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From input–output analysis to the quantification of metabolic patterns: David Pimentel's contribution to the analysis of complex environmental problems

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Abstract

This paper revisits David Pimentel's work on input–output analysis of agricultural production systems with the objective of demonstrating its (continued) relevance for the analysis of complex environmental issues. It is shown that his unique accounting procedure is grounded in complexity theory and that it effectively links expected relations over primary inputs and outputs exchanged with the ecosphere and secondary inputs and outputs exchanged with the anthroposphere (including labor). New conceptual building blocks are introduced to demonstrate that Pimentel's analysis can be extended across different hierarchical levels (crop typologies, commodity supply systems, agricultural regions, etc.) and dimensions of analysis to obtain a formal representation of the metabolic pattern of social–ecological systems. These concepts include: (i) state–pressure relation (extensive properties); (ii) flow–fund ratios (intensive properties), i.e., qualitative benchmarks to define typologies of agricultural production in relation to both the socioeconomic process (e.g., land productivity, labor productivity) and the environmental pressure exerted on the environment (e.g., water consumption, GHG emission and pesticide load per hectare); and (iii) relational analysis to scale up the analysis to higher hierarchical levels so as to acquire policy relevance. Examples of the pertinence of this formalization are illustrated using Pimentel's original data on grain cultivation in the USA. It is concluded that Pimentel's work has set an example for a holistic approach to complex environmental problems and has paved the way for a more general conceptualization of social–ecological systems as metabolic systems.

Keywords Input–output analysis · Societal metabolism · Metabolic pattern · Social–ecological system · Relational analysis

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1 Introduction

Nearly 50 years ago, David Pimentel first started to draw the attention of the scientific community and policymakers to wicked environmental problems in relation to the (un)sustainability of human development, such as the fossil energy dependence of the food system (Pimentel & Pimentel, 1979), soil erosion in agriculture (Pimentel et al., 1976, 1995), loss of biodiversity (Pimentel et al., 1997a, 1997b), and the problematic of biofuels and biomass energy (Giampietro et al. 1997a, 1997b; Pimentel et al., 1981, 2008; Pimentel & Patzek, 2005). Much of his research was inspired by the oil crises of the 1970s and the publication of a series of books, such as "The Limits to Growth" (Meadows et al., 1972), "The Population Bomb"(Ehrlich, 1971), and "Silent Spring" (Carson, 1962), that forced the academic community to critically reflect on the hitherto uncontested idea of perpetual economic growth on a finite planet. The sudden awareness of the existence of complex sustainability concerns revealed the gross inadequacy of the available (quantitative) knowledge about key biophysical factors (e.g., food, energy, water, biodiversity) and even more so about their interlinkages, i.e., the "resource nexus," in the sustainable management of natural resources (Daly, 1971). Almost 50 years later, and despite the impressive proliferation of scientific journals and publications in the field of sustainable development, this research gap persists; tangible improvements in the quantitative analysis of complex sustainability problems are yet to be achieved (Giampietro et al., 2000; Stirling, 2010, 2014).

In his attempt to address this research gap, Pimentel combined common sense about concrete environmental problems with quantitative reality checks based on relatively simple biophysical input–output analysis rather than complicated models [e.g., (Pimentel & Pimentel, 1979, 2003; Pimentel et al., 1988)]. In this sense, he may be considered a forerunner of quantitative storytelling (Cadillo-Benalcazar et al., 2021; Matthews et al., 2017; Waylen et al., 2020). He also was a pioneer in the quantitative analysis of what is now known as the water–energy–food–environment (or resource) nexus in that he was among the first to consider simultaneously and in an integrated way, distinct dimensions of sustainable development. In particular, he focused on the relation between food, energy, water, soil, biodiversity, human labor, and fertilizer and pesticide use in agroecosystems [e.g., (Pimentel et al., 1986, 1994, 2010; Pimentel et al., 1997a, b; Pimentel & Burgess, 2014; Wen & Pimentel, 1992)]. His analysis was considerably richer than the conventional input–output analysis popular in the 1970s, which was typically narrowly focused on only two variables: fossil energy input and food output (Blaxter, 1975; MacKinnon, 1976). Instead, Pimentel used a profile of inputs that referred to both the economic process (classic production factors, such as labor, capital, and technical inputs) and the environment (energy and primary agricultural resources, such as soil, water, and biodiversity), thus addressing the link between the economic and environmental dimensions of sustainable development.

Yet, despite its novelty and potential, Pimentel's vision on how to enrich conventional input–output analysis did not quite receive the attention it deserved. As a matter of fact, after its rise in the 1970s, the popularity of conventional energy input/output analysis quickly declined in the 1980s due to persistent conceptual and methodological ambiguities resulting in lack of practical applicability (Energy Research and Development Administration, 1977; Leach, 1975; Long, 1978; Slesser, 1977), and eventually conventional input/output analysis was appropriated by the fields of economics and econometrics [e.g., (Miller & Blair, 2022)]. The current impasse in sustainability research has revived the interest of the academic community and policy makers in biophysical analyses of social–ecological systems (e.g., regarding the "bioeconomy" (European Commission 2023; Robert et al., 2020) but in this quest the older but highly relevant work already performed in this field by Pimentel tends to be ignored.

In this paper, Pimentel's ideas of a relational input–output analysis of agricultural production systems are revisited to demonstrate its (continued) relevance for a quantitative *biophysical* analysis of today's increasingly complex sustainability problems. The rest of the paper is organized as follows: Sect. 2 describes the workflow of the present study. Section 3 describes the fundamental challenges encountered in "quantifying" complex sustainability problems and shows the importance of the conceptual breakthroughs implicitly associated with the use of Pimentel's profiles of inputs and outputs. Section 4 introduces several conceptual building blocks, including the state–pressure relation, the fund–flow model, and relational analysis, that permit to formalize Pimentel's analysis of the input–output profiles of agroecosystems into a more generalized analysis of the metabolic pattern of social–ecological systems (and hence complex sustainability problems). Using these concepts, Sect. 5 then walks the reader through this formalization and explains the advantages it offers for the analysis of complex environmental problems. Finally, Sect. 6 concludes.

2 Workflow

This study first examines Pimentel's essentially *empirical* work on the input–output profiles of agroecosystems and explains its relevance for the analysis of complex social–ecological systems. Following, Pimentel's empirical work is *formalized* by creating a conceptual framework. This is done by step-by-step generalizing Pimentel's empirical analysis of the input–output profiles of specific agroecosystems into a systemic multi-level and multi-dimensional assessment of the metabolic pattern of social–ecological systems. The formalization starts out from the relation between profiles of inputs and outputs, but introduces several novel conceptual features:

- It explicitly distinguishes between fund and flow elements, which allows the analyst to simultaneously consider quantitative aspects (extensive variables) and qualitative aspects (intensive variables).
- It introduces the idea of scaling the analysis across the different hierarchical levels of complex social–ecological systems through relational analysis.

