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How the Biophysical Paradigm Impedes the Scientific Advancement of Ecological Economics: A Transdisciplinary Analysis

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Abstract: Ecological economics (EE), which typically conceptualizes the economy as a biophysical entity that grows into a finite ecosystem, was poised to become "economics as a life science", or the science of sustainability, and thus an alternative to mainstream economics. However, while there is consensus among researchers that it has failed to become so, there is consensus neither on the underlying causes of this failing, nor on what exactly the heterodox alternative is. For instance, biophysical economists tend to see the biophysical paradigm (BP) as the key to scientific advancement, while institutional economists tend to see it as an impediment. The current research addresses this lack of consensus. To set the foundations for an in-depth and necessarily transdisciplinary analysis, this article first reiterates and elaborates on a fact that typically eludes modern EE: EE's scientific roots lie not in the BP, but in the analogy of the economy-as-an-organism. This article then formalizes the relationship between this analogy and the BP, to analyze it systematically using cognitive science's structure-mapping theory, which explains the role of human analogical processing in learning and the advancement of science. The findings suggest that: (1) As a scientific model, the BP is merely a partially articulated form of the economy-as-an-organism analogy, and thus suffers from a type of model specification bias. (2) This bias appears to manifest in EE as a "black box" economy, relationally operationally analogous to a life science studying an organism as if it had no organs. (3) These findings are consistent with those of a recent publication that debates the role of the BP, despite employing very different assumptions and perspectives—thus corroborating the current article's methods and findings. These findings have an overarching implication: EE may advance scientifically by identifying the economy analogs of fundamental omitted organs, thus facilitating the transfer of causal knowledge from biology to economics to further "economics as a life science" or "the science of sustainability".

Keywords: economics; sustainability; ecological economics; biophysical paradigm; life science; analogy; structure-mapping; specification bias; black box

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1. Introduction

This paper draws evidence from seminal ecological economics (EE) research to show that the discipline's roots extend beyond the biophysical paradigm (BP) and into the economy-as-an-organism analogy [1–6]—that which once inspired an "economics as a life science" approach [2]. Traversing the disciplines of economics, cognitive science, and biology, this article proceeds to explain how EE's overly rigid subscription to the BP constrains scientific progress through an "omitted object bias", a type of model specification bias comparable, for example, to the omitted variable bias that arises in regression analyses when relevant explanatory variables are omitted from otherwise useful regression models. A classic example is the omission of some measure of individuals' natural talents or ability from regressions that aim to estimate the effect of schooling on income.

This work's source of motivation is equally transdisciplinary. Motivation from economics includes studies describing the failings of ecological economics (e.g., [7,8]), disagreement about whether EE should return to its biophysical roots to remedy these failings and, generally, concerns that EE has stalled in its "paradigm shift vision of becoming an alternative to conventional economics" [8] p. 2. Motivation from cognitive science includes the overwhelming evidence of paradigm shifts and conceptual change brought about by analogical reasoning [9–11], and of analogy—not paradigm—as the cognitive foundation of scientific modeling and discovery (e.g., [9–14]). And, finally, evidence comes from the confluence of biology and economics: a Kleiber's Law for economies which suggests yet undiscovered "salient similarities" [2] between economies and organisms, and which empirically supports the scientific validity of the economy-as-an-organism analogy [1]. This qualifies the article's overarching objective: to explore, using well-established science, whether and how rigid subscription to the BP impedes or helps EE advance its vision of "economics as a life science".

Section 2 draws from the early EE literature to show that the BP is a partially articulated form of the economy-as-an-organism analogy. Section 3 formalizes this relationship and introduces cognitive science's structure-mapping theory to show why the BP may suffer from "omitted object bias" that impedes scientific progress, and why the remedy lies in "incremental analogizing" [12]. Section 4 applies the structure-mapping theory to identify the source of the BP's omitted object bias, and draws from economics and biology to triangulate its findings. Section 5 discusses these results. Section 6 concludes.

2. The Biophysical Paradigm: A Partially Specified Form of the Economy-as-an-Organism

2.1. Organisms as Models of Sustainability

Most, if not all, evolutionary biologists and ecologists would agree that natural selection has made the maximization of metabolic efficiency a, if not the, most fundamental goal of any organism. This benefits not only the organism, but also the surrounding ecosystem: "Metabolism [. . .] determines the demands that an organism places on their environment for all resources . . ." [15] p. 1772. Natural selection, that is, has "designed" organisms to carry out, as efficiently as possible, this most fundamental, dual goal: to develop and grow with as few resources as possible, while also minimizing the demands they place on the environment for all resources (e.g., [15–18]). Organisms are thus "nature's *par excellence* models of efficiency and resilience, the *sine qua non* of sustainability." [1], p. 8. In EE, the complex organism serves as a model for the economy. This is clear from fact that almost all the field's basic concepts are founded on the analogy of the economy-as-an-organism [1]. It is, therefore, perhaps unsurprising that EE eventually aspired to become "the science and management of sustainability" [19].

But today, as will become clearer, the economy-as-an-organism analogy's contribution to EE is rarely explicitly acknowledged. Instead, modern EE sees itself as rooted in the BP, and rarely—if ever—has it attempted to clearly and explicitly articulate the BP's relationship to its founding and scientifically useful analogy (of the economy-as-an-organism). Reluctance to acknowledge and articulate this relationship contributes to concerns about whether and why EE has strayed from the roots once poised to make it the science of sustainability. Hence, again, the current article's research objective: to explore how and whether this overly rigid subscription to the BP helps or hinders EE from becoming an economics as a life science or the science and management of sustainability.

2.2. Ecological Economics' Overly Rigid Subscription to the Biophysical Paradigm

EE's over-reliance on the BP is particularly apparent from studies that express discontent with the field's scientific progress and current status. Within this literature, it is widely accepted that EE has its scientific roots in "the biophysical paradigm" that sees the economy predominantly as an energy system governed by the laws of thermodynamics (e.g., [8,20]). This view is held by researchers that appear to generally favor this paradigm (e.g., [8,21–24]), as well as by those who are generally critical of it (e.g., [7]). (I say "generally" because while advocates of the biophysical paradigm focus on its irrefutable science, they also tend to be open about its limitations. And similarly, while critics tend to focus on its limitations, they acknowledge the paradigm's strengths). This is evident from research that "provides background on the shared roots of BPE [biophysical economics] and EE [ecological economics]" [8] p. 2, and that generally seeks to associate EE with "biophysical economics as a new economic paradigm" [25] p. 1. It is also clear from the ubiquity of language like "versions of Ecological Economics, rather than its *original* biophysical form" [22] p. 231 (emphasis added); "The biophysical perspective of Ecological economists" [22] p. 232; the "strong emphasis [of EE] on biophysical analysis" [7] p. 2; "biophysical approaches" as the "Historical *roots* of ecological economics [21] p. 17 (emphasis added); that "ecological economics must return to its biophysical *roots*" [8] p. 1 (emphasis added); and that "We believe that the philosophical basis of the 'biophysical economics' . . . is also, at least as part of it, the philosophical *basis* of Ecological Economics" [22] p. 235 (emphasis added).

Note that the abovementioned constitute but a few examples. There are countless other instances where "ecological economics" is purposefully linked, within the same sentence, to terms like "biophysical paradigm", biophysical *roots*", "biophysical *foundations*", "biophysical *basis*" and/or "biophysical *origins*" (emphasis added). To be clear, the current article acknowledges that the science underlying the BP is integral to EE and that it has generated significant new knowledge at the environment–energy–economy nexus. The thesis of this article is simply that the BP constitutes but a partial articulation of EE's scientific roots, thus possibly constraining the field's scientific progress. Excessive preoccupation with the BP, this paper argues, obscures an important fact regarding the scientific origins of EE: the field is rooted in a scientifically useful—but underutilized—analogy of which the BP is but a subset, the analogy of the economy-as-an-organism—the analogy upon which the vision, ambition, and potential of economics as a life science was founded.

2.3. The Scientific Roots of Ecological Economics

The fact that EE is rooted in the analogy of the economy-as-an-organism is obvious from the explicit parallels Georgescu-Roegen and Herman Daly drew between biological and economic processes, the ubiquity of these analogies, and their strategic use in the development of their scientific reasoning (e.g., [1,2]). Production, for example, is conceptualized as corresponding to (i.e., is the economy analog of) anabolism, the consumption of goods and services is conceptualized as analogous to catabolism, the metabolism is conceptualized as the biological analog of economic activity, and thus the life process is analogous to the economic process, (e.g., [1,2,26]). It is this "cognitive mapping" of metabolic and bioenergetic processes onto their economy analogs that gave form to the BP.

It is also clear, however, from the broader language of this research, that these metabolic and bioenergetic processes were not those of biological structures at organisms' lower levels of their hierarchical organization (e.g., cells or organs) but, importantly, processes specific to a whole, multicomponent organism. For example, it is "the economic process" that is "an *organism* [that] cannot live in a medium of its own waste products", an "*organism*" with a "reciprocal . . . relation of fitness" between itself and the environment, and that "If the *organism* fits the environment, then it is also the case that the environment is fit for the organism [2] p. 396 (emphasis added).

Georgescu-Roegen and Daly thus derived their ideas and infused them with scientific rigor by conceptualizing the economy as a living organism. They transferred, that is, irrefutable science and causal knowledge from biology to economics and justified this practice by pointing out the two systems' analogically similar structures. Herman Daly referred to the two systems' similar structures as their "salient similarities" [2] p. 392. In other words, by virtue of this analogical similarity, the founders of EE apparently assumed that the laws or principles that apply to living organisms might also apply to economies. The validity of this assumption is evidenced by how the laws of thermodynamics and biology's Kleiber's Law also apply to economies [1]. This also exemplifies how analogies further scientific advancement, and how paradigms emerge: as a mechanism of scientific advancement that seems to often elude EE.

