Green Complexity Economics:

Modeling Global-Scale Environmental, Resource, and Ecological Challenges

Dawn Cassandra Parker and Thomas Homer-Dixon

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Cover Photo

This dramatic image of a thunderstorm was taken by John Kerstholt in Enschede, the Netherlands, and courtesy of the Wikimedia Commons. The cover page was designed and executed by Michael Lawrence, Student Member with WICI.

Introduction

Developed over the last three decades, complexity science has engaged the imaginations of both scientists and laypeople with its novel and intellectually exciting concepts, insights, and models (Rauch 2002; Waldrop, 2009). Today, however, more than intellectual curiosity motivates a surge in interest in complexity science. Increasingly, policymakers, researchers, and the informed lay public recognize that conventional scientific theories and tools cannot effectively address many critical global challenges—such as the international financial system's chronic instability, worsening global food insecurity, and humankind's urgent need to reduce its carbon emissions. New theories and tools are needed.

Traditional science is often reductionist. It also relies heavily on simplifying assumptions made for the sake of experimental design and tractability. The scientists who study complexity argue that the heterogeneity, interconnectedness, and dynamic feedbacks of real-world systems—often assumed away in simpler models—drive outcomes of interest. Conventional researchers respond that this messiness, whatever the rationale for including it in theories and explanations, hinders learning.

But as complex-systems research has progressed, it has generated important insights: first the structure of low-level interactions in complex systems tends towards ordered states that can be formally characterized; and second these lower-scale dynamics generally result in macro-scale or "emergent" properties. Systems with emergent properties usually exhibit macro-scale behavior that is more regular—and sometimes even more predictable—than these systems' lower-scale dynamics.

Conventional researchers use traditional scientific techniques to analyze such macro-scale behavior. But their models generally represent only idealized, restricted, and radically simplified subsets of processes—for instance, system migration to a single, stable equilibrium—that invariable take place within a much larger universe of analytically intractable complex-system behaviors. Conventional researchers, in other words, tend to look where the light (from their theories and tools) shines brightest, rather than where the most interesting problems reside.

In spite of recent progress in complexity science, much needs to be done if complex-system theories and tools are to become truly useful and ultimately widely accepted by scientists. For instance, researchers need to better understand the relationship between more traditional models and complex-systems models and the extent to which these different kinds are nested (as suggested above), complementary, or exclusive.

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Moreover, complexity science needs to better integrate its *own* theories and tools. Complexity researchers use tools ranging from closed-form system dynamics models and computational simulations to inductive statistical models. What is the relationship between them? How they can be combined to represent complex cross-scale, nested, and hierarchical systems? And how can researchers use the resulting representations to conduct formal experiments spanning the full spectrum of the scientific method.

Complexity economics pointedly illustrates many of the challenges described above. Relatively small numbers of economic researchers, trained either in traditional economics or migrating from other disciplines, have adopted a complexity approach to economic problems (Tesfatsion and Judd, 2006; Hernandez, Troitzsch, and Edmonds, 2008; Irwin 2010). Mainstream economists have only slowly accepted this work, largely because they worry that a complexity approach does not allow formal mapping of relationships between model inputs and outputs (Nolan et al. 2009). Yet the multiple economic crises of the last several years have highlighted how simpler models cannot provide a deep understanding of the genesis and development of crisis, help policymakers anticipate or forecast crisis, or generate policy recommendations for resilient response to crisis. This shortfall has brought attention to alternative complexity theories and tools, some of which provide novel insights (LeBaron, 2006; Buchanan, 2008). This attention is welcome, but it means researchers must now squarely address concerns about the scientific foundations and utility of complexity economics.

The Waterloo Institute for Complexity and Innovation (http://wici.ca/), a recently founded research centre at the University of Waterloo, facilitates transdisciplinary, collaborative research to promote innovation and resilience within the complex adaptive systems at the core of human well being. The Institute is mandated to develop formal tools and methods for complexity science, building on the methodological strengths of the University of Waterloo's math, computing, and engineering programs, as well as on a strong working relationship with the Perimeter Institute for Theoretical Physics. Closely associated with the Centre for International Governance Innovation, WICI also focuses on policy by bringing new methods and analysis tools to bear on some of the most pressing governance challenges of our time.

