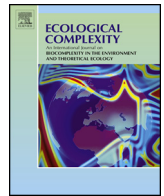




Contents lists available at ScienceDirect

## Ecological Complexity

journal homepage: [www.elsevier.com/locate/ecocom](http://www.elsevier.com/locate/ecocom)



Original research article

# Ecological complexity in the Rosennean framework

John Vandermeer<sup>a,b,\*</sup>, Ivette Perfecto<sup>c</sup>

<sup>a</sup> Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI 48109, USA

<sup>b</sup> Program in the Environment, University of Michigan, Ann Arbor, MI 48109, USA

<sup>c</sup> School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI. 48109, USA

### ARTICLE INFO

#### Article history:

Received 4 January 2017

Received in revised form 17 May 2017

Accepted 23 May 2017

Available online xxx

#### Keywords:

Dialectical complexity

Coffee

Tribolium

### ABSTRACT

Rosen's mathematical framing of the nature of complexity can be summarized qualitatively as simple systems are reducible to models that correspond precisely to nature while complex systems are not reducible in this manner. We use two examples, *Tribolium* laboratory populations and the pest control system in coffee agroecosystems to argue that either a very simple system or a very complicated system cannot be reduced to a series of simple systems and thus conform to Rosennean complexity. We further suggest that alternative framings, specifically dialectical complexity, may be equally useful.

© 2017 Elsevier B.V. All rights reserved.

Centers for the study of complex systems have emerged at intellectual centers over the world, incorporating fields ranging from physics to psychology, from economics to sociology, with ecology being one of the most affected disciplines. The corpus of study includes an eclectic collection of usually mathematical frameworks, loosely intersecting with one another. When one speaks of ecological complexity, it seems that this eclectic collection is what is spoken of. Rosennean complexity appears to encompass something different in that it attempts to articulate a simple core that provides us with a deep understanding of the complexity inherent in nature's systems. Here we review two themes that are representative of the collection of topics that most researchers in ecology regard as complexity, and suggest that, if there is insight to be gleaned from the Rosennean complexity framing, it lies at the intersection of these two themes.

At a deep level Rosen, and later several of his followers, use the mathematical framing of category theory to make deep statements about the nature of complexity, what has been referred to as Rosennean complexity. We do not intend to interrogate that mathematical core. Rather, a variety of metaphors and more generally qualitative statements that have been made in the name of Rosennean complexity will be our focus. For example, in an interview for Belgian television, in answer to the question "What is complexity?" Rosen stated:

"Complexity is really recognized by the failure of all our attempts to deal simply with these systems. Simplicity is easier

to define. I define a system to be simple if it has certain properties and anything else is a system that isn't simple; I call 'complex'. Simplicity is one of the things we inherited from physics; a philosophy of science: [*that says*] all systems can be broken up in a certain canonical set of ways and all systems are built up out of pieces that arise from such decompositions, again in a certain canonical set of ways. So, a system is simple if you can take it apart in a familiar fashion or put it together from pieces in a familiar fashion. That's what basically it means for a system to be simple. The whole idea behind physics was that all systems were simple. And that's the way science progresses, by finding the right pieces and the right ways of putting the pieces back together." (<http://www.people.vcu.edu/~mikuleck/rsntpe.html>)

This is a non-mathematical summary of a dense system of mathematical arguments that Rosen developed, first under the watchful eye of Rashevski, and then extensively elaborated, and further refined and expanded by such philosopher/mathematicians as A. H. Louie and M. Nadin, among others. Our intent here is to query some of the independent literature on ecological complexity and ask whether current literature that speaks of complexity in ecology could have been or can in the future be informed by Rosen's notions. We find, in formal treatments in the ecological and complex systems literature certain qualitative parallels.

A key element of Rosennean complexity seems to be the comparison between a natural system and the model of that system. Characterizing simple systems, Rosen notes:

"The ingredients of this ultimate description, by their very nature, are themselves devoid of internal structure; their only

\* Corresponding author at: Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI 48109, USA.

E-mail address: [jvander@umich.edu](mailto:jvander@umich.edu) (J. Vandermeer).

changeable aspects are their relative positions and velocities. Given the forces acting between them, as Laplace noted long ago, everything that happens in the external world is in principle predictable and understandable. From this perspective, everything is determined: there are no mysteries, no surprises, no errors, no questions, and no information.” (Rosen, 1986: pg 187).