In pursuing a "science of sustainability" [19], the conceptualization of the economy-as-an-organism is perhaps even more striking within the notion of economies having parts or "objects" analogous to biological organs. It is through this analogy, for example, that Daly infers that "Growth merges into development as alterations in the rates of increase of different parts give rise to new proportions" [2] p. 397. Hence, additional scientific insight comes from what economists appear to commonly perceive as just a metaphor: economies should, like organisms, purposefully alter the accumulation rates of different forms of physical capital to optimize the functioning of the economic system. This is in stark contrast to the neoclassical growth models whose primary focus is GDP growth. It is also a concept which, I posit, is perhaps the most fundamental and overarching goal of steady-state economics: qualitative development without growth. Hence, we see another example of how analogy—not paradigm—begets science, namely the science of the economy-as-an-organism or of "economics as a life science" [2].

The above constitutes easy-to-see evidence that to Georgescu-Roegen and Daly "The notion of exosomatic organs [i.e., physical economic capital as analogous to biological organs] is more than just a metaphor." [27] p. 260. Daly even identified explicitly the economy analogs of specific biological organs. He conceptualized, for example, production infrastructure (a form of capital) as analogous to a digestive tract (a biological organ system): "Just as our endosomatic organs are maintained by an endosomatic digestive tract, so our exosomatic organs require an exosomatic digestive tract" [27] p. 260. Perhaps even more striking is the notion of economies with hearts, livers, and lungs: "Our lives and wellbeing are as dependent on automobiles, airplanes, heating and cooling systems, electric and communications networks, pipelines, and sewerage systems as on our heart, liver or lungs." [27] p. 260. Thus, as far as Georgescu-Roegen and Daly are concerned, economic growth should merge into development just like an organism's growth merges into development, such that organs are in some optimal, or at least near-optimal, proportion or ratio to one another. Incidentally, this is also the field of biology known as allometric scaling (e.g., [16–18,28]): it studies organisms' highly optimized, size-independent organ–weight or body–form ratios (e.g., [28]). This observation alone alludes to the value and relevance of biology to economics.

But today, scientific economics, orthodox and heterodox alike, shows little to no interest in identifying the economy analogs of these organs or their proportions. Conventional economics altogether dismisses the notion of economies with organs—and biological analogies in general—as merely outdated ornaments of speech void of scientific substance. The same appears to be true for current-day EE: critical voices in EE, biophysical economics, and social ecological economics rarely, if ever, explicitly acknowledge the economy-as-an-organism analogy's contribution to the scientific emergence of EE, or its relation to the BP.

The objective here is not to provide an exhaustive list of Georgescu-Roegen's and Daly's biological analogies that frame the economy as analogous to a living organism. That alone would not be particularly useful. The objective is twofold and far more fundamental: to reiterate to the research community that without the analogy of the economy-as-an-organism there would be no BP or EE, and to demonstrate that "salient similarities" between capital and biological organs are central to an "economics as a life science", the science of sustainability. The roots of EE thus run deeper than the BP and into the economy-as-an-organism analogy. This is critical: conceptually, the BP emerged from, and is thus subsumed by—or is nested in—the economy-as-an-organism analogy. While the former considers the economy mostly in energy terms and as an energy system of production, the latter considers it as a whole, multicomponent organism, which its energetics are "just" a part of.

Hence this article's overarching hypothesis, and in language that may better resonate with economists and other empirical researchers: The BP is but a partially specified form of its parent analogy and, thus, similar to a regression model that omits relevant fundamental variables; it impedes conceptual change and scientific progress. It is analogous, in other words, to an underfitted regression model inherently plagued by a specification bias, i.e., an analogical model plagued by an omitted object bias. In the diagrammatic spirit of EE, Figure 1 is a conceptual model of this relationship between the paradigm and the analogy. The next section explains and develops the methods required to explore this hypothesis.

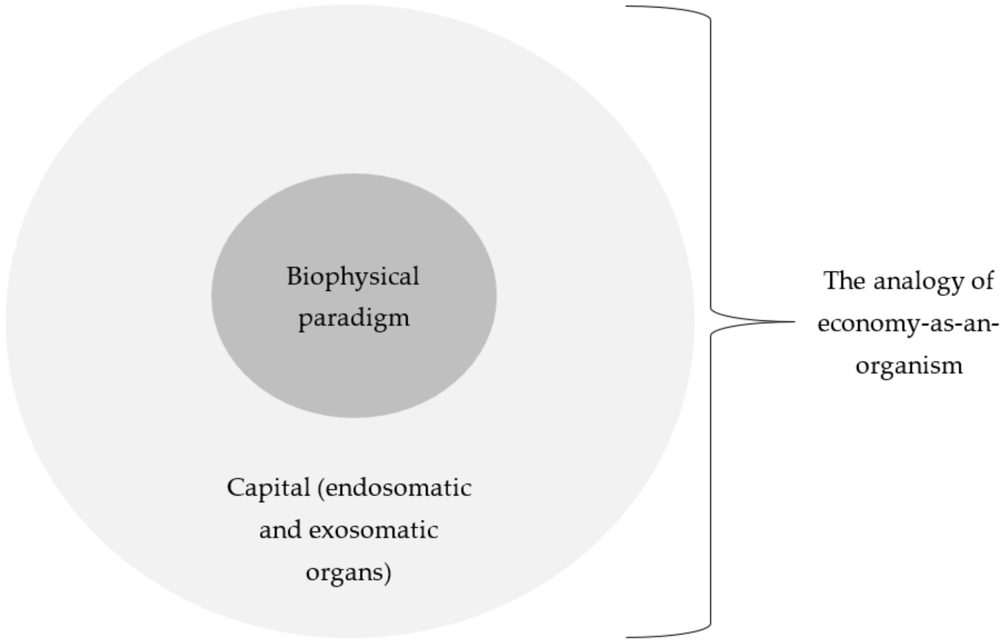

Figure 1. A conceptual model of the biophysical paradigm's relation to the analogy of the economy-as-an-organism: the former is a partial specification of the latter.

3. Methods

Terms like "subset", "specification", "technical", "omitted variable", and "identification" tend to be associated with the precision and clarity of mathematical formalism and often presuppose an established theoretical framework that guides the "specification" and "identification" of omitted variables. In econometrics, for example, the identification of potentially omitted variables and a regression model's specification are guided by the interaction of economic and statistical theory. But in the case of the economy-as-an-organism, there seems to be no widely accepted theoretical basis upon which to justify suspicions of specification bias. On what grounds, for example, are concerns of omitted objects legitimate? And what are the analogical model's most fundamental omitted biological organs and how can their economy analogs be identified? Analogies raise such questions because they tend to be qualitative and abstract, and thus open to subjective interpretation and "difficult to systematically integrate into any single analytical framework" [1] p. 2 (citing [29,30]). To circumvent this challenge, the current article employs cognitive science's structure-mapping theory (e.g., [13]): an established, empirically supported set of formal criteria used to evaluate analogical arguments, the scientific usefulness of analogies, and, in general, to explain the mechanism of human analogical processing in science.

3.1. The Process of Cognitive Structural Alignment

Structure-mapping is the conceptual, cognitive structural alignment of objects in a well-understood base system with corresponding objects in a less well-understood target system—where "corresponding" means that the two objects play similar roles in their respective systems (e.g., [13,31–36]). When this cognitive structural alignment has been established, the more familiar base system serves as a model for the less familiar target system, and the former can be used to explain and draw inferences or predictions concerning the latter (e.g., [13,36]). Omitting from the analogy objects of the base domain that apply to the target domain is, thus, not a trivial concern: it results in a loss of information that limits and/or distorts the analogy's ability to explain and generate predictions about economies and their phenomena. This idea is crystallized in Figure 2, a schematic representation of the process of cognitive structural alignment, adapted from Gentner and Maravilla [36].

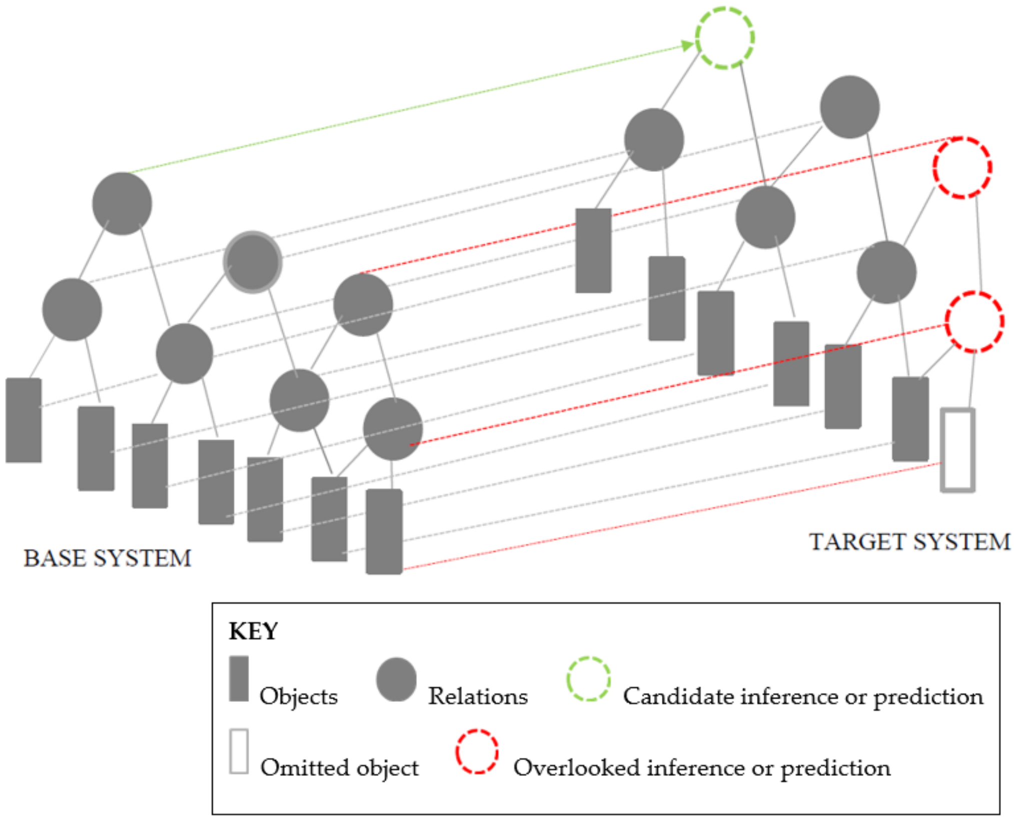

Figure 2. Omitted object bias in the process of cognitive structural alignment.

