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From Panarchy to World-Ecology: Combining the Adaptive Cycle Heuristic with Historical-Geographical Approaches to Explore Socio-Ecological Systems' Sustainability

Stefano Menegat

Department of Economics and Statistics, University of Turin, 10124 Torino, TO, Italy; stefano.menegat@unito.it

Abstract: This article investigates the dynamics of socio-ecological systems' (SESs) unsustainability. By adopting a theoretical standpoint grounded in systems' theory, the analysis shows how SESs' teleology (or final cause) is of the utmost relevance for understanding the relationship between humans and ecosystems and how it is pivotal for envisioning possible evolutionary trajectories towards sustainability. Building on the contributions of both system and social scientists, the study argues that SESs' teleology is determined by dominant social ontologies that require a dialectical lens to be properly dealt with. The article therefore proposes the adoption of the adaptive cycle heuristic complemented by an historical-geographical approach based on world-ecology theory as a means to interpret SESs' behavior. Such a perspective allows for the direct comparison between the four stages of the panarchy cycle (reorganization, exploitation, conservation, and release) and the four stages theorized by the world-ecology dialectics (expansion, appropriation, capitalization, crisis). In conclusion, the article claims that both system and social scientists would benefit from including concepts and definitions from the other field in their analysis, since both provide valuable insights about SESs' processes of change and both are necessary to envision transition pathways towards sustainability.

Keywords: socio-ecological systems; sustainability; adaptive cycle; panarchy; commodity frontiers; world-ecology

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1. Introduction

Industrial civilization continues to unrelentingly and irreversibly push its way across planetary thresholds, threatening Earth's life-supporting systems by amplifying the breach in the Earth's carrying capacity and planetary boundaries [1]. In spite of increasing scientific evidence of human-induced ecological impacts and disruptions, approaches to define a "Safe Operating Space" for humanity as a whole have substantially failed so far [2]. The reason for such a failure lies beneath the fact that the very term "humanity" hides the heterogeneous nature of human societies and their cultural, economic, and political dimensions. Indeed, to undertake "a safe and just corridor for people and the planet" [3] it is pivotal to interrogate the social dimensions of (un)sustainability, especially because "the politics of who gets what, when, where, and how is often determined by those who are more powerful in the system. Rules of access and distribution then become locked-in and difficult to transform" [3] (p. 5). The exponential, unsustainable, and uneven growth in population, wealth, resource consumption, and waste production is the result of a relatively short period of extremely rapid change initiated by the generalized use of fossil fuels as energy carriers to power industrial societies' activities. Such a period is called "the great acceleration of the Anthropocene" [4].

By definition, every period of rapid change can be described as a "crisis", but the term "crisis" takes on special meaning in the current situation insofar as it refers to the difficulty hegemonic institutions and practices are experiencing in their efforts to operate within increasing contradictions. Consider, for instance, one of the basic human activities, food production. To feed the global population food systems relying on industrial agriculture, about one third of total anthropogenic greenhouse gas (GHG) emissions are emitted [5] and cause the largest part of human-induced eutrophication [6]. In the meantime, "land grabbing" and commodity speculation raise issues of social sustainability in many countries, especially in peasant economies [7]. In addition, agro-industry's heavy reliance on fossil fuel-based inputs, such as synthetic nitrogen fertilizers, and international trade entails major risks for global food security in case of fossil fuels price shocks and/or geopolitical instability [8].

"Crisis", in this sense, becomes a synonym for *impasse* or deadlock, because some boundaries have been crossed, and the entire system struggles to keep doing what it has done in the past [9] (p. 396). However, crises are also expected to induce change at some point in time, and change can either make a socio-ecological system (SES) compatible with its boundary conditions, or simply expand those boundaries in order to allow the system to operate "business as usual". Of course, the second solution implies that the crisis is not really solved, but simply postponed. On the other hand, the first strategy (to make the system adapt to its boundaries) requires the deep restructuring of the system itself, its rules, its institutions, and its culture. Since the advent of the industrial revolution, crises have been interpreted in terms of cyclical contextual change, and therefore they have been temporarily solved by overcoming socio-technical and biophysical constraints via technology [4]. However, crises might also be manifestations of successive stages of a long-lasting process of transformation that will eventually lead the entire system to change [9].

I embrace Walker et al.'s [10] argument that to fully grasp the multiple implications of (un)sustainability, it is relevant to frame the issue in terms of complex, multi-scalar, adaptive cycles. However, this article also interrogates the teleology, or the final cause, of SESs, an element that is often overlooked by system science practitioners [2,11]. To such an extent, I analyze the concepts of panarchy and world-ecology through a qualitative, comparative method. This analysis reveals how SESs dynamics can be inscribed within the historical-geographical patterns of socio-ecological reproduction expressed over time by dominant social ontologies [12]. This article aims to elaborate meaningful interpretations of socio-ecological interactions through historical time, including the emergence of phenomena like crises, change, and evolution.

The article is organized as follows: section two introduces the ontological premises and the epistemological framework adopted in the rest of the article; section three discusses the commonalities between concepts drawn from systems theory and the world-ecology perspective; section four provides a comparative analysis of four cyclic behaviors postulated by both the adaptive cycle and the world-ecology theory; in conclusion, section five provides a few recommendations for future research.

