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Concept Paper

Perception and Representation of the Resource Nexus at the Interface between Society and the Natural Environment

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Abstract: Recent years have seen an explosion of interest in the resource nexus. This has created the co-existence of different understandings and uses of the concept. In this regard, experiences in the EU H2020 project 'Moving towards adaptive governance in complexity: Informing nexus security' are consistent with findings reported in the literature: (i) The inconvenient message of the nexus is difficult to get across, it being incompatible with the currently dominant rosy narratives about sustainability. Indeed, from a historic perspective, the nexus can be seen as a revival of the ideological fight between cornucopians and neo-Malthusians; (ii) Silo structures in existing institutions are a problem for the governance of the nexus, and so is the resulting reductionist strategy of addressing and fixing one issue at the time; (iii) Scientific inquiry is currently not providing the quality inputs needed for a meaningful discussion of the resource nexus. Entanglement of resource flows is rooted in the complex metabolic pattern of social-ecological systems, the analysis of which requires a complex systems approach and relational analysis. Contemporary reductionist models simply make the nexus invisible to the analyst.

Keywords: resource nexus; semiotic process; buzzword; metabolic pattern; social-ecological system; complex systems; relational analysis

1. Introduction

Recent years have seen a remarkable upsurge in scientific papers, projects, platforms and networks dedicated to the concept of resource nexus. This rapid explosion of interest has led to the co-existence of different understandings and uses of the term resource nexus. In response, some authors, and notably Cairns and Krzywoszynska [1], have made the case that the term nexus has turned into a buzzword and that this represents a serious reason for concern. This concern has motivated this paper, which builds on a review of the literature and experiences in the EU research project 'Moving towards adaptive governance in complexity: Informing nexus security' (MAGIC). The project's mandate is to (i) analyze the narratives endorsed by the European Commission about water, energy, food and environmental security so as to identify pre-analytical perceptions of sustainability problems; (ii) discuss the problems associated with the governance of the resource nexus with staff working in the different Directorate Generals of the Commission and European Agencies; (iii) develop quantitative models for characterizing the performance of social-ecological systems in relation to the resource nexus, and use the results in participatory processes related to specific policies and innovations (quantitative story-telling). Accordingly, in this paper the following three theses are elaborated:

1. The resource nexus represents an inconvenient narrative. Concern about the nexus has returned an old issue to the front burner namely that of external biophysical limits to economic growth. Hitherto

governance of sustainability has been perceived merely as a technical problem within isolated silos and dealt with accordingly. This has resulted in the adoption of strategies aimed at addressing and fixing one problem at the time. If we have a problem with finite fossil energy stocks, we develop new technologies for exploiting alternative energy sources. If we face land constraints, we develop novel methods of food production boosting yields per hectare. If we have a problem of water shortage, we develop innovations boosting the efficiency of end-uses. However, considering all these problems simultaneously across different scales and dimensions of analysis, under the umbrella of the resource nexus, the Cartesian dream of prediction and control [2] shatters: the underlying sustainability problem cannot be solved with technological fixes.

2. The resource nexus flags a remarkable gap in governance structures when it comes to dealing with the complexity of the sustainability predicament. Existing institutions are fragmented into silos that deal separately with narrowly defined problems corresponding to highly specific spheres of analysis [3,4]. We have institutions to deal with water, energy, food, or the environment, but on whose desk sits the resource nexus? The governance issue is elaborated with an analysis of the semiotic process taking place in society explaining why 'nexus' means different things to different actors and why society cannot properly handle it.

3. The resource nexus exposes the ineptness of the paradigm of reductionism in scientific inquiry for quantifying complex issues. We are good at generating large and complicated models, yet these only build representations of one issue (one dimension and one scale) at the time. The common solution to this impasse, combining quantitative results from different models into some sort of composite representation, completely misses the biophysical entanglement of the various resource flows across different levels of analysis and dimensions. Two simple examples are elaborated to show that tracking quantitative relations among water, energy and food flows across dimensions and scales requires a complex system approach and relational analysis.

The discussion of these three points has the aim of (i) flagging potential threats to the quality of the process of production and use of scientific information for the governance of sustainability (social science side of the process) and (ii) illustrating the capital sin of reductionism with regard to the quantitative analysis of complex phenomena (natural science side of the process).

2. The Resource Nexus as an Inconvenient Narrative

2.1. Return of the Neo-Malthusians

In the 1960s and 70s, the exponential nature of growth in population and energy consumption caused concern about the sustainability of human development [5–9]. Notably, the publication of The Limits to Growth by Meadows et al. [10] primed an intense debate between cornucopians and neo-Malthusians over the sustainability of a model of development based on the plundering of fossil energy and other non-renewable resources. Cornucopians endorsed neo-classical economic principles claiming that human ingenuity and technical innovation can and will always solve problems of shortage of natural resources ("the world can, in effect, get along without natural resources": Robert Solow [11]), neo-Malthusians a biophysical perspective on the economic process acknowledging that there are external limits to growth ("Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist": Kenneth Boulding [12]).

History tells us the cornucopians won; a victory reinforced by the globalization and financialization of the world economy in the late nineteenth and early twentieth century. Not surprisingly then, the framing of the sustainability discussion has been firmly anchored within the ideology of the cornucopians [13]: more market and more technological innovations will fix any problem of sustainability. A report of the Expert Group on Science and Governance to the European Commission [14] has referred to socio-technical imaginaries in this regard, a concept first developed by Jasanoff [15]: we are living in a "regime of economics of technoscientific promises" characterized by "the creation of a fiction in order to attract resources—financial, human, political, etc.—viz. that the emerging technology (. . .) 'will solve human problems' (health, sustainability, etc.) through a wide range of applications. The credibility of this promethean conception of technoscience is linked to 'naturalization' of technological advance, which is seen as almost a self-fulfilling prophecy (if enough resources are provided and effort is made)" [14] (p. 24).

Against this historic background the resource nexus represents an inconvenient narrative as it reintroduces the 'uncomfortable knowledge' [16] of the neo-Malthusians in the sustainability debate. Indeed, Hoff [17], in the introduction of the background paper for the Bonn 2011 Nexus Conference, where the nexus concept was first brought to world attention, starts out by mentioning the growing concern for a rapidly increasing demand for resources (especially in the third world) and the bleak outlook of producing food, energy and water for the entire world population in an integrated and sustainable way. He also recognizes that globalization carries the risk of transferring stress, through externalization, from the most powerful countries to the more marginal ones. This same message is found in many papers dealing with the nexus [18–32]. Examples are reported in Table 1. Hence, the nexus narrative (re-)introduces three key issues that are carefully avoided in the technocratic sustainability narrative of the cornucopians: (i) biophysical (rather than economic) analyses to check what is feasible and viable; (ii) population growth (hitherto taboo); (iii) politically sensitive themes, such as equity and fairness, with regard to the largely poor and malnourished population in the southern hemisphere.