As Figure 2 illustrates, the inclusion of previously omitted corresponding objects alters the form or "mental image" [7] of the target domain. This reveals a "novel perspective" of the subject of scientific inquiry (the target system) and allows for previously overlooked inferences or predictions (e.g., [13,31–36]). The analogy to regression analysis is relatively clear: just as estimated coefficients describe the relationship between dependent and independent variables, the (solid and dotted) circles in Figure 2 describe the relationship between objects, the cognitive analogs of variables. And just as including relevant omitted variables reveals new coefficient estimates, including relevant omitted objects reveals new relations, i.e., previously overlooked inferences or predictions.

Also obvious from Figure 2 is the fact that the greater the *number* of similarities, and the more similar the objects' *relation* in their respective systems, the more complete and scientifically valid the novel perspective is, and thus the more reliable the inferences and predictions are that emerge from it: "The fluidity of the predictions is heightened by the *large* number of *interconnections* among the entities." [13] p. 33 (emphasis added). Thus, whatever relational or operational properties, rules, or laws apply to the base domain are more likely to apply to the target domain. Importantly, the more likely it thus is that the causal structure of the base system applies to the target system (e.g., [12,32]) and, thus, causal knowledge of the former can be transferred to the latter. Consequently, through incremental analogizing—the process of "extending the mapping by returning to the base for more material to add to the analogy" [12] p. 28—an analogy's specification can be enriched to bring about conceptual, knowledge, and theory change, and thus scientific advancement (e.g., [10,12,35,37–39]).

This is analogous to the incremental analogizing that typically goes unrecognized in—despite being inherent to—economic and econometric modeling [40,41]: economists extend their conceptual mapping (between the variables in their model and factors perceived relevant to the actual economic process or system *being* modeled) by returning to their theory's base domain (e.g., machine, organism, or some other conceptualization of the economy or economic process being modeled) "for more material [i.e., variables] to add to the analogy [i.e., the model]". And they do so for the exact same purpose: to enhance their model's explanatory and predictive capabilities. Thus, contrary to most economists' opinion, economics, too, advances by taking a "fertile [analogy] relentlessly articulating the nature of. . ." its target domain, ". . .probing the properties of that terrain, and testing the connections between that domain and the principal [base] domain" [40] p. 35. Relational-operational analogies thus form the core of virtually all scientific models, and incremental analogizing is the key to enriching these models (e.g., [32,36]), even in economics.

That omitted object bias is a powerful impediment to scientific progress is also evident from cognitive science research's preoccupation with the *number* of parts mapped by scientific analogies (e.g., [13,38]). That literature is clear: ". . . [the scientific analogy must be] such that *substantial* parts of the relational-operational structure of B [the base system] apply in T [the target system]: that is, *many* of the relational predicates that are valid in B must also be valid in T" [13] p. 6 (emphasis added). This implies that the scientific usefulness of any analogy that draws only a handful of similarities between two largely isomorphic, complex, multicomponent systems will be limited. And the same can be said for any economic or econometric model.

Now consider Figure 1 from a cognitive structural alignment perspective: the BP is but a subset of the encompassing set of parts or relational predicates of the economy-as-an-organism analogy. Under Georgescu-Roegen and Daly's presupposition that economies and organisms are relationally operationally analogous systems, the number of similarities (objects) the BP captures between the two systems can be characterized as neither "substantial" nor "many": organisms, like economies, consist of a vast number of interrelated and interconnected objects that far exceed those captured by the BP. This observation alone legitimizes concerns of an "omitted object bias" and justifies the exploration of the current article's hypothesis.

Within the context of the economy-as-an-organism, the next subsection shows how the language of mathematics directly reflects the structural cognitive alignment process represented in Figure 2. Formalizing the relationship between the BP and its root analogy (Figure 1) is thus a natural next step, and helps elucidate the value of the structure-mapping theory as a tool of analysis. It also challenges a commonly accepted view in economics: that biological analogies cannot be subjected to mathematical interpretation and analysis.

3.2. The Economy-as-an-Organism Analogy: A Mathematical Perspective

Let the organism be the set O that contains all fundamental elements (i.e., objects) of an organism, and the economy the set E that contains all the fundamental elements of an economy. Let f also be the rule or function that associates unique elements of O with each element of E. Then, f: $O \rightarrow E$. In other words, f is a mapping of O into E. If $x \in O$, the element or object in E associated with x is denoted by $f(x)$, and is called the *image* of x under f, and the set O is the *domain definition* of f.

Taking the mathematical terms "image" and "domain definition" literally explicitly links mathematics to the process of cognitive structural alignment: $f(x)$ "describes" what x "looks like" under the "lens" or rule of f as defined in the base domain, O. In other words, $f(x)$ reveals a potentially novel perspective on x by looking at it through the base domain's definition or "lens" of f. (For example, under the "lens" $f(x) = x^2$, $x = 2$ would "look like" a 4. This is consistent with the language of mathematics: the image of $x = 2$ under the function $f(x) = x^2$ is $f(x) = 4$. If the domain definition or "lens" were $f(x) = x^3$, then the 2 would "look like" an 8. Different domain definitions, that is, produce a different image of the same (x). This interpretation bridges any perceived disconnect between this mathematical representation of the analogy and cognitive mapping: the "*image* of x under f" is thus the mathematical analog of the "mental image" of the objects in the target system.

As more such objects are added to the analogy, the target domain increasingly resembles the base domain, the former thus taking on a new "mental image" as a *system*, thus, a "novel perspective". Mathematically, the set of included objects constitutes the set of images of x under f in E, referred to in mathematics as the *range* of f. That is, how many elements of O f can identify in E: Taking the term "range" to mean literally the "range of vision" or "scope", the set of images of x under f can be interpreted as how much of O f can see in E. The "*range* of f" is thus the mathematical analog of the set of the target domain's objects captured by the cognitive structural alignment process (e.g., the target domain's gray objects in Figure 2). Therefore, the more limited the range of f, the less f can "see" of O in E, and thus the greater the omitted object bias.

The following subsection shows how the structure-mapping theory elaborates on the nature of f to capture a key characteristic of Figure 2: the sets O and E are *systems* and not—as the above might suggest—sets of unrelated objects. The mapping f must thus be such that it preserves the *relation* between objects in their respective systems, or the *role* or *operation* of objects or processes in their respective systems (e.g., [13]). Structure-mapping theory, that is, constructs f, the "lens" itself, the key tool for the identification of omitted objects. This is necessary: in the absence of an established "theory of ecological economics" or "economic biology" to guide identification, how else are researchers to identify the economy analogs of omitted objects?

The following three assertions have been taken almost verbatim from Gentner [13], with the notation adapted to fit the work above. An example is then given to demonstrate this tool's applicability.

3.3. Structure-Mapping Theory: The Identification Tool

The economy-as-an-organism analogy is a structure-mapping analogy between the economic system, E (the target domain) and the organism, O (the base domain). This asserts that:

(1) There exists a mapping f of the objects or processes $x_1, x_2, \ldots, x_n$ of the living organism O onto the different corresponding objects or processes $e_1, e_2, \ldots, e_n$ of the economic system E (as in Section 3.2, above).

(2) This mapping, however, is such that a large enough number of parts of the relational-operational structure of O apply in E. In other words, many of the relational predicates valid in O must also be valid in E, given that the correspondence between objects is defined by the mapping f: True [$F(x_{i,}, x_{j,})$] implies True [$F(e_i, e_{j,})$], where F is a function that characterizes the relation between the specified objects or processes (x_i and x_j, and e_i and e_j), or the mapping f. True [$F(O, x_{j,})$] implies True [$F(E, e_{j,})$], where F is a function that characterizes the role of specified objects or processes in their respective system (O and x_j, and E and e_j).

"Assertions 1 and 2 define the basic structure-mapping" [13] p. 6, and are compatible with the relational-operational similarities between the systems O and E. Taken together, they state that the mapping must preserve the *relationship* between a *large enough* number of objects and not their attributes: "A structure-mapping analogy asserts that identical operations and relationships hold among nonidentical things." [13] pp. 4–5.

To specify that the mapping is not between two systems that are literally similar but between systems that are analogically related, a third condition is needed:

(3) Relatively few of the valid "one-place" attributes within O apply validly in E. That is, True [$A(x_{i,})$] does not imply True [$A(e_{i,})$], where A is not a function or operation that relates two object-processes, but merely an attribute of the specified object-processes.

Condition 3 states explicitly that object-processes should correspond only in terms of their *roles* in their respective systems and not in terms of their attributes. The structure-mapping, that is, must preserve the *relation* between object-processes but not object attributes. For example, in Rutherford's scientific analogy of the solar system as an atom, it is irrelevant that the sun is orange and hot while the nucleus might be neither: relation and operation are what matter.