2. Multi-Scale Interactions, Evolution, and the Adaptive Cycle

Change and evolution are elusive concepts, especially if one considers living systems' variety and complexity. Indeed, complex behaviors do not have unidirectional causes and foreseeable consequences. As Coffman and Mikulecky stress [13], complexity is both a scientific and a philosophical challenge because complex systems dynamics forces us to acknowledge that the causal mechanisms of an epistemic domain cannot explain the variety of systems emerging from it (e.g., the variety of biological life emerging from molecular biology is not explained by the laws of the latter). Variety is the consequence of changes in the constitutive parameters (identity) of a given complex system (e.g., genome in a living organism), and the origin of such a change is a direct consequence of a process called evolution [14] (p. 344). In contrast, changes in the environment or the behavior (paths) of an organism define its trajectories of developmental change (ibid.), which can eventually create "higher level organizational constraints that persist to some extent even after the lower level material constituents of the developing system disappear" [13] (p. 64).

Such a distinction between developmental change (system's behaviors) and evolutionary change (system's identity) is fundamental inasmuch as it makes it possible to properly describe the interactions between complex systems. Development and evolution tend towards a direction through time, but only the first has a concrete teleological cause, while the second appears as a creative flow without a precise finality [14]. In contrast, the goal of developmental change is to provide a living system with adaptive capacity to ensure its survival [15]. Robert Rosen explains that adaptive capacities have to be considered as the result of anticipatory behaviors, instead of merely reactive mechanisms. While a reaction is the result of a particular cause, anticipation refers to the phenomenon of self-entailments, whereby effects are at the same time their own causes, as for example when "a change of state in the present occurs as a function of some predicted future state" [14] (p. 8). Therefore, the concept of anticipation is fundamental to conceptualize phenomena like adaptation, learning, and evolution as complex behaviors [14] (p. 319). Insofar as biological life requires adaptation, living systems operate through a process of semantic encoding (i.e., interpreting the physical or ideal world through signals), entailment (i.e., an established system giving some meaning to the signals collected), and active decoding (i.e., an action undertaken in response to the interpretation of the signals). This is most evident in the case of social "lifeworlds" [16], where people's social interactions form individual representations of the world, but it applies more broadly to the whole domain of life, from bacteria to all other living organisms [13] (p. 49). Therefore, not only is a dynamic process inherently evolutionary in the case of anticipatory systems (e.g., human societies), but it also follows a particular developmental pattern that is traced by the system's representation of itself and of the surrounding world or, in other words, by its worldview.

Evolution is a concept much more difficult to define, as it involves unpredictable qualitative change. Georgescu-Roegen's epistemological argument saw evolution as a dialectical process in which concepts are "[. . .] distinct, but not discretely distinct" [17] (p. 322). Of course, the word "dialectical" does not mean that evolution is an abstract, unmaterialized process. Indeed, evolutionary patterns are bounded by nature's laws, in particular the second law of thermodynamics [18]. Human bodies, for instance, need to intake food (endosomatic energy) at a certain rate per day. The food is then metabolized into energy carriers (i.e., ATP) to power their internal functions (e.g., motion, neural activity, and so on), their components (e.g., muscles, brain, etc.), and their constituents (e.g., tissues and cells). The relation between functions, components, and constituents is constrained by the goal of the system (i.e., surviving). An economy, on the other hand, is expected to supply its human members at least with some quantities of food per day in order to pursue its goal (e.g., profit), just as machines within an economy are expected to transform some amounts of energy carriers into useful work. The production of food and energy carriers therefore must meet the minimum requirements expressed by a society, otherwise the very identity of that system becomes unviable. If, for any reason, those minimum conditions are not met, the analytical categories simply cease to exist (e.g., a tractor without fuel is no longer a tractor, though it might become something else, like a sculpture). In this sense, SESs' evolutionary patterns have a "physiological" dimension (flows of matter and energy crossing them at different scales) that bound the variety of complex behaviors that the system can express. Within those boundaries lies a system's evolutionary potential, which will eventually reshape its knowledge, its goals, and its own worldview.

The Adaptive Cycle of Socio-Ecological Systems

First developed by the ecologist and systems theorist C. S. Holling, the concept of the adaptive cycle describes how the evolution of complex, adaptive systems tends to follow a particular pattern, or cycle [19]. This cyclic behavior is driven by three general properties of adaptive systems [20] (p. 394): (i) their inherent potential to undertake patterns of change (i.e., the option space opened by accumulated "wealth", such as materials, energy, information); (ii) their internal controllability (i.e., the flexibility and sensitivity of internal signals and feedbacks); and (iii) their adaptive capacity (i.e., their ability to anticipate change and their resilience to unexpected shocks). Together, these properties bind the development of a system to an expected pattern. So far, the adaptive cycle heuristic has found applications in the analysis of SESs in relation to the dynamics of European economies [21], the resilience and the transformability in local and regional contexts [22–24], and in exploring patterns of rural development [25–28]. More broadly, Mario Giampietro and Kozo Mayumi [29] (p. 6) showed how the iterative character of a socio-economic process can be understood in evolutionary terms using the concept of the adaptive cycle. The cycle, which Holling describes as a sequence of functionally distinct moments characteristic of ecosystem successions, can be described in four stages [29]: first, during a stage of (re)organization denoted by the letter (α), social functions and structures emerge in response to the perception that the system has of itself and of its context. Second, the behaviors of the best-performing functions are reinforced to proceed towards the full exploitation of the opportunities individuated; this moment is denoted by the letter (r). Third, a stage of *conservation* brings the system into a lock-in situation, where the accumulated "wealth" (potential) is very high, but it must be entirely invested to maintain the relations already in place; this moment is denoted with the letter (K), and in Holling's words it represents "[. . .] an accident waiting to happen" [20] (p. 394). Indeed, the increased connectedness of the system entails rigidity and therefore vulnerability to possible disturbances. Following a shock, the system enters a fourth stage of the cycle, which is denoted by the letter (Ω). This moment is called release, for the resources accumulated by the system are quickly liberated and connectedness declines steadily. Therefore, the system becomes relatively free to re-organize itself according to the new conditions, and eventually it might reiterate the cycle starting from (α).

