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Towards a Territorial and Political Ecology of “Circular Bioeconomy”: A 30-year review of metabolism studies

Running Title: Ecologies of Circular Bioeconomy: a review

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Abstract

In the context of the increasingly present policies of circular economy and the emergence of “Circular Bioeconomy” (CB), this article presents the results of a literature review on the sociometabolic research of biomasses. Six schools of thought are identified, distinguished according to their authors, their conceptions of metabolism, methodologies and social and spatial dimensions. Based on this state of the art, we propose an analytical framework that combines quantitative and qualitative approaches at the territorial scale, drawing upon the currents of Territorial Ecology and Political Ecology. This framework enhances our understanding and provides a critical perspective on the geography of CB. We compare discourses to actual practices by analysing biomass flows and power relations, while adopting a critical perspective towards circular economy policies.

Key words: territorial metabolism, circular bioeconomy, literature review, Political Ecology.

JEL classification: Q00 – General, R00 – General, Q53 - Air Pollution; Water Pollution; Noise; Hazardous Waste; Solid Waste; Recycling

Introduction

Since the 2000s, the OECD and the European Union have made the bioeconomy “the spearhead of sustainable growth, substituting the use of fossil resources with the exploitation of biomass” (Pahun et al. 2018). Biomass is considered as all non-fossil and biologically derived forms of organic matter, which are fundamental to the functioning of socioeconomic systems (Krausmann et al. , 2008). The bioeconomy involves the sustainable use of biomass, seen as renewable biological resources from land and sea, such as crops, forests, fish, animals and microorganisms, to generate food, materials and energy. It is currently aligned with another concept, namely the circular economy, which has emerged in European public policies and is intended to reduce resource consumption and valorise waste (European Commission 2015).

The circular economy is full of promises: it would enable the sustainable use of resources within the limits of the planet (Haas et al. 2020). Resource use is identified according to two loops: a loop of “technical nutrients” (non-renewable resources) and a loop of “biological nutrients” derived from all agricultural, industrial and domestic activities (Webster 2017). This second loop, also called the “Circular Bioeconomy” (CB), has gained momentum since 2018 in European policies and contains some confusions (Giampietro 2019). The ambition is to valorise, recycle and optimise all biomass materials and organic waste within the socioeconomic system (Stegmann et al. 2020). That is why it is important to adopt a critical perspective and recognise the current limits of these policies in the face of the challenge of a socioecological transformation.

The different narratives of bioeconomy have been analysed from different perspectives. The differences between the discourses of bioeconomy and transition have been highlighted for biorefineries (Bauer 2018) as well as the articulation between biotechnology and bioeconomy (Bugge et al. 2016). Although the bioeconomy as a public policy has been analysed through European strategies (De Besi & McCormick 2015) or Canadian policies (Birch 2016), it has not been linked to the schools of thought on metabolism that are interested in biomass flows. However, metabolic studies are very numerous and legitimate in questioning the implementation of the circular economy at different scales (Haas et al. 2016; Savini 2023), so it's important to extend this research into CB. This would a priori be closer to the bio-ecology vision of the bioeconomy (Bugge et al. 2016), which takes a critical look at the recent “hijacking” of the concept of the bioeconomy as developed by Georgescu Roegen (Vivien et al. 2019). In this literature review, we attempt to translate these themes by mobilising the concept of metabolism applied to societies to create an analytical framework for objectifying the political notion of a CB.

In this way, we can link the different narratives of the bioeconomy and the circular economy to other research which mobilises the concept of social metabolism of biomass to quantify, track and reveal the flows consumed and discharged by socioecological regimes into the natural environment. This allows the questioning of public policies and the very notion of CB (Fischer-Kowalski & Haberl 2007a). Which scholarships develop an analysis of CB? What criticisms are raised from the perspective of the social metabolism of biomass? What are the blind spots of these criticisms?

If literature reviews have already been conducted on the social metabolism of urban spaces (Wachsmuth 2012; Dijkstra et al. 2018; John et al. 2019; Newell et al. 2019) and sociometabolic research (Haberl et al. 2019; Gabriel et al. 2020), no state-of-the-art study has directly focused on social metabolism of biomass flows. There is therefore a knowledge gap regarding the mapping of schools of thought working on this issue, their representations and approaches, as well as the debates and disagreements among them. The interactions between transdisciplinary scientific fields are strong and a clarification of schools of thought seems pertinent to shed light on the debates surrounding CB (Debreuf et al. 2016). In order to construct our literature review, we draw inspiration from recent studies that use bibliometric analysis to map schools of thought and research communities in this field (Newell & Cousins 2014; Newell et al. 2019; Bahers et al. 2022). To mitigate possible biases in the bibliometric analysis, we complement it with an in-depth analysis of 18 literature reviews in our database.

In a second step, this literature review leads us to develop a specific analytical framework that combines two currents of metabolism studies (Territorial and Political Ecology), considering the material, territorial, social and political dimensions of biomass flow circulation. This framework will help us better understand territorial dynamics and power relations in CB, thus revealing the processes of territorialisation of these public policies by focusing on their materiality. Our approach will thus enable us to discuss the issues of competition over organic matter, the influence of public policies on flows and the key role of agricultural practices in closing the biomass loops.

Methodology: Bibliometric Analysis and Literature Review

This article builds upon previous work that identifies schools of thought in metabolism studies on specific flows, which have been the subject of in-depth literature reviews. This includes studies on the construction materials flow (Augiseau & Barles 2017) and agri-food flows (Gabriel et al. 2020). To construct this literature review, we rely on a quantitative analysis coupled with a qualitative analysis of the studied scientific production: metabolism studies applied to biomass. In the first step, we conducted a bibliometric analysis of the schools of thought using the Scopus database and the VOSviewer software. To mitigate possible biases in the bibliometric analysis, we

