A review of socio-economic metabolism representations and their links to action: Cases in agri-food studies

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Abstract

Socio-economic metabolism (SEM) occupies a central place in the study of agri-food systems. While researchers are asked to address growing environmental and social issues, the link between theoretical choices of representation and action is rarely discussed as such. We propose a cross-sectional analysis between the way SEM is described and how researchers propose to act, based on a literature concerned with agri-food systems. We distinguish the metabolism representations based on funds, flows and stocks, scales and levels, as well as socio-economic analysis. Action is seen through the operational goals pursued by the researchers, the action-research interfaces in which they engage, and the partners with whom they interact. We identified eight schools of thought related to three different types of representations: (1) space and compartment-based representations; (2) economic agent-based representations; and (3) multi-faceted and composite representations. We show that metabolism representations and action are deeply intertwined. The analysis of the biophysical basis of society is neither independent of normative claims regarding how this basis should evolve, nor of the means to get there. We then discuss the consequences of this fact on the choices of representation of metabolism and particularly the interest of anchoring SEM in pragmatism.

Highlights

1. Socio-economic metabolism (SEM) is increasingly present in agri-food studies.
2. 102 articles are examined to identify their way of representing SEM and links to action.
3. Eight "schools of thought" are described.
4. SEM representations are not neutral and are intertwined with choices of action.
5. Philosophical pragmatism is proposed to embrace this methodological pluralism.
6. This includes adopting a relational ontology and proposing multiple representations.
7. Action involves taking part in deliberative and democratic processes.

Keywords

research-management interface; participative research; metabolic networks; epistemology; pragmatism

1 Introduction: socio-economic metabolism and action

Socio-economic metabolism is seen as a paradigm for studying the biophysical basis of our societies. It " *constitutes the self-reproduction and evolution of the biophysical structures of human society. It comprises those biophysical transformation processes, distribution processes, and flows, which are controlled by humans for their purposes [and] the biophysical structures of society*" (Pauliuk et al. 2015). The notion of SEM has evolved over time and the scope of the term differs among scholars. Socio-metabolic studies translate into a wide diversity of operational concepts, such as industrial (Frosch et al. 1989), society's (Fischer-Kowalski et al. 1998), urban (Barles 2015) and socio-economic metabolism (Pauliuk et al. 2015). In the remainder of the text, we will use "socio-economic metabolism" (SEM) to refer to the paradigm in general.

Several bibliographical reviews concerning SEM studies have recently been published. They include a comparison of two frameworks (Gerber et al. 2018), a cross-sectional analysis between industrial ecology and politics (Breetz 2017), and tool oriented ones (Fernandez-Mena et al. 2016; Beloin-Saint-Pierre et al. 2017; Haberl et al. 2019).

Metabolism is indeed a tool for management. According to Odum (1971), ecologists should use metabolism as a tool to share their analysis of reality with society and, finally, to position themselves as the actual managers of the interactions between society and the environment. The final goal is to "manage" the human system with actions based on ecological laws (Madison 1997). Social metabolism is seen as a tool for socio-ecological transition (Fischer-Kowalski et al. 2009), ecological intensification (González de Molina et al. 2017) or sustainability (Haberl et al. 2019).

While action plays an important role in SEM studies, it is rarely addressed as such in the reviews. What are researchers normative and operational objectives? What do they stand for and how can they be achieved? How does action relate to choices of metabolic representation? These questions are central if we want to address the environmental, social and political challenges revealed by metabolic representations.

In agri-food studies

SEM is increasingly present in agri-food studies. Agri-food systems play a major role in the biophysical basis of our societies and strongly contribute to society's SEM in terms of material stocks and flows (Krausmann et al. 2009). Material flows and, in particular, flows of biomass or living matter are the subject of new challenges with the development of the bioeconomy (Vivien et al. 2019). Agriculture is the main producer of biomass in human economies by far, reaching 89 % in total mass. The biomass of humans and livestock surpass that of wild mammals by a ratio of 20 (Bar-On et al. 2018).

Development of SEM in the industrial age includes a metabolic rift between the city and the countryside (Foster 2000) as well as agricultural sector specialization (Lemaire et al. 2014). It translates into an environmental footprint (Courtonne et al. 2016) such as nitrogen pollution (Bellarby et al. 2017) or depletion of organic matter in the soil (Andrieu et al. 2014). The unsustainable nature of the ongoing SEM is unanimously recognized and a consensus exists on the urgency to transform it (Haberl et al. 2019).

Goals and article map

We propose a review of the literature based on SEM representation and action in agri-food systems. This includes agricultural production, food systems and their associated components such as inputs and waste flows. Several steps are followed. Firstly in section 2, methods are chosen to isolate the relevant literature, describe SEM representation and the researchers' links to action. Thanks to these tools, section 3 is an attempt to characterize schools of thought regarding SEM and action. Section 4 presents some limits of the review and discusses the fact that representations and action are linked: studies of metabolism are not neutral and "schools of thought" are also "schools for action". We conclude with a proposal of epistemological and methodological choices for SEM, anchored in pragmatism.

2 Methodology

2.1 Identification of literature dealing with SEM through keywords

A systematic exploration of the literature was carried out to identify articles that deal with SEM in agri-food systems. We looked for papers that focus on the biophysical structures of human societies, seen in terms of human-controlled processes of transformation and distribution. We interpreted the "human society" criteria in a restrictive way: the flows must have a social aspect, e.g., taking place on a scale larger than that of the farm, or involving a collective process.

Searches in the scientific literature were performed using the Web of Science, with three sets of keywords: those referring to (1) metabolic processes (e.g., *metabo**[1] *; material; flow; biomass; circulation*); (2) agri-food systems (e.g., *agri*; farm*; agrarian; agroecosystem*); and (3) social (e.g., *social, societ*, collective, politic**). Results of the search cover the period from 2000-2019. 738 articles featured at least one keyword for each category. After excluding off-topic articles, 259 publications remained. While almost no authors explicitly used the concept of SEM, we ensured that all three criteria were met in the articles' abstracts. A total of 89 articles remained. On this basis, 13 additional articles were identified via the snowball effect. The total number of articles analyzed was 102.