It is then shown that, compared to Pimentel's original empirical work, this formalization offers an important advantage. Indeed, the conceptual framework obtained is no longer based on a given protocol or specific agroecosystem, but is *semantically open*: The inputs and outputs included in the analysis will have to be decided by the analyst and will depend on the purpose and scope of analysis (e.g., the type of social–ecological system and problem under investigation). This greatly enhances the flexibility and applicability of the approach, also outside of the domain of agriculture.

3 The conceptual breakthroughs implicit in Pimentel's work

3.1 The challenge of quantifying wicked problems in sustainability science

Hierarchy theory is a branch of complexity theory that deals with the epistemological implications of the coexistence of multiple hierarchical levels at which one can observe complex processes and phenomena (Ahl & Allen, 1996; Allen & Starr, 1982). According to hierarchy theory, exact and deterministic quantitative relations over numbers can only be defined by simplifying the perception of a given set of transformations, using one spatial–temporal scale and one analytical dimension at the time. Hence, the price to pay for producing crisp numbers and indicators is having to focus on a given, limited observation space autocratically chosen by the analyst in the pre-analytical phase (Giampietro et al., 2006). This unavoidable epistemological predicament implies that most of the quantitative analyses currently adopted to assess sustainability issues are of limited use to effectively deal with their complexity (Benessia et al., 2016; Sarewitz, 2000). This is particularly problematic in policymaking where several different factors must be considered simultaneously (Saltelli & Giampietro 2016).

In complex systems, such as social–ecological systems[1], relevant processes take place at different spatial–temporal scales and mutually affect each other (i.e., impredicative relations across hierarchical levels). For example, an improvement in the local water-use efficiency of a given crop (per hectare per year) can lead to increased water consumption at the regional scale in the long term through an enlargement of the irrigated area (e.g., change in cropping patterns) (Schyns & Hoekstra, 2020). This phenomenon—known as the Jevons paradox (Giampietro & Mayumi, 2008)—is common but impossible to capture in a simple model. Indicators such as water-use efficiency, a simple input/output ratio, are implicitly based on the *ceteris paribus* assumption and simply cannot characterize simultaneously qualitative (yields) and quantitative changes (crop area) of agricultural systems across different hierarchical levels and dimensions of analysis. Complex processes can only be observed by using non-equivalent descriptive domains across different spatial–temporal scales (Allen & Starr, 1982). Indeed, to produce a coherent complex information space, we must continuously contextualize the quantitative results across different types of external referents derived from analyses carried out at different scales (Allen & Giampietro, 2006; Giampietro et al., 2006; Gomiero et al., 2006). It is simply impossible to handle sustainability indicators without a proper contextualization based on an integrated analysis of change in both qualitative (per unit) and quantitative (size) terms.

3.2 Pimentel's legacy: the use of intensive and extensive variables to create expected relations over profiles of inputs and outputs

Most of Pimentel's work focused, directly or indirectly, on the agricultural production process, including agro-biofuels. Although he did not explicitly seek to solve the epistemological challenges associated with the representation of this complex production system, Pimentel's methods of quantification were nonetheless an important step into this direction. He used his data to characterize processes of agricultural production (e.g., production of food items) and organized his data as lists of interrelated inputs and outputs relevant for

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[1] See Sect. 4.2 for an explanation of the concept of social–ecological system.

Table 1 Profile of inputs for corn production in the USA assessed on a space-time scale of, respectively, 1 hectare and 1 year. Table adapted from Table 10.7 (p. 115) of (Pimentel & Pimentel, 1996)

	Quantity (per ha)	Productivity[1]	Nexus relevance
INPUTS			
Labor	10 h	750 kg/h	Cost, jobs, energy, food
Machinery	55 kg	136 kg/kg	Cost, power capacity
Diesel	75 l	100 kg/l	Cost, energy, GHG
Gasoline	40 l	187 kg/l	Cost, energy, GHG
Nitrogen (fertilizer)	152 kg	49 kg/kg	Cost, energy[2], pollution
Phosphorus (fertilizer)	75 kg	100 kg/kg	Cost, pollution
Potassium (fertilizer)	96 kg	78 kg/kg	Cost, pollution
Limestone (fertilizer)	426 kg	18 kg/kg	Cost, pollution
Insecticide	2 kg	3750 kg/kg	Cost, pollution
Herbicides	4 kg	1875 kg/kg	Cost, pollution
Irrigation	660,000 kg	[1/88] kg/kg	Cost, water, energy
Seeds	21 kg	357 kg/kg	Cost, biodiversity
Electricity	120 kWh	29 kg/kWh	Cost, energy, GHG
Drying	2760 MJ	3 kg/MJ	Cost, energy, GHG
OUTPUT			
Corn	7500 kg	7500 kg/ha	

[1] Yield per unit of input and per hectare of land use

[2] The production of nitrogen fertilizer requires natural gas and accounts for the larger share of fossil *energy use in US agriculture* (Pimentel & Pimentel, 1996)

different sustainability dimensions (see Table 1). In doing so, Pimentel implicitly endorsed Einstein's advice regarding the representation of complex issues—"make it as simple as possible, but not simpler"—thus avoiding the fatal attractor of reductionism. Indeed, even if the main interest of Pimentel's early work was the quantitative characterization of the relation between food and energy, he never proposed a simplistic reductionist analysis in the mere form of a ratio over two individual variables (food output/fossil energy input). Instead, he always preserved the information about the size of the system under analysis, in relation to the flows considered in the assessment, and defined profiles of inputs and outputs per hectare.

Thus, a first key aspect of Pimentel's approach is that he used a variety of input and output variables related to distinct dimensions of the resource nexus, including:

1. Primary inputs and outputs derived from and going to the ecosphere. These inputs and outputs have an ecological relevance.
2. Secondary inputs and outputs coming from and going to the anthroposphere. These inputs and outputs, which include traditional production factors such as labor and capital, have an economic and technical relevance.

Indeed, by combining different variables and metrics (e.g., kg, h, MJ) the user of the data reported in Table 1 obtains a flexible information space relevant to the resource nexus that can be converted into other variables and metrics depending on the purpose of the analysis. The secondary inputs required from the anthroposphere (labor, machinery, energy, fertilizers, pesticides) can be converted from biophysical to monetary terms (using prices) and contextualized in relation to different purposes, while the primary inputs and outputs (environmental pressures) can be related to environmental impact. For instance, hours of labor have an economic cost, but they are also related to job opportunities (at the level of household/village) and labor requirements in the agricultural sector (at the level of the national economy). In the same way, inputs of energy carriers (e.g., liters of diesel) are relevant not only because of their economic cost (farm and sectoral level), but also because of energy security and GHG emissions at the national level. Inputs such as fertilizers and pesticides, besides having an economic cost and (indirect) resource consumption for their production, are directly related to productivity (agronomic and economic performance) and to environmental impact on the ecosphere side.