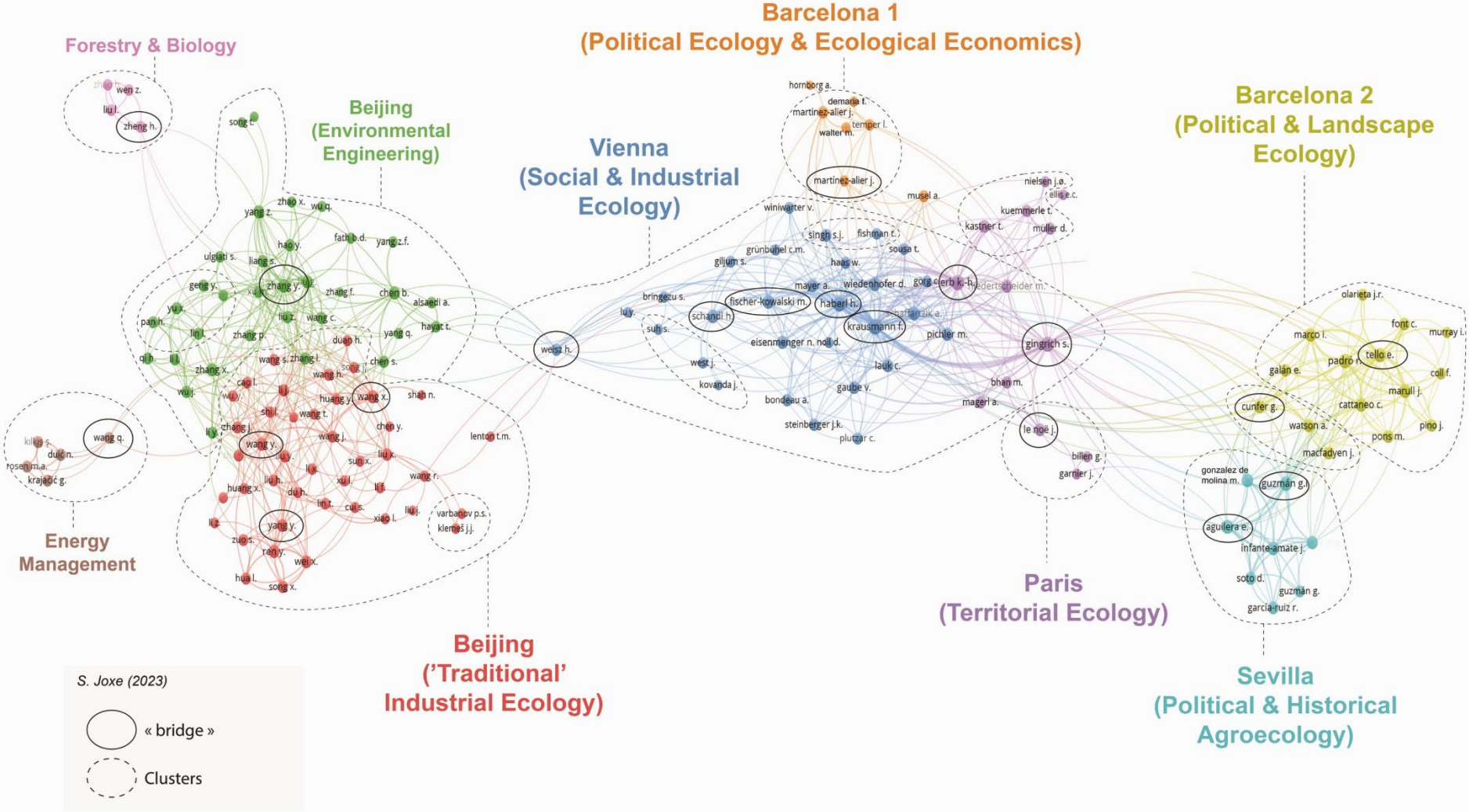
complement it with an exploration of the literature. We chose to conduct an in-depth analysis of 18 literature reviews present in the database. Although not all the authors are European or North American, the Scopus database mainly considers publications in English. However, 72 publications (8% of the total) come from South American authors (mainly Brazil and Chile), 21 publications from Iran, 16 publications from Turkey and 8 publications from south Africa. Thus, we can consider that there is a certain northern bias in this literature review due to the use of these bibliometric databases and, consequently, in the results. Although we have tried to pay particular attention to this, the geographical location from which the research emerges is used to name the schools of thought, reflecting a limit of northern dominance. This section details the methodological choices made to study biomass through the lens of social metabolism, the characteristics of the different approaches of the schools of thought (tools, methods, scales) and the typology constructed based on their disciplines, fields and currents.

Quantitative Aspect: Bibliometric Analysis

The bibliographic database was created using Scopus, with the search formula ALL ("bioeconomy" OR "biomass") AND ("social metabolism" OR "urban metabolism") to cover the field of sociometabolic research. The Scopus database allows keyword searches within the body of the article. The keywords "social" and "urban" are relevant for the study of metabolism applied to societies because they correspond to fields that are well identified by scientific communities. Also, we have chosen to retain only the keyword "biomass" as adding the keyword "food" would cover another field of study and would extend the database too far (2796 publications) and with research that is too far removed from our issues, such as nutrition, dietetics or zoology.

After constructing the database (895 articles), the second step in mapping the schools of thought involves analysing the co-authorship of articles using the VOSviewer software. To identify the main schools of thought, we selected authors within the database who have written at least 3 articles (206 articles) and have co-authored with at least one other author in the database (177 articles). The software allows for visualisation in the form of a map (Figure 1) of the selected 183 authors. They are represented by points of varying sizes based on the number of articles in the database.

Figure 1. Schools of thought in social metabolism revealed by co-authorship analysis: examining the social, political and/or material dimensions of biomass flows.



The search results cover the period from 1993 to 2021. A steady increase is observed: the analysis of biomass through the lens of social metabolism is thus increasingly of interest to the scientific community. After an initial peak in 2011 (25 papers), which doubled in 2016 (51), a strong acceleration is observed between 2016 and 2019 (101) and then in 2021 (155). However, this increase may be related to the dynamism of research in the field of urban metabolism in general (Bahers et al. 2022). Although books are not well represented in the Scopus database, there are a total of 56 (6.3%) book chapters and 35 (4%) books. Out of the 895 publications containing the keywords, 642 (71.7%) are research articles and 119 (13.3%) are review articles. Of these 119 literature reviews, a selection was made on the basis of key words in the titles and the authors, in order to cover the sceptre of schools of thought and currents already identified. Thus, the qualitative analysis is based on 18 review articles to complement the identification of schools of thought.