WICI’s current research spans a variety of themes. For illustrative purposes in this paper, we focus on WICI’s work in the area of sustainable economics. First, we outline why complex systems approaches are needed to address pressing questions in environmental, resource, and ecological economics. Second, we describe some general complex systems tools and methods whose development would aid the development of a “green” complexity economics and contribute to complexity science more generally.

Traditional environmental and resource economics: Assumptions and limits

The theories and tools of complexity science have seen limited application to environmental, natural resource, and ecological problems in economics. Nevertheless, researchers studying these problems have long debated the implications—for important policy domains, like climate change—of key assumptions inherent in conventional approaches (Review of Environmental Economics and Policy 2 (1); Nordhaus 2007; Stern et al, 2007; Perman et al. 2003). Complex-systems approaches relax many of these assumptions and can thus expand the range of researchable questions.

In this section, we review some of these conventional assumptions and the limits they create for research. In next section, we describe how complex-systems methods relax these assumptions, and we highlight relevant WICI research. The assumptions include:

Aggregation of decision makers and their environment: Most of the models used in environmental and resource economics are derived from core analytical models in micro and macroeconomic theory. They generally include one or several decision makers whose behavior represents the outcome of decisions of a much larger and more complex group—even, perhaps, one operating at a global scale. Also, interactions between the natural and human systems are generally summarized by a single, well-behaved function that represents a stream of goods and services flowing from nature to the economy. To maintain analytical tractability, these models generally have no—or at best very limited—spatial heterogeneity.

In short, these models have one or a few state variables that operate over highly aggregated spatial scales. So they provide little insight into situations where heterogeneity of decision makers or the spatial environment is central to the research question—as is the case, for example, when considering the design of tradable-permit markets for ecosystem services like biodiversity, water purification, and carbon sequestration.

Convexity: Again, in order to make their models tractable, environmental and resource economists invoke assumptions of gradual, smooth, and monotonic change. Not surprisingly, their models therefore predict that real-world change will be gradual and will lead to a single outcome state—often a long-run steady state where resource consumption rates equal depletion rates.

These models' underlying assumptions imply that policies such as carbon taxes or trading programs will be reversible and that system change will be sufficiently slow and predictable for policy makers to adjust course gradually. These assumptions exclude the possibility of abrupt thresholds and irreversible change. By corollary, they also exclude the possibility that policy makers' decisions might shift an economy permanently to one of many possible paths with widely divergent outcomes.

Substitutability of man-made and natural capital: Although contested and a lively point of debate among economists interested in sustainability, most conventional models assume that man-made inputs can substitute for natural inputs to economic production, often at comparable levels of productivity and cost. However, research increasingly suggests that human-made capital may not adequately replace some forms of natural capital, including ecosystems services essential to human health and well being.

Exogenous technological change: Some environmental and resource models acknowledge our limited ability to substitute human-made for natural capital. They nevertheless assume that technological change will raise substitutability over time, thereby overcoming productivity losses as natural capital stocks erode (Barbier and Homer-Dixon 1999). Rates of technological change are generally assumed to be exogenous; specifically, they do not depend on incentives and prices.

Discounting: Economic models usually assume that discounting—that is, valuation of future outcomes at lower rates than present outcomes—is economically optimal. Economists debate the appropriate level of discounting, but not the discounting assumption itself. But the assumption implies that a prescriptive economic model will recommend decreasing rates of resource availability and economic prosperity over time. This prescription fundamentally conflicts with standard definitions of sustainability that assume constant or increasing levels of prosperity.

Calculable risk: Most traditional environmental and resource economics models assume that decision makers maximize the expected value of a stream of future returns. Decision makers know risk distributions and outcome states, so they can use a risk-assessment approach to decision making rather than one guided by a precautionary principle. Yet real-world decision makers face deep uncertainty regarding risk distributions, especially for decisions involving entangled natural, social, and economic systems at the global scale.

Complex systems tools and methods

The Waterloo Institute for Complexity and Innovation addresses some of these challenges in its current and projected research. Below we discuss tools and methods that complexity researchers could use to develop next-generation environmental and resource economics models. We focus on those that are highest priority for WICI.