Simple systems can, in principle, be completely modeled, and even if they are composed of many components, if each of the components can be completely modeled, the overall system is non-complex. For sake of argument one might claim that physics is fundamentally a simple system, which would allow us to compare it to biology which, in Rosen’s view, is a complex system. As he notes:

“One way of describing this with a single word is to assert that organisms are *complex*. This word is not well defined, but it does connote several things. One of these is that complexity is a system property, no different from any other property. Another is that the *degree* to which a system is complex can be specified by a number, or set of numbers. . . . On a more empirical level, however, complexity is recognized differently, and characterized differently. If a system surprises us, or does something we have not predicted, or responds in a way we have not anticipated; if it makes errors; if it exhibits emergence of unexpected novelties of behavior, we also say that the system is complex. In short, complex systems are those which behave counter intuitively.” (Rosen, 1986: pg 186 [italics in original]).

We take these characterizations to mean that complex systems are not reducible to a collection of simple systems – perhaps a useful qualitative working definition of Rosennean complexity. We think a quick personal note may be relevant here. One of us (JV) was giving a presentation to a mixed group of physicists and biologists a few years ago and the topic was interspecific competition whereby the particular model being presented led to some surprising conclusions that did not correspond to standard ecological interpretations. The audience was queried as to what might be the explanation of the deviation of model from the obvious reality, and the biologists responded with many possible explanations. But then one of the physicists responded by asking what the question was in the first place. Did not the equations say that? And if they did, there was nothing to explain, the equations WERE the reality. We relate this episode because we think it speaks to the utility of what Rosen was getting at. In physics it is normally expected that, once one gets it “right”, one’s equations will indeed represent reality and the study of the equations is almost identical with the study of reality. Rosen would suggest, and we would agree, that ecology deals with much more complicated issues, and ecologists are forced to theorize in a different style. Our theories (usually in the form of mathematical equations) are thought to be only rough approximations to reality, devices to help us think through what we intuitively understand to be complexity. In this sense Rosennean complexity at its foundation seems to force us to the conclusion that ecological systems are “Rosennean complex,” since the philosophy of model-building, in both its philosophical and practical sense is arguably distinct from physics (Levins, 1966; Weisberg, 2006).

Part of what Rosen seems to have been attempting was to categorize those systems that generated “surprise.” Having settled on a model of the system, and being sure of the definitions of both variables and parameters, when sudden deviation of model and system emerges, the non-complex mind seeks to decompose the system into smaller parts. The process then repeats itself and, ultimately, all the parts can be represented by a model that is, in a deep sense, sure to represent the system. One can then study the model and be assured that one is at the same time studying the

system. Yet, a complex system, no matter how subdivided it becomes, will ultimately have behaviors that emerge from its existence that will deviate from the model that was a simple connection of its subcomponents. It is this emergence that is at the core of the idea of Rosennean complexity. Thus, even though it may appear that ecology is not the place to try and formalize Rosen’s notions to help us sort out what is complex and what’s not, if we take this soft view of the idea, we may ask questions about “surprise” in ecological systems, focusing on relatively standard and accepted models and the surprises they provide, either with post acceptance exploration or comparison with real world data.

What we believe to be closely related to what Rosen was proposing is what we refer to as “dialectical complexity.” In their discussion of dialectics more generally, Levins and Lewontin note:

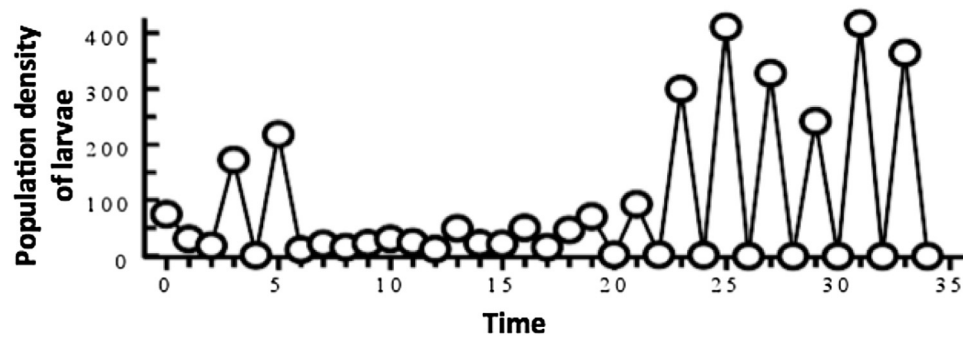
“It is not that the whole is more than the sum of its parts. But that the parts acquire new properties. But as the parts acquire properties by being together, they impart to the whole new properties, which are reflected in changes in the parts, and so on. Parts and wholes evolve in consequence of their relationship, and the relationship itself evolves. These are the properties of things we call dialectical: that one thing cannot exist without the other, that one acquires its properties from its relation to the other, that the properties of both evolve as a consequence of their interpenetration.” (Levins and Lewontin, 1985: pg 3).