A second key aspect of Pimentel's quantification is that the recorded profiles of inputs and outputs can be described per unit of area, i.e., per hectare (e.g., see Table 1) or in absolute terms. This approach permits to establish expected relations over the various inputs and outputs by combining: the quantity of the input or the output per hectare of land use (second column of Table 1) and the productivity (yield) per unit of input (third column of Table 1). Hence, the analyst or user of the data can easily establish a link between the output/input ratios defining the productivity of the various inputs (the intensive variables, such as yield per hectare, labor productivity) and extensive variables of interest. The latter can be either "funds"[2] (land use, labor requirement) or "flows" (energy carriers, fertilizers, produced crops). The profile obtained in this way refers to a typology of production process, i.e., a set of unitary relations calculated per hectare (benchmarks). However, the actual usefulness of the information provided by this set of unitary relations (patterns) also depends on the contextualization that the analyst decides to (or can) give to it, which will depend on the purpose of the study.

By establishing a relation between funds (land, labor, machinery) and flows—including biophysical inputs and outputs as well as monetary inputs (costs) and outputs (revenues)—it is not only possible to analyze the profiles in relation to different dimensions of analysis, but also to scale the observed patterns across levels of analysis by considering the size of the system. System size can be approached by either the area dedicated to a given land use (a fund element useful for scaling in relation to space) or the size of production (a flow element that can be contextualized, for example, in relation to the demand of society).

Pimentel's legacy in relation to how to carry out "input–output analysis" is mostly quantitative and descriptive in nature. He did not attempt to provide a conceptual framework for his way of presenting data, nor did he use the terms fund and flow (i.e., he never explicitly referred to Georgescu-Roegen's flow–fund model). His basic purpose was to flag the existence of complex environmental problems by using a rich characterization of the exploitation of natural processes based on relevant data profiles. Nonetheless, as will be shown in the next sections, he paved the way for a quantification procedure of the metabolism of complex social–ecological systems.

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[2] The terms fund and flow are derived from Georgescu-Roegen's flow–fund and are explained in Sect. 4. While David Pimentel did not explicitly employ this terminology, he implicitly made a distinction between funds and flows in his data analysis.

4 Conceptual building blocks

This section introduces the concepts of metabolism (and metabolic pattern), social–ecological system and state–pressure relation, as well as the flow–fund model and relational analysis. As will be shown in Sect. 5, these building blocks permit to formalize Pimentel's accounting system into a general conceptual framework describing the metabolic pattern of social–ecological systems that is apt for the study of complex sustainability problems.

4.1 The concept of metabolism

The concept of metabolism has been studied and defined in several scientific disciplines, such as physiology (Engelking, 2012; Frayn & Evans, 2019; Kim & Gadd, 2019), bioeconomics (Georgescu-Roegen, 1977; Giampietro et al., 2012; Mayumi, 2001), sociology (Cottrell, 1955; Lotka, 1922; White, 1943), non-equilibrium thermodynamics [in relation to the pressure–state relation of dissipative systems, see (Prigogine, 1980)], and complexity theory [in relation to the functioning of complex adaptive systems, see (Giampietro & Renner, 2021)]. All these fields share a common interpretation of the concept: Metabolism refers to the functional coupling of two sets of biophysical transformations carried out in a dissipative system capable of self-reproducing (metabolic network or metabolic system): catabolism and anabolism. Catabolism concerns the set of transformations that destroy favorable gradients (primary inputs) available in the context of the metabolic system, thereby transforming them into secondary inputs for use in the anabolic process. Anabolism refers to the transformations that use secondary inputs to express expected functions and maintain and reproduce the structures required to stabilize the metabolic process (Giampietro et al., 2021). By extension, in thermodynamic terms, a metabolic pattern or metabolic profile is defined as a network of energy transformations coupling a set of catabolic transformations, taking advantage of an available flux of negative entropy, to a set of anabolic transformation that express a set of functions associated with a defined set of processes of exergy degradation (Giampietro et al., 2021).

Examples of metabolism and metabolic patterns can be observed at different hierarchical levels of analysis, including cellular metabolism, the metabolism of individual organisms (human beings, other animals, plants), the metabolism of ecosystems (Lomas & Giampietro, 2017), and the metabolism of complex social–ecological systems, such as agroecosystems and economies (Giampietro et al., 2012). In the latter, the catabolic processes of the primary sectors of society use primary sources (e.g., crude oil, wind, rain, arable land) to generate secondary inputs (e.g., energy carriers such as electricity and fuels, food products, fibers) that are used by the anabolic processes inside its constituent components (secondary, tertiary and residential sector, as well as the primary sector itself) to express the functions required by society and to reproduce its structural elements.

4.2 Social–ecological systems

The concept of social–ecological system was originally proposed by Berkes et al. (1998) [see also (Berkes et al., 2003; Folke, 2006)], but has seen many different interpretations ever since (Glaser et al., 2008; Gunderson & Holling, 2002; Herrero-Jáuregui et al., 2018). In this paper, a social–ecological system is seen as the interaction between the self-organization processes of a social system and those of the ecosystems embedding it. In more technical terms, it can be defined as an “anthropo-bio-geo-physical” unit determined by the entanglement between the functional and structural elements operating within a prescribed boundary. This unit is controlled in an integrated way by the activities expressed by a given set of ecosystems (in the ecosphere) and a given set of social actors and institutions (in the anthroposphere). Examples of social–ecological systems are agroecosystems and economies.

4.3 The state–pressure relation, a concept derived from non-equilibrium thermodynamics

To understand a metabolic system, such as human society, we must look at what happens within. For instance, the activities that take place inside a society preserve, reproduce, and adapt the functional and structural elements of the system—the STATE. All these activities depend on the continuous consumption of flows of resource inputs, such as food, energy, material, water. These inputs are taken from the ecosphere, transformed, and eventually discarded into the environment as wastes and emissions. The extraction and dumping of primary flows from and into the environment represent a PRESSURE on the ecosphere. Indeed, society's context must provide the required supply capacity of primary input flows and the required sink capacity for primary output flows. The stabilization of the societal metabolism thus implies a forced relation between state (the ability of using flows to reproduce and adapt the structures and functions of a society) and pressure (the quantity of inputs and wastes to be supplied and absorbed by the environment). It follows that an analysis of the sustainability of human society must comprise two sets of factors: (i) those determining the state (inside the anthroposphere) and (ii) those related to the pressure exerted (in the ecosphere). This double task demands the use of different descriptive domains: Socioeconomic, technical, and demographic data are needed to study the internal processes inside the society (the state), whereas georeferenced biophysical and ecological data are needed to study the ability of the environment to deal with the resulting pressure and potential impact on ecological funds.