Given assertions 1 and 3, assertion 2 is the key tool that identifies the target system analogs of the base system. To see this, consider Table 1. These are "The biological metaphors that found ecological economics" [1] p. 4, i.e., the seven biological analogies (i.e., cognitive structural alignments) upon which EE built almost all of its basic concepts. (Although Makriyannis [1] documents nine such analogies, this discrepancy in the number of mappings is only due to the way they are grouped. In the present article, the objects "Organs" and "Endosomatic biological organs" listed in Table 2 in Makriyannis [1] are here simply subsumed by "Endosomatic (biological) organs" and "Complementary endosomatic organs"). Each and every mapping satisfies the three structure-mapping conditions: They are one-to-one mappings between objects that play a similar role in their respective systems (True [$F(O, x_{j,})$] implies True [$F(E, e_{j,})$]), but have no "one-place" attributes in common. The process of consumption, for example, serves a function in economies that is similar—i.e., relationally operationally analogous—to the function catabolism serves in organisms. Likewise, the role of capital in the economy is similar to the role biological organs play in complex living organisms.

Table 1. The seven structure-mappings that define the economy-as-an-organism model.

Base System: ORGANISM		Target System: ECONOMY	
Object-Process	**Maps into:**	**Object-Process**	**References**
Metabolism	➡	Economic activity	e.g., [2]
Anabolism	➡	Production	e.g., [2]
Catabolism	➡	Consumption	e.g., [2]
Metabolic waste	➡	Physical output	e.g., [2]
Life process	➡	Economic process	e.g., [2,17]
Endosomatic (biological) organs	➡	Manmade physical capital (exosomatic organs)	e.g., [2,26,42]
Complimentary endosomatic organs (e.g., forests, rivers, oceans)	➡	Natural capital	e.g., [2,42]

Now consider how the structure-mapping theory explicitly identifies production as the economy analog of anabolism, a key analogy in EE: since x = *anabolism*, then *anabolism* $\in O$, and the object in E associated with *anabolism* can be denoted by f (*anabolism*). According to its domain definition, F = *the use of energy and material to build up the system* (i.e., a definition of anabolism which most biologists would probably accept). Since this definition applies also to the process of production in the target domain, f (*anabolism*) = *production*. In other words, under the biological lens of f, the anabolic process of organisms "looks like" the production process of economies. The mapping f, that is, satisfies the condition "True [$F(O, x)$] implies True [$F(E, e)$]", where F is a function that characterizes the relational operation of x in O, and e in E. Thus the explicit form of the anabolism–production analogy: "true [F(*organism*, *anabolism*)] implies true [F(*economy*, *production*)]", where F = *the use of energy and material to build up the system.*

The structure-mapping identification tool thus makes a non-issue of a major and enduring misconception in scientific economics: that biological analogies are necessarily ambiguous and open to interpretation. It shows instead how an analogy, like any mathematical economic model, can be formally specified and take on an explicit form. And, like any scientific model, its specification can be improved—via incremental analogizing—to enhance its explanatory and predictive power. Section 4 applies these tools to explore the present article's overarching hypothesis: the BP, as a subset of the EE's root analogy, suffers from an omitted object bias that impedes the advancement of scientific economics.

4. Results

4.1. The Biophysical Paradigm's Omitted Objects

The set *O*, as per Table 1, contains all the fundamental object-processes of the organism whose economy analogs presumably represent the whole economy's most fundamental object-processes: $O = \{x_1,\ x_2,\ x_3, x_4, x_5, x_6, x_7\}$, where x_1 = *metabolism*, x_2 = *anabolism*, x_3 = *catabolism*, x_4 = *metabolic waste*, x_5 = *life process*, x_6 = *endosomatic organs*, and x_7 = *complementary endosomatic organs*. The BP explicitly only includes relations and operations related to metabolism [1]: the *life process*, that is, by which the organism ingests useful matter-energy to promote *anabolism*, necessitating also some level of *catabolism* (i.e., breakdown) and thus the need to remove *metabolic waste*. Therefore, $BP = \{x_1,\ x_2,\ x_3, x_4, x_5\}$, where x_1 to x_5 are defined as above.

We can now ask how much of the entire economy the BP actually "sees" as an organism, by defining the mapping f: $BP \rightarrow O$ and specifying the image under the f of each element in *BP* as *f* = *match each object in BP to its corresponding object in O*, thus conforming to True [*F*(*BP*, $x_{j,}$)] implies True [*F*(*O*, $x_{j,}$)]: $f(x_1) = x_1$, $f(x_2) = x_2$, $f(x_3) = x_3$, $f(x_4) = x_4$, $f(x_5) = x_5$, and the range of f is the set $\{x_1,\ x_2,\ x_3, x_4, x_5\}$. This is, of course, the entire set *BP*, but only a subset of *O*; a more formal representation of Figure 1. The omitted objects are thus x_6 and x_7: Since $BP \subseteq O$, then $O - BP = \{x_6, x_7\}$, where x_6 = *endosomatic organs* and x_7 = *complementary endosomatic organs*, respectively, are the biology analogs of physical and natural capital. True [*F*(*organism, organs*)] implies True [*F*(*economy, capital*)], where *F* = *(specialized structures that) perform specific functions*, a domain definition that any biologist and economist would probably accept.

Thus, according to the structure-mapping theory, the BP cannot "see" the entire economy as an organism—just its metabolism and its associated objects and operations: anabolism, catabolism, the intake of matter-energy, and the excretion of metabolic waste. (This is what is meant by ". . . we cannot say that [the economy-as-an-organism] analogy is scientifically useful beyond how it conceptualizes organisms and economies as metabolically analogous systems", thus limiting the analogy's scientific usefulness [1] p. 9). Via analogy, in the eyes of the BP, the economy is thus analogous to a living organism without organs, i.e., a complex but "black box" system. It is thus analogous to a life science that is agnostic about the inner workings of its subject matter, the organism. Therefore, by cognitive extension, one can infer or hypothesize—perhaps even predict—that from the BP will emerge a discipline characterized by a relative agnosticism about the internal workings of its subject matter, the economy. This implies a science that reflects its underlying, paradigmatic analogy: one that unwittingly operates under the assumption that detailed knowledge of the different forms of capital and their interconnectedness and interrelatedness is not central to understanding the complexities of economic development, and the relationship between economic development, the consumption of energy and material, and the production of waste. In the eyes of the analogy of the economy-as-an-organism—i.e., from Georgescu-Roegen and Daly's bioeconomic viewpoint [26]—that is the scientific equivalent of a life science that unwittingly operates under the assumption that detailed knowledge of the different organs and their interconnectedness and interrelatedness is not central to understanding the complex processes involved in the organism's development, and the relationship between its development, its consumption of energy and material, and its production of waste. Surely that would strike any biologist as a research paradigm of limited value. And yet that is what the tools of cognitive science suggest about the BP—explaining perhaps the "failings" of EE, including its inability to penetrate the mainstream even after fifty years of research guided predominantly by the BP.

Researchers not intimately familiar with the science behind human analogical processing and its role in science may be skeptical of the hypothesis that a single and seemingly benign analogy can have such a profoundly adverse and enduring effect on a discipline. This article's methods of analysis may compound skepticism of the hypothesis of an "organless", "black box" economy driven by omitted object bias: it is understandable that a discipline may question the theory-to-praxis value of methods relatively foreign to it. To address this potential skepticism, much like how economists often compare their empirical findings to the literature's, the next section takes this finding to the EE literature. Section 4.2.1 studies its diagrams; Section 4.2.2, its language.

4.2. The Black Box Hypothesis: Evidence from the Literature

4.2.1. The Diagrams of Ecological Economics

This subsection studies the evolution of EE's diagrammatic representations of its most basic concepts. It is both appropriate and necessary to consider diagrammatic representations of EE's founding analogies: as is clear from physics, mathematics, chemistry, biology, and even economics, "Diagrams have long been used in science" [43] p. 1. In EE diagrams have played a particularly important role in communicating the field's most fundamental concepts (e.g., how the ecosystem constrains the size of the economy). A line of peer-reviewed research indeed views diagrams as a formal language and questions the "ban of diagrams from mathematical proofs" on the grounds that they play a non-redundant role in such proofs [43] p. 1. (see also [44]). The objective is twofold: The first is to explore the hypothesis of a black box economy driven by omitted object bias. The second is to demonstrate the applicability—and thus theory-to-praxis value—of cognitive science's tools and concepts.

Studies that address issues related to the roots of EE tend to begin with language to the effect of "(EE) was formalized 30 years ago based on a biophysical paradigm . . ." [8] p. 1, typically represented by some version of Figure 3 [45]. Further, "The conceptual model represented in" Figure 3 "(and variations of it) is a starting point for the work of many ecological economists" [45] p. 205. These exemplify the powerful effect analogies and their diagrammatic representations have had on EE. But to point to this figure's literal "black box" as evidence of the BP's omitted object bias may lead to accusations of playing with words and of unjustifiably putting forth superficial similarities—i.e., one-place attributes—as evidence of this bias. It also bypasses the opportunity to see the applicability of cognitive science's tools and concepts.