However, to fully grasp the implications of adopting the adaptive cycle heuristic to describe SESs (un)sustainability dynamics, a further concept is necessary: the definition of panarchy. Complex adaptive systems, such as human societies, are organized into nested hierarchies, or systems of systems. Therefore, their evolutionary dynamics unfold through sets of adaptive cycles interacting across multiple scales. Holling defines this type of organizational structure as "panarchy" [20], where each cycle has a different speed and size. Although each cycle contributes to the pace and size of the others, each is also somewhat constrained by the largest and slowest cycles (hierarchically superior), as well as the smallest and fastest ones (hierarchically inferior). Normally, the higher cycles tend to harness the relatively large potential accumulated to facilitate the renewal of the lower cycles sustaining them; this connection is also called "remember". By contrast, the cycles lying at the bottom of the hierarchy might undermine the stability of the higher ones through a connection called "revolt", which can transmit the instability of an adaptive system to the larger ones [30]. SESs dynamics can therefore be represented as a panarchy composed of interacting adaptive cycles, each one representing a particular scale. Figure 1 provides a representation of three simplified cycles contributing to the evolution of a socio-ecological metabolism.

I labelled the adaptive cycle at the highest level of the panarchy "socio-ecological regime" to indicate a time-dependent and spatially-situated system. A "socio-ecological regime" is a SES itself, but it is also composed of lower-level SESs expressing behaviors that are fundamental to reproduce the whole organization. Since SESs have an inherent metabolic nature, the internal parts composing the whole should be distinguished between the internal components that are responsible for gathering and making external resources available to the rest of the organism (i.e., matter and energy), and the internal components that are responsible for coordinating the activity of the whole organism (i.e., information and replication). According to Mayumi, the dynamics of social systems can be thought of in terms of resonating self-entailment involving a "[...] resonance between controls generating useful energy and vice versa" [31] (p. 119). Building on the work of the theoretical ecologist and philosopher Robert Ulanowicz, [32] Mayumi defines societies as hierarchically structured networks differentiated in terms of social roles and functions among two broad sectors: (i) a hypercyclic (productive, i.e., Røpke's "provisioning systems" [33]) part, and

(ii) a purely dissipative part. Of course, a "socio-ecological regime" might also be nested within regional or global cycles that have not been included in the figure. For the purpose of the arguments developed in this article, the relevant connections are those relating the socio-ecological regime to its components. Indeed, Figure 1 shows that the largest and slowest cycle is tied to the smaller and faster ones by the "remember" and "revolt" functions. The former follows a top-down direction, inducing the whole system to reiterate its identity, from the whole (socio-ecological regime), to its organs (SESs, as for instance economic sectors), to their components (structural units like companies, farms, households, and so on). On the other hand, revolts unfolding from the bottom of the panarchy can possibly determine systemic crises within the upper cycles. Crises are of the developmental type when one or more adaptive cycles enter an unstable phase, but the upper-level systems can maintain the whole panarchy on its historical trajectory through the remember function. When major constraints manifest at some level of the panarchy and the remember function fails to keep the whole system viable, revolts can compromise the entire organization, thus provoking a generalized shift of the system towards a different configuration; this type of situation underpins the emergence of crises that need to be solved by changing the system's identity, that, in the case of SESs, implies a change of information flows and the system of values regulating them. These kinds of major shifts are dialectical (nomological) moments that characterize the unpredictable process of socio-ecological evolution.