As we argue more extensively elsewhere (Vandeemeer and Perfecto, 2017), the general field of complex systems as it is currently developing, seems very closely related to this idea of dialectical complexity, bring up the possibility that there are significant overlaps between dialectical complexity and Rosennean complexity, at least as applied to ecology. Here we explore complexity, mainly from the Rosennean point of view, since this issue is devoted to that subject.

In particular, we present two examples. The first is one in which it would seem we had discovered a simple system in Rosen’s sense, in biology, yet more cautious look found a major discrepancy between model and system, the population dynamics of the flour beetle, *Tribolium*. Furthermore, it seems clear that breaking the model down further would not help, but in the end elaborating it in a completely different direction was the key to resolving the contradiction between model and data. The second example extends from our own research and is effectively the inverse of the first example. We know, from observation and experiment that the pest control system in the coffee agroecosystem in Mexico is complicated, and we suspect it is complex. We offer it as an example where the biological system is indeed composed of subsystems, yet its complete integrity depends on the multiple connections among the subsystems, making the test of Turing compatibility difficult to even contemplate since every coupling represents yet another subsystem. With even a first approximation of subdivision we encounter unresolvable contradictions.

## 1. Simple biological system, with no simple model

Our first example is from population growth data of the small beetle *Tribolium castaneum*. A relatively simple nonlinear mathematical model does extremely well at predicting the population sizes of the beetles in these small containers. For example, one form of the model predicts that the population should oscillate between two densities, and that between those two densities it should experience an unstable point. In the real population data based on an experiment done in 1980, the population numbers over time seemed, at first, odd, as shown in Fig. 1. However, with the aid of the model that predicted a two level attractor (with populations jumping from high values to low values every two



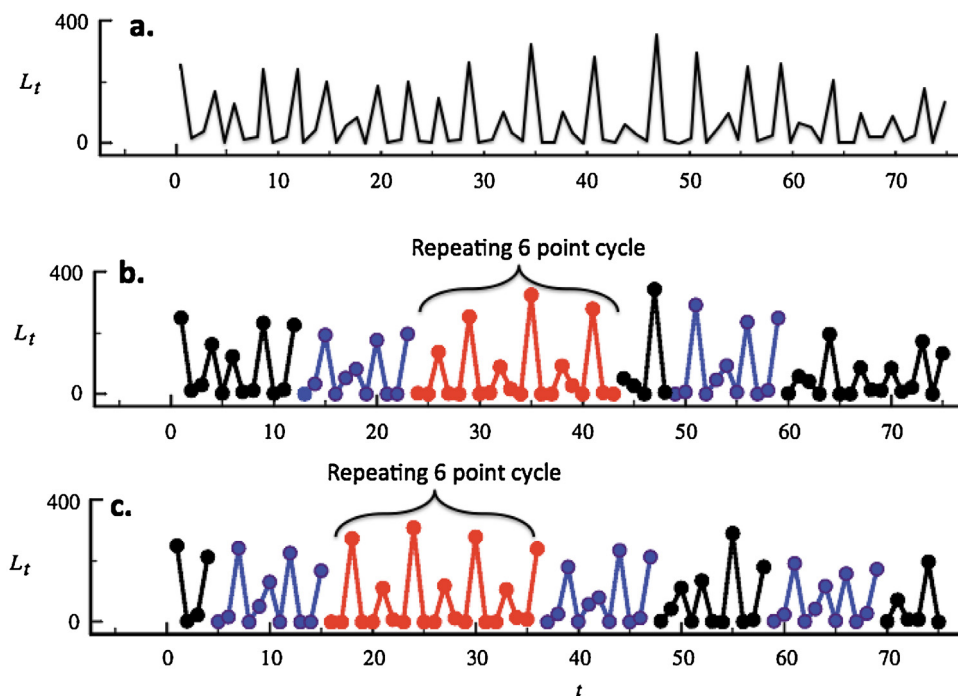
**Fig. 1.** Larval population density over time, illustrating the two major modes of population behavior, early on approaching the unstable point and lingering there for a long period of time, then moving into the expected two level oscillations (not exactly the same two points, but one high, followed by one low, followed by one high, and so forth). (Data from Jellison, 1980, adapted from Cushing, 2006).