Table 1. The return of the neo-Malthusians.

Quote	Reference
"Global human society must now attempt to solve a set of complex, interrelated problems . . . fundamental treats to human civilization."	[18]
"At present 1.2 billion people live in areas where there is physical water shortage, a number that is expected to grow in the next decades . . . Energy access is also far from universal, with 1.3 billion people living without access to electricity and 2.7 million with no access to modern and healthy forms of cooking."	[19]
"Nexus thinking emerged from an understanding that natural resources are beginning to limit to a substantial degree economic growth and human well-being goals."	[20]
"As humanity is on track to cross planetary boundaries . . . and "consume the planet to excess" . . . activists, scientists, policy makers, economists, and many others have come to join forces in order to realize a more sustainable usage of natural resources. After all, so the bleak outlook, the survival of humanity at the very species level appears to be at stake."	[22]
"Water, energy, and food systems are closely interlinked. These interlinkages intensify as the demand for resources increases with population growth and changing consumption patterns. Meanwhile, major global trends—notably climate change and competing land-use patterns—restrict the ability of existing systems to meet the growing demand in a reliable and affordable manner."	[23]
"The global human requirement for water, energy, and food is expected to increase substantially with the increase in world population that is projected to reach 9.6 billion by the middle of this century."	[32]
"Population growth is a major external stress on three primary resources: water, energy, and food."	[30]

2.2. The Ideological Struggle over the Implications of the Nexus

The inconvenient message of the nexus is incompatible with the rosy master narrative of neo-liberal economics and techno-scientific promises. The resource nexus implies that the economy cannot go along without natural resources and sustainability problems cannot be solved with the market and technology alone. This dissonance has created the coexistence of two contrasting attitudes and strategies in relation to the nexus that reflects the original debate between cornucopians and neo-Malthusians:

- 'Damage control': It is recognized that the resource nexus represents a challenge to sustainability but by reinforcing the status quo it is considered possible to handle these problems through the adoption of technocratic solutions optimized by the market (doing more of the same). This still appears to be the 'politically correct view' supported by the establishment.

- 'Taking it seriously': The resource nexus represents a serious challenge to sustainability that requires us to break with socio-technical imaginaries. The Cartesian dream of prediction and control will not work. A re-discussion of the existing pattern of economic development, acknowledging that biophysical limits to economic growth do exist and matter, is considered essential.

Given this dichotomy, any discussion over the nexus necessarily entails a political or ideological dimension that must be explicitly acknowledged and addressed in the pre-analytical phase of the process. Existing power relations (asymmetries) among the story-tellers will be the ultimate determinants of the final choice of analysis. Indeed, many of the authors addressing the nexus from a social perspective warn about the possible negative consequences that a technocratic approach can imply [1,20,22,24,25,33,34]. Examples of this type of concern include neglect of the issue of livelihood and inequity [20,24,34,35], neglect of the environment [20], and lack of transparency [34]. Verhoeven [25] explicitly suggests that the choice of a deliberately apolitical identity in the framing of the nexus is used as a strategy for ignoring the implications of power asymmetries. The same point is also signaled by Cairns and Krzywoszynska [1]. A list of statements exemplifying concerns about the semantic appropriation of the term resource nexus for 'damage control' is given in Table 2.

Table 2. Concerns about semantic appropriation of the term nexus.

Quote	Reference
Instrumentalization of global discourses to force decisions at the local level: "Analyzing 'the nexus' as a political commodity captures the instrumentalization of global discourses at the local level to legitimize or challenge authority structures and also refers to the material practices that underpin the power exercised by ruling classes through exclusionary hydropolitical economies."	[25]
Possible misuse of the term 'nexus' to avoid the question as to whose values count: " … the term is being appropriated by dominant discourses of the managerialist type, which we suggest risks turning the nexus into a 'matter of fact', 'a single discrete self-evident problem susceptible to primarily science-based solutions'."	[1]
Possible use of the nexus as a commodity in political struggles: "the narrative of the nexus—like that of sustainable development, resource scarcity or water wars—can be deployed as a commodity in political struggles, to marginalize opponents, to exclude peripheral populations, to obscure allocation patterns."	[25]
"Possible use for muddling the difference between 'facts' and 'concerns': "where 'matters of fact' are stabilized and established way of relating to the world, institutionalized by particular (knowledge) cultures … 'matters of concern' are processes rather than objects, are characterized by controversy and are not stabilized or institutionalized."	[1,36]
Possible misuse of the term nexus to avoid the question as to what we want to sustain and how: " … the problem of security is no longer that of fixing or demarcating the territory, but of allowing circulations to take place" … "One must, however, dare to ask what is really at stake in terms of the water, energy, and food-security nexus. Is it survival of mankind or is it the preservation of current economic setups?"	[22]
"to date the nexus literature has not explicitly identified how water-energy-food securities are interlinked with livelihoods to enhance water-energy-food security at the livelihood level."	[35]

3. Governance of the Resource Nexus

There is general consensus in the literature on the nexus that it is urgent to improve the quality of both the scientific inquiry about the nexus and the integration of policies and actions in the water, energy and food sectors [1,17–31,33–35,37]. This consensus flags a shared experience of a generalized failure of the process for generating and using scientific information for governance of the nexus.

3.1. The Semiotic Process in the Phenomenon of Autopoiesis of Human Society

Peirce [38] envisioned the process of formation of transmittable knowledge as an endless loop of iteration based on the following three steps with their respective verbs in parentheses: $\hookrightarrow$semantic (interpret)$\rightarrow$syntax (represent)$\rightarrow$pragmatic (apply)$\rightarrow$. In order to tailor this process to the meanings of and the discourses over the resource nexus, an additional conceptual element is needed to describe the very system in which the semiotic process is taking place, that of social-ecological system.