4.4 The flow–fund model of Georgescu-Roegen

Georgescu-Roegen studied the bioeconomic roots of the economy and first introduced the distinction between funds and flows (Georgescu-Roegen, 1971, 1975). Fund elements preserve their identity during the duration of the representation (e.g., a given year), whereas flow elements either appear or disappear during the duration of the representation. Examples of funds are population, land, and power capacity. Examples of flows are the crops produced, water used for irrigation, and gasoline or electricity consumed in a defined period. The combination of the size of the funds and the flows (extensive variables) on the one hand and the value of flow/fund ratios (intensive variables) on the other hand enables the analyst to establish a bridge among different hierarchical levels and spatial scales of analysis. In this way, it becomes possible to define the characteristics of functional and structural elements (e.g., hours of labor or hectares of land use) across different levels of organization (e.g., household, community, region, nation).

The flow–fund model is helpful to recognize that not every accounting of flows of matter and energy necessarily classifies as a metabolic analysis. For instance, the accounting of a set of transformations of food taking place in a human body or a set of transformations of primary energy sources in a society belongs to the field of metabolic study only if it considers the quantitative and qualitative relations between the fund and the flow elements of the system under analysis. The former relation concerns the size of the funds and flows, the latter the pace of the metabolism implied by the flow/fund ratios. Indeed, what is metabolized (the flow) does affect and is affected by what is metabolizing it (the fund), and hence, metabolic relations are extremely specific. For example, hay is food for a horse but not for a person, and electricity can feed a microwave but not a freighter. This means that in metabolic studies we cannot use generic definitions of "energy" or "matter" for the accounting of flows. In the pre-analytical phase, we must tailor the taxonomy of categories of energy forms and materials to the purpose of the analysis (for more details, (Giampietro et al., 2021). For instance, Pimentel aptly distinguished among a mix of different flows of energy carriers (expressed per hectare per year)—i.e., gasoline, diesel, electricity—required for the various production steps involved in the production of grain.

4.5 Relational analysis

Combining the insights provided by the state–pressure relation and the flow–fund model, we can apply relational analysis, a concept developed in relational biology (Louie, 2017; Rosen, 2005), to characterize the metabolic profile of structural and functional elements of a social–ecological system across different levels of analysis. In doing so, the analysis acquires a strong semantic framing. Starting from the identification of a final cause (i.e., answering the question "why do we have this process in the first place?"), one can track the functions expressed inside the metabolic pattern to achieve a specific task (the efficient cause). A functional element is always composed by structural elements, whose identity is associated with a formal cause (the information needed to reproduce the specific structural elements, i.e., the blueprint). Relational analysis acknowledges the complex relation between functional and structural elements whose quantitative representations do not coincide (Giampietro et al., 2006). Finally, the material cause of the metabolic process can be associated with the primary and secondary flows used and transformed within the metabolic pattern. This logic of analysis can be implemented using a *metabolic processor*.

A metabolic processor is an accounting system that organizes relevant data across different dimensions and scales of analysis in a data array. It was specifically developed in a recent EU Horizon 2020 project, MAGIC, to implement the concept of metabolic pattern (Giampietro et al., 2021). The metabolic processor represents both the functional and structural elements of the system in terms of two distinct profiles of inputs and outputs: (i) one profile describing secondary inputs "from and to" the anthroposphere (providing information relevant for socioeconomic analysis) and (ii) one profile describing primary flows, both inputs and outputs "from and to" the ecosphere (providing information relevant for ecological analysis) (see Fig. 1).

An important feature of this way of organizing the data is that it allows the integration of conventional quantitative analysis based on statistics (top-down data) and process analysis based on technical coefficients and local observations (bottom-up data). The latter can be georeferenced in spatial analysis which is useful to identify potential ecological impacts. An example of these two different scaling processes is illustrated in Fig. 2. The upper graph shows the scaling of the pattern of flows and funds implied in corn production to a defined area in production (50 ha), using the intensive properties (productivity) from Table 1, while the lower graph shows the scaling up to a desired total production of 2000 t of corn (using the same data from Table 1). Although the calculation method is the same, the logic of the two scaling processes is different.

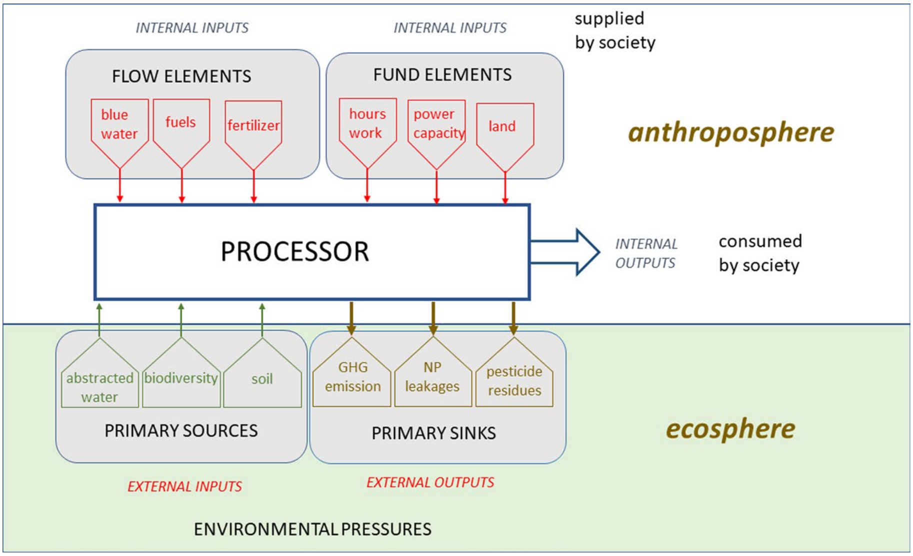


Fig. 1 Categories of inputs and outputs considered in the metabolic processor

The upper graph concerns a bottom-up aggregation based on knowledge of technical coefficients and represents a scenario that considers the available land in production (fund) as a potential *external* constraint (determined by the quality of soil, availability of water, the slope, climatic conditions). It addresses the question: What if we apply our technological package to 50 hectares of land?

The lower graph represents a top-down assessment starting out from the required or desired useful output, i.e., the demand for corn of society. It addresses the question: What if we need 2000 tons of corn and we use this technological package?

The combination of these two logics creates a triangulation of information across different data sources which increases the robustness of the information space:

1. *Bottom-up information derived from technical coefficients* This refers to the qualitative aspects of a unitary process (flow/fund ratios or intensive properties) and boundary conditions determined by the ecological context. How much can possibly be produced given the available fund elements?
2. *Top-down information derived from statistical data* This information refers to the context of the production process, i.e., information given in the form of extensive variables of flows (total quantities observed in flow/flow ratios). How much is required by the society?