2.2 Literature description and classification

The articles are described according to their SEM representation and their links with action (Table 1). Theoretical articles were used to describe the school of thought, and case studies to illustrate methodological choices. Complementary articles, not described in the review, and not specialized in agri-food, were used to describe the schools of thought. These articles are mainly theoretical or seminal. Each school is then described in a synthetic way, according to how the metabolism is represented, as well as its relationship to action. Two to three case studies are proposed as an illustrative example for each school.

Based only on the SEM representation, we identified eight "schools of thought" in which the various articles are classified. When various but similar names coexisted (e.g., *industrial*

[1] *metabo** means that all words starting with metabo were investigated, e.g., metabolism, metabolic, metabolized, etc.

Items	Areas of analysis	Existing modes
Representation	(a) Stocks flows and funds	Stocks and flows; economic funds and flows; ecological funds and flows; humans and non-humans as funds and flows
	(b) Scales and levels	Large-scale spaces; middle or small scales; physical black boxes; individual companies or sectors;
	(c) Socio-economic context	Historical material transitions (Marxist) ; social performance analysis ; power structure analysis; local stakeholder analysis; actor-networks
Action	(d) Claimed research goals	Limit the size of the metabolism; change the system; relocalize the economy; foster economic performance; limit environmental impact; close the loop ; preserve the ecological and economical funds; develop an ecological-process-based and socially fair food system; enhance diverse and locally-based sustainability programs
	(e) Research-management interface	Trickle-down; user-push; transfer-and-translate; research-with-management
	(f) Tools	Transition analysis; critical analysis; stakeholder analysis; management tools; post-normal-science-based tools; extended description
	(g) Actors and partners	Leaders of countries; civil society; local authorities and stakeholders; companies; trade associations ; farmers and civil society; various stakeholders.

Table 1: List of literature classification criteria according to the type of SEM representation and links with action

ecology, industrial clusters and industrial symbiosis), a compromise was made (e.g., *industrial ecology and symbiosis*). For the sake of simplicity, only the most prominent and contrasting frameworks were chosen.

2.2.1 The representation of socio-economic metabolism: stocks/flows/funds/scales levels and socio-economic context

Articles are classified according to their SEM representation, especially the way they deal with (a) stocks, flows and funds; (b) scales and levels; and (c) socio-economic context. These three criteria are used to distinguish schools of thought.

(a) We followed Georgescu-Roegen's (1971) proposal to represent human-mediated metabolic processes using three distinct categories: stocks, flows and funds. A *stock* is what is present in the system at a given moment of time. A *flow* represents change: it is usually used for representing an input or an output of a given process. *Funds* are durable entities, which are the "active agents of the process", while flows are "used or acted upon by the agents" (Georgescu-Roegen 1971). A diversity of entities can be taken into account. These include *economic or ecological processes, human and non-human agents.*

(b) Living systems present parallel levels of organization on different scales and levels. Spatial scales (e.g., region, state, global, etc.) and functional levels (humans are made of organs, cells, molecules, etc., which at the same time are part of a household, part of a community, part of a country)(Giampietro 2004). For each study, we attempted to describe the scales and levels that are taken into account in metabolic representations. For scales, these include: *large-scale spaces, middle or small scales*; for levels: *physical black boxes, individual companies or sectors.*

(c) The biophysical basis of our societies is rarely described alone. It is regularly integrated into a socio-economic context. Its analysis encompasses the diversity of the social sciences: historical, sociological, political, etc. The main types of analyses used were derived from the reading of the corpus. These include *historical material transitions, social performance analysis, (Marxist) power structure analysis, local stakeholder analysis, actor-networks.*

2.2.2 Action: goals, interfaces, tools and partners

The links between SEM representation and action are analyzed on the basis of four criteria: (d) problem definition and the researcher's goal; (e) type of research-management interface; (f) type of analysis or tools used; and (g) the chosen actors and partners.

(d) Problem definition and the researcher's goal are deduced from what the author states in the article. These objectives can be expressed explicitly or make reference to theoretical articles, e.g., *limit the size of the metabolism, change the system, re-localize the economy, foster economic performance and limit environmental impact.*

(e) The types of research-management interfaces are characterized using the typology of Gosselin et al. (2018), which distinguishes four types of interfaces between research and management: trickle-down, transfer-and-translate, user-push and research-within-management (Fig. 1).

1- In *trickle down* interfaces, knowledge is generated with no direct link to management. Researchers produce research, independently of topics of interest to users. Users can adopt it if they wish, but the researcher makes no effort in that direction.

2- In *transfer-and-translate* interfaces, scientists make an effort to transfer their results, while managers translate them into coherent management practices (e.g., extension officers at the interface between scientific knowledge and farmers).

3- In *user-push* interfaces, the users commission research on topics they are interested in. Managers may ask researchers to produce knowledge that will inform their future management.

4- *Research-within-management* is based on strong interactions through bidirectional flows of knowledge. Researchers and managers work together, pushing and pulling knowledge to define research questions and to conduct research relevant to their mutual skills and needs.

(f) The type of analysis or tools provided by the researcher for the action is described. It includes *transition analysis, critical analysis, stakeholder analysis, data and management tools, post-normal-science-based analysis and exchanges and extended descriptions.*

(g) The actors described as potential agents for change as well as the ones who are partners with whom the researchers collaborate are identified. These include *leaders of countries, civil society, local authorities and stakeholders, companies, farmers and civil society, as well as various stakeholders.*

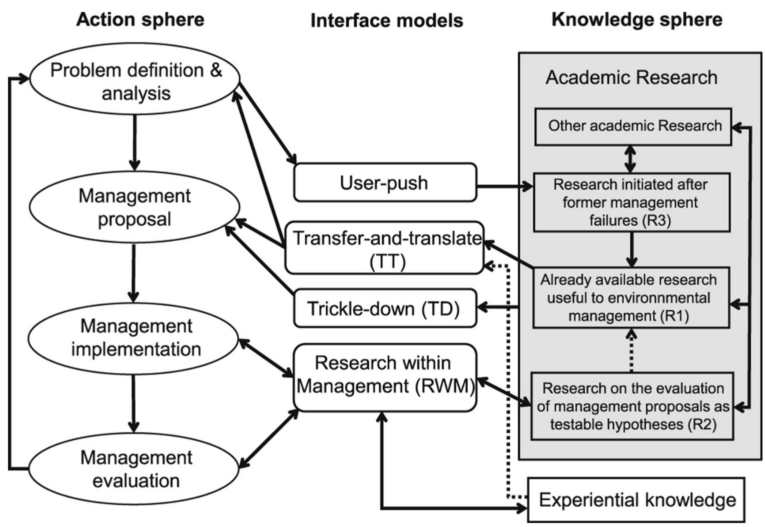

Figure 1: Scheme of research-management interfaces (Gosselin et al. 2018).

