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WHEN LOGIC FAILS ECOLOGY

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ABSTRACT

Ecology plays an important role in society, informing policy and management decisions across a variety of issues. As such, regularities in processes would indicate higher levels of predictive outcomes and would reduce the amount of research required for specific issues that policy makers need addressed. Scientific laws are considered the pinnacle of success and usefulness in addressing regularities or universal truths. Ecology studies complex interactions of individuals with unique behaviors, making the identification of laws problematic. Two equations, Malthusian growth and the logistic equation, continue to receive attention and are frequently cited as exemplar laws in ecology. However, an understanding of scientific laws shows that neither are good candidates for law status. In this paper, I will discuss why ecology is not well structured for scientific laws, as they are currently understood. Finally, I will consider alternative proposals for the role of laws in ecology and alternate forms of laws that may be applicable.

INTRODUCTION

IN A NEVER ENDING STREAM of papers, ecologists, philosophers, and mathematicians produce a steady list of suggested laws of ecology (Ginzburg 1986; Brown 1997; Murray 2000; Turchin 2001; Berryman 2003; Colyvan and Ginzberg 2003). But ecology does not seem to have generated a strong theoretical construct supported by the necessary data to point to an obvious set of laws. Plenty of detractors argue that ecology is devoid of laws and others argue that it does not admit laws. As a science with likely the broadest set of subdisciplines, universal statements seem difficult to come by. Many would argue that ecology is fundamentally different from other sciences, such as physics and chemistry. The differences include limitations on experimentation, the historical nature of the systems under study, and the complexity and variation of the interrelation of the elements of ecological study (individuals or populations). Even though these differences seem substantial, there is strong support for laws of ecology that, as stated by their proponents, model themselves on the laws of physics.

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The most frequently proposed laws of ecology involve exponential growth and logistic growth dynamics. Given a reasonable definition of a scientific law, I will show that neither model satisfies the requirements for a law. If these do not meet the criteria of scientific law, it must be asked: Are there laws in ecology? And, if not, what does that mean for the science?

Why Laws in Ecology?

Given the constant interest in ecological laws, one must ask why laws are important to ecology. The simple answer is that ecologists believe that their field is a "hard" science, and since the hard sciences of physics and chemistry have laws, so too should ecology. This "physics envy" answer may seem flippant, but there is, no doubt, truth to it, given the number of comparisons between the two sciences made by ecologists (Lawton 1999; Murray 2000; Turchin 2001; Lange 2005). Clearly this is not the only reason, and, Freudian arguments citing a deep-seated inadequacy in ecologists aside, other more important reasons for the apparent necessity of ecological laws need to be addressed.

The role of ecology in society has changed dramatically since Haeckel first coined the term over 140 years ago. As humanity has increased its ability to alter the ecosystems of the planet, ecology has become a vital tool to understanding the effects of humans on the biosphere. Since ecology is the underpinning of conservation biology, fisheries biology, agroecology, and much of environmental science, it takes on an important role in the design and implementation of management decisions. Laws in ecology can be considered vital, as policy makers need information to make decisions, and, without statements with law-like qualities, the ecologists are forced to address only particular cases, or unique incidents, and to qualify any prediction with caveats and limits. The pace of policy-making decisions leaves little room for developing predictive models based upon any sort of first principles. Thus, without universally true rules that can inform us on the outcome of an ecological process, ecology is limited in how much it can contribute to policy.

Defining Laws—or I Know It When I See It

Ecologists provide a vigorous defense of proposed ecological laws. To address whether these proposed laws are truly scientific laws, we must first address the question: What is a scientific law?

If we turn to the ecological literature that discusses scientific laws, we find descriptions that range from simple definitions of the word found in a dictionary (Lawton 1999; Berryman 2003) to definitions by exclusion, informing us what a law is not (Colyvan and Ginzburg 2003). Some use the term law (or "universal law," "scientific law," "ecological law") without explicitly defining the term. O'Hara (2005) considers two notions for laws, correlative and causative. Other discussions of ecological laws avoid the term altogether and use "principles" instead (Berryman 2003). These definitions of laws provided by ecologists differ substantially from stricter scientific phrasing of laws, particularly by failing to address necessity, nature of the truth, and counterfactual support.

