Chapter 10
Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism

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10.1 Introduction

The field of ecological economics was born out of the perceived need for a novel framing of the sustainability discussion, breaking away from the obsolete narratives of orthodox economics and the pitfalls of reductionism (Christensen, 1989; Martínez-Alier and Schlüpmann, 1987; Røpke, 2004). Early proponents emphasized the importance of the biophysical dimension of the economic system and the key role of non-equilibrium thermodynamics and systems ecology in shaping societal functioning and development (Georgescu-Roegen, 1971, 1975, 1977; Hall et al., 1986; Odum, 1971; Prigogine, 1980; White, 1943; Zipf, 1941). Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) was developed precisely to respond to these fundamental challenges. Indeed, MuSIASEM can be aptly described as a semantically open accounting framework for quantifying the complex biophysical interactions between human society and its natural environment that shape the metabolic pattern of social-ecological systems.

MuSIASEM is firmly grounded on the main conceptual pillars that drove the foundation of the field ecological economics:

1. Hierarchy theory provides the recognition that a complex system (such as social-ecological systems) can only be studied by integrating representations referring to different scales of analysis (Allen & Starr, 1982; Giampietro et al., 2006).

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2. Non-equilibrium thermodynamics provides the systemic definition of the state-pressure relation in the representation of the metabolic pattern across different levels of analysis (Prigogine, 1980).
3. Theoretical ecology provides the definition and quantification of concepts such as adaptability and evolution of the identity of social-ecological systems (Odum, 1971).
4. Georgescu-Roegen's biophysical economics, and in particular his flow-fund model, provides for the assessment of the inputs in the extended biophysical production function (Georgescu-Roegen, 1971).

MuSIASEM is a unique approach, both in terms of its process of quantification—based on relational analysis describing impredicative entanglement across scales (Louie, 2009; Rosen, 1991)—and in terms of its applications—the production and use of quantitative information for governance in the form of quantitative storytelling.

In the remainder of this chapter, I first provide a brief history of MuSIASEM. Following, I present an overview of its theoretical foundations and its working. I then cite examples of recent applications. The chapter concludes with a reflection on the current impasse in the field of ecological economics and the potential role of the Barcelona School of Ecological Economics in moving forward.

10.2 Brief History of MuSIASEM

MuSIASEM was first put forward as a multi-scale quantitative accounting framework by Mario Giampietro and Kozo Mayumi in 2000 (Giampietro & Mayumi, 2000a, b). Fruit of previous work on the subject (Giampietro, 1994, 1997; Giampietro et al., 1997; Giampietro & Mayumi, 1997), it aimed to provide a coherent quantification of the biophysical factors determining the feasibility, viability, and desirability of the metabolism of social-ecological systems. Early applications of MuSIASEM focused specifically on the metabolic pattern of food production (Giampietro, 2003) and energy (Giampietro et al., 2009, 2012, 2013b; Ramos-Martín et al., 2007, 2009). Pioneering work on integrating water metabolism into MuSIASEM soon followed (Madrid et al., 2013; Madrid-López & Giampietro, 2015). In 2012–13, a first attempt was made to extend its application to the complex water-energy-food nexus (Giampietro et al., 2013a, 2014), thus paving the way for the development of a comprehensive biophysical picture of the metabolic pattern.

In the EU-funded Horizon2020 project "Moving towards Adaptive Governance in Complexity: Informing Nexus Security" (MAGIC) (2016–2020), a series of important conceptual breakthroughs were made that solved earlier limitations of MuSIASEM related to the openness of social-ecological systems (e.g., trade in a globalized economy) and the quantification of the metabolic pattern across scales. Notably, the use of "metabolic processors," an instrumental tool developed in relational biology, enabled the analysis of impredicative relations over structural and functional elements across different levels of the metabolic pattern of the social-ecological system (Giampietro et al., 2021). This progress resulted in the development of the "MuSIASEM toolkit," a set of defined tools based on the MuSIASEM accounting framework that, used in combination, effectively organizes a multi-level and multi-dimensional quantitative characterization of a metabolic pattern in relation to four criteria of performance: feasibility, viability, desirability, and security (openness) (see, Giampietro et al., 2021).