3 Results: eight schools of thought to represent SEM and their links with action

We identified eight schools of thought related to three different types of SEM representations. Each of these types contains several schools of thought. The way each school represents the metabolism and the relationship to action is described below (Sections 3.1 to 3.3), and summarized in Table 2.

3.1 Space and compartment-based representations

Space and compartment-based representations were developed, in particular, by Fischer-Kowalski (2015). These types of approaches consider society as a set of black boxes within which flows of matter and energy pass and are disposed of (Gomiero 2017).

We identified three main schools of thought: (1) social ecology; (2) metabolic rift and Marxist ecology; and (3) urban and territorial ecology.

3.1.1 Social ecology

In this school of thought, articles are generally far-reaching descriptions of metabolic changes and dynamic studies, taking the evolution of agri-food systems into account. They focus on large-scale spaces like countries or regions, and link them to broad historical analyses such as long-term socio-ecological transitions. Flows represent materials (e.g., biomass production and appropriation of the net primary production of a country (Kohlheb et al. 2009)), energy (e.g., the systemic account of a nation's carbon budget, comprising socioeconomic as well as ecological carbon flows in a historic time series (Erb 2012; Cusso et al. 2006)). Stocks consist of human and non-human populations such as livestock, infrastructure or land use (Fischer-Kowalski et al. 2009). These "black box" representations do not describe agents or "funds" as such (Frankova 2017). Instead, authors take an holistic or whole system approach, for example describing the effect of a whole country's metabolism in terms of environmental

School of thought (number of articles)	Representation	Action	Articles
	Space and compartment-based representations (39)		
Social ecology (20)	Stocks and flows at large scale spaces or between physical black boxes analyzed through historical material transitions	Limit the size of the metabolism through trickle-down and transition analysis directed at leaders of countries	"Bouwman et al. 2013; Cusso et al. 2006; Díaz de Astarloa et al. 2018; Fischer-Kowalski et al. 2009; Fischer-Kowalski et al. 2015; Fischer-Kowalski et al. 1998; Frankova 2017; Grešlová et al. 2019; Grešlová et al. 2015; Gueldner et al. 2017; Guzman et al. 2015; Guzman et al. 2018; Kohlheb et al. 2009; Krausmann 2009; Krausmann 2004; Kuskova 2013; Magalhães et al. 2019; Soto et al. 2016; Yuan et al. 2011; Zhang et al. 2012"
Metabolic rift and Marxist ecology (9)	Stocks and flows at large-scale spaces analyzed through Marxist frameworks	Change the system through trickle-down and critical analysis directed at civil society	"Clausen et al. 2015; Foster et al. 2014; Gomiero 2017; Gunderson 2011; Martinez-Alier et al. 2010; Moore 2000; Moore 2011; Schneider et al. 2010; Schneider 2017"
Urban and territorial ecology (10)	Stocks and flows at middle or small scales analyzed through stakeholder analysis	Develop and relocalize the territory's economy through transfer-and-translate and provision of management tools directed at local authorities	"Barles 2014; Barles et al. 2011; Barles 2015; Barles 2007; Billen et al. 2012; Buclet 2011; Buclet 2015; Cerceau et al. 2014; Oliveira et al. 2016; Tedesco et al. 2017"
	Economic-agent-based representations (26)		
Supply-chains-based metabolism (11)	Stocks and flows at individual companies or sector level analyzed through stakeholder analysis	Limit environmental impact and foster economic performance through user-push or transfer-and-translate and provision of management tools directed at companies and trade associations	"Blengini et al. 2009; Courtonne et al. 2016; Filippini et al. 2016; Kulak et al. 2016; Kytzia et al. 2004; Miranda-Ackerman et al. 2017; Pagotto et al. 2016b; Sellitto et al. 2018; Wirsenius 2003; Xu et al. 2016; Yazan et al. 2018"
Industrial ecology and symbiosis (15)	Stocks and flows at individual companies or local scale analyzed through stakeholder analysis	Close the loop and foster economic performance through user-push or transfer-and-translate and provision of management tools directed at companies	"Alfaro et al. 2014; Bellarby et al. 2017; Chance et al. 2018; Fernandez-Mena et al. 2019; Frone et al. 2017; Hobbes et al. 2007; Iacondini et al. 2015; Niutanen et al. 2003; Nowak et al. 2015; Nuhoff-Isakhanyan et al. 2017; Pagotto et al. 2016a; Shastri et al. 2011; Simboli et al. 2015; Tamura et al. 2014; Zabaniotou et al. 2015"
	Multi-faceted and composite representations (37)		
Multi-scale analysis of agroecosystems (8)	Economic and ecological funds and flows at multiple scales analyzed by their social performance	Preserve the funds through a research-within-management interface and post-normal-science-based tools directed at various stakeholders	"Brunori et al. 2016; Gamboa 2011; Giampietro 2004; Gomiero et al. 2001; González-Acevedo et al. 2016; Grillot et al. 2018; Scheidel et al. 2015; Serrano-Tovar et al. 2014"
Agroecology within food systems and landscapes (18)	Ecological funds and flows at the food system and landscape scales analyzed through power structure frameworks	Develop an ecological-process-based and socially fair food system through research-within-management interfaces directed at farmers and civil society	"Altieri 2002; Bonaudo et al. 2014; Dumont et al. 2013; Francis et al. 2003; González de Molina et al. 2020; González de Molina et al. 2017; Guzmán et al. 2012; L. Resque et al. 2019; Martin et al. 2016; Méndez et al. 2013; Méndez et al. 2017; Moraine et al. 2017; Rivera-Ferre 2018; Rosset et al. 1997; Mier y Terán Giménez Cacho et al. 2018; Ryschawy et al. 2017; Vaarst et al. 2018; Wezel et al. 2018"
Pragmatic sociology and earthbound ecology (11)	Humans and non-humans as funds and flows along non-scalar biomass flows analyzed jointly as actor-networks	Enhance diverse and locally-based sustainability programs through research-within-management and extended descriptions directed at human and non-human entities	"Akrich et al. 2006; Callon 1984; Coq-Huelva et al. 2012; Glover et al. 2018; Goodman 2001; Gray et al. 2013; Kristensen et al. 2016; Le Velly et al. 2016; Mol et al. 2006; Onyas et al. 2018; Wegerif et al. 2016"