Qualitative Aspect: Review of Literature Reviews

In a second step, we complemented the findings of the bibliometric analysis with a qualitative analysis to describe and characterise the identified schools of thought. This qualitative analysis aimed to identify schools of thought in the field of metabolism studies that may not be adequately represented through the quantitative analysis of scientific production, thus providing a comprehensive synthesis. To conduct the qualitative analysis, we examined a sample of literature reviews from the database. Out of the 119 literature reviews in the Scopus database, we conducted an in-depth analysis of 18 review articles (Aguilera et al. 2020; Daniel 2018; Fernandez-Mena et al. 2016; Fischer-Kowalski & Haberl 2007b; Gabriel et al. 2020; Grillot et al. n.d.; Otero et al. 2015; Padró et al. 2019; Paes et al. 2019; Palafox-Alcantar et al. 2020; Pietzsch et al. 2017; Redlingshöfer et al. 2020; Schandl et al. 2015; Torres et al. 2019; Urrego-Mesa et al. 2018; Wachsmuth 2012; Zhang et al. 2019, 2018). We have chosen these literature reviews because they are closest to the theme of our review and highlight blind spots in our bibliometric research. This review of literature reviews allowed us to identify the absence of certain schools of thought, particularly Marxist ecologies such as “metabolic rift” or “Urban Political Ecology” which are essential in metabolism studies (Newell & Cousins 2014). By combining the bibliometric analysis with the review of literature reviews from the database, we were able to generate a synthesis of schools of thought in the social metabolism of biomass.

When metabolism studies consider biomass flows: a 30-year review of schools of thought

This section presents the results of the bibliometric analysis, including an analysis of the overall scientific landscape of the data, the qualitative analysis of the review of reviews and finally, a table summarising the key concepts covered by the analysed literature. We have chosen to link the currents of thought developed by the co-authors to their geographical locations, i.e. the universities where the majority of co-authors are based. For example, although the publications of the Barcelona and Seville schools are based on South American authors, we have chosen to group them geographically according to the reference institution located in Spain around the most cited authors (Martinez Allier and Gonzalez De Molina).

The mapping of schools and currents of thought (Figure 1), conducted using co-authorship analysis with the VOSViewer software, highlights six schools of thought that focus on the study of biomass using the concept of metabolism. The “bridge” circles indicate authors who collaborate with authors from other schools of thought, establishing connections between different metabolism studies. The dashed circles define schools and sub-currents more precisely through an analysis of authors (institutions, publications, fields). The classification is based on various criteria, including conceptual frameworks, points of divergence and debate, as well as points of convergence and porosity. These criteria were used to identify and group these schools of thought, facilitating a better understanding of the different perspectives and approaches in the field of metabolism studies on biomass.

The first group corresponds to the *Vienna School of Social Ecology* (blue and purple group), particularly the most prominent researchers in the field, Marina Fischer-Kowalski, Simone Gingrich, Fridolin Krausmann, Helmut Haberl and Karl-Heinz Erb, who have developed extensive work on environmental assessment methods, such as the analysis of material and energy flows (Fischer-Kowalski et al. 2011). To study bioeconomic systems at the global scale, they refine this method to address specific issues related to biomass flows:

“This paper introduces a method to comprehensively account for global socioeconomic biomass flows on a national level, taking regional characteristics of the land use system and of biomass use patterns into account.” (Krausmann et al. 2008)

Thus, biomass is one of the four major flows studied in these analyses of social metabolism of territories, which refer to the study of biophysical flows exchanged between societies and their natural environments, as well as flows within social systems and between them. The evolution of the bioeconomy is also considered through the lens of the “Human Appropriation of Net Primary Production (HANPP)” indicator, which

quantifies the changes induced by humans on the productivity and harvest of biomass flows (Haberl et al. 2013). Firmly rooted in ecological economics, their work aims to explain the transition of metabolic regimes in the long term, particularly at the national level. Their understanding of socio-economic metabolism applies to quantifying ecological cycles of biomass as a cornerstone of circular bioeconomic strategies, considering that biomass is already in high demand and subject to competition for uses such as animal feed, biofuel production, or renewable materials (Haas et al. 2020). Finally, as shown in Figure 1, they have developed numerous collaborations with the Beijing School of Industrial Ecology, the French Territorial Ecology, the Barcelona School and the Spanish Agroecological currents, playing a pivotal role between schools of thought.

The second group is the *Barcelona School of Ecological Economics and Political Ecology*, mainly affiliated with the Autonomous University of Barcelona (orange group). These researchers align with the degrowth conception of the bioeconomy, also known as ecological bioeconomy, inspired by Georgescu Roegen. The Barcelona School draws inspiration from the activist and scientific movement of “environmental justice” and Marxist Political Ecology (see the EJAtlas1). It revolves around Joan Martinez-Alier, one of the pioneers of ecological economics, who has worked on “ecological debt” (Hornborg & Martinez-Alier 2016) and land and biomass grabbing through the lens of environmental justice with Isabella Angelovski and colleagues:

“A range of Environmental Justice Organizations concepts and policies have been borne of environmental injustices related to biomass. Complaints against eucalyptus, acacia, and gmelina tree plantations for wood or paper pulp that deprive local people of land and water, gave rise twenty years ago to the slogan and movement “Plantations are not forests”” (Martinez-Alier et al. 2014).

This work also proposes the perspective of making the link with materialist ecofeminism through work and care and the role of women in struggles (Mellor 1997). The research of the Barcelona School reveals the low circularity rate of biomass flows in the global economy, leading them to advocate for a real degrowth of supply chains (Martinez-Alier 2022). This school is also closely linked to South American authors working on the Political Ecology of biomass (Palme et al. 2018; Pérez-Rincón et al. 2019; Valenzuela-Levi 2019) , notably the “Ecologia Politica” research group of CLACSO (Latin American Council for Social Sciences).