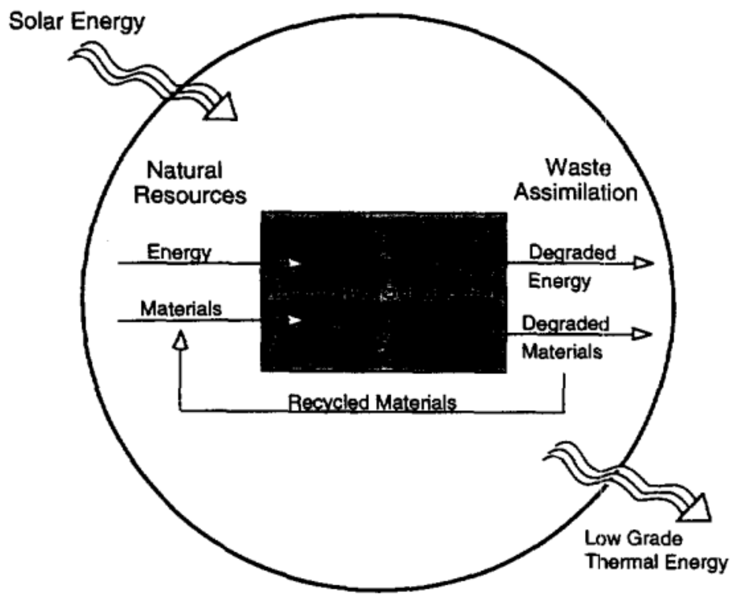

Figure 3. The starting point for the work of many ecological economists: the biophysical paradigm.

To best understand the emergence of EE's black box and its implications, one must go back more than 30 years to the first diagrammatic representation of the BP and observe its evolution under the lens of cognitive science—i.e., mindful of the concepts of structural alignment and incremental analogizing, and their role in shaping these representations, with the express purpose to predict, explain, communicate, and project a "novel perspective" on economies.

Figure 4 is Daly's [2] first published diagrammatic representation of the economy as analogous to a metabolic system [46]. It is obvious that Daly cognitively structurally aligned the relation of objects of METABOLISM (representative of an organism) with those of ECONOMICS (representative of the economy): as if familiar with Figure 2, he placed the two systems side-by-side to serve, respectively, as his base and target systems (see [2] p. 395). The goal was, as most cognitive scientists would probably agree, the transfer of knowledge from the former to the latter.

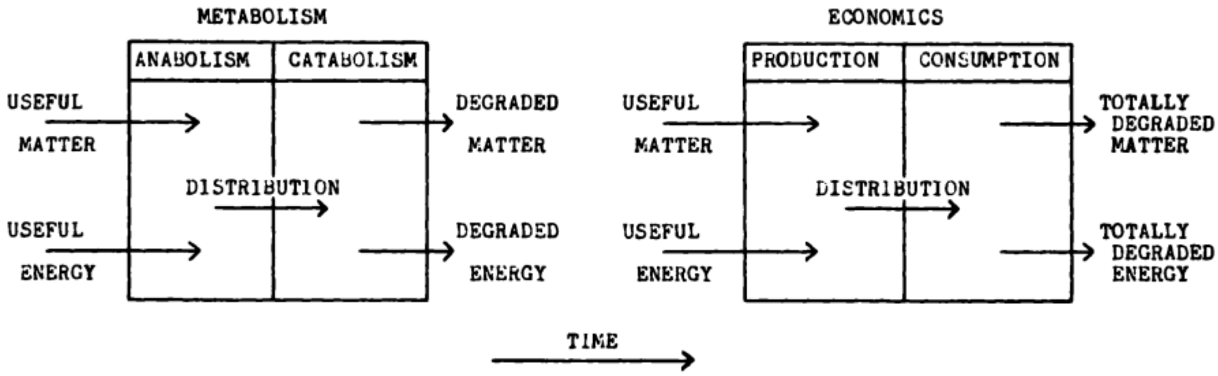

Figure 4. Daly's first diagrammatic representation of how organisms and economies are metabolically analogous (sourced from [2] p. 395): Omits the finite ecosystem.

This diagrammatic functional form of the analogy explicitly and effectively communicates—even to non-experts—why the laws of thermodynamic economics must also apply to economies: organisms and economies are—not in a metaphorical sense, but in a true relational-operational sense—metabolically analogous systems. This is the key concept underlying the BP. In 1968, this was obviously a "novel perspective" on the economy, and one that struck a chord even with some renowned economists. An example is Frank Knight, at that time a reviewer of the *Journal of Political Economy*, who appears to have had a keen interest in the economy-as-an-organism analogy: it is thought that his circular-flow diagram, one of the first ever, was inspired by the human circulatory system discovered by William Harvey in the early 17th century [47,48].

With the novel perspective that emerged from Figure 4 emerged also new predictions and inferences, and new hypotheses could be put forth. Looking at this diagram, for example, even a non-expert might predict that an economy will grow "simply" by consuming more useful energy and matter, and that it will need, in turn, to "excrete" more degraded matter-energy. A more astute non-expert might even predict or infer that the destiny of all ingested useful matter-energy is metabolic waste: Another key concept at the core of the BP and EE.

However, contemplating Figure 4 with some transdisciplinary knowledge of biology and cognitive science, one might even infer or hypothesize that the economy's DISTRIBUTION represents a transport (sub)system relationally operationally analogous to that of an organism's, and consisting perhaps of forms of capital that play a role similar to those of some biological organ systems: that is, precisely Georgescu-Roegen and Daly's notion of economies with organs. Further, taking this analogy seriously, any economist with some familiarity with cognitive science and biological scaling research would have been correct to predict or infer, for example, as has been recently shown, that nearly all countries' (economies') energy consumption per unit time will scale approximately to a power of 0.75 to 1 of their size (as measured by either GDP or population) depending on their level of activity [1]—such, after all, is the case for nearly all living organisms [16–18].

And yet, despite this scientific potency, this "functional form" of the analogy does not readily lend itself to the prediction, inference, or hypothesizing of two of EE's most basic principles: that an economy's scale relative to the scale of its surrounding medium is of consequence to its overall performance and longevity, and, relatedly, that there is a limit to how much an economy can grow. Much like a regression model, that is, this functional form omits the relevant objects (i.e., variables) needed to specify a relationship between the scale of the economy and the scale of the ecosystem.

Realizing, apparently, this omitted object bias (an identical bias exists in the neoclassical macroeconomic paradigm, one that EE has for decades criticized: nothing constrains the size of the economy. That paradigm has other well-known shortcomings, but they are, of course, beyond the scope of the current article), and how it enervates the analogy's scientific usefulness and ability to bring about the desired conceptual change, Daly pushed the analogy further—he incrementally analogized, that is—by importing into it the one critical, previously omitted object that serves in both systems a similar set of functions: the finite ecosystem—the surrounding medium or "object" with which both organisms and economies exchange matter and energy, and in which they both grow, develop, function, and are contained. True [*F*(*organism*, *ecosystem*)] implies True [*F*(*economy*, *ecosystem*)], where *F = medium that surrounds the system with which it exchanges matter and energy, and in which it grows, develops, functions, and is contained*: a domain definition that applies equally and unequivocally to both systems. Thus emerged yet another novel perspective.

This novel perspective, the result of a relatively minor specification improvement to the analogy, gave it great—and at times threatening—power: Great because it gave way to variations of Figure 3, the starting point of many of today's ecological economists (see the citations above). And threatening because it challenged the orthodox establishment's view of economic growth as a panacea, as evidenced, for example, by the World Bank's now well-known reaction to it. Thus follows an example from economics that affirms the findings of cognitive science: analogies, including their diagrammatic representations, can bring about radical, conceptual change (e.g., [9–11]).

Over the decades, "with various modifications" [46] p. 68, variations of Figure 3 gave way to variations of Figure 5: the analogy's perhaps most contemporary and developed diagrammatic functional form, the currently well-known and quite influential "empty world" to "full world" diagram. Now, no longer agnostic on a surrounding medium, any scientist—layperson, even—can contemplate Figure 5 and predict or infer a fundamental characteristic of any economy, one underlying all basic concepts of EE and its BP: an ultimate, biophysical, ecosystem-imposed limit to growth. And, with a little knowledge of biology, one might now even predict or infer from these figures, or at least put forth as a testable hypothesis, that, as for all living organisms, there must be quantifiable limit to how much an economy can grow, as well as a quantifiable optimal size for every economy [1].

I posit, however, that this significant theoretical advancement (i.e., the inclusion of the ecosystem, a previously omitted but obviously highly relevant corresponding object), and the resulting conceptual change, came at a cost. A cost readily visible only through the lens of cognitive science: the abandonment of the base domain altogether, the source of EE's scientific causal knowledge which Georgescu-Roegen and Daly transferred from biology to economics to beget economics as a life science—the living organism, represented by the METABOLISM diagram in Figure 4.

Cognitive science elucidates the implications of this tradeoff. Figures 3 and 5 no longer allude to any "salient similarities" between organisms and economies. Thus, from these figures alone, one can no longer readily infer or predict, for example, that organisms and economies are metabolically analogous systems, or that all countries' energy consumption will scale approximately to a power of 0.75 to 1 of their size [1], or that economies' internal structure may be relationally operationally analogous to that of organisms in some fundamental way, possibly sparking the next new novel perspective and EE's long-awaited and overdue paradigm shift. Instead, in moving from Figure 4 to Figures 3 and 5, DISTRIBUTION has been substituted by a "black-box" ECONOMY that has, for decades, remained vacuous. This is consistent with the results in Section 4.1, and thus likely a manifestation of the BP's omitted object bias.