week period), with an unstable equilibrium point between, those data make perfect sense. The population approaches the unstable point and lingers there for some time, but eventually moves toward the two-point oscillatory framework, conforming nicely to the expectations of the theory.

In a series of highly influential papers this system and the model representing it, were very “physics-like” in that every possible behavior of the system could be predicted from the basic model. Irregular trajectories, various periodic cycles, and chaos were all predicted by the model and when the system was parameterized to correspond to even the most bizarre predictions of the model, it behaved within normal statistical boundaries as the model predicted. At the time of the publication of the authors’ collective summary of the research in a volume entitled “Chaos in Ecology,” it seemed that reducing a system to its most “simple” variant (small beetles living in homogeneous flour in small vials), could indeed be represented by a model and that model could be studied providing a complete characterization of nature (the beetles in the vials).

However, in a later examination of one of the population trajectories that had been placed in the category of chaos (by choosing the parameter values that the model predicted would be in chaos), the population indeed seemed to correspond to a chaotic attractor, as illustrated with the raw data presented in Fig. 2a. A close look at the chaotic trajectories revealed, not surprisingly, an 11-point cycle, something the model had predicted would be embedded within the chaos. However, surprisingly at the time, the actual data (the system) also generated a clear 6-point cycle (see Fig. 2b). The unusual aspect of this case is that the underlying theory, while clearly predicting a chaotic attractor for the parameter settings, could not generate a 6-point cycle. The model could not replicate this feature of the chaos. What had been a remarkable synthesis of model and reality suddenly became contradiction. The *Tribolium* system and its model, in the end, was not a simple system.

However, redirecting the model, by placing the whole model on a lattice (both population and time modeled as integers – rounding predicted population numbers to the nearest integer) and



**Fig. 2.** Results of adding a stochastic factor to a basic population model (Hensen et al.). a. The empirical data illustrating a chaotic attractor. b. The empirical data color-coded to show the repeating six-point cycle (also visible in blue is an 11 point cycle). Note that the cycles are not perfect cycles, but rather generalized modes. c. The model predictions after adding the stochastic force in the model. (data extracted from Henson et al., 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