The concept of social-ecological system evolved from the seminal work of, among others, Holling [39,40], Berkes et al. [41,42], Gunderson and Holling [43], and Glaser et al. [44], and can be defined as the complex of functional and structural components operating within a prescribed boundary that is controlled in an integrated way by the activities expressed by a given set of ecosystems (in the biosphere) and a given set of social actors and institutions (in the technosphere). In order to survive social-ecological systems have to be capable of (re)producing their multilevel organization of structural and functional elements while adapting in time [45]. The evolution of their identity is shaped by a continuous process of adaption to changes in both external constraints, imposed by processes outside the realm of control, and internal constraints, associated with the viability and desirability of biophysical processes of self-organization under direct control. Human society uses recorded information to build and organize knowledge for guiding action and, therefore, the social part of the social-ecological system carries out the role of the interpretant in the semiotic process [45]. We can thus define a social-ecological system as an autopoietic system (a system making itself) that uses the semiotic process for expanding and validating its knowledge base and reproducing and adapting its structural and functional elements. The semiotic process shapes the human ability to share meaning associated with information by using languages. In this way society organizes itself, guides action and learns from the experience done in its interaction with the context. The different spheres of the semiotic process are illustrated in Figure 1.

The four spheres shown in Figure 1 shape the formation and use of societal knowledge about the nexus:

1. The perception of the autopoietic process as a whole: this refers to the political process that determines the identity of society required for adjusting and (re-)shaping its institutions [46]. When the information generated by the semiotic process flags the need for a radical change away from the business-as-usual mode, society must re-discuss its given identity and the purposes associated with existing institutions. Therefore, when considering this sphere, it is essential to study how the implications of the message given by the resource nexus affect the political struggle for power.
2. Scientific inquiry (represent): this refers to the scientific process providing validated narratives (explanations), data, and models that are used to discuss, select, and monitor the effectiveness of policies. What matters in this sphere is the reliability and the usefulness of the representation of the interaction of society with its context in relation to the resource nexus. Scientific information must be useful and two key criteria for defining its quality are (i) relevance (for whom?) and (ii) reliability (how to handle uncertainty?).
3. Institutions for governance (interpret): this refers to the processes of maintenance, adjustment and reproduction of elements making up the institutions. An effective organization of the process of governance is essential to elaborate, test, and adjust policies depending on the inputs received from the external world (apply), the political process, and scientific inquiry (represent). What counts in this sphere is the ability to adapt and react in adequate time to these three different types of inputs by re-adjusting both the decisions made and the processes through which they are made.
4. External world (apply: experience from action): this refers to what happens in the external world. It is the most difficult sphere to handle. In fact, no one can possibly know the totality of events taking place in the external world, observing them at all possible scales in relation to all existing definitions of relevance. As a matter of fact, the semiotic process can only know the external world through the choices made by the interpretant about how to represent its interaction with the external world. Therefore, the politically defined identity of society always introduces a bias in the observation of the external world. Societies with different political identities observe different external worlds.

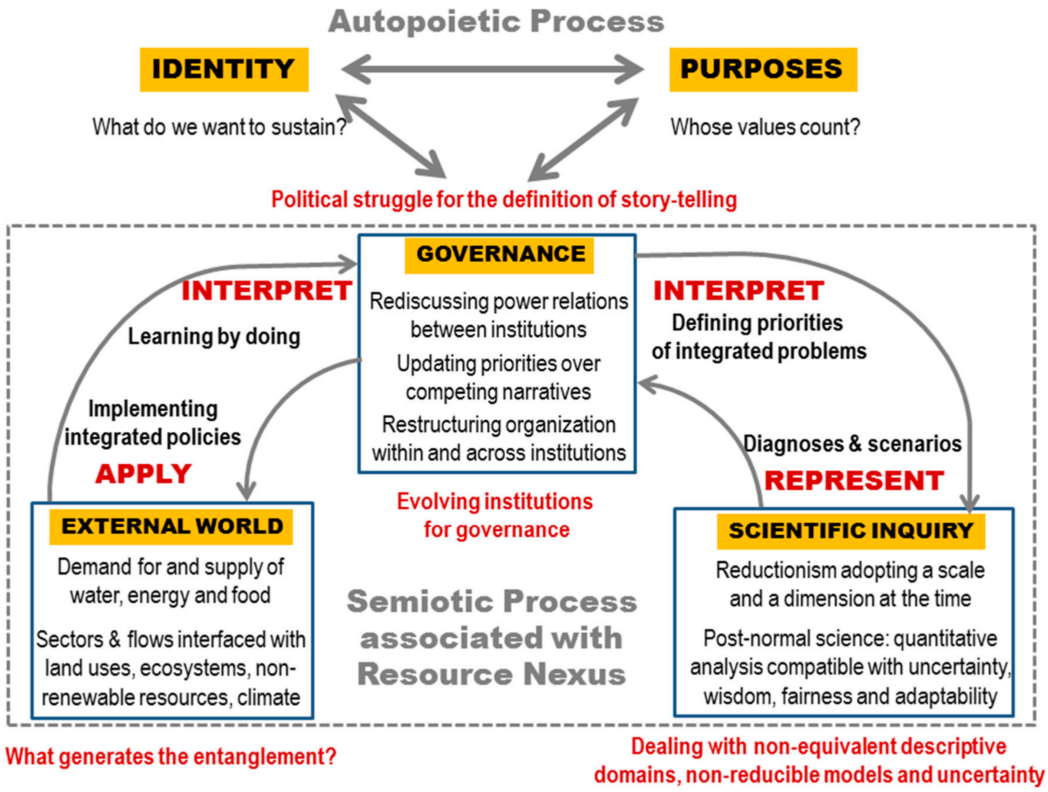

Figure 1. The spheres associated with the semiotic process: (i) survival of the autopoietic process (political/ideological); (ii) developing scientific inquiry (represent); (iii) operating institutions for governance (interpret); (iv) learning from biophysical processes of interactions (apply: experience from the interaction with the external world).

The sphere of the external world becomes highly relevant when it forces a change in the other three spheres: (i) when it forces science to develop radically new approaches and narratives; (ii) when it forces institutions of governance to develop totally new mechanisms and to re-shuffle existing power relations; and (iii) when it forces society to re-discuss its very identity in order to adopt new (or old!) purposes.

The recent upsurge in popularity of the resource nexus can be taken as a signal that the external world is forcing changes in the other three spheres (through a massive wave of excitation). This process can also be described in plain terms as society being forced to deal with the sudden discovery of an elephant in the room; the elephant being the unsustainability of the current pattern of economic growth.