The existence and importance of scientific laws in general is controversial (Cartwright 1980; Armstrong 1983; Van Fraassen 1989; Carroll 1994; Lewis 1994; Giere 1999; Lange 2000; Maturana 2000; Murray 2000). Philosophers argue about definitions of laws and, more importantly, how these definitions either allow for the existence of scientific laws or eliminate them as instruments of science. Since ecologists are strongly attached to the idea of these laws, the debate regarding their existence will not be addressed while consideration of scientific laws in ecology will.

A working definition for law is a factual truth that is spatiotemporally universal, supports counterfactuals, and has a high level of necessity (Lockwood 2007). Note that the factual truth provides an important distinction from "logical truth," which can be derived from mathematical principles but need not have empirical support (e.g., the Hardy-Weinberg principle in population genetics). The philosophical concept of necessity is important as it separates statements describing accidental situations of the known universe from those that fundamentally describe some observable phenomenon. The classic example is the comparison of the two statements, "There are no spheres of gold one kilometer in diameter" and "There are no spheres of uranium one kilometer in diameter." The first statement is simply a contingency of the current state of the known universe, whereas the second is a necessity due to the physical properties of uranium.

THE PROBLEMS WITH ECOLOGICAL LAWS—A CASE STUDY

One of the most cited candidate ecological laws is Malthusian Growth (Ginzburg 1986; Brown 1997; Turchin 2001; Berryman 2003). Simply put, the law states that a population will grow or decline exponentially (or geometrically), provided the environment remains constant for all individuals and that sufficient resources exist for the population. Mathematically, this verbal description has a simple formulation,

$$N(t) = N_0 e^{rt}. \qquad (1)$$

The number of individuals, N, at time, t, is a function of the number of individuals at time 0, N_0, and the growth rate, r. Although this mathematical expression is used to describe numerous processes, including radioactive decay, compound interest, and Moore's Law, its applicability as an ecological law is fraught with difficulties. First, consider the requirement for spatiotemporal universality in the definition of a law. Berryman points out, in defense of a Malthusian Law, that "geometric growth is a fundamental and self-evident property of all populations living under a certain set of conditions (unlimited resources)," which hints at the first major problem with the proposed law (2003:696). The law itself violates any possible temporal universality. Within a few generations, even at a relatively small growth rate, any population obeying equation (1) would exceed the capacity of this planet to sustain it. This is, of course, the point Malthus was making when he formulated the expression. For $t \rightarrow \infty$, equation (1) produces the absurd result that $N \rightarrow \infty$. Thus, temporal universality is violated. Spatially, it is easy to see that any organism occupies some nonzero volume of space, and that the amount of habitable space for the species is finite. As time increases, the volume of organisms will exceed the total habitable space. Thus, the spatial universality condition is violated.

Now, consider the factual truth requirement of the definition of a law. As aforementioned, a scientific law's truth must be factual and not merely logical. Empirically, there are no natural populations that demonstrate a sustained Malthusian growth pattern. Textbooks on population ecology generally begin with a logical argument to derive Malthusian growth. While these texts will sometimes provide a sample dataset that appears to support exponential growth for a very short period of time, it is important to note that these datasets are presented without measurement error associated with them, thereby weakening the argument. Clearly, the factual basis is in trouble when, as was put forth by Berryman (2003), the law holds for a set of conditions that are factually impossible—namely, unlimited resources.

Finally, the definition of scientific law as stated requires the support of counterfactuals, which are conditional statements that describe what would be the case if the antecedent were true. Although counterfactuals are difficult and often context specific, theoretical population ecology provides ample evidence for the lack of counterfactual support for Malthusian growth. Without substantial evidence for Malthusian growth in natural populations, it could be argued that the law operates but is hidden by numerous processes that also operate on populations (such as interactions with other populations or environmental stochasticity). Therefore, the most straightforward counterfactual should be that, in the absence of these extrinsic factors, Malthusian growth will occur. However, a vast array of population models exist that describe the dynamics of a single population and yet no exponential growth occurs (e.g., the logistic model, the Ricker model, the Beverton-Holt model, self-organized criticality, percolation). It could be argued that these models are conceptual counterfactuals, but they are developed based on empirical datasets that operate as empirical counterfactuals. In this case, there is not even logical support for the counterfactual claim for exponential growth.

Given the lack of support for Malthusian growth as a scientific law, the question becomes, why do ecologists insist that it is, in fact, a law? There are several underlying reasons. The first is its robustness as a mathematical construct. Turchin (2001) points out that the results are qualitatively similar over a range of assumptions, including adding age/stage structure, demographic stochasticity, simple diffusion, and environmental variability. In each instance, the results are logical mathematical extensions of the original equation. The lack of data validating these results cannot be overlooked. In arguing for the robustness of the construct, the law remains a logical truth, but not a factual one.