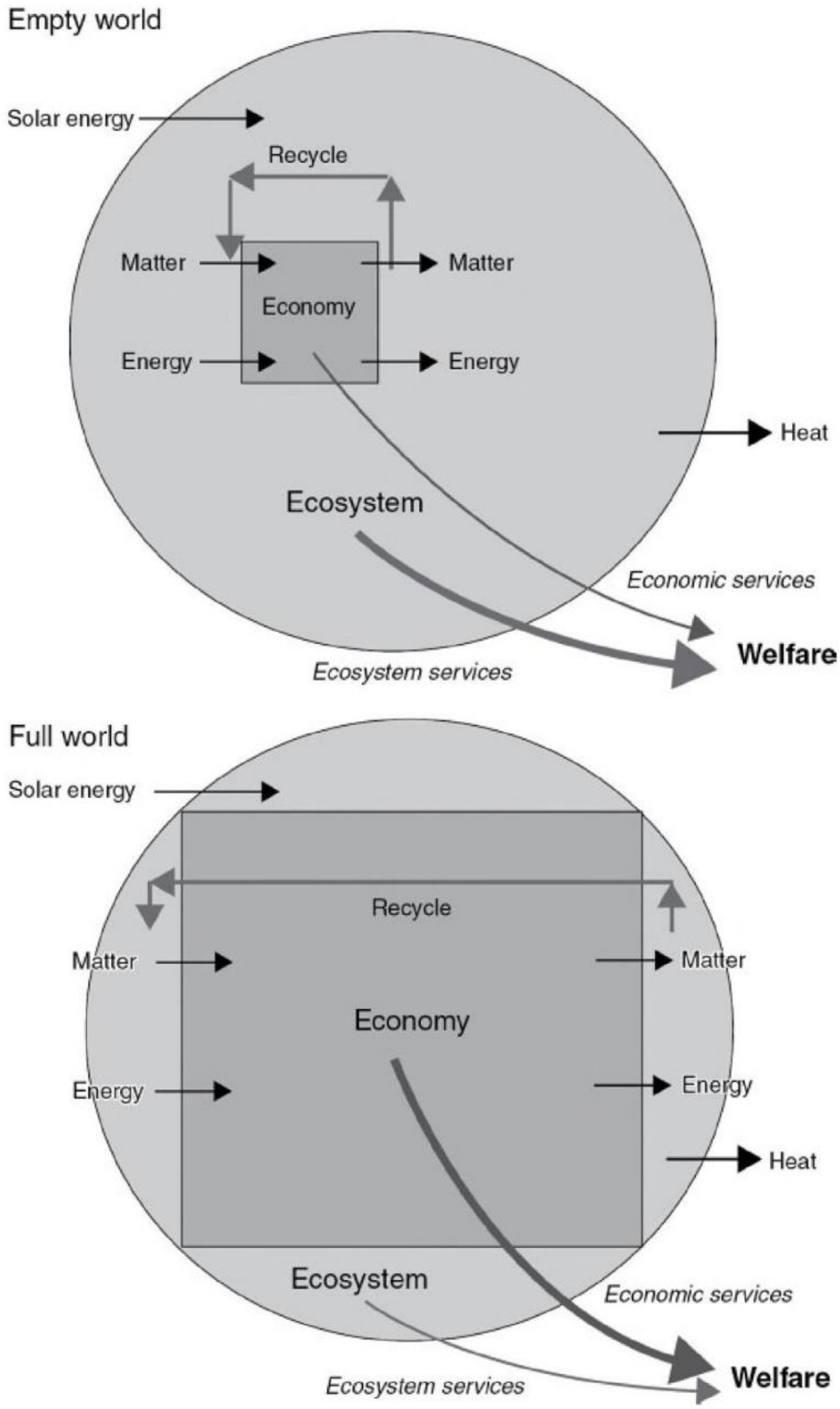

Figure 5. Diagrammatic representation of how organisms and economies, as metabolically analogous systems, grow into a finite ecosystem (sourced from [49] p. 18).

Worse yet, by omitting the METABOLISM diagram (previously in Figure 4), Figures 3 and 5 discard the base domain, as if no longer useful, as if the economy-as-an-organism analogy—the foundation of Georgescu-Roegen's bioeconomic view and Daly's economics as a life science—has run the course of its scientific potential. It is as if biology is no longer of use to economics. Not only is this reminiscent of the neoclassical thought EE has for decades criticized, but it also obscures the field's conceptual origins, thus discouraging the exploration of additional similarities between the two systems. The lesson from history and cognitive science is, however, clear: divorce from the base domain is divorce from incremental analogizing, and thus divorce from theoretical development and scientific advancement. This is particularly true as it relates to the economy's "organs" and thus its inner workings—the different forms of capital, that is, and their interrelation and interconnection, including their associated institutions and people.

4.2.2. The Language of Ecological Economics

Evidence supporting the black box hypothesis does not emerge only from diagrammatic representations of EE's founding concepts. It is ubiquitous in the language of most of the EE-related literature, and particularly apparent in the research that debates the BP's potential to address EE's failings. This subsection examines relatively recent work that represents this literature.

Pirgmaier and Steinberger [7] appear to echo the concerns of several prominent heterodox economists regarding EE's preoccupation with the BP. These authors' "three realisations" summarize the BP's fundamental shortcomings and the "failings" of EE—all of which, it is argued here, appear to support the current article's black box hypothesis. For example, in addressing their "first realization" (the first realization "is that the core ambition of ecological economics, that of addressing the scale of human environmental resource use and associated impacts, often remains an aspirational goal, rather than being applied within research." [7] p. 1), the authors acknowledge the BP's contribution to advancing EE's understanding of "...the *interface* between specific flows or types of resource extraction, land-use change, pollution, and environmental impacts...," [7] p. 3, (emphasis added). "Resource extraction", however, and "land-use change", "pollution", and "environmental impacts" are all processes that involve the exchange of chemicals, material, and energy at the *interface*—i.e., the boundary—of the economy and the natural environment.

In biology, this "interface" of "exchange" between the organism and the natural environment is referred to as the organism's "external exchange surfaces" (e.g., [50,51]). The focus on this type of exchange supports this article's black box hypothesis: disproportionately more attention has been paid to economies' external exchange surfaces relative to their "*internal* exchange surfaces" (e.g., [50,51]), i.e., the diverse forms of capital (organs), and their associated markets, institutions, and people that exchange money, resources, energy, information, and final goods and services. This is, hence, one example of how the BP's omitted object bias impedes progress in scientific economics: it omits what economics and the economy are ultimately about—exchange via markets, people, institutions, and capital. However, as in organisms, it is what, where, how, and how much is exchanged *inside* the system that ultimately determines what, where, how, and how much is exchanged between the system and its external environment (e.g., [15,50,51]): A scientific and sustainability-related fact the black box tends to overlook.

As additional evidence, consider also how EE is, for example, "lacking, sadly, ... on the *socio-economic* side of ecological economics.", including on "economic *structures* and *institutions*" [7] p. 3, (emphasis added). EE, that is, lacks the economy's inner workings: most socioeconomics, structures, and institutions are internal to the economy—but obscured by the black box. Consider also how the, "*vague* ... *general* macro-economy ..." obscures "... the *nitty gritty* of supply chains, international trade relations of extraction–manufacturing–consumption, and *specific sectors* and *firms*." [7] p. 3, (emphasis added). The macro-economy's vagueness and generality mirrors, it appears, its black box representation, one that cannot sufficiently account for the authors' "nitty gritty" inner workings, and certainly not for the tremendous diversity and heterogeneity in the "internal exchange surfaces"—i.e., the different forms and levels of accumulated capital—that exist across nations.

Their "second realization" is that the "focus on biophysical and economic quantification methods" has diverted attention away from "systems thinking" as well as the "social drivers" underlying environmental impacts. This, too, supports this article's black box hypothesis: the BP will concern itself primarily with the input–output analysis of matter-energy at the economy–environment *interface*, and will tend to omit social drivers and system complexity. Further supporting this article's findings is Odum's [52] own admission: ". . . when systems are considered in energy terms, some bewildering complexity of our world disappears; . . ." (as quoted by [8] p. 4). Fifty years ago, we could perhaps have afforded to ignore some of this "bewildering complexity". Today, however, most scientists would probably agree that understanding at least the fundamentals of this complexity is vital to addressing modern-day economies' most pressing problems, including climate change, large-scale environmental degradation, inequality, persistent poverty, and inequitable access to resources.

Further, preoccupation with a black box that grows into a finite ecosystem diverts attention from studying "monetary, social, and biophysical flows in parallel" as well as from social drivers like money, profits, and value [7] p. 2. To put it simply, black-box thinking strips much of the economy out of economics. This, the analysis suggests, explains at least partly why EE is often forced to "either adopt neoclassical reasoning or give up on economics altogether." [7] p. 2.

Further still, while the BP helps generate "evidence" of "ecological overuse", a black box surely "cannot explain" this overuse, or provide "A causal understanding . . . necessary to comprehend the magnitude of social, political, and economic changes required . . ., [or] for devising viable strategies to attain those changes." [7] p. 4. Most scientists would agree that explaining and "causal understanding" require broad and detailed knowledge of a system's inner workings, i.e., the "*nitty gritty*" of supply chains, extraction, manufacturing, consumption, and specific sectors and firms [7] p. 3 (emphasis added)—all of which require the intimate interaction between diverse forms of capital, i.e., the economy's internal organs. And yet the BP tends to conceal this "nitty gritty"—explaining perhaps why EE has stalled at its 1960′s systems theories' roots that see economies as "black boxes" whose "regularities could be observed by scrutinising inputs and/or outputs" [7] p. 4, at economies' external exchange surfaces.

Their third realization is that neoclassical theories operate in EE at a level much deeper than is commonly perceived, where "many ecological economists adopt mainstream theory, tools, and techniques" [7] p. 6. An example of the neoclassical extensions in EE is the conceptualization of the economic process as merely the "transformation of matter-energy into goods and services," [7] p. 6. This is exactly as inferred by Figures 3 and 5, and much like the neoclassical conceptualization of the economy as a machine of production. To be explicit: EE often borrows from the neoclassical school probably because it lacks a well-developed causal theory of its own. And it lacks such a theory—our results suggest—largely because it has invested very little in incrementally analogizing upon its BP to develop its original theory of the economy-as-an-organism. And this, I posit, probably explains much of Pirgmaier's and Steinberger's [7] third realization. In the life sciences, after all, broad and detailed knowledge of an organism's inner workings is the ultimate prerequisite of "causal understanding". The BP's "black box" impedes the accumulation and transfer of this causal knowledge from biology to economics.