3.2. The Different Understandings and Usages of the Term Nexus

This section classifies and organizes different understandings and usages of the term nexus found in the literature in relation to the conceptual map represented by the different spheres of the semiotic process shown in Figure 1.

(i) *The process of governance*. As shown in Figure 1, the sphere of governance has to do with the re-production, adjustment, and maintenance of the role of the interpretant in the semiotic process. Hence, it refers to the internal (re)organization of the institutions dealing with the nexus and the selection of effective procedures. In this regard, there is a general consensus in the literature on the need for more integration and coordination: vertical coordination between international and national administrations to focus on livelihood in order to protect local communities [35]; and horizontal coordination between international development partners to reduce the risk that actions to achieve the Sustainable Development Goals could later undermine one another [32]. This integration and coordination process has to be extended to policy fields [17,24,26], explicitly address the environment and future generations [20,24], and balance the different goals and interests of the parties using water–energy–food (WEF) resources [24,30]. Last but not least, the process of governance has to be able to preserve its legitimacy: "integrated and multi-objective planning and transparent processes are vital in order to avoid public distrust in implementing new projects and also to ensure fair and equitable access to water by different users" [34].

(ii) *The interface between the external world and governance (object/interpretant).* In relation to the interface between governance and the interaction of society with the external world, there is general agreement in the literature on a common list of goals: guarantee water, energy, and food security by balancing the budget between demand and supply [17,18,22]; integrate WEF policies while integrating WEF sectors [17,19,21,23,26,29–32]; manage the synergies and trade-offs through an improved understanding of how these interactions are shaped by environmental, economic, social and political changes [24]; and avoid externalization [17,23].

(iii) *The interface between governance and scientific inquiry (interpretant/sign).* The interface between scientific inquiry and governance gives rise to several questions: How to decide whether the semiotic process is dealing with facts or concerns? [1]; How to integrate the existing approaches and analytical tools into a holistic vision of the issue? [30]; and How can we capitalize on the knowledge over the nexus and share experience and skills? [29]. In relation to the use of models and indicators it is considered essential to guarantee credibility, relevance (salience), and legitimacy by respecting stakeholders' divergent values and beliefs [28]. A list of general definitions of the role of the nexus in the semiotic process is reported in Table 3. It shows that society has not yet managed to fit the concept of the nexus into the semiotic process.

Table 3. Implications of scientific inquiry for governance—definitions of the role of the nexus in the semiotic process.

Quote	Reference
"integrative imaginary"	[1]
"a natural framework for rethinking sustainability as a complex adaptive system"	[29]
"a conceptual framework to facilitate integrated planning and decision making"	[32]
"a new approach in support of security and sustainability"	[30]
"a methodological framework to analyze the nexus in its multidimensionality of accounting for feed-back loops and cascading effects"	[29]
"a structured way of thinking about the whole system rather than its parts"	[37]

4. Scientific Inquiry: The Need for Novel Analytical Tools Based on Complex System Thinking

This section explores the nature of the entanglement of resource flows and proposes the concept of metabolic pattern of social-ecological systems as the external referent for the term resource nexus and the basis for the operationalization of its quantitative representation.

4.1. The Resource Nexus: The Nature of the Entanglement of Natural Resource Flows

In Latin the term nexus means 'something binding', 'tying together'. The Oxford Dictionary refers to 'a connection over elements or a connected group'. These definitions suggest that it is important to focus first of all on the nature of this binding. What is it that generates binding or connection and how? In the nexus literature, we find a diversity of 'answers' to the question 'what is observed' in the nexus: (i) sectors [17,23,24,26,29–32]; (ii) resources [21,24]; (iii) WEF systems [19,21,31]; (iv) parties using WEF resources [30]; and (v) interactions over flows, sectors, policies, and different ways of thinking [1]. As to the question 'what is the effect of the nexus?' we find: inextricable links [19,24,26]; inseparable links [35]; interlinkages [23]; critical linkages [37]; interrelationships [18]; an interrelated nature [24]; an interdependency (17,26,31,32); highly interconnected [20,21,27,30]; high levels of interconnectivity [29]; and complex relationships [1]. However, no attempt is made to explain what generates these interlinkages, the interconnectivity or interdependence, and how. Indeed, there is no holistic vision in the literature of what exactly is observed when we study the nexus in the external world (see Table 4); the external referent is simply not defined [47].

Table 4. The domain of activity of scientific inquiry: Definitions of the nexus.

Quote	Reference
"nexus deals with "wicked problems" extremely difficult to model properly and solve ... detailed process systems models for it do not yet exist at a level satisfactory for important decisions"	[27]
"nexus represents a multi-dimensional means of scientific enquiry which seeks to describe the complex and non-linear interactions between water, energy, and food, with the climate and further understand wider implications for society"	[29]
"A problem that is impossible to grasp or respond to adequately from within the partial framings of individual academic disciplines" ... "academia has lost its way"	[1]
The concept consists of multiple disciplines, as well as interdisciplinary and transdisciplinary research results	[24]

In describing relations over resource flows the term 'entanglement'—used in quantum physics to express the impossibility of describing a particle independently of the others—is enlightening. "Even when the particles are separated by a large distance a quantum state must be described for the system as a whole" [48]. Entanglement thus explicitly refers to the need of carrying out a holistic analysis of expected patters expressed by individual metabolic elements (not flows!) belonging to a larger whole. This is the approach used for studying the entanglement of different flows going through a metabolic system (e.g., human body, social-ecological system).

Acknowledging that the nexus is about studying the metabolic pattern of social-ecological systems, the following epistemological premises must be recognized:

- Identification of the flows of water, energy and food to be measured can only be carried out by using the rationale of non-equilibrium thermodynamics: we have to acknowledge that social-ecological systems are open, complex adaptive systems reproducing themselves.
- The different flows considered in the analysis cannot be handled in isolation. In metabolic systems flows of water, energy, food and minerals are meaningful only when considered in relation to the specific structural/functional elements by which they are metabolized (either consumed or produced). For example, electricity is not energy for a mule or a jumbo jet, just as lard is not energy for a car or a Muslim. In the metabolic view the various metabolic elements have to be described as specific sets of expected relations (inputs and outputs) over fund and flow elements associated to the expression of specific tasks (expected patterns) at different scales;
- In the metabolic pattern, we do not observe individual quantities in a flow, but expected profiles of flows getting simultaneously inside or outside of the structural and functional elements metabolizing them.