Table 2: Articles classified in the eight schools of thought. NB: The 7 criteria used are made explicit within the table. The text follow the same pattern, with the criteria described in order. In the column "Representation" : (a) funds and flows, (b) their scale, (c) analyzed through their socio-economic-context. In the column "Action": (d) Goal, (e) the research-management interface, (f) the tools with (g) the actors.

impacts or pollution (Gueldner et al. 2017), or an analysis of the transition between different metabolic regimes (Soto et al. 2016). On this scale, it is not easy to deal with actors and their deliberate efforts. The agents in charge of governance are out of scope: socio-economic context is often disconnected from the description of stocks and flows. Researchers aim for the sustainability of resource use or the resilience of societies. They are interested in the size of the metabolism and, more or less explicitly, seek to reduce its size to a sustainable level. Research-management relies on a trickle-down interface: stakeholders are rarely involved and they almost never commission the research to promote change themselves (Fischer-Kowalski et al. 2009). Researchers promote change through knowledge, which is provided in a top-down way without taking the needs of any specific agents into account or trying to translate this knowledge in terms more suitable for policy making. When described, the potential actors are often public actors (e.g., national governments or international institutions). Facts come with no insight into what should be done, e.g., how global governance of flow could be implemented in the real world.

3.1.2 Metabolic rift and Marxist ecology

These articles explore a range of metabolism-related themes inspired by Marx's theories. The focus is on the same scales as those of social ecology (e.g., stocks and flows in a region-wide agricultural sector, long-term transformations), although the quantitative analysis of flows is often more succinct. What could act on metabolism and, consequently, on the capitalist system, is rarely described. Marxist descriptions of metabolism are, according to Georgescu-Roegen (1971), of the stocks-and-flows type. Funds or agents' abilities to change the system are not central. When they are mentioned, it is recalled that their capacity to change the system is limited (Gunderson 2011). Authors rely explicitly on Marxist concepts such as the metabolic rift. This concept refers to the rupture between humanity and nature and, extensively, between the city and the countryside (Foster 2000; Moore 2011). The metabolic rift perspective has been since used in a large variety of case studies. Performance is measured in terms of rifts in soil nutrient cycles or in terms of structural changes in relation to global carbon, nitrogen and water cycling (Gunderson 2011). The metabolic rift presents strong and multiple connections with other Marxist analyses, refering to the socio-economic context, such as these concerning capital or labor, and emphasizing power structures and exploitation (Foster 2000; Gunderson 2011).

The claimed goal is to change the system towards more social or environmental justice. To propose an alternative and support their arguments, several authors rely on comparisons with non-capitalist economies, e.g., Cuba (Clausen et al. 2015). The research-management interface is mainly based on a trickle-down model, and rely on critical analysis to generate change. Links with ongoing actions, when mentioned, associate social metabolism with environmental justice struggles lead by the civil society (Martinez-Alier et al. 2010).

3.1.3 Urban and territorial ecology

Urban and territorial ecology describe flows at local scales (e.g., territories or cities). At these scales, local authorities, economic agents, populations and living beings are described as active agents and funds. This gives rise to stakeholder analyses, sometimes inscribed in a broader historical context. Barles et al. (2007) analyzed metabolic interaction between Paris and the Seine during the industrial era. Funds at the scale of a territory are extensively described (administrative authorities, city-scale policies). Other levels are also described: lower ones (individual companies, civil society), or higher ones (changes in the technological or economic landscape, state-driven planning). Buclet et al. (2015) described different subsystems within a territory (agri-food system, wealth creation system, etc.) and explained the dynamics in the light of global factors and individual institutions. The goal is to produce analyses and representations at the scales of local stakeholders in order to reach a sustainable development of the territory e.g., through flow relocalization. These studies regularly involve a transfer-and-translate interface with the local authorities, to whom data and management tools are provided. The terms and concepts used are often very close to those used by administrative agents, making exchanges easier.

3.2 Economic agent-based representations

Articles in this type of SEM representation describe metabolism in terms of material flows between individual economic agents. We distinguish two forms: (1) a linear representation, the supply chain, where actors are distributed according to their place in the production process, "from cradle to grave", or from resource extraction to waste management; and (2) an ideal form, the perfect circle, in which there is no external resource or waste: the industrial symbiosis.

3.2.1 Supply-chains-based metabolism

These studies are concerned with the organizations involved during the production process of a product, from the extraction of resources to the delivery of the finished product to a consumer (or beyond). They take a functional level standpoint and distinguish processes according to the role played in the chain, e.g., production, transformation or distribution. Studies exist at all levels (local individual companies to global supply chains), and characterize metabolism through life-cycle analysis (LCA) or material flow analysis (MFA). Socio-economic context is integrated through economic and stakeholder analysis such as economically-extended MFA (Kytzia et al. 2004), social networks (Xu et al. 2016) or scenario building (Kulak et al. 2016). The goal is to help economic agents to limit environmental impacts (e.g., resource extraction, waste, pollution or carbon footprints), while maintaining or fostering economic performance. Most of the studies are related to a "transfer-and-translate" interface. The results are intended to be directly discussed with the decision makers, mainly the companies, but also trade or sector associations. The fact that the results or the tools can be directly mobilized by the actors is regularly a top priority. For example, Kulak et al. (2016) analyzed the bread supply chain using LCA to generate scenarios with experts during a collaborative design workshop, and then discussed the scenarios with farmers on a feedback loop basis. Blengini and Busto (2009) discussed the environmental impacts of alternative rice production systems using LCA and proposed their results as a tool for communication between suppliers and their customers.