Among heterodox economists, there is largely universal agreement about these failings and the three realizations. More detailed knowledge of the economy's inner workings is therefore not only the call of research that is critical of the BP. It is also the duty of research that perceives the BP to be the key to "opening the black box" [22] p. 238. Melgar-Melgar and Hall [8], for example, like Pirgmaier and Steinberger [7], also call for more "systems thinking" as necessary for the future of ecological economics [8], p. 4. As another example, consider how Ji and Luo [22] and Melgar-Melgar and Hall [8], like Pirgmaier and Steinberger [7], also call for money and the monetary economy to be better integrated in EE's sustainability "vision of developing a new economic paradigm embedding the social and economic systems in the biophysical world" [8] p. 1. But, as the present article argues, more systems thinking and the integration of money and the monetary system into EE may not successfully materialize while subscribing rigidly to the BP—it may perhaps materialize through elaborating on the economy-as-an-organism analogy to include the economy analogs of fundamental organs. Once the economy's fundamental inner structure begins to take shape, other omitted objects, like "*Homo economicus* as a person-in-community" [53], for example, and the general social sphere [54,55] can in turn be incrementally analogized into the analogy.

The fact that research within EE can hold polar-opposite views on how to reach a common objective (i.e., more systems thinking) only validates the science in the present article. The disagreement, as cognitive science dictates (see above citations) is likely the result of the different "mental images" different researchers have of the economic system, images from the analogies that form their perspectives (see Figure 2) and thus guide their research. Biophysical economists, for example, who are often trained in ecology and conceptualize the economy as a metabolic system, will tend to think more in terms of matter-energy flows—a clear reflection of Figures 3 and 5. As an example, consider how "In other words, material-energy-money flow is not only the operational base of the economic system, but it is also the key to open the black box of economic dynamics." [21] p. 236. From this perspective, integrating the flow of money into the flow of material-energy is indeed a step towards systems thinking.

On the other hand, social ecological economics sees EE's "foundations [as those] that inform it as a paradigm both biophysically and socially" [55] p. 1 (see also [56]). From this perspective, the closer integration of the social sphere into the black box economy [54,55] is also a step towards systems thinking. The lack of consensus on whether and how the BP's contributes to, or impedes, systems thinking stems from differing views of what the economic system "looks like". Hence the current article's contribution: it provides the necessary transdisciplinary tools biophysical and social ecological economics need to integrate their omitted objects—respectively, money and objects of the social sphere—into a theory that unifies their views, despite their different perspectives, the theory of economics as a life science. The theory, that is, of the economy-as-an-organism whose essence is the discovery of additional "salient similarities" between the two systems and the subsequent transfer of causal knowledge from biology to economics.

It is unequivocal in cognitive science that flawed analogical reasoning can mislead science. In economics, however, it is not always possible to produce direct evidence of flawed analogical reasoning misguiding economics research: in contemporary research—unlike, for example, in the work of Georgescu-Roegen and Daly—we can rarely directly observe the analogies behind economists' perspectives and research paradigms. Exceptions emerge, however, and make for useful case studies.

Ji and Luo [21] are an example of such an exception. Their paper advocates for the BP and appropriately traces EE back to classical economics where biological analogies were common. In the spirit of classical economics, the authors make use of their own biological analogies to draw similarities between the economy and biological organs. And yet, as the tools of cognitive science predict, the BP's black box seems to emerge even from within these analogies: "In analogy, if society is a human body, then the economy is its digestion system, digesting and absorbing material to supply the body with energy." [21] p. 241. The objective here is not to thoroughly dissect the scientific accuracy of the several analogies embedded within this statement. A simple observation sufficiently makes the point: the economy is a digestive system—by definition this excludes from the economy Georgescu-Roegen and Daly's exosomatic hearts, livers, lungs, and other organs, and thus provides more support for the black box hypothesis.

To its credit, their study subsequently acknowledges that "the digestion system itself is also affected by the other systems" [21] p. 241. But in the context of its own analogy, this otherwise scientifically sound statement only adds to the black box body of evidence: if the entire economy is society's digestion system [21], where are these "other systems"? Surely not within the economy. Thus, the conceptualization of the economy as a "digestion system" further supports the black box hypothesis: the conceptual reduction of the entire economy to a digestion system. In a true relational-operational sense, that is scientifically analogous to the conceptual reduction of a complex animal—e.g., a rat, mouse, or monkey—to a digestion system. A simple question elucidates the scientific implications: how much would biology and medicine have advanced if these fields conceptually reduced complex animals to a digestion system?

Countless examples can be drawn from the EE literature that point to the black box as an impediment to the field's progress. Together, however, Pergmaier and Steinberger [7], Melgar-Melgar and Hall [8], and Ji and Luo [21] quite comprehensively capture the essence of this literature: they are relatively recent, of broad scope, and together summarize the diverse perspectives of some of the most prominent ecological economists. (Ecological economists cited systematically within and across this work include, but not are limited to, Baumgärtner S., Costanza R., Daly H., Georgescu-Roegen N., Howarth R.B., Kallis G., Martinez-Alier J., Norgaard R.B., O'Neill J., Røpke I., Spash C., and Victor P.).

The foregoing subsection illustrates the potential extent of the BP's omitted object bias and that the current article effectively addresses the lack of consensus within the relevant literature. But it achieves one other important objective as well: it shows that research with assumptions and perspectives different from those of the present article—and even with polar-opposite views on the BP itself—all come to the same conclusion. This conclusion can be summarized by a handful of words: not enough economy in EE. In other words, EE lacks detailed knowledge of the economy's internal "nitty gritty", a finding that supports the present article's black box hypothesis. This galvanizes the scientific validity of the present article's methods and findings: scientific work that affirms what has already been discovered despite employing different assumptions and perspectives is characteristic of work that can result in the accumulation of knowledge [57,58]. It is thus also "The epitome of 'methodological triangulation' (due to Denzin [59]), a time-proven strategy for validating scientific methods and results..." [1] p. 4.

Finally, it is critical to note that evidence of overlooked similarities (i.e., beyond the realm or metabolism) between organisms and economies is not found only at the confluence of EE and cognitive science. Importantly, it is found also at the confluence of economics and biology. The next subsection elaborates.

4.2.3. Kleiber's Law of Economies

Perhaps nothing alludes to yet undiscovered "salient similarities" more than Kleiber's Law [60] of economies: empirical and scientifically compelling evidence that economies and organisms are not just metaphorically similar, but that the two systems share scientifically fundamental relational-operational similarities that elude the BP and EE [1].

Kleiber's Law of economies states that the energy consumption per unit time of nearly all countries (analogous to the metabolic rate of nearly all organisms) scales approximately to the power of 0.75 to 1 of their size, as measured by GDP and population (mass, in the case of organisms), depending on their level of activity [1]. The fact that Kleiber's Law applies to both organisms and economies suggests that the two systems must share a most fundamental internal system. So fundamental, in fact, that its omission by the BP may significantly limit the scientific scope, applicability, and perceived validity of the economy-as-an-organism analogy. By "validity" I mean adequate proof-of-concept, i.e., whether the degree to which organisms and economies have been scientifically shown to be similar justifies the use of the former as a scientific model for the latter. By "scope", I mean the number of different *cases* to which the model can be validly applied, and by "applicability", I mean the number of different *ways* that the model can be applied. This proposition follows from what is known about Kleiber's Law.

Among organisms, the universality of Kleiber's Law is a manifestation of common physical and geometric constraints [16–18]. This suggests that at a "most basic level", despite their astonishing complexity and diversity, all organisms share the same "design criteria" [28] that "are independent of detailed dynamics or specific characteristics" [16]. Therefore, that Kleiber's Law applies also to economies, suggests not only that economies share common design criteria, but that these design criteria are the same, or at least very similar, to those of organisms. This logically congruent argument justifies the search for omitted objects with strong scientific correspondence to at least some biological organs, á la Daly and Georgescu-Roegen: it suggests that it is not a matter of whether any such organs exist, but that they must be explicitly identified. In other words, what are the most fundamental organs involved in this "most basic level", "design criteria" that all economies and complex organisms share regardless of their "detailed dynamics or specific characteristics" [16]? Here, too, Kleiber's Law continues to guide.

Metabolic rate is the most fundamental biological rate [15]. Metabolism is, after all, the totality, or summary, of the bioenergetics of the interactions of all parts and processes involved in the exchange of material and energy, both within an organism and between the organism and its external environment (e.g., [15,50,51]). Further, the internal exchange of energy and material is the most fundamental way in which any organism's parts interact [15,50,51]: to stay alive, every organism, and every one of its organs and cells, *must* exchange materials and energy with its surrounding environment. Note that the "surrounding environment" of complex organisms' organs and cells is *inside* the organism. Biology refers to the exchange of matter and energy inside an organism as "internal exchange". Most economists or other scientists will probably agree that the same holds true for every economy, industry, firm, form of capital, and individual. And yet the BP concerns itself primarily with economies' "external exchange surfaces" [50,51] and almost completely ignores their internal exchange apparatus.

Kleiber's Law thus appears to validate the results of the current article's analysis: the BP's most fundamental omitted objects are the economy analogs of the core internal biological organs and organ systems involved in the exchange of energy, chemicals, and other matter, i.e., organisms' "internal exchange surfaces" [50,51]. This observation is a useful complement to the present article: by explicitly identifying each of these organs—and subsequently their economy analogs—causal knowledge related to their structure, function, interrelatedness, and interconnectedness may be transferred to economics, thus beginning to address the "lack of a clear articulation of what the heterodox alternative is, spelled out from its basics." [7] p. 7. The scientific implication is obvious: just as biology and medicine advanced by gaining detailed knowledge of complex organisms' internal structure, scientific economics may be able to advance by transferring this knowledge to economies. This is exactly how Georgescu-Roegen and Daly initiated the movement towards their "bioeconomics" and "economics as a life science".