In the next sections, two examples of integrated analysis of metabolic flows are elaborated based on the pre-analytical identification of the system determining the entanglements over the considered flows. These examples neatly illustrate the predicament of reductionism when dealing with the resource nexus.

4.2. Examples of Entanglement: The Human Metabolism

This first example is based on the human metabolism, a type of analysis familiar to everybody. To study the pattern of entanglement over the set of metabolized flows we must first identify the external referent that defines the 'expected' entanglement. In this example the external referent is the expected set of relations among nutrients associated with the endosomatic metabolism of human beings (what does our body need?). The term endosomatic metabolism, as opposed to exosomatic metabolism, was proposed by Lotka [49], and later endorsed by Georgescu-Roegen [50], to describe the metabolic pattern of food inside the human body. As shown in Figure 2, two different sets of expected relations are relevant:

- A specific combination of flows (e.g., water, energy, protein) required by the human body to maintain and reproduce its structural and functional elements. This entanglement over the required mix of flows (in quantitative and qualitative terms) is defined at the level of the human body as a whole by its physiological characteristics; and
- A mix of flows (e.g., water, energy and protein) associated with the set of food items in the diet (quantitative and qualitative composition). In turn, each food item entails an entanglement of flows at the level of dietary component. This information is needed to describe the supply.

The dynamic equilibrium between what has to be consumed (dietary requirement) and what is supplied (the combination of food items eaten) translates into a forced entanglement over flows (water, energy, and protein) across the different levels of analysis. To verify whether or not this metabolic pattern is sustainable we must check two non-equivalent conditions: (i) whether the metabolized throughput in the human body (derived from the food) matches the required profile (the latter is estimated by recommended dietary allowances); (ii) whether the correct dietary supply (in terms of quantitative and qualitative composition) is available in time and place.

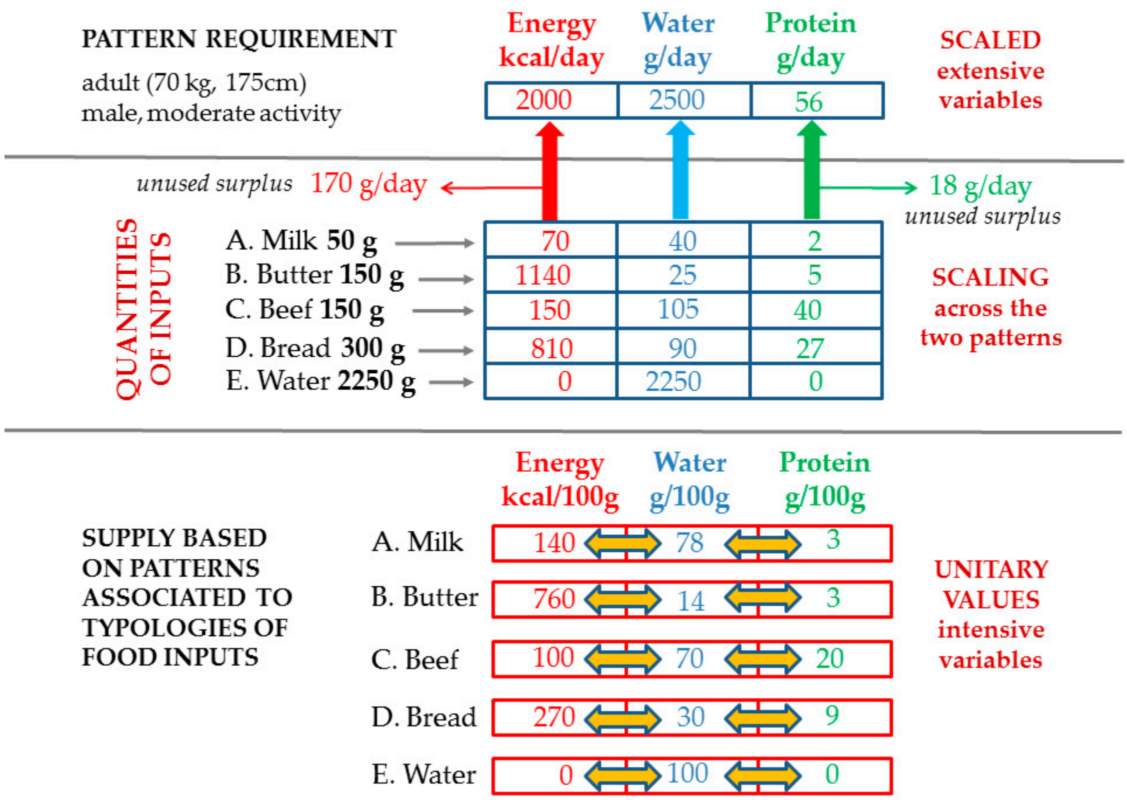

Figure 2. Analysis of a simplified human diet based on patterns of water, energy and protein flows, considering both requirement and supply side. The pattern of required flows is based on recommended daily allowances; the patterns of nutrient and energy flows supplied by foods are from the Italian food composition table [51].

In this case, the external referents for studying the entanglement of flows are obvious: (i) the need for establishing a dynamic equilibrium between the requirement for and supply of food in the metabolic system; (ii) the physiological characteristics of the human body; and (iii) the nutrient composition of available food items, which in turn reflect the process of their production. Four important points about the quantitative analysis of metabolic processes can be made in relation to this example:

1. To evaluate whether or not we are dealing with a sustainable metabolic pattern we must consider simultaneously two sets of flows that require non-equivalent analytical approaches for their quantification: (i) internal flows: referring to the physiological processes taking place inside the human body (a pattern of requirement based on a given set of accounting categories, e.g., energy, protein, water); (ii) external flows: processes taking place outside the human body that determine the availability of and access to primary sources of food aliments (a pattern of supply based on a given set of accounting categories, e.g., milk, butter, beef). A single mathematical model, no matter how complicated in terms of variables and fancy algorithms, cannot describe both the processes inside and outside the human body.
2. The relation between requirement and supply (the metabolic pattern) is not deterministic, but subject to a certain degree of impredicativity. The dynamic equilibrium may or may not be achieved depending on the chosen scale of analysis (e.g., a yearly versus a daily basis) and can be explained in terms of top-down causality (e.g., what do we need to eat to meet our physiological needs) or bottom-up causality (e.g., given what is accessible, to what extent are we meeting requirements?). Therefore, the analysis of the metabolic system must be tailored to the given time scale and deal with a range of possible solutions (handling contingent relations, many-to-one mapping) because different combinations of food items can satisfy the same dietary requirement and changes in life style (e.g., physical activity) can change requirements.
3. We can simultaneously use three criteria to assess the sustainability of the metabolic pattern (diet): (i) feasibility: the availability of food products generated by processes taking place outside the human body (agricultural production; import); (ii) viability: the effectiveness of the energy and nutrients absorbed into the human body to perform metabolic processes without causing functional impairment; (iii) desirability: the acceptability of the food consumption and resulting physical well-being to the consumer. Again, these criteria cannot be described by a single model, no matter how complicated.
4. The analysis of the metabolic process and its sustainability (feasibility, viability, desirability) is based on relations over patterns of numbers rather than individual numbers themselves. Patterns can be conveniently described by combining: (i) the profile of intensive variables or unitary operations (e.g., energy and nutrient content per 100 g product), as shown in the lower part of Figure 3; and (ii) the profile of extensive variables (e.g., profile of inputs in a diet as shown at the top of Figure 3). This illustrates that the analysis of the metabolic process involves a complex information space.