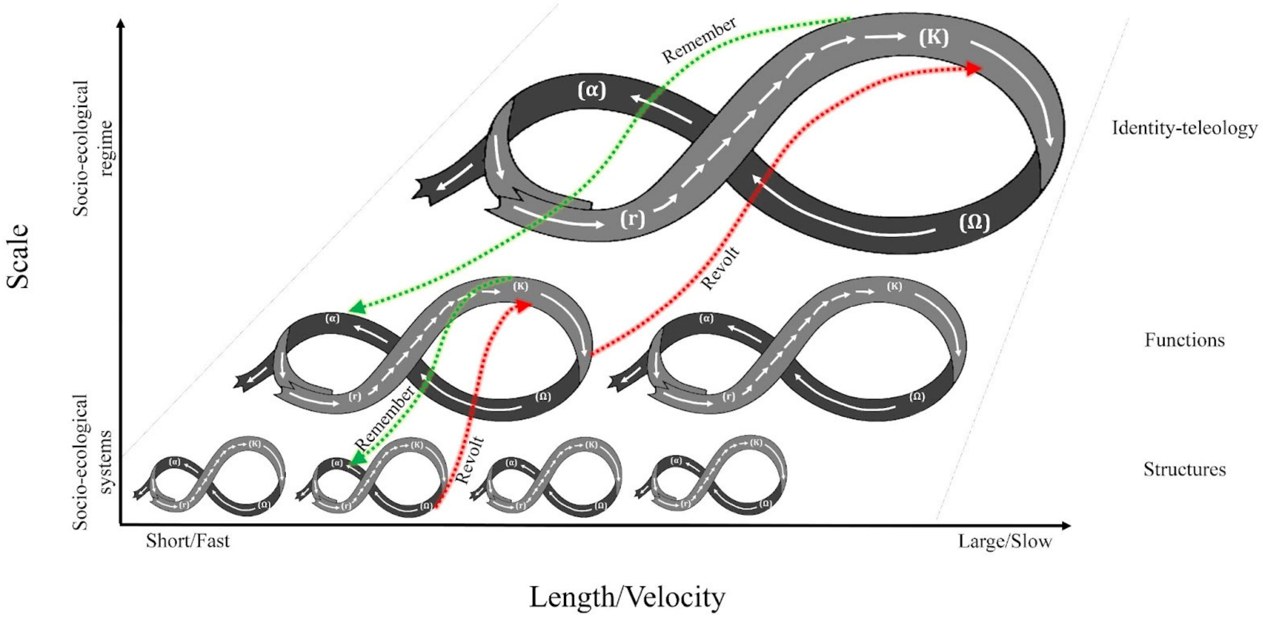

Figure 1. Evolutionary change as a panarchy of nested adaptive cycles. Cross-scale interactions are represented by two functions: "remember" (**green lines**) and "revolt" (**red lines**). Source: own elaboration based on Gunderson and Holling [30] (pp. 74–75).

3. Historical-Geographical Patterns of Socio-Ecological Reproduction

To summarize, the panarchy concept helps to understand how SESs interact among themselves across scales by exchanging flows of information, matter, and energy in a way that is functional to reproduce the identity of a socio-ecological regime. According to environmental historian and historical geographer Jason Moore, the system as a whole ("socio-ecological regime" in Figure 1) is not only a metabolic process, but also a metabolic project [34] because it is the fulcrum of an entire semiotic complex regulating socio-ecological value relations and their relative information flows. Consistently with a complexity-driven approach, a metabolic project emerges by following several steps: (i) the historical construction of a socio-ecological regime defines the fundamental "rules" (e.g., "laws" and "tendencies") shaping a specific social ontology. (ii) Unfolding from the latter, social identities (e.g., narratives and institutions) produce models of reality designed to anticipate future states in view of pushing the whole system to undertake anticipatory (adaptive) behaviors; those, in turn, ensure the proper functioning of a mechanism of “metabolism and repair” [14], or “reproduction and regulation” [35]. (iii) The models thereby generated are essential to the stability of the metabolic pattern undertaken, determining both its viability and desirability in relation to its internal agents. Models and narratives are nevertheless transient entities [36], meaning that they tend to emerge, or else disappear or mutate, depending on their potential to fulfill the meaning expressed by the underlying social ontology. (iv) Finally, such models and institutions determine how the biophysical flows characterizing the socio-ecological regime evolve over time, while these flows in turn support the physical existence of the underlying metabolic project. As Jason Moore notes:

> Our reality is one in which humans live in a peculiar kind of civilization, capitalism. Capitalism is absurd in all sorts of ways. In the terms of this discussion, one absurdity is especially powerful: capitalism is premised on the separation of Humanity and Nature. The whole thrust of capitalist civilization develops the premise that we inhabit something called Society, and act upon something called Nature [34] (p. 600).
>
> In Moore’s view, “Humanity” and “Nature” are categories produced by a specifically capitalist social ontology. The capital “H” and the capital “N” are intended to reveal a Cartesian dualist perspective imposed by capitalist narratives and institutions. In this sense, a particular pattern of social reproduction (e.g., capitalism) is an ontological formation having the power to define and therefore organize both human activity and nature. The system’s scale of geographical penetration determines its dominance with respect to other social ontologies, while the power to separate humans from nature defines its degree of control over the broader web of life. Indeed, capitalist modes of societal reproduction have been tremendously successful in pursuing both objectives [36] (p. 235), and for this reason, Moore terms the societal identity that is currently dominant as “capitalist world-ecology” [34] (p. 601).

3.1. The Capitalist World-Ecology and Its Mode of Reproduction: Cheapening and EFT2-Mania

History is the product of the evolving configurations of human and extra-human natures [37] where not only knowledge and information, but also energy, shapes social relations [38]. According to Moore, the goal of capitalist societies is to accumulate plus-value by extending their control to ever-increasing portions of the web of life [39], but of course, to be profitable, the relative “cost” at which nature is appropriated must be as low as possible. The strategy pivoting on the increasing appropriation of natures at decreasing costs is therefore defined as “cheapening” [37] (p. 3). Accordingly, capitalist ecologies tend to organize human and extra-human natures (material processes) by establishing sets of rules, modes, and institutions (semiotic processes) geared to perpetuating and reinforcing the pattern of reproduction undertaken. In these terms, the capitalist world-ecology represents the social identity of the system, whereas cheapening represents its mode of reproduction. As Moore further explains, in deploying their common strategy throughout history, capitalist world-ecologies established:

> [. . .] Durable patterns of governance (both formal and informal), technological innovations, class structures, and organizational forms that have sustained and propelled successive phases of world accumulation since the long sixteenth century [39] (p. 158).