A second school from Barcelona emerges in bibliometrics, focusing on *landscape and Political Ecology*, in yellow. It is organised around influential authors who co-write together, such as Elena Galan del Castillo, Inés Marco, Enric Tello, Roc Padro and Joan Marull. Their research domains are diverse, including agricultural history, ecological economics, landscape ecology, bioeconomy, socio-ecological systems, feminist

economics and soil sciences. They position their work in continuity with the Vienna School but with a focus on landscape ecology:

“This paper intends to contribute to the dialogue between these two lines of research: the economic ecological accounting of energy flows and the study of land-use changes (Fischer-Kowalski and Haberl, 2007) as seen from Landscape Ecology.” (Marull et al. 2010)

They study the evolution of agriculture with a historical perspective and ecological economics at local scales, such as the farm and municipality. The originality of their approach lies in using economic modelling while considering the evolution of agricultural landscapes. For example, their aim is to:

“(…) to reveal how institutional settings and landownership inequality played a role in maintaining the real socio-agro-ecological structure away from these optima, and the existing potential of possible eco-functional intensification practices aimed at reducing the land cost of agrarian sustainability” (Padró et al. 2019)

The issues of CB are primarily related to agriculture, landscapes and agroecological land in their work. It involves combining an agroecological perspective with the accounting of energy and material flows in agricultural systems, while connecting models to ecological processes in the landscape with a historical perspective on the environment.

The analysis of the research domains of the scholars from the *School of Seville* shows that they mainly belong to *political and Historical Agroecology* (light blue group). Specifically, they are interested in studying the long-term metabolisms of agroecosystems (Molina et Toledo, 2014), either through the historical evolution of social metabolism in agricultural systems (Soto et al. 2016) or through the political and institutional aspects of agroecology (Molina et al. 2019). The School of Seville is concerned specifically with the metabolism of agricultural biomass from the perspective of ecological economics. While sharing the same scientific vocabulary, the authors distinguish themselves from the Vienna School by specifically studying the links between biomass uses, agricultural industrialisation and pressure on “agroecosystems”², adopting a metabolic perspective that considers indirect flows:

“[biomass] has gone from being the main source of energy and materials to specializing in two essential functions, the provision of raw materials for industry and the supply of food. The Spanish case confirms that the industrialization of agriculture has led to an increase in pressure on the Spanish agroecosystems. But there has also been a transfer of pressure on agroecosystems of other countries through international trade.” (Soto et al. 2016)

Traditionally focused on the scale of the farm and plot, agroecology is increasingly developing approaches at the territory and community scales, as well as across multiple scales. The analysed metabolic processes (Molina et Toledo 2014) include nutrient cycling, interactions between crops and livestock and material flows in food systems (Gabriel et al. 2020). They suggest incorporating an analysis of power dynamics between farmers and public policies to drive transformation within ecological systems and foster stronger urban-rural relationships along product chains managing agricultural biomass or organic waste:

“However, at the same time, the limited (political) influence of small local operators is acknowledged, as well as the need to broaden territorial governance schemes beyond the economic dimension. This requires incorporating agency and power relations to the (social-ecological) sustainability assessment of the local food system, as well as local actors’ access to political decision-making.” (López-García & de Molina 2021).

Additionally, they claim to rely on ecological services and social justice for their agronomic and ecological analyses. In a recent study on climate change adaptation strategies, among these strategies, the recycling of organic matter in the soil is considered essential for water retention, erosion reduction, improvement of biodiversity and prevention of soil degradation in general (Aguilera et al. 2020).

The *school of Territorial Ecology* includes French researchers, whose network is partially structured in *Paris*, notably around Josette Garnier, Sabine Barles and Gilles Billen, who does not appear in the figure but whose publications are well represented in this database. At the core of their research is the territorial approach to agri-food systems, which allows for an examination of urban metabolism through urban-rural relationships (Barles 2017; Kim & Barles 2012). They have produced work, particularly on long-term socio-ecological trajectories of nitrogen and phosphorus flows in the agri-food sector, at the regional level (Le Noë et al. 2018) and at the global scale (Billen et al. 2018). Their work tends to link land-use changes, sociopolitical drivers and carbon flux dynamics over long periods (Le Noë et al. 2019, 2021) This leads to the proposal of a CB based on optimising the relationships between agricultural systems, organic waste management and sanitation. Their methods draw inspiration from substance flow analyses and spatial environmental foot printing to highlight the disconnection between the agri-food system, which imports a significant amount of chemical fertilizers and the management systems for solid waste and wastewater, which result in the release of numerous nutrients into the environment (Esculier et al. 2018).

The *Beijing school* can be defined as emerging from a traditional stream of thought in *Industrial Ecology* (pink, brown, green and red groups). Most of the researchers from this school come from the engineering and environmental sciences departments at Beijing Normal University, such as Professor Zhang Yan. These highly modelling

approaches, combining statistical models and geographic information systems, are designed as decision support tools aimed at coordinating the control and reduction of regional carbon metabolism. The school also conceptualises the Urban Food-Energy-Water Nexus by proposing a three-dimensional framework (resource interdependence, resource provision, system integration) based on the methods used (Zhang et al. 2019). In the context of CB, the focus is on optimising biomass flows within urban and regional metabolisms.

Qualitative analysis to complement bibliometrics

To complement the bibliometrics, qualitative analysis of literature reviews allowed us to identify certain schools of thought in the field of metabolism studies that were not represented. Although the Marxist Ecology currents of thought are well identified in the publications present in the database, the main authors do not appear in the database, with the exception of Alf Hornborg. On the other hand, the publications of the main authors of these currents (Kaika, McClintock, Heynen and Swyngedouw) appear in the database using the word “food”, so we assume that they simply don't use the term “biomass”. Schools of thought are defined here more by the theoretical currents to which they belong (although they take place in specific laboratories) because we are basing ourselves on previous work (Gabriel et al. 2020; Newell et al. 2019). Within this work, schools of thought are sometimes defined according to theoretical current, sometimes according to geographical location.