MuSIASEM became part of the Barcelona School of Ecological Economics in 2007. Nonetheless, being firmly based in complexity theory, it retained its own identity, clearly differentiating itself from the more conventional applications of material (and energy) flow analysis.

10.3 Theoretical Foundation

MuSIASEM explicitly recognizes that "production" and "consumption" are intricately linked and cannot be studied separately—something that is, unfortunately, still routinely done in conventional economic and biophysical analyses. The way a society produces secondary inputs invariably affects the way it consumes secondary inputs in an *impredicative relation*. Hence, as argued by Zipf as early as 1941 (Zipf, 1941), human societies must be studied as complex sociobiological systems. MuSIASEM, therefore, starts out from the basic premise that the metabolism of social-ecological systems is not a mere metaphor; social-ecological systems *are* complex metabolic networks.

Indeed, in MuSIASEM, the external referent for the entanglement between biophysical flows and funds is the metabolic pattern of social-ecological systems (Giampietro, 2018). This means that the various conversions of energy and material inputs taking place in the system—needed to reproduce its structural elements and express the expected functions—impose a set of relations over the profiles of the inputs and the outputs of the system: energy, water, food, other materials on the input side and waste, and emissions and other pollutants on the sink side. The relation between the expression of a given metabolic pattern inside the system (inputs and outputs of the parts), on the one hand, and the requirement of a specific profile of inputs and outputs of the whole exchanged with the environment, on the other hand, is governed by the *state-pressure relation* typical of dissipative structures and well defined in the field of non-equilibrium thermodynamics (Giampietro & Renner, 2021; Glansdorff & Prigogine, 1971; Prigogine, 1980). The state-pressure conceptualization is crucial as it allows a definition and quantification of the DPSIR framework (driving forces, pressures, states, impacts, responses) across different levels and dimensions of analysis.

In the operationalization adopted in MuSIASEM, social-ecological systems are defined as "metabolic networks in which constituent components stabilize each other in an impredicative (self-referential) set of relations in presence of favorable boundary conditions" (Renner et al., 2021). The characteristics of the stabilized metabolic network represent the *state of the system* and the characteristics of the favorable boundary conditions the *associated pressure* exerted on the environment. Such a representation of the state allows for the analysis of characteristics such as the relative size of constituent components (parts), their metabolic rates, and, more in general, a definition of societal identity (Renner et al., 2021). More specifically, the state of a social-ecological system is defined as the specific combination of relations among structural and functional elements (parts). These relations must guarantee an internal dynamic equilibrium between the aggregate requirement of goods and services needed to support the metabolism of the various constituent components of the system and the ability of the internal structural and functional elements to produce and/or import these goods and services.

In the analysis of the state of the system (viability seen from the inside), only the metabolism of secondary flows is observed (i.e., energy carriers, food products, and other material goods consumed in the economic process). On the contrary, in the analysis of the interaction of the system with its local environment (feasibility seen from the outside), the state of the system (what is going on inside the socio-economic system) is coupled with the set of environmental pressures resulting from the interaction of the system with the environment (what is going on in the ecological systems). The analysis of viability and feasibility requires the adoption of two different descriptive domains and different metrics. (For example, in a metabolic analysis, 1 joule of coal—a primary energy source produced by the biosphere—is not "the same" as 1 joule of electricity—an energy carrier or secondary energy produced and consumed in the technosphere). The study of the state-pressure relation demands an accounting system that can track primary flows: flows crossing the interface between the socio-economic and the ecological system, either extracted from primary sources (e.g., coal mines, wind, aquifers, rain) or discharged into primary sinks (e.g., GHG emissions into the atmosphere). Thus, the analysis of primary flows is prerequisite to study the environmental pressures and related environmental impacts (feasibility).