This example wants to show that the metabolism of complex metabolic systems—even the familiar case of the human metabolism—invariably involves a relational analysis of patterns across different levels of analysis. Only in this way is it possible to handle impredicative relations.

4.3. Examples of Entanglement: The Metabolism of Society

Remaining with the terminology proposed by Lotka [49] and endorsed by Georgescu-Roegen [50], the exosomatic metabolism of human society refers to the set of metabolic conversions of energy and matter taking place outside the human body, but under human control. These conversions are required to maintain and reproduce the structural and functional elements of the social-ecological system. The two concepts of exosomatic and endosomatic metabolism combined are useful to study the metabolic pattern of social-ecological systems, as together they represent the external referent for the entanglement over the flows of water, energy, food, material, money, and land use in the metabolism of human society. This idea is illustrated in Figure 4, which shows a simplified representation of the metabolic pattern of rural communities of the Great Plains (U.S.) in the 1930s. This example neatly shows that the development of U.S. industrial agriculture—replacing horses with tractors—was borne out of a resource nexus problem.

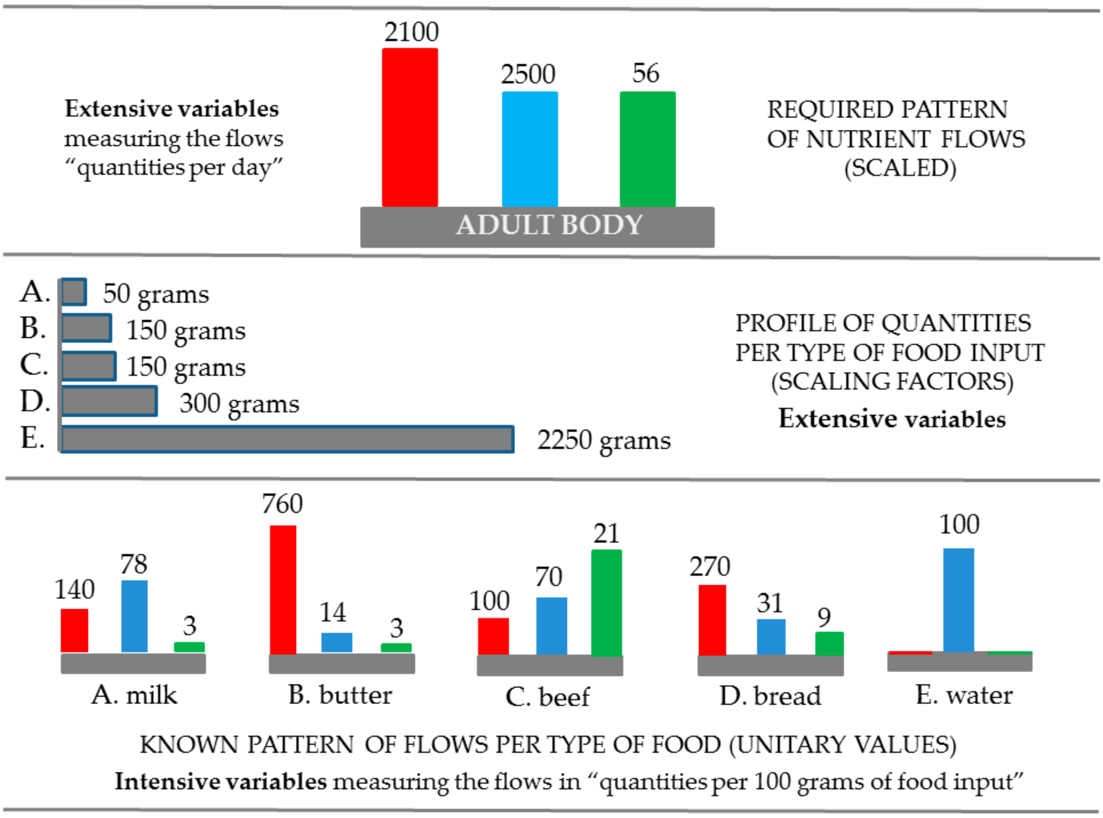

Figure 3. A set of metabolic relations in the endosomatic metabolism using the concept of patterns. Energy (red) is expressed in kcal, water (blue) and protein (green) in grams (g).

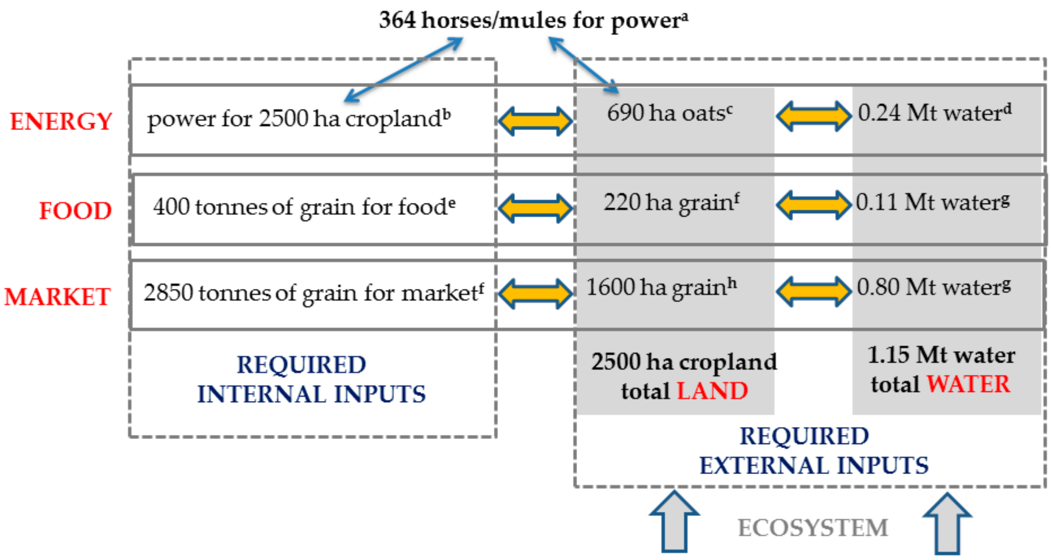

Figure 4. Relational analysis of the resource nexus problem with the cultivation of monocultures on the Great Plains in the 1930s: the forced sharing of water and land for food, energy, and income.