These include Marxist Ecologies such as “metabolic rift” or “Urban Political Ecology”, which are essential in metabolism studies (Newell & Cousins 2014). The “metabolic rift” school, represented by John Bellamy Foster, Paul Burkett and Brett Clark, aims to demonstrate that soil degradation and environmental deterioration are linked to the intensification of agriculture, industrialisation and spatiotemporal disconnections between urban and rural areas (Foster 1999). There is thus an ecological perspective within Marx's framework that connects environmental crises to the social metabolism itself, which is alienated by capitalism (Foster 2009)

Researchers in Urban Political Ecology also mobilize the concept of metabolic rift, but with a focus on its urban dimension. For example, Nathan McClintock (McClintock 2010) as explored the role of urban agriculture, delving into the social dimension of metabolic rift in addition to its ecological aspects. In his analysis, he proposes an original framework in which the three main dimensions of metabolism—ecological, social and individual—are co-produced: the rupture of nutrient cycles, the commodification of food and alienation from working the land. This highlights the “fault lines and fractures” (McClintock 2010, p. 203) in the current bioeconomic system.

Moreover, there are researchers in Political-Industrial Ecology, such as Jennifer Baka, who have critically examined bioeconomy policies in India, particularly the production

of biofuels, through the analysis of energy flows and Political Ecology (Baka & Bailis 2014). Research has also been conducted on the Food-Energy-Water (FEW) nexus to demonstrate interdependencies at the urban scale and propose a multi-disciplinary approach to FEW metabolism (Newell et al. 2019).

Finally, a central figure is missing from the network of schools of thought presented: Mario Giampietro from the Autonomous University of Barcelona, that has a background in engineering and environmental assessment. He has developed specific methods of Multi-Criteria Analysis of Sustainability for the bioeconomy (Gabriel, 2020). He notably reveals the confusion surrounding the notion of CB, between a perspective of technological progress and growth and an entropic and thermodynamic narrative about the limits of growth (Giampietro 2019). Thus, a certain version of the bioeconomy advocates for the maximal exploitation of biomass through biotechnologies, disregarding new development strategies guided by strict sustainability rules based on accessible renewable inputs (Vivien et al. 2019).

Summary of schools of thought on the social metabolism of biomass

This qualitative analysis allowed us to complement the synthesis of schools of thought on the social metabolism of biomass. In this section, we examine various aspects of metabolism studies, including the conceptual frameworks used, divergences and criticisms among research currents, as well as points of convergence and porosity.

Based on literature reviews on previous schools of thought, we selected several criteria capable of identifying the schools (reference currents, conception of metabolism and methods employed). We then refined the criteria to bring out the elements of interest to our analytical framework, i.e. the exploration of the spatial, social and scale dimensions of metabolism applied to biomass flows. Thus, we have identified six criteria to differentiate and debate them (see Table 1). These criteria are Reference currents, Conception of metabolism, Methodological, Spatial dimension and Scale(s), Social dimension, actors, governance.

¹ <https://ejatlas.org/>

² "In short, agroecosystems are part of the general metabolism of society, specifically dedicated to the appropriation of the products of photosynthesis." (Gonzalez de Molina & Guzman Casado 2017)

Table 1. Synthesis of schools of thought on the social metabolism of biomass (Scopus database and complementary analysis).

School of thought	Reference currents	Conception of metabolism	Methodological	Spatial dimension and Scale(s)	Social dimension, actors, governance	Examples of authors
Vienna	Ecological economics and Industrial Ecology	Socio-economic metabolism	Modelling approach (EW-MFA) Environmental accounting (EW-MFA)	National International trade	Descriptions of governance regimes	Fischer Kowalski, Krausmann, Haberl,
Barcelona 1	Political Ecology Ecological Economics	Social metabolism	Marxist analytical framework Environmental accounting	International Local conflicts	Actors of the conflicts and struggles (land and biomass grabbing)	Martinez Allier, Walter
Barcelona 2	Landscape Ecology	Socio-metabolic perspectives	Local modelling approach Landscape Ecology indicators	Regional, at the scale of farms Spatial landscape patterns	Land-use policies	Tello, Padro Marull, Marco et Galan del Castillo
Sevilla	Historical Agroecology	Agrarian metabolism	Modelling approach Long term biomass production	National Impacts on other territories	Rural society and agroecosystems	Molina, Soto et Toledo
Paris	Territorial Ecology as a mix of Urban Ecology and Industrial Ecology	Urban and territorial metabolism	Substance flow analysis Environmental imprint Water-agro-food system	River, city City- peri urban relations Spatial distribution	Territorial actors Planning policies	Garnier, Billen, Le Noè, Barles

Beijing	Traditional Industrial Ecology Engineering sciences	Urban metabolism	Modelling approach Carbon footprint	Region, city, national Interregional relations	Resource policies	Zhang, Fan, Xiu
Multi-scale integrated analysis	Engineering sciences Energy	Societal metabolism	Multi-scale integrated analysis of societal and ecosystem metabolism	Nation, city Multi-scale of economic activities and ecological constraints	Societal system Agricultural sector	Mario Giampietro
Metabolic rift	Marxist Economics Sociology	Social metabolism	Marxist analytical framework City-country relationships	World-ecology	Society-nature relations Capitalist policies	Moore, Foster, Clark
Urban Political Ecology	Critical Geography Marxist Economics	Social or urban metabolism Urban environmental governance	Marxist analytical framework	Social and power relations within the city	Local actor struggles and inequalities Civil society	Swyngedouw, Gandy, Kaika, Heynen
Political-Industrial Ecology	(Urban) Political Ecology and Industrial Ecology	Urban FEW metabolism	Systemic and power relations approach	Environmental impacts of company, city, region.	Actors of supply chains Uneven relations of impacts	Newell, Cousins, Pincelt

The first criterion corresponds to reference currents. Some schools of thought refer more to traditional Industrial Ecology in engineering sciences, while others draw from ecological economics or the critical geography of Urban Political Ecology. Environmental and agroecological history and economic Marxism are also mentioned. The traditions are therefore very different, which implies controversies over the methods and concepts employed. The appropriation of the notion of metabolism is thus interesting to differentiate these schools. They may refer to urban metabolism to focus on the spatial scale, or to social and socioeconomic metabolism to interrogate actor dynamics and production. Some schools also have more explicit conceptions of metabolism that provide precision on the methodological approach or the object of study.