Computational laboratories using agent-based models (ABMs): Agent-based modeling is a simulation method increasingly used in the social sciences (Berry, Kiel, and Elliot 2002; Hernandez, Troitzsch, and Edmonds 2008) to study systems with heterogeneous agents and out-of-equilibrium dynamics (Arthur, 2006). Whereas traditional mathematical and computational techniques used in economics identify and model system equilibrium, ABMs model system behavior. The behavior results from interactions among lower-level entities and between these entities and their social and physical environments.

Although ABMs may produce equilibrium behavior, it is by no means inevitable. Moreover, multiple equilibria are possible. ABMs are thus suitable for modeling domains where the complex relationships between agent heterogeneity, interactions among agents and their environments, feedback loops, and cross-scale connections make traditional equilibrium models analytically intractable (Parker et al. 2003).

By necessity and design, ABMs relax traditional economic models' assumptions of full rationality, acknowledging that economic agents have limited information, computational capabilities, and resources (Simon 1996). In ABMs, agents exhibit bounded rationality, but they can optimize their behavior within these limits through learning and adaptation.

ABMs can be used as computational laboratories—or "test beds"—to explore future trajectories for systems of interest and to understand how different arrangements of economic incentives, institutions, and regulatory regimes change system outcomes (Tesfatsion and Judd 2006). For instance, ABMs are ideal for testing different designs for tradable-permit markets for ecosystems services. They can incorporate the spatial, temporal, and agent-level heterogeneity that creates the very rationale for, as well as the design challenges of, such markets. They can also incorporate adaptive, heterogeneous, and uncertain representations of risk.

Researchers can link agent-based socioeconomic models to spatially disaggregated and independent ecosystems models, thereby representing changing levels of natural capital and ecosystem services. Such linked models allow the study of thresholds, non-linearities, and path dependencies in complex socio-ecological systems (see www.chans-net.org for many US NSF funded examples of such models).

Finally, researchers can use ABMs to study technological innovation, thus endogenizing resource-related technological change (Barbier and Homer-Dixon 1999). Because equilibrium assumptions are relaxed, these models can incorporate alternatives to exponential discounting into their decision functions. WICI researchers are currently using agent-based land-market models linked with carbon sequestration models to explore the effects of ex-urban residential landscaping practices (as moderated by land market interactions) on the carbon balance of ex-urban landscapes (http://www.cscs.umich.edu/research/projects/sluce/). This research builds on previous work exploring the impacts of heterogenous risk perceptions on land markets (Filatova, Parker and Van der Veen 2009).

Marrying complexity and resilience using system dynamics: As noted in this paper's introduction, interactions and feedbacks between lower-level entities in complex systems often lead to structured and more ordered aggregate properties at higher levels. Researchers explore possible outcomes at these higher levels with system dynamic models incorporating a few state variables. Often model developers in different disciplines have not communicated. Also, within the complex-systems community, some researchers have created models to study bifurcations, path dependence, and the emergence of power-law distributions, whereas others have developed models to study the resilience of natural and human systems in response to perturbations.

WICI researchers are currently undertaking a multi-disciplinary synthesis of dynamic models of complex systems, with a particular focus on models of threshold behavior. This review strives to incorporate, and potentially unify, models from physics, ecology, and the social sciences—and specifically to reconcile complex-systems and resilience approaches. The group is exploring questions such as:

- What formal mathematical representations of resilient systems have been or are being developed, and how are these applied conceptually in different disciplinary domains?

- What models of thresholds, path dependence, and bifurcations are found in complex-systems research across disciplines?
- What common features, empirical signatures, and parameterizations of these models can be identified?
- How can key findings be generalized across disciplines?
- What is the formal mathematical relationship between systems dynamics approaches in complexity science (especially those generating scaling and power laws) and those found in resilience theory?
- What lessons can be learned from these models about how to recognize and respond to early-warning signals of critical transitions in human and natural systems?

In addressing these questions, WICI aims to develop alternative system dynamics representations for environmental and resource economics that allow for the nonlinearities and path dependence inherent in natural systems.

"…WICI aims to develop alternative system dynamics representations for environmental and resource economics"

Linking micro and macro scales: Conventional macroeconomic models can be characterized as restricted versions of system dynamics models of economies. Similarly, conventional microeconomic models can be seen as restricted cases of more complex agent-based representations.

