Policy Brief: Thermodynamics, Complexity and the Climate Crisis
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The dominant neoclassical paradigm in economics and the reductionist paradigm in the natural sciences have long overlooked the implications of physical realities identified by the field of non-equilibrium thermodynamics. As a result, these paradigms are severely limited in their capacity to address the complex challenges associated with anthropogenic climate change. The fields of systems thinking and ecological economics provide the key theoretical insights and methodological tools necessary for navigating the climate crisis toward feasible and desirable outcomes. This brief will provide: 1) a short description of basic concepts and theories pertaining to complexity theory and non-equilibrium thermodynamics; 2) a critical discussion on the challenges associated with the complex nature of the climate crisis; and 3) recommendations on policies and methodological tools that may prove useful in realizing sustainable and desirable futures.

1: Complexity and thermodynamics: Climate change is not a single problem. Rather, the climate crisis is characterized by a complex of interrelated social, economic and ecological crises coalescing across temporal and spatial scales. In general, we can say that complex problems arise when interactions between complex systems become problematic. Although there are many conceptions and definitions as to what constitutes "complexity", it is generally observed that complex systems are distinguishable from "simple" systems in that the former exhibit the following characteristics.

1.1: Self-organization and Feedback: Systems, in general, are networks of interacting functional and structural components. "Organization" within systems refers to the specific configurations of, and relations between, these components (von Bertalanffy 1968). *Complex* systems are unique in their ability to continually reproduce and/or adapt the organizational configuration of components in such ways that they are capable of perpetuating in response to environmental perturbations (Kay, Waltner-Toews, and Lister 2008). The Russian physicist and Nobel laureate, Ilya Prigogine, was among the first to observe that this phenomenon is exclusive to thermodynamically open, far-from-equilibrium systems. That is, systems that continually import high quality (i.e. low entropy, or "negative entropy") energy resources across system boundaries. Due to the inviolable Second Law of Thermodynamics (i.e. thermodynamic systems *always* tend toward maximum entropy), systems in far from equilibriums states will attempt by any means to achieve thermodynamic equilibrium (maximum entropy) by dissipating the very energetic gradients that animate them. To achieve this, complex systems spontaneously *self-organize* networks of dissipative pathways that export high entropy (low quality) wastes back into their surrounding environments. These pathways manifest as energy is converted to work and dissipated, resulting in small fluctuations that expand into positive feedbacks transferring flows of energy, information and materials to and between functional subsystems in self-reinforcing cycles (Prigogine and Stengers 1984).

1.2: Resilience: Independently, negative feedbacks will invariably lose coherence whereas positive feedbacks will "just blow up" (Ulanowicz 1986). In order to maintain stable patterns, positive/growth feedbacks and negative/regulating feedbacks must be coupled in a delicate balance within complex systems (Berkes, Folke, and Colding 2002). Self-organization is stable so long as 1) the system maintains access to sufficient energy and material gradients; 2) the system is not dramatically disrupted by environmental influences; and 3) positive feedbacks do not overwhelm the negative or vice versa. The "zone(s) of vitality" in which these patterns are stable are referred to as "attractors" in recognition of the fact that complex systems are drawn towards them and actively resist disruptive forces (Ulanowicz 1986; Kay and Schneider 1992). In the face of disruptions, complex systems exhibit "resilience," referring to the degree of disruption necessary to cause a system to either reorganize around other local attractors, or simply collapse altogether (Schneider and Kay 1994). "Adaptive resilience" refers to a system's capacity to reorganize rather than collapse (Gunderson and Holling 2002).

1.3: Uncertainty and Emergence: Attempting to predict future states of non-equilibrium systems is much, in Prigogine's words, like attempting to predict "the fall of dice" (pg. 162). In other words, it is not possible to determine precisely the position of attractors or the thresholds at which complex systems will spontaneously "flip" into new organizational modes. The synergistic relations between systems components result in "emergent" behaviors and properties in which the whole is other than the sum of its parts. While we can observe general trends and possibilities, exact futures in complex systems are inherently uncertain.

1.4: Hierarchy: Complex systems exist in scalar hierarchies of "holons" (i.e. systems that are simultaneously *whole* and *part* of a larger whole) in which any one system and its associated canon of feedback loops is invariable a constituent part of a larger system with feedback loops operating on greater spatial and temporal scales (Allen and Ahl 1996; Koestler 1968). Larger systems provide admissible contexts for their nested subsystems. Subsystems, in turn, provide essential functions that enable the greater whole. Systemic collapse, therefore, can occur top-down (when the resilience of the contextual holon is overwhelmed) or bottom-up (when essential functional components are eliminated).

Although closed patterns of positive and negative feedback loops allow researchers to define the boundaries of systems and their nested subsystems, it is impossible to know for certain whether these boundaries are ontologically real or simply imposed by the observer (Allen and Hoekstra 1992). Like perfect circles, boundaries are ultimately "useful abstractions" (Salthe, 1993, pg. 35). In addition, because causation in complex systems is non-linear and impredicative (i.e. every event is its own cause and effect), the locus of change will always be subjective to the individual observer (Rosen 1985). Complex, non-equilibrium systems can, therefore, be characterized within any number of non-equivalent descriptive domains, while they can never be described entirely within any one model (Giampietro 2003).