3.2.2 Industrial ecology and symbiosis

Industrial ecology stems from Ayres's (2002) analogy between the ecosystems of ecological sciences and the industry. SEM representations represent products or substance flows, and focus on economic agents at different scales: an individual agent, e.g., a collective facility

(Chance et al. 2018), a couple, e.g., an olive farm and a mill (Zabaniotou et al. 2015), or a large network of farmers or industries (Nowak et al. 2015; Frone et al. 2017). Studies are divided between retrospective case studies (Nuhoff-Isakhanyan et al. 2017) and scenarios of industrial symbiosis (a real, linear, unsustainable system is compared to a closed and ideal system). For example, Alfaro et al. (2014) studied a small farming system at a village scale. A scenario of rural symbiosis was presented in the aim of increasing productivity and decreasing waste. While most studies do not rely on deep socio-economic analysis, some explore factors that are internal to economic agents such as knowledge, attitudes or practices. Multiple stakeholders are taken into account (e.g., farmers, extension agents) (Bellarby et al. 2017).

The goal of these approaches is to "close the loop" of materials and substances. Natural ecosystems are proposed as models for industrial activities: *"Our industrial system [would] behave like an ecosystem, where the wastes of a species [are] a resource to another species. The outputs of an industry [would] be the inputs of another, thus reducing use of raw materials and pollution"* (Frosch et al. 1989). The paradigmatic vision of sustainable industrial systems is characterized by minimized physical exchanges with the environment (Wassenaar 2015). Researchers regularly work closely with companies and operators. They are involved in the choice of research directions and are the subject of particular attention in terms of translation of the results. Resource-use optimization is often considered to be synergistic with economic performance (or profit making). Researchers seek to provide data or tools that allow companies to better manage interactions within their economic ecosystem. Most of these studies rely on user-push or transfer-and-translate interfaces. In some cases involving long-term relationships, researchers take part in a research-within-management interface, aimed at building a planned industrial symbiosis (Iacondini et al. 2015).

3.3 Multi-faceted and composite representations

The articles in this type of SEM representation do not describe agri-food systems in terms of large-scale stocks and flows, nor do they propose an economic-agent-based funds and flows analysis. We present these "atypical" multi-faceted and composite representations of metabolism through three examples: (1) multi-scale analysis of agroecosystems; (2) agroecology within food systems and landscapes; and (3) pragmatic sociology and earthbound ecology.

3.3.1 Multi-scale intergated analysis of agroecosystems

This framwork is more broadly termed as Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). It provides analysis of agroecosystems in terms of material and energy flows as well as biophysical and socio-economic funds. It provides theory and operational tools for characterization across multiple hierarchical levels of the performance of socio-economic activities (Giampietro et al. 2009). Serrano-Tovar et al. (2014) characterize the socioeconomic activities by a series of quantitative indicators at different scales (individual process, household, community). Humans workforce and the land are represented as funds, while flows are both material and economic. The main goal is the assessment of technical performance and better consideration of the biophysical constraints at the basis of economic activity. The sustainability is assessed in terms of viability (resources used and waste produced at rates compatible with those of the biophysical environment), feasiblity (human labour available), and desirability. The aim is to preserve the economic and ecological funds which ensure the metabolism works. In this sense, MuSIASEM is in direct continuity with Georgescu-Roegen's approaches.

When dealing with action, theoretical articles of MuSIASEM often refer to post-normal sciences. This method is intended to be a response to situations in which *"the facts [are] uncertain, values in dispute, stakes high and decisions urgent"* (Funtowicz et al. 1995). It recognizes that each description of the metabolism is necessarily partial. There are mutually multiple descriptions of the metabolism, provided by different scientific communities, mutually irreducible to each other and nevertheless relevant. Post normal science includes practices typical of research-within-management interfaces such as communication of uncertainties, taking part in social negotiation about desirable changes, and the co-evaluation of results within an extended peer community, including stakeholders. For example, Bruonori et al. (2016) assess local and global food chains across different commodities and countries through multi-scale metabolic and participatory evaluation. The results are then discussed in workshops with stakeholders.

This negotiation and participatory part, although described as essential in theory (Giampietro 2004), is nevertheless not described in every case study. Many studies follow similar methods without referring to MuSIASEM in the strict sense, nor following a post-normal approach. Gonzalez-Acevedo et al. (2016) compare different coffee systems according to ecological economic indicators (e.g., economic, energy performance and self-sufficiency), on the scale of households and society. The results are provided to coffee traders through a trickle-down interface.

3.3.2 Agroecology within food systems and landscapes

Agroecology is *"the integrative study of the ecology of the entire food system"* (Francis et al. 2003). It emphasizes the interrelatedness of all agroecosystem components and the complex dynamics of ecological processes (Altieri 2002): agronomic and ecological analyses are combined with social or cultural aspects. Metabolic processes are given special attention (González de Molina et al. 2017). These processes include nutrient cycling, crop-livestock interactions (Bonaudo et al. 2014; Martin et al. 2016) and material flows in food systems (Francis et al. 2003; Vaarst et al. 2018). Whereas traditionally focused on farm and plot scale, the landscape, community and multi-scale approaches are receiving increasingly more attention. The description of the socio-economic context is based on analyses of power structures.

Science and action are considered together. Agroecology provides the basic ecological principles for how to study, design and manage agroecosystems (Altieri 2002). It is both a science, an agricultural practice and a political movement (Wezel et al. 2009). Researchers claim normativity as their goal. They aim at a more sustainable agricultural system based on a strong dependence on ecological processes or services as well as on social justice. Action is considered broadly and involves civil society, NGOs, academics, local authorities, etc. Farmers are integrated into the construction of knowledge in participative action-research within a research-within-management interface (Méndez et al. 2013; Guzmán et al. 2012). For example, Moraine et al. (2017) propose a framework to perform integrated assessment of crop–livestock systems at the territorial level, combining ecological (crops, grasslands and animals) and social (farmers and chain actor interactions) systems. This framework is used as an intermediary object with stakeholders in participatory design approaches. However, many studies only provide elements of diagnosis or analysis in a trickle-down way. Resque et al. (2019) analyze agrobiodiversity, and how it relates to public mediated food chains. Stakeholder knowledge and perception is analyzed in relation to these programs. The results provide areas for management improvement.