Cheapening is the ontological praxis of capitalist accumulation geared towards generating value through the historical creation of “natures” that are rendered increasingly “affordable” thanks to the periodic reduction of the socially necessary labor-time required to produce or extract them [39]. Cheapening unfolds through the gathering of increasing quantities of "*potential* work/energy" and its transformation into concentrated forms of wealth [39] (p. 24), including both the "produced means of production" [40] and social power [38,41].

From a systems science perspective, "cheapening" directly recalls the "principle of maximum energy flux" or "efficiency of type 2" (EFT2), which indicates the pace at which the system can harness energy from its outer environment, as opposed to "Efficiency of Type 1" (EFT1), which measures the ratio between input and output. As Mayumi explains:

> A higher speed of throughput, implied by an increase in EFT2, has beneficial effects on the ability to maintain more complexity and hierarchy in society. This higher speed is benign to the economic process, since it can be related to a higher level of production and consumption of goods and services. [...] The definition of value is generated by the system itself, such as when humans are concerned with their standard of living [31] (pp. 99–100).

Therefore, social complexity requires high rates of production in the productive (hypercyclic) sectors of the economy, and, consequently, the proportion of human activity invested per unit of output must decrease over time. Indeed the "cheapness", or the relative cost of carrying on the functions necessary to sustain a particular socio-ecological metabolic pattern, is determined by the proportion of human activity (e.g., labor time) that *must* be invested in production. On the other hand, increasing the rates of production in the productive sectors of the economy makes it possible for a society to invest additional human activity and resources in other social (dissipative) activities. This kind of efficiency is therefore the key element paving the way towards increasing functional differentiation and increasing adaptive capabilities at the level of the whole society. Indeed, SESs' EFT2 and the identity of the socio-ecological regime are intertwined by a reinforcing feedback loop, where increasing rates of production result in increasing complexity, which in turn induces a growth in EFT2. Whenever the system is unable to perpetuate this pattern, it becomes unstable and, therefore, it periodically needs to expand its frontiers towards horizons where EFT2 gains are easily accessible (entailing new innovations and/or geographical expansion). At several moments in history, capitalist societies faced this issue, and whenever they failed in expanding their "commodity frontiers", their potential to achieve global hegemony ceased completely [38]. However, it is only with the rise of the fossil fuel-subsidized economy that EFT2 growth became a seemingly unconstrained "mania" [38] (p. 96). Thanks to "fossil" energy surpluses, modern economies were able to expand their frontiers to extend globally, thus attaining unprecedented size, complexity, and velocity. What is often called the "great acceleration of the Anthropocene" [4] is the fruit of a very particular social identity, or a very specific metabolic pattern, perpetuated through "cheapening", or "EFT2 mania".

Both the social and the biophysical organization of a society (as well as their boundaries) are therefore tied to the meaning—the system of values and the goals that a dominant social identity promotes among its members. In this sense, the socio-ecological regime is both a material and a semiotic generative structure, which defines a space for causal mechanisms to emerge. The dominant regime within which socio-ecological change takes place manifests itself in the form of a specific social ontology (capitalist world-ecology), purpose (the realization of plus-value through the appropriation of portions of the web-of-life), and mode of operation (the strategy called "cheapening", or "EFT2-mania").

3.2. The Appropriation/Capitalization Dialectics

Jason Moore's theory entails that "cheap natures" should guarantee not only the material reproduction of the capitalist world-ecology, but also the realization of a certain "surplus". Higher production rates in a SES (e.g., the agri-food system) achieved without increasing capitalization (i.e., increasing use of technical and financial capital) correspond to an "ecological surplus" in Moore's terminology [38] (p. 96). Such surpluses are indispensable for the initiation and reiteration of successive cycles of accumulation, which in turn are necessary conditions for the further appropriation of ecological surpluses. The more a society tends to accumulate and consume resources in its dissipative functions, the faster the productive ones *must* extract and produce such resources. The only alternatives would be to compensate for the gap between the rate of production and consumption through international trade and/or forced relative under-consumption. In summary, an ecological surplus is a necessary condition for the deployment of a strategy of "cheapening", although it might emerge either directly from the geographical extension of the system (e.g., colonization of fertile soils) or indirectly from the production of the inputs required to maintain high production rates (e.g., easily accessible fossil fuels to power machinery). This entails that "cheapening" not only requires rates of production that must be higher than the societal rates of consumption, but also that the cost of the inputs must be as low as possible. In this sense, Moore argues that a capitalist world-ecology needs an integrated regime of "cheapness", which is not limited to only one commodity (as one might think of energy, for instance). Indeed, at least four categories of "commodities" must satisfy the condition of "cheapness" to guarantee the reproducibility of the system: food, energy, raw materials, and labor [38]. The definition of the fourth category (labor) requires a specific focus on the inner functioning of the capitalist world-ecology. According to Moore, "cheapening" must increase the rates of production of the commodities extracted from the environment while simultaneously inducing a constant pressure to lower the cost of labor. This is done through a specific feature of the capitalist world-ecology: the capacity to organize semiotic and biophysical flows within a specific "circuit of capital" [38] (p. 84). In systemic terms, the latter can be thought of as the semiotic flow informing SESs about the opportunities, the constraints, and the societal effort required to increase the rate of production in the primary sectors. In Mayumi's terms, the semiotic flow is composed by a system of values assigning great importance to EFT2 growth [31]. In a similar way, Moore argues that the strategy of "cheapening" rests on the definition of what he calls a standard of "value-in-nature" [38] (p. 74). Accordingly, the system of value of a capitalist world-ecology is informed by two fundamental tendencies: (i) the rate of production of basic commodities entering the sphere of market transactions, and (ii) the potential work/energy that can be appropriated for free outside the market space [34]. The cheapness of the circuit of capital is therefore constrained by the possibility of achieving increases in the production rates of the four "cheaps" (food, energy, raw materials, and labor) *and* the possibility of appropriating "free" work/energy outside the market sphere in order to reduce the overall cost of both processes of production and reproduction [34]. Accordingly, the elements mentioned above enter directly and indirectly into the circuit of capital and are related to the ecological surplus through a dialectical tension between two forms of capital accumulation: accumulation by appropriation and accumulation by capitalization.