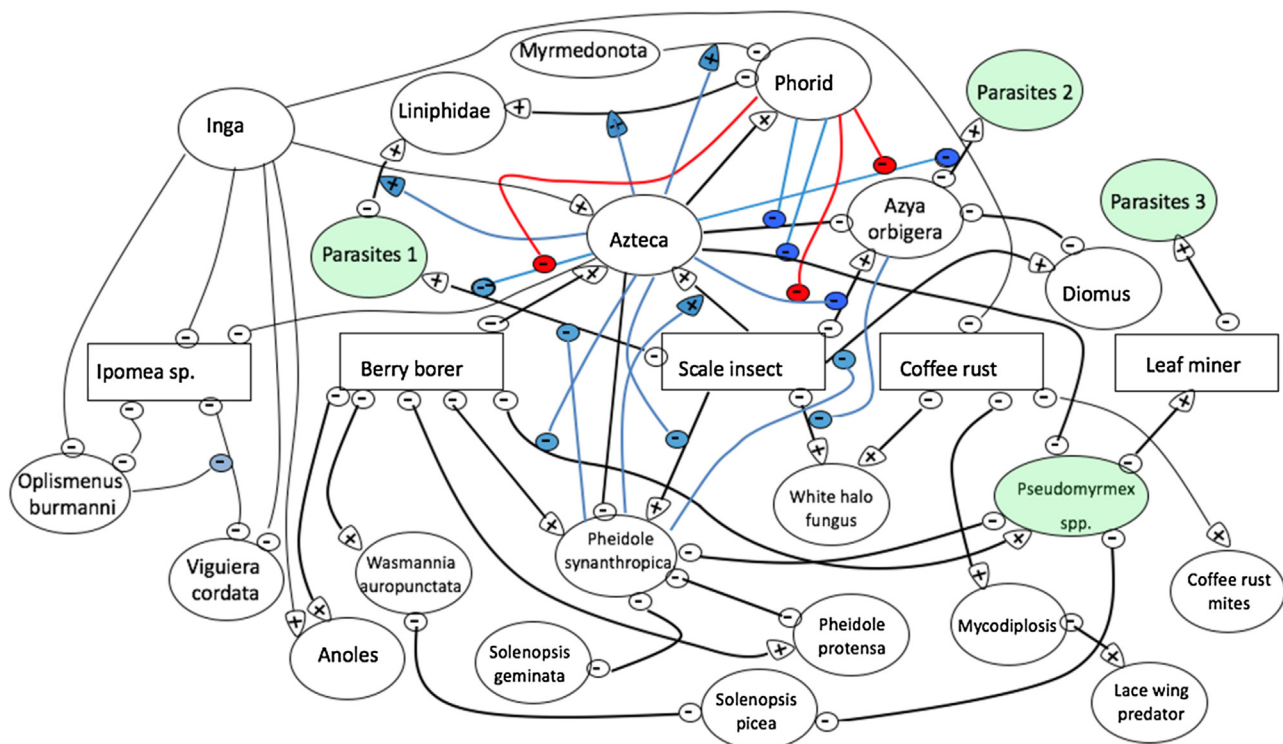
imposing a local stochastic force a modified chaotic attractor was able to produce the six-point cycle that the real data had suggested (Fig. 2c). We are left with the question as to whether the new model now corresponds precisely with the natural system or not, but at least the seeming precision of model and reality correspondence was illusory, suggesting the system was not simple after all, which means it must have been “complex” in the Rosennean sense. We emphasize that the intention of the construction of the model was an attempt to find a level of “simplicity” that would be sufficient to represent observed data accurately. That there was a dramatic deviation from the model did not cause the researchers to subdivide the model into simpler components, which would have been the strategy if the system were Rosennean simple, but rather to expand the model to incorporate a distinct level of complexity (stochasticity added to chaos).

In the end, this same research group carefully analyzed the chaotic attractor of this system and identified four basic modalities that could be recognized within the attractor (a six-point cycle, an 11 point cycle, a three-point cycle and an eight-point cycle). They conclude that it is “transient but recurrent cyclic patterns generated by [chaos], woven together by stochasticity, that distinguish chaos as it is manifested in noisy discrete-state population systems” (King et al., 2004). In the end it would have to be admitted that perhaps now the system has become simple, in that there is a model that corresponds very well with the system. But the history of this research program suggests that further observations of the real system are likely to generate yet further interesting deviations from the exact predictions of the model, which, it would seem, is the essence of Rosennean complexity. As we emphasize elsewhere (Vandermeer and Perfecto, 2017) this is perhaps an example of a system that is known to have simple rules, but in the end generates complicated behavior.

## 2. Complicated ecological system: higher order interactions induce complexity

From this very detailed look at a seemingly simple system, we move to the other end of the spectrum and examine a system that is known to be extremely complicated both in the number of elements represented and in the complicated nature of how they are interconnected, the pest system in the coffee agroecosystem. In a review of our work of the past 15 years (Perfecto and Vandermeer, 2015) we presented a complex network of dynamical connections, not a food web which looks at energy transfer among components, but rather a summary of the complicated way in which the system is constructed. It should be noted that the system is a “novel” system in the sense that all the elements that are used in its construction have been brought together only within the past century or so. Further research on this system since the publication of our book results in the diagram of the system, as our understanding of it emerges, as presented in Fig. 3. All the connections represented in the figure have been either directly observed in the field or emerged from detailed laboratory or field experiments. Undoubtedly other connections exist, but we have not discovered them as of yet.