2: Societal and Ecosystem Metabolism: All systems relevant to the climate crisis are complex, non-equilibrium systems that exhibit the characteristics described above. Living organisms, ecosystems, human societies and the biosphere itself are all expressions of fundamental, self-organizing phenomena, manifesting in different configurations across levels of scalar hierarchy (Capra and Luisi 2014; Allen and Hoekstra 1992). Like organisms, all complex systems rely upon specific patterns of positive and negative feedback to supply "metabolites" necessary to maintain organization around stable attractors. From systems ecology, the term, "ecosystem metabolism" refers to biophysical flows of chemical and solar energy, water and abiotic nutrients that traverse biotic components within ecosystems (e.g. individuals, communities, species and trophic levels) (Odum and Odum 1976; Odum 1971; Ulanowicz 1997; Kay 2000). "Societal metabolism," from ecological economics and industrial ecology, refers to flows of food, water, energy carriers and economic goods within the various compartments of human societies (e.g. individuals, communities, urbanities and productive sectors) (Giampietro and Mayumi 2000; Krausmann et al. 2008).

Although industrial societies are considerable in scale, they are nonetheless unique types of ecosystems that rely upon the larger ecosystemic holons they are situated within. Societal metabolism is, therefore, always fundamentally predicated upon the stability of ecosystem metabolism for provisional flows of renewable resources as well as regulating, cultural and supporting ecosystem services (Bunch and Waltner-toews 2015; Duraiappah et al. 2005).

3: The Entropy Problem in Economics: Few nowadays are aware that the foundational models and equations informing the dominant neoclassical paradigm in economics were explicitly adapted from dubious and quickly abandoned theories from mid 19th century physics (Nadeau 2015; Mirowski 1988; 1989). The circular flow of income model that arose from these theories mistakenly conceives of economic processes as reversible and independent of biophysical context (Daly 1997; Daly 1973). Ecological economists have long cautioned that these models are inconsistent with the Second Law of Thermodynamics, which mandates that energy and material resources are subject to irreversible, qualitative degradation as they are transformed within productive processes (Georgescu-Roegen 1971; 1973). As a result, traditional economic theories and approaches, oriented toward maximizing efficiency, utility and growth, effectively depict the economic process as a perpetual motion machine whereby issues of resource scarcity and environmental degradation are regarded as market failures than can be resolved through pricing mechanisms, technological innovation and resource substitution. By ignoring the entropy law, neoclassicists regard issues of resource scarcity as moot (Solow 1974). By ignoring the non-linearity and uncertainty associated with complex systems, economic welfare models, based on arbitrarily defined discount rates, depict modest impacts from a benign and gradually shifting climate (Nordhaus 2007).

The dangers inherent to these assumptions cannot be overstated. From the perspective of ecological economics, traditional economic theory is flawed because it is incapable of conceiving of a world with biophysical constraints in both source and sink capacity. Further, ecological economists are quick to point out that that natural processes are "agnostic" to human valuation schemes. As such, they argue, economic tools are fundamentally incapable of sufficiently addressing issues related to the environment.

4: The Pathology of Resource Management: From a systems perspective, neoclassical economics is flawed for the assumption that biotic and abiotic processes operating at higher levels of organization can be subsumed and endogenously controlled through mechanisms operating at the scale of industrial society. In reality, the biosphere is far more complex than human civilizations could ever be. Just as no single model can fully describe a system as complex as the biosphere, no mechanisms ever devised by humanity will ever fully control our ecosystem context (Kay, Waltner-Toews, and Lister 2008). Similarly, the inherent uncertainty related to complex systems is problematic when observed through the lens of traditional disciplinary science. Historically, western science has operated within a reductionist paradigm that views events in nature as mechanistically unfolding in accordance with natural law. Since the days of Newton, nature has been regarded as operating much like a complicated machine, where all past and future states are assumed to be calculable so long as sufficient data is available. The view that ecosystems can be controlled has led to what Gunderson and Holling refer to as “the Pathology of Regional Development” in which the attempted optimization of economically lucrative, target variables has frequently resulted in catastrophic ecosystem collapse (Gunderson and Holling 2002).

5: Recommendations: As with all complex systems, the stability of societies and ecosystems is reliant upon *coupled* positive and negative feedbacks*.* In essence, the climate crisis represents a cascade of positive feedbacks decoupling from their regulating counterparts. Extractive capitalism, predicated upon a demand for perpetual economic growth and consumption, has generated runaway positive feedbacks within human systems that threaten the source and sink capacity of the very ecological holons that serve as our admissible contexts. Through unmitigated pollution and extraction, industrial societies are systematically undermining and overwhelming the regulating, negative feedbacks provided by healthy ecosystems. To address the climate crisis, the myth of perpetual growth must be abandoned. Further, we must implement policies, methods and decision making frameworks that serve to identify and promote opportunities for negative feedback mechanisms within our own societies while we work to maintain and defend the resilience of the systems we rely upon. New policies and methodological approaches are needed if we are to regain balance. The following recommendations are made to address the specific challenges identified in the previous discussion.