3.3.3 Pragmatic sociology and earthbound ecology

In agro-food studies, this school of thought brings together constructivists approaches that have challenged previous understandings and include frameworks such as the actor-network-theory (Goodman 2001) or convention theory (Kristensen et al. 2016; Coq-Huelva et al. 2012). They focuses attention on hybridity and the role of heterogeneous associations in complex networks (Goodman 2001), and seek to understand what is happening in the process of building and stabilizing networks. Both humans and non-humans entities are considered as active agents (Callon 1990). The researchers follow the actors in the situations they encounter, and provide qualitative descriptions of links. In agri-food studies, this implies following material flows through their transformations, in markets and technical devices. Representations describe composite consisting of heterogeneous elements including humans, materials and technical devices that flexibly adjust to one another and act collectively (Çalışkan et al. 2010). No scales are explicitly described.

Akrich et al. (2006) studied the process of network building around cane straw as a source of energy for households. The evolution of the straw flow is followed, and its transformations are analyzed in connection with other agents (technological tools, institutions, etc). The straw flow is not only a flow, in Georgescu-Roegen's terms, but also a real agent, that actively transforms other agents around it. Wegerif et al. (2016) use an ethnomethodological approach to follow the agents implied in the food chain of a town, and trace interactions between them, highlighting transformations of food, people and ideas throughout the process. Socio-economic aspects are not considered as context, but rather considered as an integral part of the metabolism. These are described jointly as actor-networks.

The goal of pragmatic sociology is not normative, but procedural: it intends to bring attention to the network of ties that binds us to all life forms. These attachments sometimes described as "down-to-Earth", "earthbound" or "terrestrial" form the basis for a new definition of ecology (Latour et al. 2017). They aim to bring out different visions of metabolism concerning its sustainability (Onyas et al. 2018), resilience (Wegerif et al. 2016) or possible future arrangements (Kristensen et al. 2016). These works are considered as performative by the researchers. Following the internal logic of the school, we consider these works as relying on research-within-management.

4 Discussion

4.1 Limits and weaknesses

Our literature survey did not capture all the diversity of metabolic approaches. The keyword approach has made it possible to identify a variety of approaches from distant disciplines. However, it excluded relevant work only for vocabulary reasons. This is problematic since our field of study presents strong conceptual variability. Harvesting additional articles via the snowball effect has at least partially filled this gap. On the other hand, the method underestimates the non-English documents or books that were recovered only indirectly.

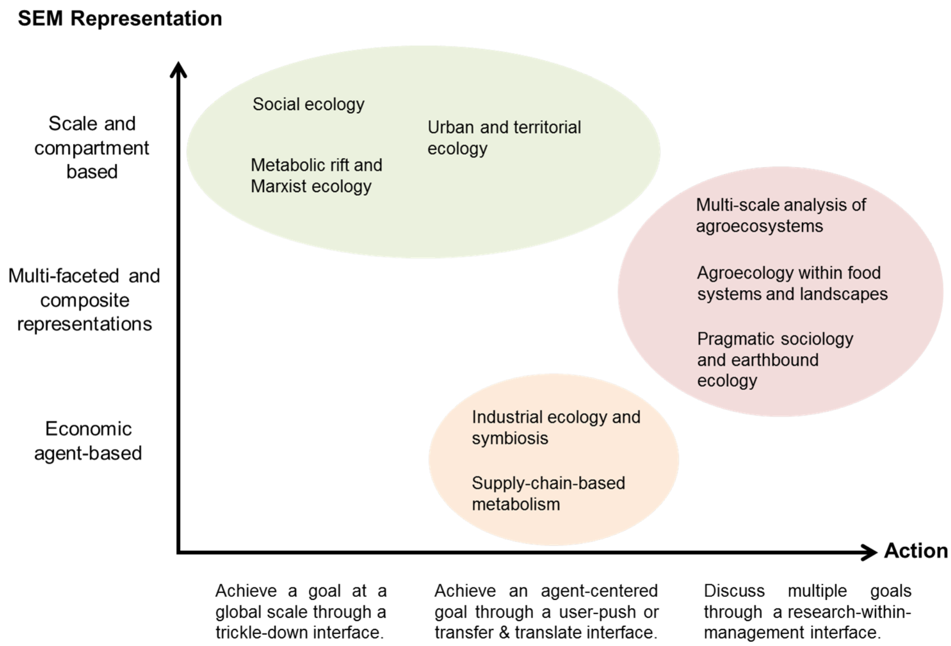

Figure 2: Summary diagram of schools of thought according to modes of representation and action

The stock/flow/fund framework proposed by Georgescu-Roegen (1971) is sometimes difficult to operationalize. In practice, it is not always easy to distinguish whether an author refers to stocks or funds. Concerning socio-economic analyses, criteria such as quantitative/qualitative or micro/macro would also have led to a different classification. For science and technics scholars, the relationship to action is considered as a process of translations where representations and actors mutually transform each other through a dynamic process (Callon 1984). This type of interpretation would further require qualitative description work, which would be difficult to integrate into a simple analysis grid.

The schools of thought are constructed according to our reading of SEM representations and links with action that we perceived in the articles. The authors of the papers do not always claim to be from the schools in which they are classified. For example, the article by Mol et al. (2006) is mainly based on descriptions characteristic of the school of thought "Pragmatic sociology and earthbound ecology". However, these authors claim to rely partially on industrial ecology, without endorsing its goals.