Methodological approaches are inherently diverse and multifaceted. Some schools (Vienna, Barcelona 1 and 2, Seville, Beijing and the currents of Multi-scale Integrated Analysis and Political-Industrial Ecology) partially or entirely apply environmental accounting methods, inspired by Material Flow Analysis, or develop new environmental modelling approaches. However, these currents complement these methods with other approaches related to Marxist analysis, environmental history, landscape issues or systemic approaches. Some schools of thought (Urban Political Ecology and Metabolic Rift) focus on the qualitative study of metabolism and are critical of schools of thought (Vienna School of Social Ecology, Beijing school, etc.) that use methods of accounting for material and energy flows, criticising them for “depoliticising” the concept of metabolism applied to the functioning of societies, by focusing only on the narrow issues of measuring flows.

The spatial dimension varies among schools: it can be applied at national, regional, urban or local scales. Moreover, some schools attempt to go beyond the metabolic “black box” which, using the material and energy flow balance method (inputs/outputs), sees space only in terms of administrative borders. It examines the relationships and flow circulation between territories, such as from supply territories to consumption territories, from rural to urban areas, from peri-urban to urban centres, or to characterise exchanges between regions. Finally, other currents attempt to conceptualise space as a political and social production, leading to a higher level of sophistication in these dimensions (such as the Barcelona 2, Paris, Urban Political Ecology and Political-Industrial Ecology currents).

The last criterion corresponds to social, political and actor dimensions. Schools have very different approaches in this regard. They may focus on the actors within the systems, sectors, or territories studied (Barcelona 1, Seville, Paris, Urban Political Ecology and Political-Industrial Ecology) or on the policies and governance related to the case studies (Vienna, Barcelona 2, Beijing, Multi-scale Integrated Analysis, Metabolic Rift). Moreover, it is important to note that approaches to address social and

political issues can be prescriptive and normative, or highly critical, focusing on power dynamics and domination.

A hybrid analytical framework for Territorial and Political Ecology of CB

This synthesis of schools of thought on the social metabolism of biomass enables us to identify hybridisation avenues for original research. In the same vein as recent proposals from Political-Industrial Ecology (Newell et al. 2017), a Social and Political Geography of materials (Choplin 2023) or an integrated perspective of social metabolism and political economy within the Vienna school (Schaffartzik et al. 2021) leading to a Social Ecology of capital (Pineault 2023), we propose a hybridisation between Territorial Ecology and Political Ecology for the study of biomass flows.

An analytical framework bridging Territorial Ecology and Political Ecology

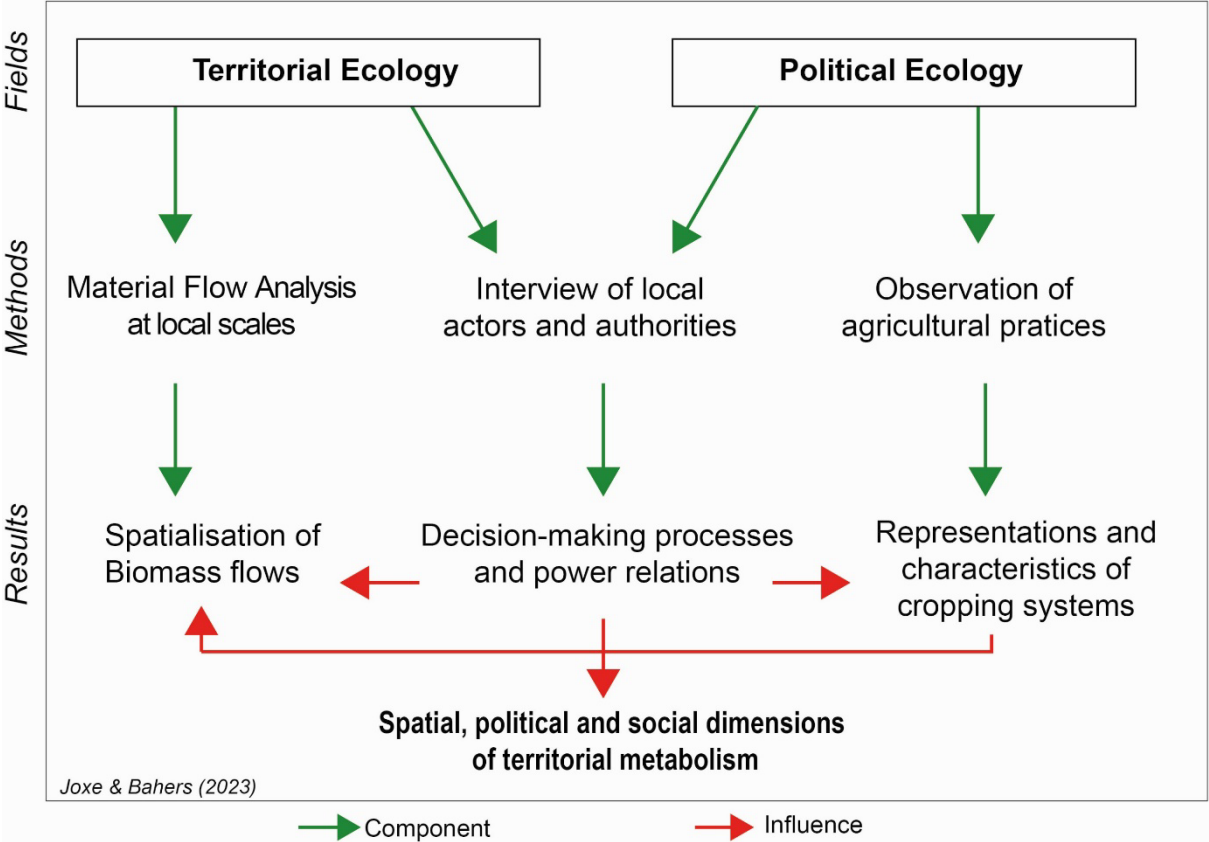
This bibliometric and qualitative analysis shows that these schools of thought remain highly compartmentalized. Responding to the call to develop interdisciplinary frameworks on these issues of biomass metabolism (Broto et al. 2012; Dijst et al. 2018; Gabriel et al. 2020) we propose a framework that reinforces the exploration of the spatial and territorial dimensions of CB from a critical perspective. This framework is designed from the four schools within the currents of Territorial Ecology and Political Ecology: the Paris school, the Seville school, Barcelona 1 and Barcelona 2. It is detailed in three aspects: the hybridisation of Territorial Ecology and Political Ecology, with a proposed cross-definition of the concept of territorial metabolism, a presentation of the methods derived from it and their objectives and how the social and spatial dimensions of biomass metabolisms are exposed by this framework.