Accumulation refers to a search for social power, which depends on the recognition by a collective organization that some of its members have a certain "potential for action", or some degree of control over other people's actions. This type of social control is enforced through culture, social norms, and institutions composed of a particular system of values. Within a system of value, it is possible to have some sort of object, or token, commonly recognized as a symbol of "degree of action and/or power to control". This symbol allows one to recognize other people, their roles, and what is expected from them [42]. In capitalist societies, such processes of accumulation of symbolic power take the form of accumulation of plus-value. According to Moore, capitalist world-ecologies are systems characterized by a particular way of defining value and therefore plus-value:

> "On the one hand, the system turns on a weird coding of what is valuable, installing human work within the commodity system as the decisive metric of wealth. This work is usually conceptualized as wage-labor [...]. In this domain, the exploitation of labor-power is the pivot upon which all else turns. On the other hand, the exploitation of wage-labor works only to the degree that its reproduction costs can be checked. The mistake is to see capitalism as defined by wage-labor, any more than it is defined by the world market. Rather, the crucial question turns on the historical-geographical connections between wage-work

> and its necessary conditions of expanded reproduction. These conditions depend on massive contributions of unpaid work, outside the commodity system but necessary to its generalization. Sometimes this is called the domain of social reproduction [38]" (p. 25).

Seen in this light, capital accumulation means accumulation of (plus-) value produced through the exploitation of wage-labor and appropriation of work readily available outside the circuit of capital. This idea is reminiscent of Huber's definition of "wage-relation [43]". Like Moore, Huber defines wage-labor as a fundamental engine of capitalist accumulation, together with the availability of cheap energy carriers (i.e., oil) necessary to further appropriate unpaid work. Accordingly, cheap energy is necessary to shape geographies of societal reproduction that not only must keep laborers alive, but also maintain the cost of labor as low as possible, thus boosting the rate of creation of new plus-value (and moreover, economic growth). This process requires every component of society, from the worker, to the entrepreneur, to the State. Indeed, although plus-value is (mainly) produced within the private sector, which controls the means of production, the appropriation of sources of uncommodified work stems from the coalition between private interests and the State, where the latter develops strategies and institutions to pursue the creation of new cheap natures.

The process of increasing the rate of production by substituting labor with technical capital is what Moore calls "accumulation by capitalization". The process of increasing the rate of production by enclosing new "commodity frontiers" is an "accumulation by appropriation" in Moore's terms. The two concepts interact dialectically: there is no discrete separation between them. They materialize simultaneously as tendencies underlying the reproduction of capitalist societies. The dialectical tension manifests itself because appropriation and capitalization, though complementary, are also symmetrical: appropriation sets the biophysical basis for the development of capitalization, and the latter provides the semiotic signals necessary to re-initiate the former. The alternate manifestation of the two tendencies therefore designs patterns (or cycles) through historical time.

4. Panarchy and the World-Ecology

Moore's dialectical model has a fundamental implication: economic facts are always endogenous to a particular world-ecology. Economic events obviously include innovations (i.e., "technics" in Moore's terms) deployed to achieve economies of scale while reducing diseconomies of space [38], as well as economic growth and financial instability (e.g., great accelerations and crises). The rhythm at which economic events appear is regulated by a forced relation linking appropriation to capitalization: the tendency of the ecological surplus to fall, and the tendency of capitalist institutions to compensate for diminishing rates of profit by increasing the capitalization of production processes. These two interacting tendencies are linked to the following observation: increases in social complexity (i) manifest in the growing weight of the dissipative sectors of the socio-ecological metabolism, and (ii) are associated with increases in the rates of production in the hypercycle. Similarly, Moore's argument [39] can be read as: (i) growing capitalization of the hypercycle for effect of increasing social complexity and (ii) eroding ecological surplus, which is driven by declining marginal returns to capitalization. Consequently, the evolutionary pattern of a capitalist world-ecology is expected to produce a cyclical behavior. The argument runs as follows: first, a commodity frontier is opened, allowing the system to extract high rates of easily accessible work/energy with small amounts of capital. Second, capital begins to flow into the commodity frontier, attracted by high returns and low costs, thus boosting the appropriation of the ecological surplus. The point at which the ecological surplus per unit of capital invested is at its maximum represents a threshold called "peak appropriation". Third, after such a threshold, declining marginal returns in terms of ecological surplus per unit of capital invested mark the decline of the commodity frontier, the ecological surplus of which falls sooner or later. After a commodity frontier has been opened, four causes tend to lead to the fall of ecological surplus: (i) the entropic nature of the economic process; (ii) capitalists' race to increase profits, leading to overcapitalization; (iii) the temporal mismatch between the pace of capital accumulation, and nature's rhythm of reproduction; (iv) the rise of negative values in response to ecological deterioration (e.g., climate change) [39]. Fourth, to compensate for declining marginal surpluses, capital flows increasingly faster, which temporarily extends the profitability of the commodity frontier. Fifth, rising capitalization reaches its maximum height, marking a period of "peak capitalization". Sixth, after this peak, increasing capital flows have no effect on the rates of production, and therefore the whole system becomes overcapitalized. Exhaustion eventually paves the way towards "developmental" crises; in Moore's terms:

> "[. . .] Exhaustion is not a substantial property. It is a *relational* property of the specifically capitalist oikeios. [...] *Exhaustion* occurs when particular natures-crystallized in specific re/production complexes-can no longer deliver more and more work/energy. At this point, the share of unpaid work/energy in a given production complex falters, and the share of capitalized work/energy rises. The rising capitalization of re/production registers in rising prices for the Big Four inputs-almost always unevenly-unless new sources of unpaid work/energy can be located [39]" (pp. 124–125, emphases in the original).

Following this argument, it becomes possible to compare the succession of each phase of a socio-ecological panarchic cycle (Fid. 1) with the cyclic steps described in Moore's theory.

$\alpha \rightarrow$ r: (re)organization of SESs' functions and structures to assess the external potentiality and to allow new behaviors to emerge through innovation [10]. The direction of such processes is co-determinate by the higher levels of the panarchy through the "remember" function. In Moore's theory, this phase corresponds to capitalist world ecologies' systemic efforts to open new commodity frontiers. The system therefore has to expand its control over uncolonized sources of potential work/energy, including, for instance, the unpaid work invested by people in the household sector (e.g., childcare), the work performed by ecosystems (e.g., micro biota in fertile soils), the work done in distant geographical places (e.g., colonial control), or the import of unpaid workforce (e.g., slavery). Obviously, each process of appropriation involves some kind of cost (e.g., human time, control strategies, or military expenses). As such, "cheapening" also refers to the possibility of reducing these costs and making new frontiers of appropriation viable. The "remember" function enables the anticipatory behaviors necessary to mobilize financial capital, knowledge, and labor to proceed towards the exploitation of the new commodity frontier.

r $\rightarrow$ K: Exploitation generates accumulation of potential for action, which results in expanding funds (i.e., human activity, colonized land, capital); inflated funds and higher societal complexity require higher flows of resources [29]. The system quickly becomes committed to its own maintenance, or conservation. In a world-ecology perspective, this phase corresponds to the appropriation of a commodity frontier. Throughout the exploitation phase, production costs decline and capital investments increase, fueled by the high surplus generated. Peak appropriation occurs when the ecological surplus generated per unit of capital invested reaches its maximum point. Henceforth, capitalization outpaces appropriation in the search for higher ecological surpluses, which entails higher fixed capital (expanded funds, increasing connectedness) and an increasing overhead to support it.

K $\rightarrow \Omega$: Conservation entails high connectedness and systemic rigidity because the over-expanded funds absorb most of the resources generated. Signals are geared towards maintaining the identity of the system; however, disturbances can destabilize the cycle. Revolts coming from lower levels can cause the rapid collapse of the system and force it to release the resources accumulated (i.e., human activity, land, and capital). In a world-ecology perspective, the point at which the ecological surplus attains its maximum value marks the moment of peak capitalization. Signals pushing the system to further increase the ecological surplus bring forth overcapitalization. Overcapitalized systems become vulnerable to fluctuations both in the value composition (i.e., cost) of the inputs and in the stability of the funds (i.e., land or human activity). Henceforth, any shock has the potential to enact a crisis.

$\Omega \rightarrow \alpha$: The release of resources and a lower level of complexity may allow the system to re-organize itself. This moment of creative destruction can have two outcomes: (i) the cycle can be re-iterated if the higher levels of the panarchy are still expressing the desirability and guaranteeing the viability ("remember" function) of the pattern already undertaken through (α); (ii) if the "remember" function is not enforced, the system is free to exit the loop and find other viable configurations. In Moore's view, sooner or later a developmental crisis can blow up the established pattern of accumulation. Capitalization declines, the ecological surplus collapses, and prices skyrocket. However, the system might find a way to avoid the effects of the exhaustion of the commodity frontier and to reiterate the whole cycle starting back from (α). To such an extent, it is necessary that new natures to be appropriated are considered as both viable and desirable opportunities by the capitalist ontology in place. A new commodity frontier therefore might be opened to support another period of accumulation by appropriation.

The steps mentioned above are therefore the "footprints" of the waves of accumulation unfolding within a capitalist world-ecology. The cyclical component is determined by the fact that the ultimate stage (the developmental crisis) can represent the starting point for a new wave of accumulation. Of course, the re-iteration of the process requires the expansion of the existing commodity frontiers, or the opening of new ones, through a renewed process of appropriation. In this sense, developmental crises are transformational but not revolutionary, insofar as the existing modes of production are not put in jeopardy. Conversely, if for any reason the system cannot restore the ecological surplus by its own mode of operation, a structural transformation of the societal identity of the system becomes necessary. This transformation eventually results in "epochal crises", or, by recalling the system sciences perspective, the beginning of a phase of evolutionary change.