4.2 Representation and action are deeply intertwined

Our work showed a diversity of schools, described in terms of the way they deal with SEM (representation and action) (Fig. 2). The way in which representations and action are intertwined is discussed by type of representation:

4.2.1 In space and compartment-based representations

In space and compartment-based representations scales usually correspond to administrative scales, e.g., countries or regions (Fischer-Kowalski et al. 2009), which are usually "black-boxed". Action is not explicitly the main goal of these studies: researchers outline the problem and describe some of the quantities to be dealt with. The goal is normative and global, whether it is to change the economic system (Marxist ecology), or simply to drastically reduce its size (social ecology). Stakeholders are rarely involved and they are usually mobilized in a trickle-down interface. This contrasts with studies focused on smaller spatial scales such as urban or territorial ecology. They focus on smaller spatial scales and their goal is more agent-centered (e.g., sustainability of a given territory in urban and territorial ecology). Biophysical constraints are expressed at a territorial scale in a way favorable to their being taken into account by institutions: e.g., an Austrian-wide description is well suited to the Austrian authorities. Furthermore, when the metabolism is described at the scale of a given region, the administrative authorities of that region are regularly mentioned as partners. Policymakers and beyond them, governments or states, are assumed to be interested in handing collective problems such as the excessive size of SEM (Görg et al. 2017).

4.2.2 In economic agent-based representations

In economic agent-based representations authors explicitly claim their interest in action. The operational goal is agent-centered: economic, technical or environmental performance (e.g., closing the loop) is considered to be synergistic with the economic interest of companies.

Representation and actions are closely intertwined and this is reflected, in particular, by the place given to economic actors. Economic agents are given a central role since businesses are seen as the main actors able to handle change and technological innovation, and these are seen as essential for environmental improvement (Ayres et al. 2002). They are considered as economic funds, analyzed as stakeholders, and considered as partners in research-management interfaces. Agents that are described as funds in SEM representations are the same as those that are considered as potential partners through user-push or transfer-and-translate interfaces.

4.2.3 In multi-faceted and composite representations

Multi-faceted and composite representations offer descriptions that are neither centered mainly on economic actors, nor on predetermined spaces or compartments. Multi-scale analysis of agroecosystems, agroecology or pragmatic sociology do this in different ways: they question scales, challenge the science/politics divide or integrate humans and non-humans, respectively. All rely on a representation of multiple funds and actors at different scales or in a non-scalar way. Each of these approaches proposes a renewed way of dealing with action. All these approaches explicitly consider that the relationship to action must be taken into account in scientific representations (by post-normal science, by taking into account indigenous knowledge, or by the performativity of descriptions, respectively). The authors insist on the importance of taking multiple agents into account when generating representations (choice of scales, entities to be represented), and discussing them through collective deliberation in a research-within-management interface.

4.3 The theoretical and practical limits of schools of thought

Each school of thought chooses to open different black boxes and focuses only on a part of the system. Representations focused on specific scales or actors favor certain (agricultural) models over others, e.g., a large-scale SEM representation would favor the dominant systems, masking a variety of alternative models. The fact that companies are described as central in industrial ecology helps to rule out any alternative model. Historians' work shows that this legitimization of industries through metabolic representations has roots that go back to the beginning of industrialization in the 19th century (Fressoz 2016). Thus, each school defines different incommensurable visions of what a sustainable SEM should be and how it should be changed: schools of thought are also "schools for change". However, these positions are not definitive: there are not only variations within schools of thought, but also exchanges between them.

4.3.1 Practical cases diverge from theoretical claims

In some situations there is a discrepancy between the positions defended in the theoretical articles and what is actually described in the case studies. For example, MuSIASEM follows the proposals of post-normal science and states that researchers should take part in social negotiations and co-evaluate the results with stakeholders with a communication on uncertainties (Giampietro 2005). However, these recommendations rarely appear in case studies. Agroecology claims that science and politics cannot be separated, and farmers, researchers and civil society must be associated in the construction of knowledge, practices and social struggles (Altieri et al. 2011). Nonetheless, the case studies do not always show such a transdisciplinary posture. This difference generates dissensions and different competing narratives (Rivera-Ferre 2018).

4.3.2 Schools of thought transform in relation to each other

The different schools of thought interact and define themselves in relation to each other. For example, agroecology presents itself as being opposed to input substitution like that proposed by industrial ecology (Rosset et al. 1997), and opposes the idea that sustainability could be attained through a mono-supply chain approach (Francis et al. 2003). MuSIASEM proposes to focus on funds, as opposed to the stock and flow descriptions found in social ecology, and proposes decision-making based on social negotiation as opposed to the reductionist computer-based optimization found in industrial ecology (Giampetro 2002). Territorial ecology considers itself different from industrial ecology seen as focusing exclusively on resource-use optimization or on industrial societies, and leaves room for non-material flows in its analysis (Buclet 2015).

The different schools also influence each other. Social ecologists turn to multi-level analysis or downscale to get closer to actors (Fischer-Kowalski et al. 2009). Urban ecologists look for quantitative tools in industrial ecology (Beloin-Saint-Pierre et al. 2017). Social agrarian metabolism is described as a fusion between agroecology and social ecology, analyzing agroecosystem components through a metabolic lens, as funds and flows (González de Molina et al. 2020). Concepts such as agro-industrial ecology are proposed as mixes between agroecology and industrial ecology in the aim of more sustainable agricultural systems (Dumont et al. 2013; Fernandez-Mena et al. 2016).

4.4 Epistemological and methodological consequences

SEM studies find themselves in a balance between two epistemologies, positive and practical. While the majority of researchers aim to a certain extent to produce positive or neutral results (Pauliuk et al. 2015), many SEM studies have a practical focus, judging their results by their usefulness in influencing reality.

This raises the question of unstructured methodological pluralism (Spash 2013). In order to "unite the community", encourage "fruitful exchanges" or favor "change", "action", a certain number of authors have proposed definitions, epistemological or methodological positions and a set of attributes to be preserved in metabolic representations and in SEM in particular (Wassenaar 2015; Pauliuk et al. 2015; Breetz 2017; Beloin-Saint-Pierre et al. 2017). We suggest that an appealing path lies in the pragmatic philosophy.

4.4.1 Pragmatism, a philosophy anchored in empiricism

This current of thought is born in the United States at the beginning of the 20th century with Charles Peirce, William James and John Dewey. It has made a major contribution in linking ideas and their consequences, and particularly their usefulness for action.