Territorial Ecology (Paris school) is of interest for its analysis regarding the circulation of flow of material and energy, notably developed by the Vienna school of Social Ecology, but at more local scales to consider the material dimension of space. Additionally, this approach aims to explain the conditions of production and the consequences of the circulation of materials and energy beyond descriptive analysis. The multi-scalar analysis enables thus understanding of the relationships between spaces involved in the extraction, transformation, consumption and disposal of materials and energy, thereby spatializing circular economy and bioeconomy by focusing on the material dimension of economic systems. To simultaneously study the material, multi-scalar and socio-political dimensions of territorial metabolisms, we propose to focus on biomass flows. The aim is to highlight orders of magnitude to evaluate the circular or bioeconomic nature of a system.

In Political Ecology, the aim is to understand the interactions between actors around the circulation of a flow. It is based on a critical approach to the dynamics of capitalism. Political Ecology, which is strongly inspired by critical geography (Robbins 2019), “investigates connections between political economy and environmental change” with a critical lens questioning and destabilizing apolitical accounts of environmental change (Newell et al. 2017). Mobilised by the schools of Seville, Barcelona 1 and 2, it is valuable for combining economic or socio-ecological analyses with the study of power mechanisms, inequalities and environmental conflicts. Furthermore, this political dimension is reflected in researchers' engagement with the social movements they study. Political Agroecology recognizes the importance of coupling agroecosystem and power relations that shape agrarian metabolism (Molina et al. 2019). It lies at the heart of the Urban Political Ecology, Political Agroecology and Political-Industrial Ecology currents.

Our proposal is to hybridize these schools, based on analyses at local scales. To observe the social and political dimensions of CB, it is necessary to adopt a critical stance towards the socio-spatial dynamics of capitalism based on a reading of Political Ecology, paying detailed attention to the norms that influence actors' practices and, therefore, the circulation of materials and energy as in Territorial Ecology. For example, the influence of institutional frameworks and inequalities on flow circulation can be demonstrated to maintain a real socio-agro-ecological structure away from the intensification of practices (Padró et al., 2019). To complement the analysis of local biomass flows, drawing inspiration from schools aligned with Political Ecology involves studying power relations, norms and practices of actors involved in biomass flow circulation. Our framework aims at revealing the destructive dimension of capitalism on ecosystems and promoting agroecology. This hybrid approach can involve conducting a series of interviews with actors to understand their roles in relation to one another and how they impose, negotiate, or experience flow circulation. In this framework, the aim is to bring together analyses in terms of flow circulation, public policies and agricultural practices (Figure 2). By combining an analysis of public policy documents, power relations and farmers' practices, we can shed light on analyses of biomass flows. The socio-political processes that influence the circulation of organic waste flows can be elucidated and spatialized through the study of the development of dedicated infrastructures and the agricultural practices that allow, or not, their return to the soil.

Figure 2. Proposal for an analytical framework to observe the social and political dimensions of CB.



Moving from mixed quantitative and qualitative approaches to cross-analysing (flows, actors and practices) territorial metabolism

The current state of the field of Territorial ecology demonstrates a significant interest in the socialization and *spatialization of analyses of material and energy flows*. However, no framework that connects the analysis of flows with those of actors and practices exists. We propose to further explore this perspective, starting from agricultural practices, assumed to explain the circulation of flows and influenced by public policies and power dynamics within and among sectors.

Most methods used in the fields of urban metabolism and sociometabolism research are quantitative, as in territorial ecology, traditionally based on material and energy flow analyses (Athanassiadis et al. 2015; Haberl et al. 2016). The aim is to objectify the material weight of cities, territories and countries through material accounting. In Territorial Ecology, the MFA tool is linked to analysis of social-ecological regimes through the mobilisation of multiscale views (Barles 2009), public policy analyses (Verhaeghe 2021) or the history of agricultural systems (Le Noë 2018).

In the same vein, the TRACAST (Tracking Corporations Across Space and Time) method, from the field of Political-Industrial Ecology, aims to tell the story behind a product by

tracing it back through supply chains using in situ (interviews, surveys, fieldwork) and ex situ (document analysis, mining of trade data) analyses (Goldstein & Newell 2020). their objective is. Bridging the gap between Territorial Ecology and Political Ecology means favouring mixed methods to understand the influence of relations of power and domination, social inequalities, governance or agro-ecological practices on the circulation of biomass flows. We postulate that politicising and *territorialising analyses of material and energy flows* helps us to understand and therefore transform territorial biomass metabolisms.

We thus propose to intersect an analysis of flows, actors and practices of the territorial metabolism of biomass. For the flows, we rely on the *MFA (Material Flow Analysis)* methods. The principles of MFA have given rise to different types of analysis, including energy flow analysis (EFA), substance flow analysis (SFA) and nutrient flow analysis (NFA) (Le Noë 2018, Papangelou, 2021). "All these approaches raise at least two crucial methodological issues: the choice of the unit and the delimitation of the system perimeter." (Le Noë 2018). These choices must therefore be politicized to highlight import and export flows linked to more or less distant hinterlands, domestic production processes and all the waste flows inherent in these sectors, from extraction to management. Despite the challenges it may pose, we propose using a unit of kiloton of materials, as in EUROSTAT method and grouping biomass flows into fine categories. The objective is to establish orders of magnitude without claiming to be complete exhaustiveness or to convert flows into environmental impacts as in Life Cycle Assessment. It is important to spatialize and measure the flows circulating between production, consumption and discharge territories as well as the infrastructures that centralize and redistribute these flows. It enables an analysis of material flows adapted to a local scale, specifically focusing on biomass flows, while opening the metabolic black box (Guibrunet et al. 2017).

To identify actors and power relations, Territorial Ecology can draw from Political Ecology and methods inspired by critical geography to study *the decision-making system and power relations between actors* involved in the circulation of material flows in a given area (Swyngedouw 2004; Lepawsky & Mather 2011; Linton & Budds 2014). A geographical approach analyses social metabolism by combining an approach based on everyday objects and a follow-the-things approach to trace supply chains (Choplin 2023). By combining analysis of the circulation of products, actors and the political frameworks that enable a global value chain to be set up, it reveals the structures that set materials in motion by varying the scales. These hybrid methods provide a protocol for our analytical framework for objectifying governance, power relations and domination and social and territorial inequalities.