This approach represents a powerful analytical tool for checking “what if” scenarios (Giampietro et al., 2021).

The conceptual building blocks presented in this section are perfectly compatible with Pimentel’s approach to the quantification of the factors associated with the sustainability of agroecological processes. In fact, Pimentel’s approach allows us to: (i) establish a bridge in the quantitative representation between different inputs and outputs that are relevant for studying the sustainability of the STATE and the PRESSURE; (ii) combine intensive and

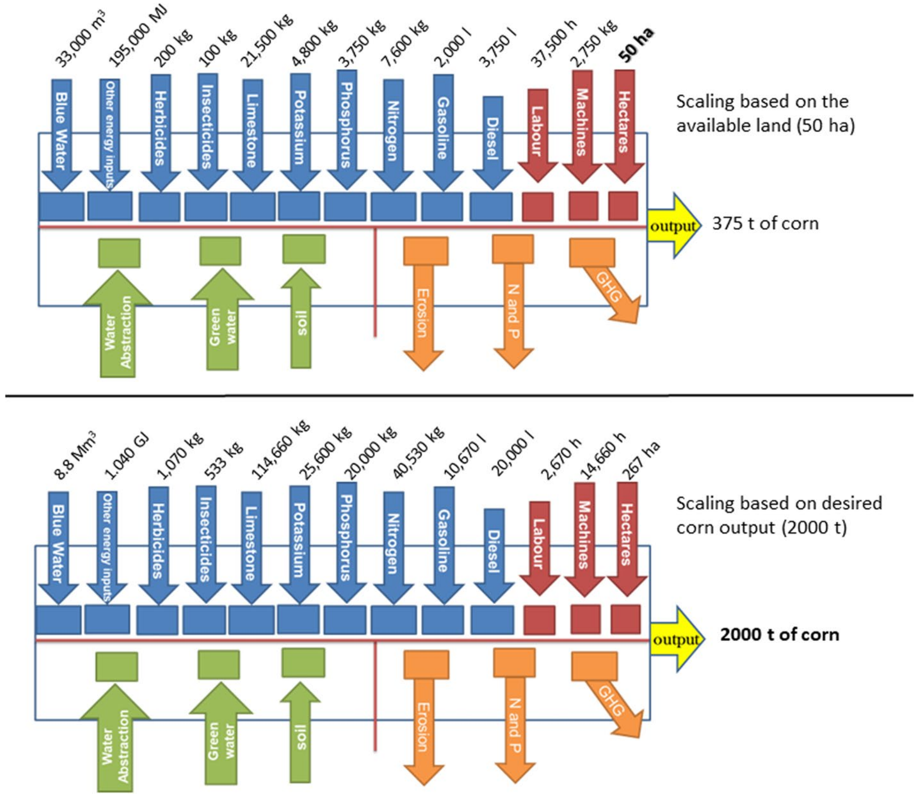
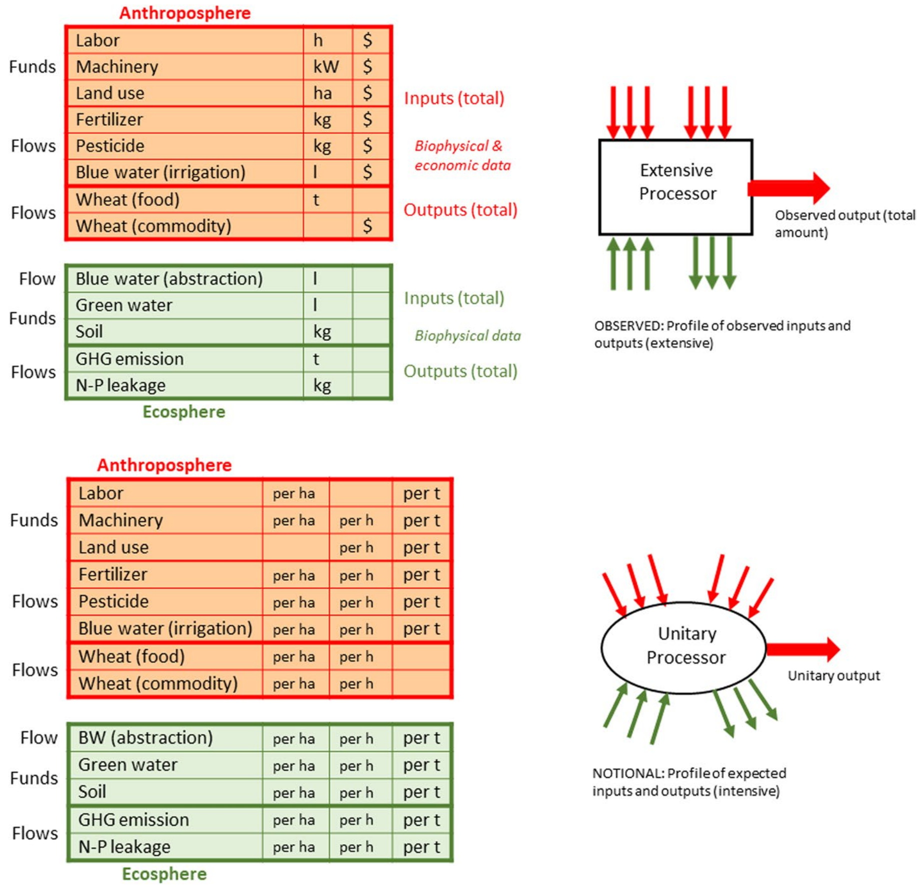


Fig. 2 Scaling the metabolic profile of corn production to the desired size of fund (50 ha of land) (upper graph) or the desired size of flow (output of 2000 t of corn) (lower graph). Data are from Table 1

extensive variables—a choice of indicators consistent with the flow–fund model of Georgescu-Roegen; and (iii) identify and link functional and structural elements in the agricultural sector using relational analysis.

5 From input–output analysis to the study of metabolic patterns

This section describes the formalization of Pimentel's analysis of the profiles of inputs and outputs of agroecosystems into a conceptual framework for the analysis of the metabolic pattern of social–ecological systems, drawing on the conceptual building blocks introduced in the previous section. Original data of Pimentel are used to illustrate the procedure. Note that the first attempt to develop a coherent conceptual (theoretical) framework based on Pimentel's approach was published in the late 1990s (Giampietro, 1997; Giampietro et al. 1997a, 1997b; Giampietro & Mayumi, 2000). These attempts were subsequently refined (Giampietro et al., 2009, 2013; Giampietro & Ramos-Martin, 2005), and a corresponding semantically open accounting framework was recently put forward (e.g., Cadillo-Benalcazar et al., 2020; Giampietro et al., 2022; Renner et al., 2020).