5.1: Addressing the challenge of uncertainty: Futures are uncertain within complex systems. Thus, deterministic operating models are of limited value, at best, or otherwise dangerously misleading. The potentially catastrophic effects of “runaway” climate change are well documented, as are the many potential “tipping point” thresholds at which positive climate feedbacks become uncoupled and grow out of control. Although we know that these threshold points exist, we do not know for certain if and/or when they will be triggered. **Scenario analysis** offer a flexible alternative to traditional forecasting methods, enabling researchers to imagine futures “that could be” rather than “futures that will be” (Peterson, Cumming and Carpenter 2003, pg. 359). Scenarios allow decision makers to envision a range of possible outcomes and contingencies. In addition, Kay et al. (2008) argue that scenarios can even act as aspirational attractors for societies working to achieve desirable outcomes. Realizing desirable futures, however, requires that scenarios are also *feasible* with respect to biophysical limits*.*

5.2: Understanding and Respecting Biophysical Limits: Within traditional economic theory, the “feasibility” of a given undertaking is generally determined through cost-benefit analysis. Advancing into the Anthropocene, priority must be given to “ecological feasibility filters” used to determine whether implementing specific economic developments can occur without encountering or exceeding biophysical constraints. In addition to more common methods to sustainability assessment (e.g. environmental impact assessment or ecological footprint analysis), systems-based approaches should be employed in order to provide holistic analyses of the complex interactions of systems and subsystems across multiple scales.

Resilience thinkers suggest *adaptive management* approaches in which feedback patterns are assessed across three to five levels of scale. The goal of these approaches is to determine which variables or systems components are most critical in maintaining adaptive resilience (Gunderson and Holling 2002). *Integrated analysis* methods, such as Giampietro and Mayumi’s *Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism* (MuSIASEM), provide a means to simultaneously assess the interactions between the different types of metabolic feedback patterns associated with ecosystems and societies (Giampietro, Mayumi, and Sorman 2011). It is worth noting that proposed scenarios may only be *plausible* if they are both socially *viable* as well as ecologically *feasible*. Transitions toward the widespread use of renewable resources, organic agriculture, sustainable transportation systems or cogeneration are paramount for addressing the climate crisis. However, these interventions must be demonstrated to be consistent with social goals (e.g. health, wellbeing and security) to be politically realistic.

Furthermore, mutually supportive relationships with ecosystems must be maintained and enforced through policy and law. Brown (1992) has suggested the widespread adoption of a fiduciary trust framework (FTF) as a decision making alternative to the dominant market framework paradigm. Within the FTF model, he argues, “the integrity of the Earth’s ecological systems acts as a constraint on the pursuit of ever higher levels of consumption” p. 216). Similarly, Garver has called for the adoption of “ecological law” to enforce a “degrowth” economic paradigm characterized by “local economic autonomy, equitable sharing of work and resources, low-impact technologies, a narrow view of private property, food sovereignty and floors and ceilings on income, as well as on monetary reform, trade reform, constraints on advertising and restrictions on harmful technologies” (Garver 2013, pg. 317).

5.3: Addressing the challenge of non-equivalent descriptive domains: The complexity of a given system is a function of the number of non-equivalent models that can be used to describe it. Economists, ecologists, hydrogeologists, farmers, activists and local residents will all identify different relevant attributes when observing the same system. In addition, stakeholder valuation of ecosystems and ecosystem services vary significantly depending on economic, cultural or spatial relations. Participatory and interdisciplinary problem framing exercises, such as *mediated modelling* (Van den Belt 2004) or *soft systems methodology* (Checkland and Scholes 1990) are useful techniques for integrating a plurality of perspectives in order to identify leverage points for interventions toward common goals. Finally, *multi-criteria decision analysis* (Munda 2005) and *qualitative valuation of ecosystem services* (Tuvendal and Elmqvist 2011) are effective alternatives to cost-benefit analysis for determining preferences within a complex option space.

6: Conclusion: Navigating the Climate Crisis: Integrating insights from complex systems theory and non-equilibrium thermodynamics into economic, political and analytical processes will be critical if human societies are to navigate the climate crisis effectively. This will not be a simple task. Climate change represents the single greatest threat our species has ever encountered. As these crises multiply, we must learn to address them with fewer biophysical resources than we have previously had at our disposal. Decision stakes are high and matched only by the degrees of uncertainty surrounding them. Above all, we must exercise the precautionary principle, having recognized that we may already have stressed the resilience of our ecosystemic contexts too far.

Systems thinking and ecological economics may provide many of the theoretical and methodological means necessary for realizing sustainable and desirable future. What is now required is the education, political will and leadership necessary to promote the widespread adoption of these crucial concepts, policies and scientific tools.

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