Within the broader realm of sustainability, it is worth noting how this "bioeconomics" relates to the more contemporary concept of the "circular bioeconomy" of sustainability (e.g., [61]). Within Georgescu-Roegen's bioeconomic framework, the economy, akin to a living organism, faces biophysical limits to growth. In contrast, the circular bioeconomy advocates for a proactive utilization of biomass to perpetuate economic growth, eventually achieving sustainability through advancements in biotechnology (e.g., [62]). Despite this fundamental difference, there need not be a fundamental conflict in scientific or policy interests between the two models. A more structurally detailed characterization of the economy-as-an-organism analogy could potentially harness the strengths of both viewpoints, fostering a harmonious convergence rooted in shared objectives. For instance, a biological perspective on economies' internal exchange surfaces might unveil deeper leverage points for both current and future biotechnologies. This, in turn, could catalyze the transition toward the sustainable utilization of natural resources and economic development within the regenerative capacity of ecosystems.

5. Discussion

This article applies established theories from cognitive science and biology to provide EE with a useful, scientifically sound, and novel perspective on its scientific history, current status, and future methodological potential. With respect to its history, this article affirms that EE's scientific origins lie not in the BP but in an analogy that encompasses this paradigm: the analogy of the economy-as-an-organism. This alone is important: much of the modern EE literature appears unable or unwilling to examine this relationship and analyze its implications.

The existing literature also presents divergent views on whether the biophysical paradigm impedes or facilitates the scientific advancement of ecological economics. In the context of the current state of EE, this article offers a scientifically sound explanation for why excessive preoccupation with the BP can indeed impede the scientific progress of EE: it is but a partially specified form of the economy-as-an-organism analogy. As a model of scientific inquiry, it thus suffers from an "omitted object bias" that is relationally operationally very much analogous to the omitted variable bias that arises in econometrics. It leads, that is, to a loss of information that limits and/or distorts the analogy's ability to explain and draw predictions about a broad range of economic phenomena. However, while the omitted variable bias of any single underfitted regression is often limited by that regression's narrow scope in relation to its broader scientific discipline, the bias inherent in a discipline's analogical foundations tends to permeate, as cognitive science research suggests, into that discipline's entire theoretical and/or conceptual structure. In EE, this article argues, there results a discipline-wide cognitive bias which manifests as the "black box" economy.

Applying the structure-mapping theory, this article proceeds to identify the BP's omitted objects: Georgescu-Roegen and Daly's exosomatic and endosomatic organs, i.e., the economy's "insides", the economy analogs of biological organs. In the spirit of methodological triangulation, this article gathers from biology and economics evidence that appears to support the article's "black box" hypothesis, which it identifies as a key cause of EE's scientific failings and shortcomings.

The current article incidentally also addresses a paradoxical omission in the existing EE literature: despite clear evidence that the field is founded on the economy-as-an-organism analogy, it largely overlooks approximately fifty years of research demonstrating that scientific models are essentially analogies. In contrast, the current article delves deep into this research, bringing to EE a central, novel message: science advances through incremental analogizing, and the analogy of the economy-as-an-organism has proved to be a scientifically useful base domain for such analogizing—a base domain, however, largely and unjustifiably ignored by scientific economics, orthodox and heterodox alike. While a detailed analysis of the factors underlying this inadequacy is beyond the scope of this article, they are worth noting, at least briefly. They include the mathematization of economics' mechanistic metaphors by the large numbers of physicists and engineers who entered the field in late 19th and early 20th centuries (e.g., [41]); the stigmatization of biological analogies due to the late 19th to early 20th century eugenics movement initiated by misconstrued interpretations of Darwinian evolution (e.g., [3]); many economists' failure to recognize the role of analogical reasoning in economic modeling (e.g., [40]); and economics' relative isolation from the other sciences, including the cognitive science documented in the current study.

Finally, while the current literature is unclear about the heterodox alternative, the current article clearly articulates an alternative whose methodological framework is grounded in science and supported by the EE literature. To regain the scientific momentum, vigor, and rigor of its heyday, EE needs to see past its BP and ask: beyond, and due to, their metabolic commonalities, how else are economies and organisms similar? This would contribute to EE's scientific advancement in areas where the two systems share scientifically useful commonalities, as identified by the structure-mapping theoretical framework—the science, concepts, theories, laws, and predictions of biology are likely to apply to economies. This framework is, in effect, the "economics as a life science", the science validated by the applicability of the laws of thermodynamics to economies, Daly's "salient similarities", the concept of endosomatic and exosomatic organs, and Kleiber's Law of economies.

Importantly, and in contrast to the complexity-obscuring BP, the complexity-embracing economy-as-an-organism analogy may be elaborated upon to capitalize on the decades-long tradition of empirical bioeconomic modeling exemplified, for example, by the Beijer Institute of Ecological Economics (e.g., [63]). For instance, modeling the economy as a living organism whose complexity interacts with the complexity of the surrounding ecosystem could conceivably enhance our understanding of how the ecosystem and the economy are interconnected, as well as these interconnections' role in sustainable nation building.

This discussion presents an opportunity to elaborate upon a most fundamental difference between the BP and the analogy of the economy-as-an-organism. "Biophysical" implies the physics of life, and thus presumably the application of the tools of physics to study biological structures and processes. But biology—the life science itself—at least as spelled out from its basics, is much more than the application of the tools of physics: organisms differ from machines. This does not invalidate the BP. It simply underscores its inadequacy for an "economics as a life science".

Further, biological "structures" and "processes" exist at all levels of biological hierarchical organization (e.g., from cells to organs to organ systems and their energetics), and thus a BP alone need not prioritize—or even require—the study of a biological system as a whole, multicomponent organism. A BP can thus take any form and be applied to any level of organization—i.e., focus on any part or process of the organism—depending on researchers' scientific background, interests and/or biases. A discipline, therefore, that relies mostly on a BP that has made little effort to articulate its subject at the macro level, is likely to highly "specialize" in some aspect of the organism, overlooking perhaps its overall complexity or even its most fundamental components. This is mirrored in EE whose BP tends to "specialize" in the exchange of matter-energy at the economy–environment *interface*, while overlooking the exchange of money, goods, services, and energy and other resources at the capital–institutions–people interface. A biophysical paradigm alone, that is, leaves room for a life science that is agnostic about the phenomenology of its subject, i.e., one that lacks detailed knowledge of its subjects' structure and function.

As the present article argues, biological phenomenology must precede, or at least accompany, any BP; if we are to have a maximally useful BP—and ultimately an economics as a life science—biology must come first. In reviewing Cotterill's (2003) *Biophysics: An Introduction* [64], perhaps Stuart Lindsay put it best: "The requirements are clear: Biologists must describe the system at the appropriate molecular or physiological level. Then biophysicists can make appropriate measurements and models. But the biology must come first." The BP—a paradigm that sees only a part of the economy as an organism—surely does not put the biology first. This is in stark contrast to the economy-as-an-organism analogy.

By virtue of its focus on the "organism", this analogy has an earnest and strong desire to "see" and describe the whole multicomponent economic system, thus embracing its inner workings, including the complexity, interrelatedness, and interconnectedness of all its parts. This is exactly as in biology, the life science itself: biology neither sees organisms as merely biophysical or energy systems, nor does it study them using merely a "biophysical paradigm". Detailed knowledge of the system's internal structure is the ultimate prerequisite. In the context of EE, for example, while its widely familiar BP dismisses the notion of exosomatic hearts, livers, or lungs, its forsaken analogy will insist on probing its base and target domains—using the structure-mapping theoretical tool—to discover their economy analogs, and thus putting biology first and laying the foundations for "economics as a life science", the science of sustainability.

Despite its contributions, the current article has its limitations. Chief among these limitations is the assumption that economies and organisms are indeed relationally operationally analogous beyond their metabolic functioning. In reality, however, the extent to which these two systems are isomorphic remains mostly uncharted scientific terrain. Both systems are extraordinarily complex, and their "salient similarities" may not extend to all domains of their functioning. For example, while the laws of thermodynamics and Kleiber's Law appear to apply to both systems, other biological laws, principles, or phenomena may not apply to economies. In that case, the value of the economy-as-an-organism as a scientific explanatory predictive model would be limited. For instance, most socio-economic outcomes would not be predictable using this analogy, nor would the analogy generate meaningful, empirically testable, hypotheses. Further, but relatedly, the article assumes a transdisciplinary infrastructure to explore this uncharted territory. But, in reality, disciplinary barriers (e.g., differences in language, methodologies, assumptions, and ideologies), path dependence, and the stigma against biological analogies in economics, significantly hinder the accumulation of essential transdisciplinary knowledge. Additional research is necessary to assess whether and how these limitations can be overcome.

6. Conclusions

Much has been written about the role of the BP and the failings of EE. Absent from this research is consensus on whether and how this paradigm contributes to these failings or helps to overcome them. The present article thus provides EE with a potentially problem-solving orientation in the following manner: the black-box economy is a pathogeny of the BP's omitted object bias, a pathogeny underlying many of the scientific failings of EE. The remedy lies in exploring additional salient similarities between organisms and economies, what cognitive science identifies as incremental analogizing, as per the structure-mapping theoretical framework. The most potent prescription comes from biology and Kleiber's Law of economies: together they suggest a yet undiscovered but very fundamental similarity in the internal exchange structure of multicellular living organisms and economies. Discovering these similarities should thus hold some place in EE's future research agenda.

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