It is clearly the case that the pest control system in coffee is a complicated system and no single model could create the required Rosennean collection of simple systems. Indeed it seems absurd to even suggest that one could reduce what we know is a highly interconnected system to a collection of Rosennean simple systems. Nevertheless, the spirit of Rosennean complexity is the failure of model/system conformity to emerge at any level of reduction. This feature suggests that if the system were not complex, there should be a way to subdivide it such that a model, even a conceptual model, will emerge that encapsulates at least the qualitative nature of the system. We believe this may be possible,



**Fig. 3.** The coffee pest system in southern Mexico. The main pests of coffee in this region are the five species contained in the small rectangles. Related species are contained in ovals, functional groups of species in shaded ovals. Direct effects (usually consumer resource effects) shown by positive/negative arrows or circles, trait-mediated effects, effectively nonlinearities in the system, indicated by connections from a species to one of the connectors between two elements (shaded arrows or circles indicating the trait-mediated nature of the connection; blue for first order trait-mediated indirect effects and red for the second order trait-mediated indirect effects). The ‘base’ of the system (coffee plants) is not shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



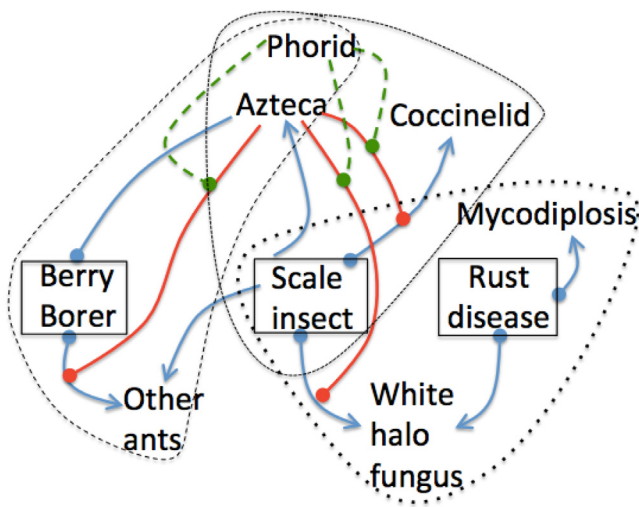


Fig. 4. Isolating three “subsystems” of the overall system of Fig. 3.

which, if true, would suggest that the coffee pest system is indeed not necessarily complex in the Rosennean sense.

Within this framework, it would initially seem that the complicated system of Fig. 3 could be decomposed into a subsystem, and that subsystem into further subsystems. While the ultimate goal may be to show that there are no subsystems that are simple no matter how much they are divided, it is also within the spirit of Rosennean complexity that each subdivision should make biological sense. We can, for example, divide the body into circulatory system, skeletal system, nervous system and so forth such that they can be studied as relatively isolated units. This is not saying that they are themselves Rosennean simple, but that the first step of reduction does not seem unreasonable. Can we do something similar with the coffee system?

At a first pass, we can consider only three of the five pests in the system, the coffee berry borer (*Hypothenemus hampei*), the scale insect (*Coccus viridis*), and the coffee rust disease (*Haemelia vastatrix*). The basic elements and their relationships to one another are illustrated in Fig. 4. Note that even the most elementary of the connections among components does not make sense. That is, it would represent a major misunderstanding of the system if we regarded the berry borer, the scale insect and the coffee rust as separable subsystems, if we take seriously all the direct and indirect interactions known to exist. It might make sense to consider overlapping subsystems, as we indicate with dashed lines in Fig. 4 (the phorid/Azteca/coccinelid/scale insect system, the scale insect/Mycodiplosis/rust disease/white halo fungus system, and the phorid/Azteca/berry borer/other ants subsystem). Yet it is clear that in doing so we have had to incorporate major elements of each subsystem, such that they would seem to be not compartmentalizable. Thus the first requirement in search of Rosennean simplicity is evidently not met. Our understanding of the system as philosophically simple fails at the first step of reduction.

### 3. Discussion

The two examples we present in this paper suggest that ecological systems are complex in the Rosennean sense. It may be suggested, however, that such an observation is not all that surprising. Thinking of the sense that Rosen and his followers have of the difference between simple systems (like physics) and complex systems (like biology), they have taken on a much more difficult task in considering those subdisciplines of biology that might be considered more “physics-like.” While it will surprise no

one to suggest that ecological systems are complex in the Rosennean sense, the argument that some biological systems (protein folding, for example) might indeed be formal simple systems, may not be surprising. What then does it do for us to claim Rosennean complexity for ecological systems? More importantly, can we see important distinctions between Rosennean complexity and what we call dialectical complexity? And would those distinctions be relevant to the enterprise of ecological science.