The relations reported in Figure 4 refer to assessments per 1000 persons and are based on data from Olmstead and Rhode [52]: (a) one power animal needed per each four people (rural population); (b) 2.5 ha of cropland per capita (rural population); (c) 1.9 ha of oats per mule/horse; (d) 350 t of irrigated water per ha of oats; (e) 400 kg per capita per year of gross grain consumption, including feed of animals for human consumption; (f) 1.8 t/ha yield of grain for food; (g) 500 t of irrigated water per ha of grain for human consumption; (h) 1.60 ha p.c. = the total of 2.50 ha per capita minus the land required for food (0.22 ha) and energy (0.69 ha).

Introduction of the exosomatic metabolism enriches the information space: besides food, society metabolizes many other flows that must be produced and made available to the various functional elements in the system. In this particular example we consider energy, money, and technical capital. Technical capital is particularly important with regard to the concept of energy security. Indeed, the example aims to illustrate that energy security is not a mere question of matching requirement and supply of energy carriers, but also about meeting the requirement of power capacity. In fact, in order for society to express any activity it must have access to devices (e.g., horses and mules in this example) capable of converting the available energy carriers into useful end-uses.

Returning to Figure 4, in the 1930s U.S. agriculture in the Great Plains faced a problem of power requirements for harvesting (energy services) grain monocultures. It is well known that tasks that have to be completed in short periods of time (e.g., harvesting) require peaks of power delivery. This requirement made human muscle power based on endosomatic metabolic conversions inadequate and explains why horses and mules were essential for cultivating early monocultures [53]. However, using 40 mules once a year to harvest a grain monoculture, one faces the problem of having to feed these animals also during the remainder of the year. As a matter of fact, in the 1930s the maintenance and reproduction of animal power for harvesting (feed production = energy security for agronomic production) competed for land and water with food production for human consumption and cash income. Indeed, an average of 30% of cropland was needed for feeding power animals [52]. As farming communities increasingly needed land and water for food and income, the adoption of tractors in U.S. agriculture quickly made its way; more than 10 million mules disappeared between 1930 and 1950 and were replaced by less than 2 million tractors [52]. For a detailed discussion on the advantages of machine over animal power in agriculture, see [54].

The example shown in Figure 4 underlines four important points regarding the metabolism of social-ecological systems:

1. When dealing with the exosomatic metabolism it is impossible to define in a deterministic way the set of flows that are needed in consumption and therefore have to be supplied in production. Some of the flows can be identified as essential, such as food, water and the energy carriers required for essential activities. However, others (e.g., economic products) can be produced and consumed at different paces depending on the circumstances. Therefore, a quantitative analysis of exosomatic metabolism must be ready to handle this challenge.
2. Even if we identify the set of flows to be metabolized, the relation between requirement and supply of these resource flows is subject to a high degree of impredicativity. Indeed, impredicativity between bottom-up causality (land uses defined by human needs/wants) and top-down causality (land uses defined by relief or climate and soil quality) is much more pronounced for exosomatic than for endosomatic metabolism. In this specific example, virtually unlimited access to fertile land made power security become a bottleneck for U.S. farmers to pursue their desire to maximize the economic return. Had the plots cultivated per family been only about 1.0 ha in size (land per capita only 0.2 ha), the logic of land-use optimization would have been completely different. Most likely, farmers would have minimized the risk of harvest failure in relation to food security and the issue of shortage of power capacity would have been completely irrelevant. This example shows that before choosing a narrative to frame a nexus problem and selecting the relative model(s) for describing system dynamics (i.e., before crunching numbers) it is essential to contextualize the problem in relation to the characteristics of the metabolic pattern of the social-ecological system under study.
3. To analyze the stability of metabolic patterns of social-ecological systems we must consider distinct sets of flows that require non-equivalent approaches for their quantification. In this example, we have seen among the 'inside flows': (i) the food, water, energy, and land required by the farmers and their families as food (endosomatic metabolism: nutritional sphere);

(ii) the fodder, water, and land needed for reproducing the animals supplying power capacity (exosomatic metabolism: agronomic sphere); and (iii) the food, water, energy, and land required by the farming community to generate the monetary flows that keep them economically viable (monetary variables—economic sphere). In the category of 'external flows', we have to include; (iv) the flows associated with environmental services (e.g., biodiversity, soil, rain, aquifer, irradiation) determined by processes beyond human control and, therefore, representing a set of external constraints limiting the option space (ecological sphere). This link is shown in Figure 5.

4. The analysis of the metabolic process (e.g., the sustainability of a farming system) is based on relations over patterns rather than relations over individual numbers. The set of relations illustrated in Figures 4 and 5 is subject to: (i) external constraints imposed by biophysical processes (boundary conditions) beyond human control (e.g., soil type, aquifers, slope, solar irradiation, wind potential); and (ii) internal constraints determined by technological processes and market transactions (setting prices) under human, but not farmer control. The co-existence of these constraints implies that individual resource flows (water, energy and food) within these sets of relations cannot be changed independently of each other. In fact, the external flows present themselves in given (spatial) patterns (beyond human control), while the pattern of resource flows expressed by the farming system is the result of the forced congruence between the different types determined by a mix of constraints under and outside of human control.