Practices can have a major impact on flows and they are conditioned by decision-making processes, particularly where agriculture is concerned, at European, *national and local public policies*. Farmers may have different cropping systems depending on

whether or not they have access to organic matter, which can be directed by optimising tillage, soil or cash crops. Territorial configurations can have an impact on practices and therefore on flows. Interviews with a typology of *local actors* is useful to understand who influences the circulation of flows (local authorities, farmers, managers of a methanisation and composting facilities, etc). The interview guides can be tailored to different actor groups, but the topics addressed should, at a minimum, reveal power relations, the relationship with norms and agricultural practices, such as agro-ecological or intensive.

By combining this analysis of biomass flows with interviews and *direct observation*, we can identify *public policies, local powers and agricultural practices* that influence the circulation of flows in the territory and thus gain a critical understanding of territorial metabolism which can take a more or less linear, intensive and outsourced trajectory (Gandy 2021). The results of the interviews shed light on the relationships between flows, decision-making process and practices towards a Political and Territorial Ecology of metabolism.

Exploring spatial and social dimensions of territorial metabolism

The *biomass flow-based approach* brings a database that shows orders of magnitude in the appreciation of the material relationships between entities and the actors approach allows us to understand the power relationships behind the circulation of flows. Both approaches are necessary and complementary, even in their political and transformative scope. These mixed approaches provide an understanding of the social production of space. The concept of the social production of space, as theorized by Henri Lefebvre, delves into the intricate relationships between society and the spaces it inhabits. According to him, "The spatial practice of a society secretes its space (...) it produces it slowly and surely by dominating it and appropriating it" (Lefebvre 1974, 48-49). Developing a spatial way of thinking, in the context of metabolism studies, therefore means studying the way in which social groups appropriate space, while emphasising the material dimension through studies of flows; studying the social processes that produce territorial metabolism means not neglecting the way in which space is shaped by relations of power. This perspective allows us to recognize that flows of people, goods and information not only shape infrastructure but can also be influenced, blocked, or politicized by various social groups. A politicized MFA (Material Flow Analysis) emerges as a more intelligent approach to understanding the dynamics of space and power in this context (Cousins & Newell 2015; Guibrunet et al. 2017; Goldstein & Newell 2020).

Our framework also aims to *examine finer scales*, beyond the research carried out mainly on large cities and metropolises. It provides a framework to examine the role of norms and public policies in shaping infrastructure and circulation flows focusing on

municipalities and infrastructures. The emphasis on smaller areas (Mohareb & Perrotti 2023) becomes crucial in understanding material consumption, its potential control and reduction and to reveal the functioning of sectors that might be overlooked in broader studies. Our objective is also to investigate rural areas with high bioeconomic stakes. These may be small areas with a high level of food resilience, areas where large agri-food chains are concentrated, or supply areas located in the suburbs of metropolitan areas. These singular territories reveal other dynamics and metabolic profiles than cities that consume large quantities of resources.

We also aim at conducting detailed analysis of material flows across specific geographical areas, through “spatially explicit” MFA (Cousins & Newell 2015; Yeow & Cheah 2019), integrating spatial information such as the *location of sources, destinations and infrastructures for an in-depth understanding of material dynamics* in a given spatial context. It allows for a comprehensive spatialization of sourcing, exports and organic waste disposal within and through the territorial system. By focusing on territories less studied by metabolism studies, we gain a more comprehensive understanding of the complexities inherent in the social production of space and the interplay between infrastructures, flows and societal dynamics.

Conclusion

In conclusion, this article has undertaken a comprehensive examination of the evolving fields of Territorial and Political Ecology, over the past 30 years. Through a blend of bibliometric analysis and literature review, the study has provided insights into the diverse schools of thought that have studied biomass flows in metabolism studies. By mapping these schools of thought and employing qualitative analyses to complement quantitative data, the research has not only synthesized the existing knowledge but also shed light on the social and spatial dimensions of territorial metabolism.

The integrated approach proposed in this article encourages researchers to explore the nuances of Territorial and Political Ecology, fostering a deeper comprehension of CB. This article proposes a hybrid analytical framework which enriches critical geographies of CB. Territorial and Political Ecology provides tools and perspectives and reveals the limited nature of CB through current public policies concerning material issues. By integrating sociopolitical dimensions into the study of flows, this framework also allows for a better understanding of the production of spaces through the structuring of organic waste chains.

Adopting a “critical” perspective allows for the association of the analysis of socioecological dynamics at work in the development of organic waste value chains with an intention to understand the spatial dynamics of the capitalist waste regime (Gille 2010; Gregson 2023) and the social and political processes that explain them

(Gille 2022). It is crucial not to overlook the power dynamics that occur within a territory among economic actors. This is the main contribution of Political Ecology to metabolism studies, which, within the framework of our analytical framework proposal, is coupled with a socioecological analysis of biomass flows.

While economic actors have now become adept at communicating their activities as “sustainable”, “decarbonised” and “circular” this article opens a research path to document and critique metabolic transformations from a geographical perspective. It proposes a methodological contribution rooted in Territorial and Political Ecology to examine the CB. Furthermore, given the significance of critical geography in metabolism studies, a theoretical research avenue could be explored around the notion of “chains”. The aim would be to carefully identify methods that complement our analytical framework, like research that seeks to trace and characterise “chains” using bottom-up approaches in geography (Choplin 2023), to further study the sociospatial dimensions of metabolic transformations.

Such an analytical framework offers a variety of research perspectives. Biomass flow analysis can show the discrepancies between material flows and the objectives of public policies focused on CB and bioeconomy in general. These mixed methods can also be useful for showing the rebound effects of CB development through the prism of recycling. They demonstrate the role and influence of industry in unsustainable territorial metabolisms. Finally, they can support the hypothesis that a “truly” CB (Arnsperger & Bourg 2016) must challenge the discourses and materiality of economic growth at all spatial and temporal scales.

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Endnotes

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