The openness of modern economies through international trade represents a major challenge for the analysis of the state-pressure relation across hierarchical levels/scales of analysis. We can define local feasibility in relation to the state-pressure relation observed inside the boundaries of the social-ecological system. However, we also have to consider the set of externalized pressures to the biosphere outside of the borders of the system. Openness is, therefore, a crucial piece of information for deliberating about resource security and burden shifting. In order to account for the openness of the system in the analytical framework, MuSIASEM distinguishes between:

1. Internal or domestic supply systems operating inside the system, for which we can calculate both feasibility and viability from observed data.
2. Externalized or "virtual" supply systems that are embodied in the imported commodities.

For the latter, we can only define notional representations of the inputs required for producing the imported commodities (relevant for feasibility and viability). These can be assessed by measuring the flows of imported commodities (food, energy, and products), a task that requires the use of yet another metric. The relative share of the internal consumption that is produced internally provides an indication of the "metabolic security" of a society (and hence its degree of biophysical resource security) as well as the burden-shifting outside of its boundaries.

10.4 How Does MuSIASEM Work in Practice?

MuSIASEM has three main practical goals:

1. To generate a useful quantitative characterization of the *state* of the system. This includes an operational definition of: (i) the system that we want to study (the whole), (ii) its parts (those relevant for the purpose of the study), and (iii) the state-space of the system for describing relevant changes, i.e. the set of attributes of the metabolic pattern considered relevant for studying (changes in) the performance of the system.
2. To provide a quantitative characterization of the *state-pressure relation* of the socio-economic system with its ecological environment. This characterization is based on the coupling of two distinct metrics in that the internal process of dissipation (the internal state) must be compatible with the existence of favorable boundary conditions in the environment (an admissible environmental pressure). The state-pressure relation is studied by linking the representation of the processes under human control inside the society (on the socioeconomic side) to the representation of processes beyond human control outside of the society (on the ecological side). A simple example would be to link the process generating the required hydroelectricity (measured in kWh) to the processes generating falling water (measured in terms of kinetic energy). This coupling allows analyzing expected impacts on the environment of the studied pressures.
3. To assess how much the state-pressure relation is altered by *trade*. The option to import allows a social-ecological system to ease:

   (a) The internal requirement of production factors by avoiding the labor and technology (funds) and secondary inputs (flows) required for the production of the imported goods and serves, thus overcoming potential *viability* constraints.
   (b) The resulting environmental pressures, by avoiding the use of local natural resources (e.g., land use) and sink capacity for the production of the imported goods, thus overcoming potential *feasibility* constraints.

   For instance, importing electricity avoids the need of building and operating power plants (end-uses inside the society) and the need for primary energy sources to fuel it (environmental pressure inside the system boundaries). The practice of externalizing required production factors to other social-ecological systems has become so common today in developed countries that there no longer is a direct relation between what is produced and what is consumed inside their borders.

An integrated quantitative representation of the metabolic pattern of social-ecological systems is obtained by combining the different 'lenses' of the analysis across non-equivalent descriptive domains:

1. Through the lens of the *macroscope* we observe and describe the metabolic characteristics of its constituent components (the parts inside the black box), as observed from the inside, using a metric useful to study the *state*. It characterizes the sizes (absolute and relative) of the individual constituent components, their interactions, and the role they play in the expression of the emergent property of the whole—i.e., the observed metabolic state.
2. Through the lens of the *mesoscope* we observe the *openness* of the system, using a metric useful to study the degree of dependence on imports. This permits to identify how much of the total internal consumption of commodities is produced domestically and how much is imported. In this way, we can assess the dependence of the system on imports for a given set of commodities and define a series of 'virtual' supply systems (operating elsewhere) required for producing what is imported. This information is then further elaborated through the lens of the virtualscope (see below).
3. Through the lens of the *microscope* we describe different views of the interaction between the socio-economic and ecological system at the local scale, using a metric useful to study the *state-pressure* relation. This description provides the set of expected profiles of: (i) funds associated with processes under human control, such as human labor, land uses, and power capacity, that define a *size* for the structural and functional elements; (ii) flows associated with processes under human control, i.e., secondary inputs (e.g., electricity, fuels, fertilizers, materials) transformed into secondary outputs (products). Specific combinations of secondary inputs map onto *end-uses* needed for the generated outputs; and (iii) primary flows associated with processes beyond human control, i.e., primary flows derived from environment and the wastes dumped into the biosphere by the *end-uses*. These primary flows map onto *environmental pressures*. A comparison of these pressures with the locally available supply and sink capacity of ecological funds (e.g., flows per unit of land use) provides an indication of the *environmental impacts*.
4. Through the lens of the *virtualscope* we describe the characteristics of a notional set of *virtual processes* that would be required to produce the imported goods and services. Indeed, by combining the information obtained through the mesoscope and the microscope, we can calculate the amount of secondary and primary production factors required by 'virtual supply systems' to produce the imported goods. This can be done in three different ways, depending on the purpose of the analysis:

    (a) Track the countries of origin of the imports and use the observed identities of the metabolic processors of the producing (exporting) countries.
    (b) Generate a notional identity for the metabolic processors of imports based on a representative (average) mix of production processes used to supply that commodity on the global market.

(c) Use the identity of the metabolic processors of the system under study (the local supply system) to calculate the amount of secondary flows (end-uses) and primary flows (environmental pressures) that would be needed to internalize the production of the imported commodities.

Thus, the analytical framework of MuSIASEM characterizes the metabolic pattern of a given social-ecological system based on four integrated sets of data:

1. Internal end-use matrix—the secondary inputs (flow and fund elements) used *inside* the socio-economic system for expressing social practices across levels (the local technical processes needed to reproduce the internal state).
2. External end-use matrix—the secondary inputs (flow and fund elements) used by the socio-economic system *outside* its borders to produce the imports (the externalized technical processes needed to reproduce the internal state).
3. Internal environmental pressure matrix—the primary flows exchanged with the biosphere *inside* the boundaries of the social-ecological system (the local environmental pressures associated with the reproduction of the internal state).
4. External environmental pressure matrix—the primary flows exchanged with the biosphere *outside* the boundaries of the social-ecological system to produce imports (the externalized environmental pressures associated with the reproduction of the internal state).

It is important to recognize that MuSIASEM is a semantically open accounting framework. While this guarantees a broad applicability, it also implies that the specific choices of accounting must be tailored to each specific case selected. A "one size fits all" protocol does not work in metabolic analysis. Further details on how to apply MuSIASEM are available in (Giampietro et al., 2021).

10.5 Selected Applications of MuSIASEM

As mentioned in Sect. 10.2, in the early years, MuSIASEM was predominantly applied to describe the feasibility, viability, and desirability of the societal metabolism of energy and food production. While this type of study remains highly relevant and has gained popularity in societies under severe biophysical pressures, such as China (Geng et al., 2011; Han et al., 2018; Lu et al., 2016) and Latin America (Silva-Macher, 2016), recent years have seen a remarkable expansion of the types of application of MuSIASEM, including:

1. Assessments aimed at improving the quality of the *analysis* of sustainability issues, for example, in relation to biofuels (Ripa et al., 2021a), desalination for irrigation (Serrano-Tovar et al., 2019), arid land crop production (Cabello et al., 2019), energy efficiency (Velasco-Fernández et al., 2020a, b), the aging of fossil energy sources (Parra et al., 2018, 2020), waste management (Chifari et al., 2017), urban metabolism (Pérez-Sánchez et al., 2019) and ecosystem health (Lomas & Giampietro, 2017). This type of study focuses on advancements in the theoretical framework in relation to specific applications.