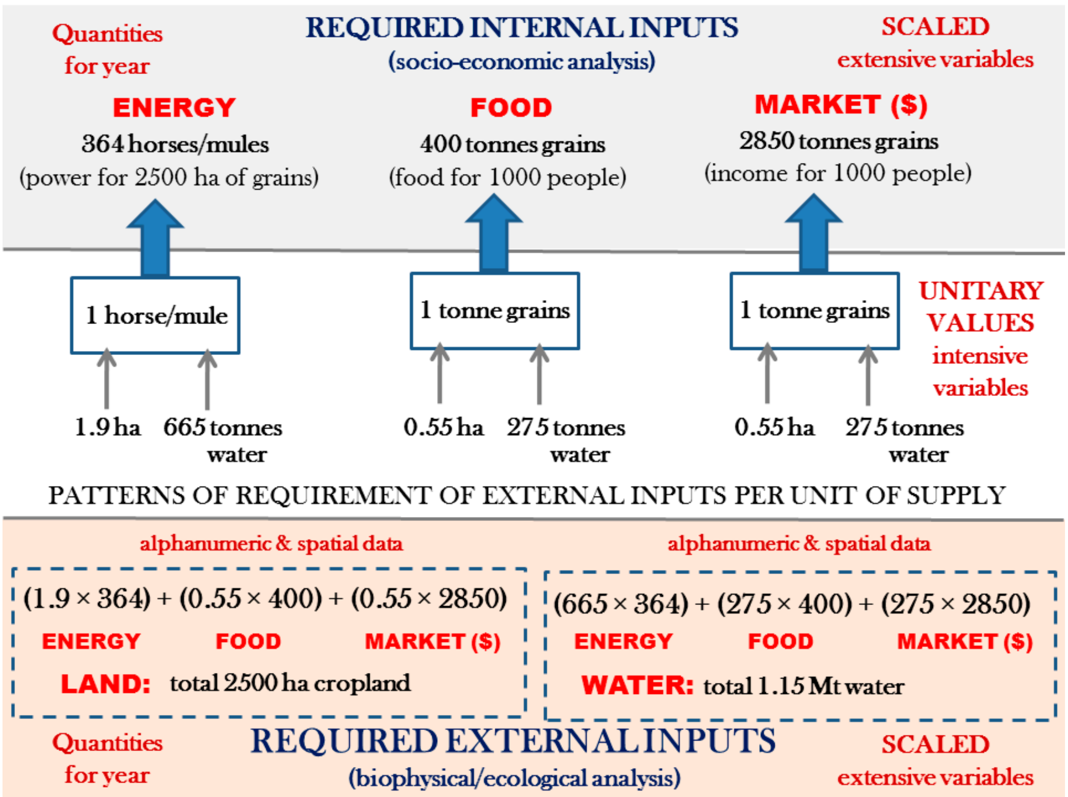

Figure 5. The different typologies of representation that must be combined to generate an effective analysis of the resource nexus.

Thus, an analysis of the complex set of relations associated with societal metabolism has to be based on different dimensions and scales of analysis. It will generate representations referring to non-equivalent descriptive domains and, as a consequence, require the simultaneous use of models that are not reducible to each other [55]. In this situation a quantitative exploration of the option space can only be done by examining relations of congruence over the different quantitative representations similar to a sudoku game [56].

4.4. Lessons Learned from These Examples

The two simplified examples of expected relations among the characteristics of the elements operating in a metabolic pattern show that it is possible to address the complexity of the resource nexus without 'solving' it. We want to keep the nexus (the set of expected relations that must be expressed) in order to be able to study the factors determining the option space (diagnostic mode) and anticipate possible future troubles when some of the data input in the sudoku generates a situation of unfeasibility, unviability or undesirability. However, the accounting of the characteristics of metabolic processes across scales and dimensions must remain semantically open to: (i) allow integration of non-equivalent views of the functional and structural elements of the system across hierarchical levels of organization; (ii) accommodate adjustments and changes in the metabolic pattern; and (iii) handle impredicative relations: in metabolic systems it is impossible to make a clear distinction between dependent and independent variables or top-down and bottom-up causality. This requires integrating different logics of scaling of data arrays when coupling spatial analysis (the structural view) to non-spatial analysis (the functional view) [57].

This new approach is being explored and validated in the MAGIC project and preliminary results confirm that abandoning reductionism (based on the 300-year old Newtonian strategy) is a good idea [58–60].

5. Conclusions

In this paper, three points have been made regarding the perception and representation of the resource nexus at the interface between society and the natural environment:

First, the inconvenient message of the resource nexus in relation to sustainability is incompatible with the rosy master narrative of neo-liberal economics and techno-scientific promises and this hampers its communication and practical uptake. From a historic perspective on the sustainability debate, the resource nexus can be interpreted as the re-surfacing of the ideological fight between cornucopians and neo-Malthusians. It demands that we reconsider the relevance of the uncomfortable knowledge put forward by the neo-Malthusians. The majority of social actors, policy makers, scientists, and activists alike, are unaware that the story-telling of cornucopians may not be 100% reliable. This unawareness is linked to the concern that dismissing the rosy master narrative as a mere techno-fantasy could destabilize existing institutions. It is therefore to be expected that the divide in the sustainability debate—'yes we can' versus 'Houston we have a problem'—cannot easily be bridged.

Second, there is a problem of governance in relation to the resource nexus due to the existence of silo structures in existing institutions. Contemporary institutions have been built on a model of reductionism, addressing and solving one problem at the time. The resource nexus sits on no one's desk. This can explain why water, energy, and food security tend to be handled as mere economic and engineering problems. The complexity inherent in the resource nexus requires simultaneous consideration of all its relevant components across various dimensions and scales. Unless the message of 'Houston we have a problem' is recognized in the governance of the nexus, it is unlikely that more effective institutions will be developed. Also in this case it is to be expected that 'lip services' will be the only possible solution for the existing institutional settings. The governance of the nexus must be adaptive and based on an information space that is co-produced and continuously updated through the interaction of all social actors inside the semiotic process. This requires that the current technocratic, top-down approach, unlikely to solve any sustainability problem, is abandoned.

Third, traditional scientific inquiry based on reductionism does not provide the required quality inputs for the discussion of sustainability policies. Two simplified examples have shown that the epistemological challenges associated with the quantitative analysis of the resource nexus require novel models of analysis based on complex system thinking. Rigor of quantitative analysis must be combined with semantically open quantitative representations of the entanglement of resource flows. This can be obtained by defining forced relations over patterns of numbers defined across different hierarchical levels of analysis and non-equivalent descriptive domains (involving different dimensions and scales). The concept of social-ecological system lends itself particularly well to this purpose, the external referent of the resource nexus being represented by the expected characteristics (relations) of its metabolic pattern.

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