5. Discussion and Conclusions

It is clear how the "unsustainable" character of current economic systems is not due solely to psychological or behavioral issues of Westernized "consumers". Indeed, what Coffman and Mikulecky call "global insanity" [13], which postulates a situation of cognitive dissonance between SESs' attitudes and perceptions, is derived by the acknowledgement that unsustainability is driven by ineffective models, narratives, and institutions that are deeply rooted in a specific worldview and are supported by a biophysical infrastructure that is perceived as viable even to this day.

This article makes the claim that to effectively explore SESs' sustainability, a careful treatment of teleological causes is required. What Rockström et al. call "the politics of who gets what, when, where" [3] (p. 5) is not a mere issue of isolated episodes of corruption, authoritarianism, or other forms of contextual abuses. On the contrary, "the politics of who gets what, when, where" is how social ontologies organize fluxes of matter, energy, and labor in order to survive and reproduce themselves. What Rockström et al. [3] call the "[r]ules of access and distribution" are nothing more than the SESs' ontological praxes.

To account for SMSs' teleology, there are two consequences: first, system scientists cannot overlook the systemic (complex) nature of social relations, which are fundamental drivers of human actions oriented to a common goal: to reproduce the system in place (or to overturn it). This entails a commitment to explicitly deal with issues of power, dominant narratives, and values, elements that are foundational of a soft system methodology. As Matthew Turner bluntly states: "Yes social, economic, and ecological systems develop, expand, self-organize, decline and collapse ... but without some normative stance as to what is preferred and a defense of why, the panarchy framework, as applied to social systems, becomes an age-old truism of growth and decline as shaped by the second law of thermodynamics and life-cycle biology" [11] (p. 621). Second, social scientists cannot overlook the systemic (complex) nature of socio-ecological relations, which necessarily involve the manifestation of cross-scale biophysical constraints and option spaces. This entails that the viability of policy options is not only given by their desirability, but also by their feasibility within a given socio-ecological regime. Again, to use Turner's words, the phases of a panarchic cycle: "[...] involve significant struggle, pain, and dare I say injustice within ecological communities—features that motivate the interest of resilience scholars in ecology and socio-ecological systems, but which are, through abstraction to the systemic level, largely ignored (at least in their modeling work). Translating this highly abstracted and thus seemingly unbiased perspective to ecosociological systems [...] could lead to a disturbing voyeurism—coming too close, for many social scientists, to social Darwinism and lifeboat ethics (Hardin, 1974). Populations and individuals may come and go but structures and systems remain and prove resilient (which is good?). Eventual reorganization associated with ecological and human demographic collapse opens up resource space for new adaptions in the [...] panarchic cycle" [11] (p. 621).

This article helps to explore SESs' dynamics further. By assuming that the world-ecology perspective has something to say about dominant ontologies, the paper makes the case that development and crises are expressions of the contradictions arising from the dialectics of capitalization and appropriation. Seen in this light, elements such as inequality, exclusion, innovations, state regulation, and financial power are considered endogenous to the socio-ecological process, and they absolve a specific role in the SESs sustaining the socio-ecological regime. In Moore's words: "The "limits to growth" are not external, but derive from relations internal to capitalism" [39] (p. 101). According to Moore, capitalism has not yet experienced any epochal (evolutionary) transition, the last example of which is the crisis of feudalism between the thirteenth and the fifteenth centuries. The rise of multiple "limits to growth", or "planetary boundaries" is a major factor requiring current socio-ecological change. If such a change is to remain inscribed within the historical-geographical pattern of current dominant social identities, the ecological crisis and its impacts will only be postponed.

The framework developed in this paper offers a fertile ground for developing insightful analyses of SESs across geographical scales and systemic levels of organization. Consider, for instance, agricultural systems as systems whose stability is increasingly threatened at both local and global scales. Climate change, eutrophication, soil depletion, emerging herbicide-tolerant weeds, and spreading antibiotic resistance are what Jason Moore [39] calls the rise of a "negative value." From a panarchy perspective, such a negative value is threatens not only food security, but also the stability of other adaptive cycles at different levels of panarchical organization. Through its impact on farm profitability, food prices, and social welfare, the accumulation of negative value represents a "revolt" function warning the other sectors of the economy, as well as their encompassing institutions of social coordination, that the behavior that is expected from agri-food systems could become unviable at some point in the near future. The "*revolt*" in one sector of the economy may spread throughout the entire socio-economic system via financial markets, for instance, or inflation, or even social unrest. According to the framework proposed in this article, the systemic impact of a "revolt" function could nevertheless be offset by "remember" functions enacted in different levels of the panarchy—for example, through the development of new technologies, changing lifestyles and consumption patterns, or through financial innovations. The assessment of agri-food systems' sustainability is therefore a matter that requires a multi-scale lens to be properly dealt with. This entails assessing not only the biophysical capacity of a local (or even the global) agricultural system to feed a given population through more or less carbon-intensive techniques, but also assessing agri-food systems capability to support a particular type of societal organization, and evaluating SESs' vulnerability and resilience to shocks caused by the dialectical tension between "revolt" and "remember" functions.

Given the impredicative nature of the connection between the "release" and the "(re)organization" phases of the adaptive cycle, it is not possible to make predictions on when SESs' evolution towards sustainability will take place. However, acknowledging the role that current social identities and institutions play is a fundamental step for interpreting the current situation and to start envisioning what sustainable SESs could look like in the future.

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