Following this reasoning it makes sense to ask the deeper question of what ecologists mean when they say ecological systems are complex. The largely correct observation that ecological systems are complicated, is really quite different from the claim that they are complex, at least in the modern usage of those terms. Complicated does not equal complex, especially in either the Rosennean or dialectical sense, but even in more general modern use of the term. A “complicated” system is a system with many components; by understanding each component you may be able to understand the whole, thus making them formally “simple” in Rosen’s formulation. In contrast a complex system, by common acceptance in today’s burgeoning field of complexity science, is characterized by interdependencies and it is the relationships among the parts that give rise to the whole. Therefore, understanding each component does not necessarily lead to an understanding of the whole. Complex systems have, in recent years, taken on a meaning that is more sophisticated and subtle than in the past, similar to, we would argue, the sense that Rosennean complexity sought to capture. Examples of what current “complexity” scientists regard as complex systems range widely, with applications in disciplines ranging from physics and chemistry to sociology and economics, to neurobiology and behavior, and, of course, ecology. But the statement that a system is complex, means more today than simply that it has many components (i.e., that it is complicated). A general flavor of the idea is incorporated in the seemingly contradictory pair of ideas that 1) simple systems can exhibit very complicated behavior and 2) complicated systems can exhibit very simple behavior [we here do not refer to Rosen’s notion of simple, rather a more colloquial use of the word]. Frequently complex systems, as viewed through a contemporary lens, take on one or another of these forms, sometimes appearing to incorporate both at the same time. We have sought to highlight both of these extremes with our presentation of the *Tribolium* system (a simple system exhibiting complex behavior) and the coffee pest system (a complex system exhibiting simple behavior – regulation of pests). And we offer more extended examples elsewhere (Vandermeer and Perfecto, 2017).

In the end, we suggest that it may be an approximate reflection of Rosennean complexity to note, as Levins and Lewontin did some time ago, that the very large (e.g., clusters of galaxies) and the very small (e.g., the internal structure of the atomic nucleus) actually “behave well.” Contrarily, systems of intermediate size cannot be said to behave well. That we can deduce what will happen at the event horizon of a black hole with the relatively simple equations of Einstein, even though we could never even see that horizon let alone get near it, attests to the fact that physical systems are Rosennean simple. The parallel situation in ecology would suggest that we could understand the structure of an Amazon rain forest with some simple measures of critical traits. Our sense, easily gleaned from the two examples offered here, if not from the canonical example of a tropical rainforest, is that no matter how much we “reduce” those traits, any model based on them will fail the test of Rosennean simplicity.

Although it would seem evident that ecological systems are Rosennean complex, we are less sanguine about suggesting such a framing will help in our further understanding of ecological complexity. We tentatively propose that dialectical complexity, as

described by Levins and Lewontin (see quote above), may be a better general categorization of what most contemporary ecologists are getting at when they claim that ecological systems are complex.

## References

- Henson, S.M., Costantino, R.F., Cushing, J.M., Desharnais, R.A., Dennis, B., King, A.A., 2001. Lattice effects observed in chaotic dynamics of experimental populations. *Science* 294 (5542), 602–605.
- King, A.A., Costantino, R.F., Cushing, J.M., Henson, S.M., Desharnais, R.A., Dennis, B., 2004. Anatomy of a chaotic attractor: subtle model-predicted patterns revealed in population data. *Proc. Natl. Acad. Sci.* 101 (1), 408–413.
- Levins, R., Lewontin, R.C., 1985. *The Dialectical Biologist*. Harvard University Press.
- Levins, R., 1966. The strategy of model building in population biology. *Am. Sci.* 54 (4), 421–431.
- Perfecto, I., Vandermeer, J., 2015. *Coffee Agroecology: A New Approach to Understanding Agricultural Biodiversity, Ecosystem Services and Sustainable Development*. Routledge.
- Rosen, R., 1986. On information and complexity. *Complexity, Language, and Life: Mathematical Approaches*. Springer, Berlin, Heidelberg, pp. 174–196.
- Vandermeer, J., Perfecto, I., 2017. *Ecological Complexity for Agroecology*. Routledge (forthcoming).
- Weisberg, M., 2006. Forty years of 'The strategy': Levins on model building and idealization. *Biology and Philosophy* 21 (5), 623–645.

## Further reading

- Robert Rosen, 1977. *Complexity and system descriptions Systems: Approaches, Theories, Applications* Springer Netherlands; 169–175.