The first pragmatists developed their ideas in opposition to the idealistic philosophers of their time. They criticized them for giving value to abstract concepts with no direct link to reality. To the idealistic attitude, pragmatism opposes an empirical one. The philosopher's work consists in inquiry, investigation. Ideas, concepts or representations have no value in themselves and must be tested in accordance with the facts. Thus, pragmatism is a generalization of the scientific and experimental spirit to the whole of our human experience.

Pragmatists propose to focus on the practical, factual consequences of our ideas. They enjoin us to *"consider the practical effects of the objects of [our] conception. Then, [to consider that our] conception of those effects is the whole of [our] conception of the object"* (Peirce et al. 1923).

4.4.2 The issue of pluralism

How do pragmatists approach the issue of pluralism, which is of interest to us here? William James describes two opposing philosophical positions: monists and pluralists. For the monists, the world has an intrinsic and absolute unity. For pluralists, it is disjointed, and there are as many worlds as there are points of view. Pragmatists refuse to decide between these two extremes, seeking instead a mediating way. Wondering about *the One and the Many* from a pragmatic perspective means answering the following question: *"Granting the oneness to exist, what facts will be different in consequence? [...] What is the practical value of the oneness for us?"* (James 1907).

4.4.2.1 A relational ontology

The pragmatic way consists in investigating what unites different elements, one by one. The world is one in the measure of the sum of the connections that we can discover in the experience. Oneness is described in the terms of links or relationship, i.e in a relational ontology.

4.4.2.2 *Multiple representations*

Nevertheless, the criteria for judging links are innumerable, the experience is multiple (James 1907). The diversity of criteria for satisfaction (or assessment) implies that there is necessarily a plurality of values, and therefore a plurality of possible representations.

4.4.2.3 *Collective action and deliberation*

The world is also multiple in the sense that the future of the world is indeterminate, it holds possibilities that cannot be predetermined. It always has something incomplete, something in the making. This means that the action and perspective of each human being counts. Pragmatism attaches great importance to collective action (Madelrieux et al. 2010), and especially deliberative and democratic processes that respect this pluralism (Rorty 1999).

4.4.3 Socio-ecological metabolism from a pragmatic perspective

Our results show that the practical consequences of pragmatic thinking are already and variously taken into account by many schools of thought:

4.4.3.1 *An empirical approach: metabolism as a reality rather than an analogy*

Flows in industrial systems used to be compared to flows and processes internal to an organism. The reference to physiology is less used today, and it is the reference to ecology, the science which actually describes the movement of materials and energy through living communities, that is preferred (Pauliuk et al. 2015; Wassenaar 2015). Social ecology proposes representations which describes social and natural metabolisms in the same ecological terms (Fischer-Kowalski et al. 2009; Kohlheb et al. 2009). MuSIASEM uses the funds/flows framework to investigate both human and non-human-made funds in economic processes. Pragmatic sociology and ”earthbound” refer, often explicitly, to ecology.

4.4.3.2 *A relational ontology through metabolic networks*

Most schools refer more and more explicitly to a relational ontology. In industrial ecology and supply chains, some authors refer to “metabolic network”, i.e., “a subset of a complex system of interconnected transformative processes across all scales of life”, or rely on social and material network analysis (Schiller et al. 2014; Wassenaar 2015). In Marxist ecology, non-binary concepts such as the “metabolic shift” are recently preferred to the historic “metabolic rift”, in order to focus on the transformations, rather than on the rupture between two ideal systems (Moore 2017). In pragmatic sociology, it means abandoning levels or scales and focusing instead on intensifications and extensions of entangled dependencies (Conway 2016).

4.4.3.3 *Multiple representations: multiple scales, agents and values*

Pluralism in terms of representations is widely shared: the SEM does not prescribe a specific level of aggregation or definitive boundaries (Pauliuk et al. 2015). Social ecology proposes representations at multiple scales, from local to global. In agroecology, scales such as the agroecosystem, the food system and the landscape are all considered as legitimate for investigation (Francis et al. 2003). Some schools take a step further and consider that multiple representations should be taken into account at the same time: MuSIASEM explicitly considers the existence of different "value systems" found among stakeholders. Their incommensurability implies that multiple and irreducible representations are inevitable (Giampietro et al. 2009). The same position is defended by pragmatic sociology or urban and territorial ecology which describes agents with different representations of the reality (Buclet 2015; Latour et al. 2017).

4.4.3.4 Collective action and deliberation: multi-criteria-debate-based goals

Concerning action, most schools value collective action and deliberation, to a certain extent. This implies a shift from scientific-knowledge-based action to multi-criteria-debate-based one. Görg et al. (2017) propose anchoring social ecology in critical thinking and transdisciplinarity with the help of political ecology. This leads to considering several goals together, e.g, composing industrial ecology's goals with animal health, pollution or diversity, thanks to a multi-criteria analysis (Bonaudo et al. 2014). Wassenaar (2015), speaking about industrial ecology argues that goals or "desirable changes" "would best be based on locally debated criteria". Multi-faceted and composite representations adopt this posture more extensively: MuSIASEM acknowledges that decisions have to emerge from negotiation and are not a prerequisite engraved in stone. Industrial ecology's goal of "closing the loop" is nuanced with other social goals (Boons et al. 2009). Pragmatic sociology, by taking an interest in the multiple representations of the actors and the particular situations in which they are linked, contributes to giving them a place in the social debate without imposing any normative goal. Agroecology gives a central place to the knowledge and choices of farmers, and re-anchors the choices regarding food systems on a societal scale.

5 Conclusion

This work offers some cross-sectional analysis that may be of value for SEM practitioners with an interest in social changes, including sustainability or transdisciplinary practices. It provides an understanding of the multiple schools of thought and can be used to acquire a better grasp of their sometimes implicit presuppositions. It also allows them to be discussed in relation to their choices of representation of metabolism, and in terms of goals and means of action. Our results suggest an opportunity to move away from a positivist and value-free epistemology in the study of SEM. Pragmatism provides tools to deal with the multiple incompatible values at play in the transformation of SEM, which echoes a vision of Ecological Economics with weak comparability of values (Martinez-Alier et al. 1998).

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