Funds	Labor	h	$
	Machinery	kW	$
	Land use	ha	$
Flows	Fertilizer	kg	$
	Pesticide	kg	$
	Blue water (irrigation)	l	$
Flows	Wheat (food)	t	
	Wheat (commodity)		$

Flow	Blue water (abstraction)	l	
Funds	Green water	l	
	Soil	kg	
Flows	GHG emission	t	
	N-P leakage	kg	

Funds	Labor	per ha		per t
	Machinery	per ha	per h	per t
	Land use		per h	per t
Flows	Fertilizer	per ha	per h	per t
	Pesticide	per ha	per h	per t
	Blue water (irrigation)	per ha	per h	per t
Flows	Wheat (food)	per ha	per h	
	Wheat (commodity)	per ha	per h	

Flow	BW (abstraction)	per ha	per h	per t
Funds	Green water	per ha	per h	per t
	Soil	per ha	per h	per t
Flows	GHG emission	per ha	per h	per t
	N-P leakage	per ha	per h	per t

Fig. 3 Two possible representations of the metabolic processor describing the metabolic profile of a typology of crop production: the extensive (top) and the unitary processor (bottom)

5.1 Constructing a metabolic profile for corn production

The construction of a metabolic processor is illustrated in semantic terms in Fig. 3 for corn production, using the variables proposed by Pimentel. In line with the concept of the metabolic pattern, the inputs and the outputs in this data array are divided into four groups:

1. The profile of secondary inputs derived from the anthroposphere (upper part of the processor). These secondary inputs are divided into: (i) flow elements, such as fertilizers, pesticides, and blue water used for irrigation, and (ii) fund elements, in this case hours of work, machinery, land use.
2. The profile of secondary outputs going into the anthroposphere. This concerns the crop produced (on the right of the processor) and possibly useful byproducts (not shown). Note that the output of the process must be useful for the anthroposphere; it constitutes the reason justifying the production process (the function associated with its final cause).
3. The profile of primary inputs coming from the ecosphere (bottom part of the processor). These inputs are supplied by nature, i.e., by processes outside of human control.

4. The profile of primary outputs going into the ecosphere (bottom part of the processor). This concerns the sink capacity that is required to absorb these outputs, which is also provided by processes that are beyond human control.

As illustrated in Fig. 3, the statistical data describing the pattern of inputs and outputs associated with corn production in the USA (the extensive values used to represent the set of relations) can be used for an analysis of both the economic and the ecological performance. Data of inputs and outputs represented in red color can be linked to monetary values. For instance, the overall cost of the inputs and the overall revenue of the output can be obtained by multiplying the biophysical quantities (e.g., kg of output) by their monetary value. At the same time, we can use the biophysical assessments to answer research question related to technical coefficients, such as labor requirements, amount of fertilizer required, and fuel consumption. Inputs and outputs represented in green (Fig. 3) can be used for assessing the environmental pressure exerted on the embedding ecological systems. They refer to the metabolic characteristics of the land use, which are relevant to study the compatibility with environmental constraints.

The stabilization of primary inputs and outputs, even if taking place outside the economic process, is essential, because the agricultural production process depends on them. For example, an adequate availability of green water (coming from the rain but made available to the plants by the soil) and other soil services (making available nutrients) are associated with the quality of the agricultural land (that can be low or high). In this method of accounting, green water and soil are classified as ecological fund elements, given that they are services provided by the ecosphere that can be disrupted by soil erosion or deregulation of the rain supply (climate change). The flows exchanged with the ecosphere in this example are: (i) abstraction of blue water from the aquifer (note that this quantity is larger than the one used as input for irrigation because of the losses in distribution); (ii) GHG emissions associated with the use of inputs in the anthroposphere and changes in land use; and (iii) leakage of nutrients (NPK) and pesticides into the aquifer. The alteration of these flows is often a consequence of human actions and are assessed using the concept of environmental loading ratio (ELR) introduced by (Odum, 1971). The value of ELR is obtained by comparing (i) the density of the flows determined by human alteration to (ii) the density of the flows that we would expect in a terrestrial ecosystem, of the same type, not stressed by human activity (Lomas & Giampietro, 2017).

Note that the amount of green water, leakage of nutrients, contribution of the soil to the production of biomass, and the threshold levels of water abstraction can only be calculated using extensive variables referring to a specific location (area). Indeed, it is impossible to calculate the exact size of primary inputs and outputs and compare them to the supply and sink capacity of local ecological funds without geolocalizing the analysis. This procedure requires us to consider both the qualitative and quantitative characteristics of the specific ecological funds affected by agricultural production (the specific soil, aquifer, climate, ecosystem, etc.) and the level of pressure of the agricultural production on the landscape (level of habitat destruction in relation to biodiversity preservation).

As illustrated in Fig. 3, this characterization of the metabolic profile associated with a local process of agricultural production of a specified crop (e.g., corn) in the form of a data array can be obtained and represented in two different ways:

1. By using extensive variables—for example, by measuring the flows and funds on an actual commercial farm of a given size of hectares; or using the statistics referring to

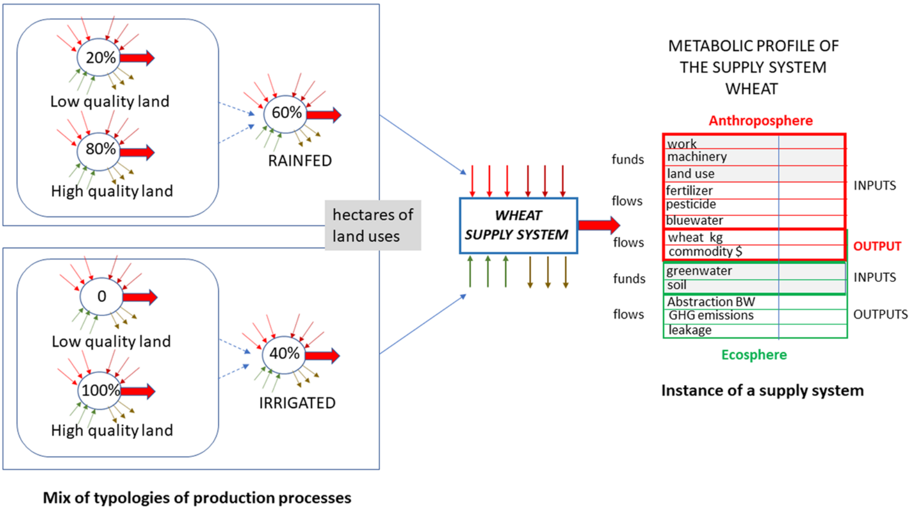


Fig. 4 Combining the metabolic profiles of different typologies of wheat production to assess the processor of the overall wheat supply system at the regional level

the production of the crop in question for a given area (the extensive processor at the top of Fig. 3).