2. Assessments aimed at improving the quality of the *conceptualization* of sustainability policies, also referred to as "quantitative story-telling," for example, in relation to biofuels (Cadillo-Benalcazar et al., 2021), alternative sources of electricity (Renner & Giampietro, 2020), aquaculture (Cadillo-Benalcazar et al., 2020a), and the circular economy (Giampietro, 2019; Giampietro & Funtowicz, 2020). These applications aim to integrate the 'politico-institutional structure' into the picture, thus responding to the criticisms on MuSIASEM raised by Gerber and Scheidel (2018) and connecting with the limits to growth discourses.
3. Assessments of the socio-economic and environmental pressure exerted by developed countries (EU and USA) on other countries, such as the labor hours (worker equivalent) embodied in EU and US imports (Pérez-Sánchez et al., 2021); the externalization of primary energy source requirements by developed countries (Ripa et al., 2021b); and the externalization of food production by the EU, showing the impossibility of achieving local food security by re-internalizing the production of imported commodities (Cadillo-Benalcazar et al., 2020b; Renner et al., 2020). This type of studies explicitly connects with the ecological distribution conflicts addressed by the Political Ecology stream of the Barcelona school.

MuSIASEM has been criticized for providing a static rather than a dynamic picture of the metabolic pattern of social-ecological systems (Gerber & Scheidel, 2018). As a matter of fact, no model of complex systems can represent real evolutionary change (see the concept of complex time in (Giampietro et al., 2006)). Conventional models can only predict futures by applying the ceteris paribus hypothesis to observed quantitative relations. To avoid this predicament, MuSIASEM uses contingent definitions of the option space of expected metabolic relations between fund and flow elements considering their metabolic characteristics, their relative size, and their combination. In this way, MuSIASEM can assess changes in structural and functional elements at different scales using historic series (comparing apples with apples and oranges with oranges across levels of analysis), as shown in several applications (Giampietro & Mayumi, 2018; Ramos-Martin & Giampietro, 2005; Velasco-Fernández et al., 2015).

10.6 Concluding Remarks

Ecological economics was established out of the belief, shared by a group of interdisciplinary scholars, that both the master narratives and the quantitative models used to describe the sustainability predicament were not only useless but outright misleading when used to inform policy. For this reason, ecological economics called for less simplistic narratives and more transdisciplinary and effective representations of the economy; representations that describe the whole system, the context, and the parts, as well as the interactions between parts/parts, parts/whole, and whole/context. Despite the significant progress made by various scholars in this regard, as eloquently shown by the contributions in this book, recent years have seen conventional economic approaches regain a foothold in the field of ecological economics (Plumecocq, 2014).

Probably the explanation for the relative lack of success of biophysical approaches to the economic process lies in the institutional setting. Given the prolonged economic stagnation of the past decade, policy-makers are thirsty for simplistic models and indicators, and win-win solutions, and many scientists have been happy to satisfy their needs. We are increasingly witnessing a change in the way decisions are made in relation to sustainability: We have moved from 'evidence-based policy' to 'policy-based evidence'. The policy legend of the circular economy is a striking example of this phenomenon (Giampietro & Funtowicz, 2020).

It is time that we recall the wisdom of great scholars. Albert Einstein observed, "Everything should be made as simple as possible, but not simpler," while Joseph Schumpeter remarked, ".. the general reader will have to make up his mind whether he wants *simple* answers to his questions or *useful* ones—in this as in other economic matters he cannot have both" (Schumpeter, 1930). It is the very aim of societal metabolism studies to address the complexity of the sustainability issue from the point of view of both analysis—avoiding the pitfalls of reductionism—and narrative—selecting adequate criteria to guarantee the quality of the process of production and use of scientific information in decision making. The recent focus on the nexus between water-energy-food-environment has clearly shown that there is a direct relation between silo-governance (a main cause of policy failures in the sustainability domain) and the lack of appropriate analytical tools capable of dealing with the complexity of the sustainability issue at hand (Giampietro, 2018). While orthodox economic research develops simplistic models and indicators aimed at the governance of complexity, the Barcelona School of Ecological Economics collectively provides a forward-looking line of research that develops decision support tools for multi-level governance in complexity.

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