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

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

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

3.2. Analytical framework of bioeconomy systems' sustainability issues

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

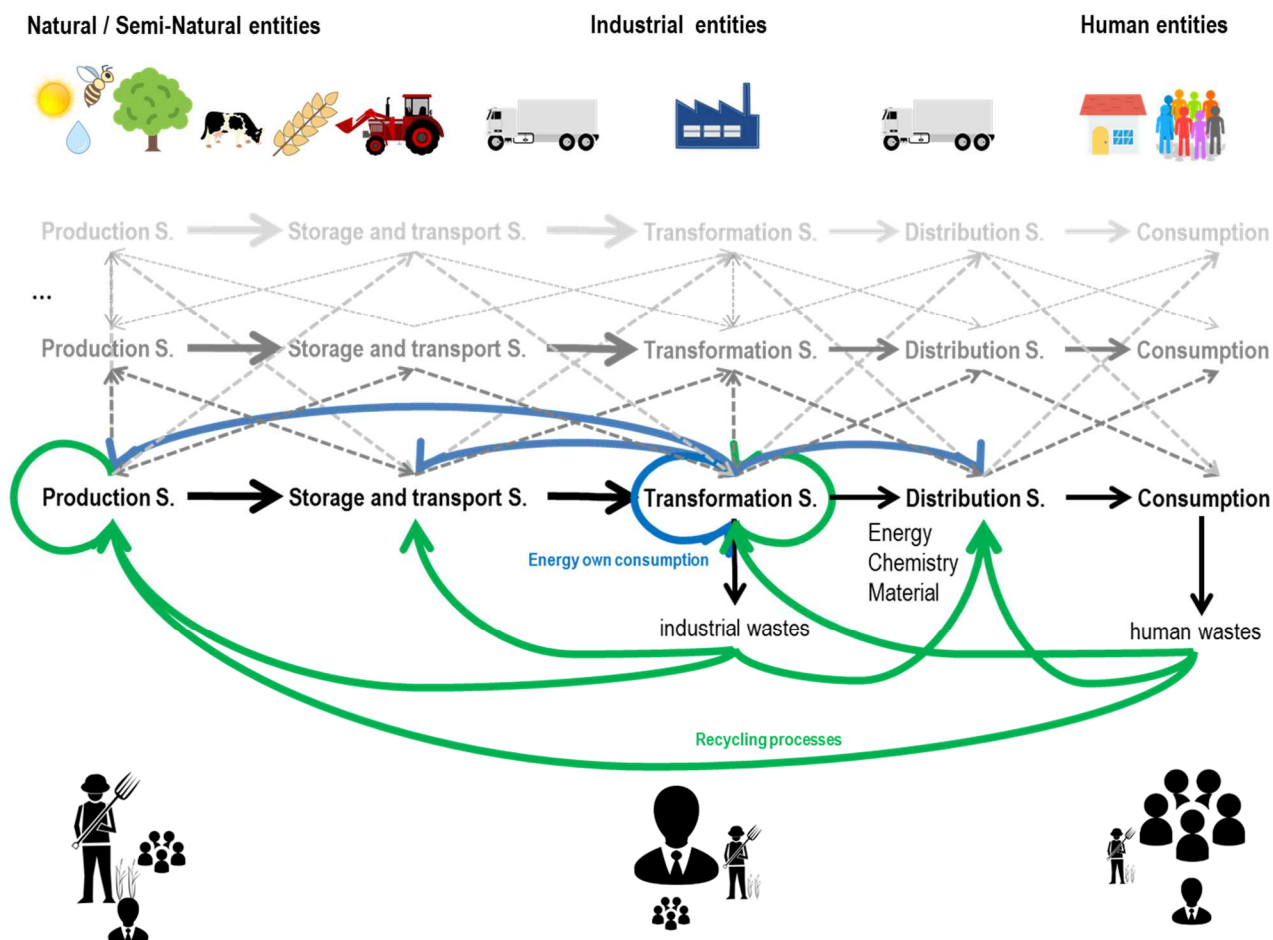
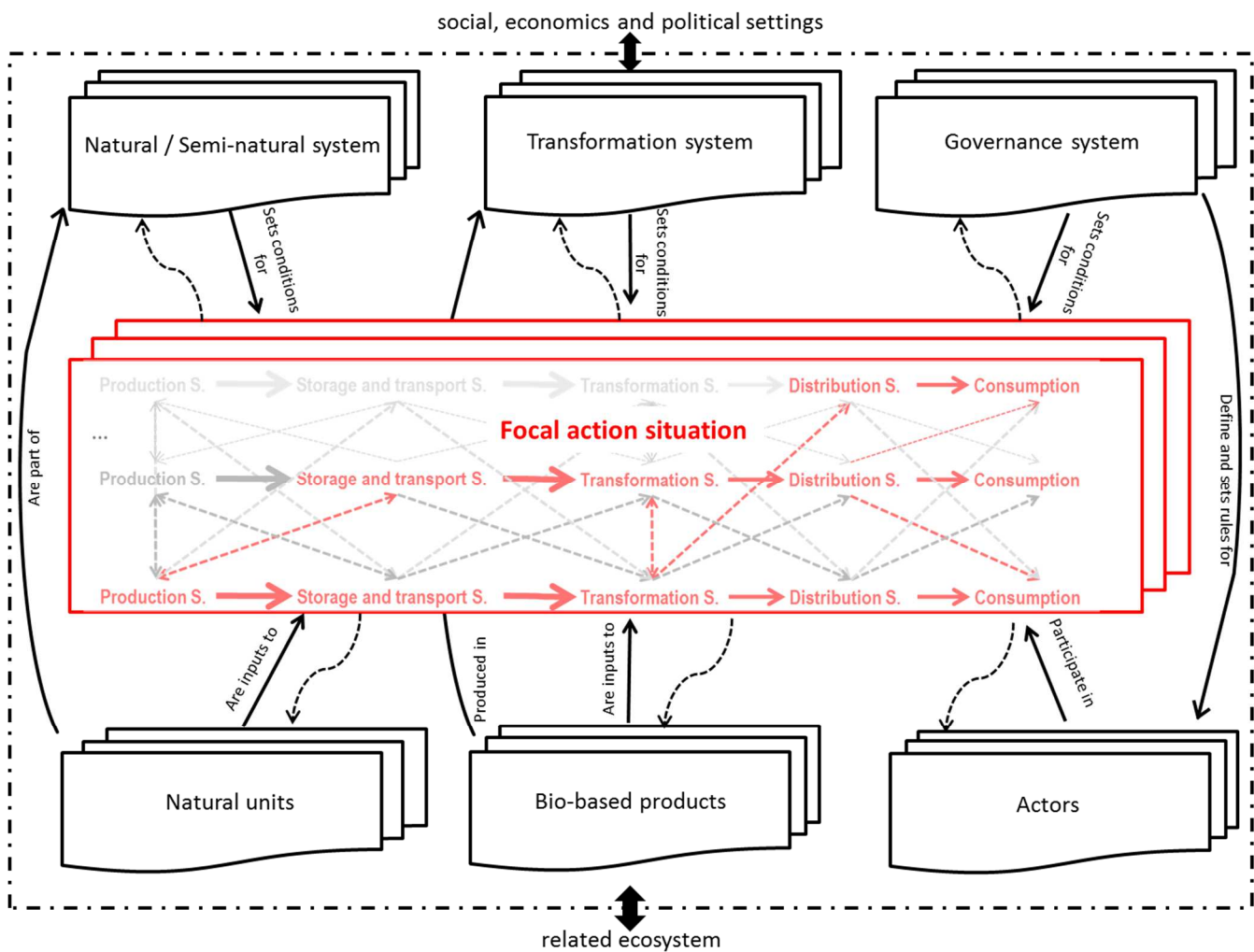


Figure 2: Bioeconomy system functioning and organization

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



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

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

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

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

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

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

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

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

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

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

4.1.Necessity of an integrated assessment and modeling approach

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

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

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

4.1.1. Modelling frameworks to assess bioeconomy systems' sustainability

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

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

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

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

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

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

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

4.1.2. Improving bioeconomy system monitoring

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

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

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

4.2. Involving stakeholders in the IAM approach

4.2.1. Sharing visions on bioeconomy systems

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

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

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

4.2.2. Methodological proposals

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

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

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

5. Conclusion

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

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

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

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

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