2. By using intensive variables—for example, by measuring the different flows and fund as benchmarks, that is the quantities of flows and funds required per hectare of land, per hour of labor, or per unit (t or kg) of crop production. We refer to this as "unitary processes" (see the oval unitary processor in the lower part of Fig. 3). Note that the labor requirement (or farm labor availability) represents an important piece of information for the analysis of farming systems as well as for the study of the profile of human time allocation in social practices.

Thus, the combined use of intensive and extensive variables allows the bridging of dimensions of analysis (integrating information coming from different descriptive domains) and of different levels of aggregation (scaling). This will be further elaborated in the next section.

5.2 Crossing levels of analysis with the metabolic processor

Once one has assessed the metabolic profile of relevant typologies of crops (as exemplified for corn in Fig. 3), it is possible to carry out a quantitative analysis across different levels of analysis, considering relevant attributes of agricultural cultivation. This is illustrated in Fig. 4 for wheat cultivation in relation to the quality of the land (e.g., soil quality) and whether the crop is rainfed or irrigated. (Multiple crops and other attributes may be considered.) Both attributes will entail a difference in the crop productivity. Hence, to assess the overall metabolic profile of wheat production in a defined geographic area of interest, one must consider different factors, for example, (i) the mix of unitary processors referring to the local characteristics of wheat production in relation to the specific attributes selected (e.g., for rainfed wheat production on high-quality

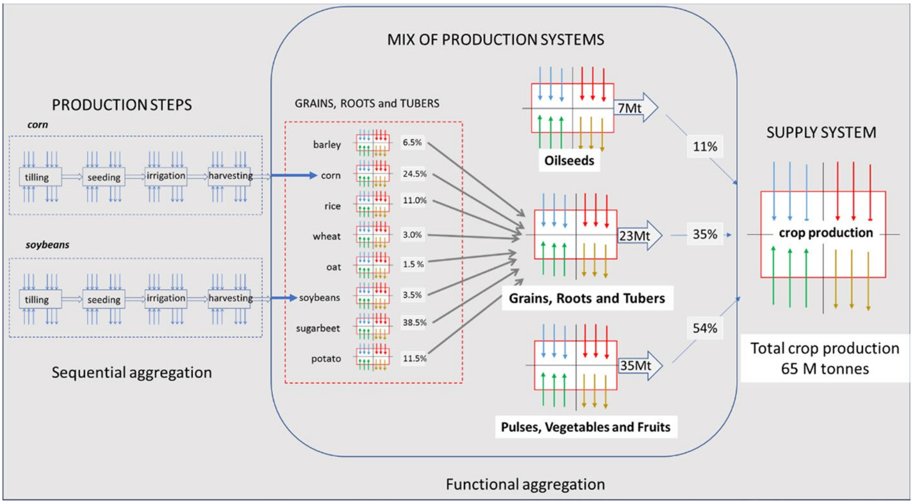


Fig. 5 Extending the analysis from individual crops to the whole crop production system

land); (ii) the relative mix of high-quality and low-quality land uses; and (iii) the relative mix of rainfed and irrigated cultivation in the area.

Indeed, it is important to observe that depending on the purpose of the analysis, different types of data are needed. For instance, the metabolic processor describing typologies of production (what is produced and how, see Fig. 3) deals with relations among inputs and outputs that are solely based on technical coefficients. These technical coefficients relate to the characteristics of the production techniques used and the types of land cultivated (unitary processors). On the other hand, the assessment of the overall metabolic profile of a supply system in a defined region (Fig. 4) does not only require information on technical coefficients for the assessment of the metabolic profiles of the various relevant typologies of production processes (bottom-up approach), but also top-down (statistical) data for the assessment of the relative share of high-quality/low-quality land used and the relative share of rainfed/irrigated production in the supply system (top-down approach).

Similar metabolic processors can be constructed for crops other than wheat, and an example of extending the analysis from individual crops to the whole sector of crop farming is shown in Fig. 5. The procedure shown is based on the same logic as that used in Fig. 4.

Metabolic patterns can also be constructed for supply systems other than crops. For instance, Fig. 6 illustrates how to proceed with the assessment of the metabolic pattern of a water–energy–food nexus complex, composed of a desalination plant, a wind farm and a farmers cooperative producing a variety of crops. In this case, the performance of the system is studied in relation to water, energy, food, and the environment (Serrano-Tovar et al., 2019). It clearly shows the flexibility provided by the accounting scheme proposed by Pimentel. In this particular example, different boundary conditions can be adopted: (i) for the isolated structural elements; (ii) for the functional elements; and (iii) for the overall combination of the structural and functional elements, all of which can be located in space (see Fig. 6). More details and data on this case study are available in (Serrano-Tovar et al., 2019).

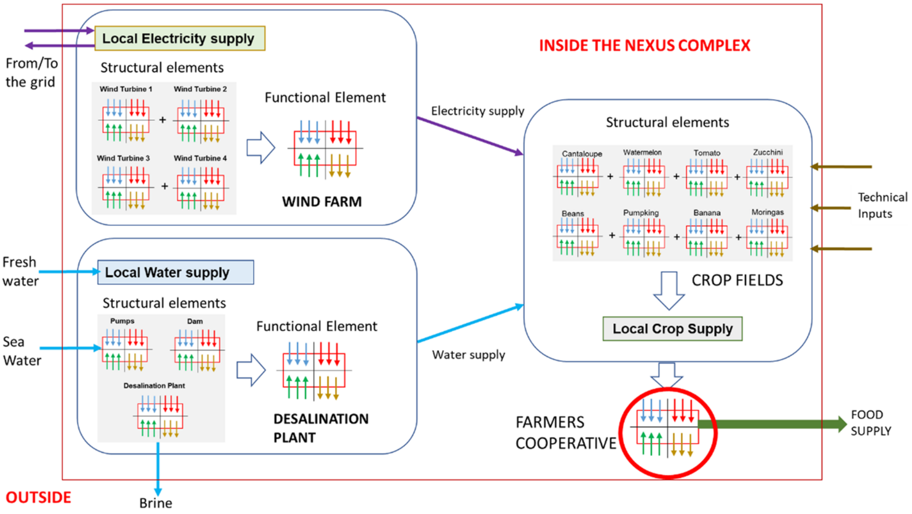


Fig. 6 Schematic assessment of the metabolic pattern of a water–energy–food nexus complex, composed of a desalination plant, a wind farm and a farmers cooperative producing a variety of crops. Figure based on the case study presented in Serrano-Tovar et al. (2019)