Complexity science has yet to fully explore the link between micro-scale simulation and macro-scale system dynamics models, although some researchers are pursing this agenda (for example, Axtell et al. 2011). The challenge, in short, is to build micro-scale models at the level of the lowest-level decision maker that can be scaled up to regional, national, and even global system dynamics models (Parker, Hessl et al. 2008).

The community of researchers modeling land-use and land-cover change recognizes the need for cross-scale models. It wants global projections of land-use change—grounded in local spatial agent-level heterogeneity—that can be plugged into global climate change models (Parker, Entwisle et al. 2008, Verburg et al. 2006). Designers of global markets for ecosystem services face the same methodological challenge, because they need to aggregate the behavior of local markets through regional and global markets to determine market-clearing prices of ecosystem services.

Techniques to analyze complex systems data: Complexity researchers need new statistical and visualization techniques for analyzing and interpreting the enormous quantities of often opaque data that complex systems generate. Specifically, they need better ways to link model inputs to macro-scale model outputs.

Traditional curve-fitting methods and algorithms generally assume that relationships between driving parameters and endogenous outcomes are linear, or at least characterized by continuous, clearly defined functions, and that input and output variables have Gaussian distributions. But complex systems generate outcomes exhibiting non-linearities, thresholds, and discontinuities, and outcome variables often have power law, rather than Gaussian, distributions.

Practically speaking, if researchers are to make use of output from computational laboratories for scenario and policy analysis, they must be able to map the relationship between model drivers and model outputs. New methods of statistical analysis and visualization could alleviate the concerns of traditional economists that complex-system models are black boxes that do not allow for a full understanding of the system's behavior. This work is a high priority for WICI.

Representing and engaging stakeholders: WICI is studying new methods for engaging stakeholders in the modeling, analysis, and decision-making process. The Cognitive Affective Modeling project has developed a method to represent the beliefs, emotions, and motivations of stakeholders and decision makers. WICI is also exploring new forms of collective participation and decision making that exploit principles used in open-source projects. Finally, through the SLUCE2 project and others, the Institute is working on tools to make it easier for researchers, model users, policymakers, and stakeholders to generate and share knowledge about how complex systems, including economies, are structured and behave.

Discussion and conclusions

In this short paper we have described, with a broad brush, recent developments and some major challenges in complex systems research. We have specifically discussed the rationale and opportunities for development of an environmental, resource, and ecological economics grounded in complexity science. To illustrate new tools that could be applied to pressing environmental and resource challenges, we have used examples of work in progress and planned at the Waterloo Centre for Complexity and Innovation.

Such tools could make it easier to develop resilient responses to crises in coupled natural and human systems. They should also allow us to explore key questions about how economic institutions foster or inhibit innovation, such as:

- To what extent do current market structures, especially considering externality-induced relative price distortions, create and/or inhibit incentives for ecosystem service preservation and throughput-reducing economic innovation?
- How might modified market structures enhance incentives for innovation? Under what conditions (locations in time and space) might local synergies and feedbacks create a critical mass of innovation events, resulting in a regime shift in the direction of a more sustainable economy?
- What policies and/or market incentives can maximize the probability of such a transition?
- In short, how can we modify economic incentives to harness path-dependent innovation to induce structural change towards a more sustainable economy?

The recent global economic crisis highlighted the limitations of today's economic models. Policymakers had warning of structural instability, but few anticipated the scale of the ensuing crisis. They also had limited options to design resilient responses. The tight interconnectivity of the global economic system allowed disruption to cascade through across the global economy at lightening speed. Local entities had little capacity to protect themselves against the shock. Policy options seemed total inadequate given the scope of the crisis, with little scope for experimentation and adaptation.

New economic models must first acknowledge that the global economy is a complex, interconnected, path-dependent system. They could potentially provide vastly enhanced capacity for experimentation—using computational laboratories to anticipate crisis and make economies more resilient when crisis happens.

Both conventional and complexity researchers are working to develop better models of the global financial system. We argue here researchers need to invest similar effort in a complex-systems approach to humankind's environmental and resource challenges. A "green complexity economics" that relaxes the restrictive assumptions of conventional economics would help policy makers design, analyze, and adapt the world's economies to meet most pressing environmental challenges of our time.

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