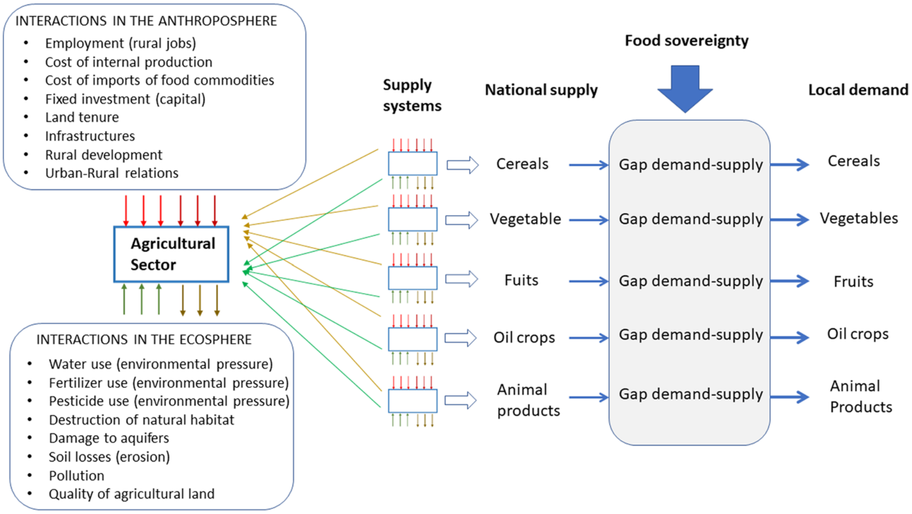


Fig. 7 Scaling of the metabolic profiles of food supply systems to achieve policy relevance

Obviously, the more we enlarge the scale and/or the scope of the analysis, the more additional information is needed. This is further illustrated in Fig. 7 for the agricultural sector at the national level, by confronting the metabolic profile of the entire food supply system with that of the demand/requirement (the profile of consumption of food commodities). To obtain the metabolic profile of the required overall supply, we need to aggregate the overall mix of different supply systems related to the relevant food commodities (wheat, barley, legumes, etc.). In the characterization of the overall profile of inputs and outputs, the relevant factors are no longer only of a technical (agronomic) and environmental (e.g., need to protect biodiversity and habitats) nature but also of a socioeconomic nature (e.g., lack of farmers, infrastructures).

Furthermore, at this level, international trade (imports, exports) can play a key role in determining the pattern of supply and demand. As shown in Fig. 7, the internal production of food commodities—i.e., the local (e.g., national) supply—must be contextualized against the requirement of food commodities, i.e., the local (e.g., national) demand. The difference between the required amount of a food commodity and the amount locally produced indicates the degree of dependence on imports (e.g., international market). The metabolic profile of the required imports can be used as an indicator of performance for food sovereignty and provides an indication of the size of the imported "embodied" resources (e.g., dependence on available land and water and cheap labor elsewhere) and exported environmental impacts. An (non-exhaustive) overview of the biophysical, technical, socioeconomic, and international factors relevant for the metabolism of food commodities is shown on the left side of Fig. 7.

Thus, integrating the interactions within the anthroposphere (top left of Fig. 7) and those within the ecosphere (bottom left of Fig. 7) into a comprehensive representation of the metabolic profile of the agricultural sector is extremely useful to study the sustainability of the system and to address issues relevant to several different policy domains (agricultural, environmental, social, and economic). In this way, it is possible to provide deliberation support for a wide range of complex and wicked environmental problems that often represent uncomfortable knowledge (e.g., Renner et al., 2020).

6 Conclusions and future prospects

This paper has demonstrated the (continued) relevance of Pimentel's vision on the quantification of the sustainability of agri-food systems by giving it a conceptual foundation that is firmly grounded in complexity theory. In particular, the concept of metabolic pattern describes and integrates the different attributes of performance of the production process used by Pimentel, in both theoretical and practical terms. The following aspects of this conceptualization stand out:

1. 1. The pattern of inputs and outputs is represented both by unitary processors and extensive processors. Unitary processors are calculated either as profiles of inputs and outputs per unit of a given fund element (e.g., per hectare of land or per hour of labor); or as profiles of inputs and outputs per unit of a given flow element (e.g., per unit of product or per unit of abstracted water). Extensive processors, on the other hand, are scaled and georeferenced in relation to specific instances of agroecosystem typologies (e.g., the production of a specific crop in a defined aquifer region), thus allowing the assessment of the impacts of the environmental pressure of the production process.
2. 2. Flow–fund ratios (intensive properties) are used as qualitative benchmarks to define typologies of agricultural production in relation to both the socioeconomic process (e.g., land productivity, labor productivity) and the environmental pressure exerted on the environment (e.g., water consumption per hectare, pesticide load per hectare), which is relevant for the assessment of ecological impact.
3. 3. The various flows and funds are intrinsically linked to each other in a resource nexus. This entanglement is operationalized through the concept of metabolic pattern

> of social–ecological systems and represented by processors that can be defined across different levels of analysis. The analysis of the secondary inputs and outputs (inside the anthroposphere) is relevant to study the state of the metabolic pattern expressed by the socioeconomic part of the system (anthroposphere). The analysis of the primary inputs and outputs is relevant to study the environmental pressures on the embedding environment (ecosphere). The size of the resulting environmental loading ratios in relation to the supply and sink capacity of the ecological funds is used to define the impact on the environment and hence the external limits to the production process (feasibility).

Thus, Pimentel's work has represented a breakthrough in the framing of quantitative analysis of agricultural production and has set an example for a holistic approach to complex environmental problems. The idea of combining intensive (qualitative) and extensive (quantitative) variables that are defined simultaneously using different narratives (technical, economic, ecological) has enabled to identify and integrate the analysis of structural and functional elements of complex systems (the epistemological conundrum that reductionism cannot handle) and has paved the way for the more general conceptualization of social–ecological systems as metabolic systems proposed in this paper.

Regarding future prospects, the current impasse in sustainability science has sparked interest in societal metabolism studies. In this emerging field, the adoption of relational analysis frees the quantitative analysis from the obsessive use of differential equations (an analytical tool developed by Newton in 1671!). It has been shown in this paper that, rather than generating deterministic relationships over data in simplistic models, it is possible to explore the option space of a given state–pressure relation by looking at the relations over the values of different families of data used in the representation across levels and dimensions of analysis. A state–pressure relation must be feasible (congruent with environmental constraints), viable (congruent with technical and economic constraints), and desirable (congruent with values and aspirations of people). With this different way of crunching numbers, the analysis becomes more transparent (the assumptions in the building of the model are no longer hidden) and therefore more useful for social deliberation. Indeed, when dealing with complex environmental problems there is no "optimal solution" revealed by rigorous models, but only a large dose of uncertainty in the representation of the different types of relationships over data. A relational analysis of the characteristics of the different elements described across different levels and dimensions of analysis allows the consideration of several, non-equivalent, but legitimate criteria of performance. This makes it possible to strive for governance in complexity, rather than governance of complexity.

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Declarations

Conflict of interest The author has no relevant financial or non-financial interests to disclose. All data generated or analyzed during this study are included in this published article.

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