The second apparent reason for supporting the law is a strong reductionist philosophy. Berryman (2003) suggests that the law is self-evident for populations living under certain conditions, namely unlimited resources. Although resource availability is one condition, it is not the only one that is required for the law to have applicability. Malthusian growth, in its basic form, has numerous implicit assumptions, including that the population interacts with no other populations, it has unlimited resources, and that individuals within the population are interchangeable. The unlimited resources assumption is more complex than it would appear, as not only does the population have all the food necessary, it also has a spatial structure that generates no density dependent effects. The individuals are never too crowded nor too spaced out to find mates and food. Thus, for any population, this approach assumes that it can be idealized to a Malthusian population with the appropriate reduction in complexity. It is unclear whether this reductionism is informative, and, if the law only holds in the absence of any biological reality, it seems to be impractical at best.

The third line of reasoning used to support Malthusian growth as a law relates to physics and a misunderstanding of Newtonian Mechanics. “Lawhood by analogy” is a common theme in the literature that asserts that Malthusian growth is a law. The arguments vary, but the general theme is that Malthusian growth is to ecology as Newtonian Mechanics are to physics. Ecologists point out that Newton’s First Law defines the motion of a body in the absence of forces acting upon it and, therefore, is factually impossible. As is pointed out in Lockwood (2007), this approach fails to address the nuance of the meaning of the First Law. The law addresses an object with a net force of zero, of which there are numerous examples. Newton’s First Law obviously works for all objects sitting on a desk or a bookshelf. These have a net force of zero in the frame of reference of the room in which they are located, and, as predicted, are not moving. It can easily be seen that objects with a constant velocity, such as objects falling at terminal velocity, also obey Newton’s First Law. The failure to place Newton’s First Law in proper context weakens the law and creates a false sense of artificiality about it, which allows for a stronger argument for Malthusian growth.

Colyvan and Ginzburg (2003) argue that since laws are not exceptionless, the exceptions that prevent Malthusian growth from predicting the state of a population do not prevent it from being a law. Of course, this argument rests on the faulty assumption that Malthusian growth is operating at all. To eliminate the causes of the exceptions is to obviate that which is a population; hence, we have a law of populations that is contrary to the essence of what it is to be a biological population.

One of the most important issues regarding the interpretation of Newtonian mechanics is the argument that the laws are valid only for certain conditions. These laws have certain *ceteris paribus* clauses that limit their applicability to reality. In essence, it is argued that Newtonian Laws are highly idealized. Likewise, it is also recognized that Malthusian growth must have *ceteris paribus* clauses associated with it, which are among the assumptions of the model. Philosophers have deep disagreements about the role of *ceteris paribus* clauses in scientific laws, as these clauses are, in effect, allowing for reductionism within a more complex system. Newton's Second Law, mathematically expressed as,

$$\vec{F} = m\,\vec{a}, \tag{2}$$

demonstrates that a single law of physics, such as gravity, holds even in the presence of other forces. The net force on an object is the sum of all the forces acting on the object, hence the vector notation in equation (2). Thus, although it is argued that the law of gravity only works in idealized systems, the law of gravity works additively with other forces operating on an object. Colyvan and Ginzburg's (2003) claim that a snowflake falling at a different rate than a hailstone violates the law of constant acceleration fails to account for the simple additive effects of multiple forces. The force of air resistance summed with gravitational pull results in two different constant velocities. It is not that a law operating on an object must do so to the exclusion of all other laws; rather, laws can operate in conjunction with each other.

LOGISTIC GROWTH—ECOLOGY JUST DOES NOT ADD UP

The laws of physics described by forces are elegantly additive. Thus, a system can be decomposed into individual elements. The same notion underlies the assumptions required to allow Malthusian growth to be a law. Hence, there needs to be additive structure to population dynamics. The logistic equation (or the Pearl-Verhulst equation) would appear to be the next step in additive laws, and it is accordingly championed as an ecological law. It can be written as:

$$\frac{dN}{dt} = rN - \frac{rN^2}{K}, \tag{3}$$

where r is the growth rate and K is the carrying capacity. The first term on the right hand side of (3) is Malthusian growth written in differential equation form. Thus, by subtracting a single term, equilibrium population dynamics is achieved. While this appears to have the same additive nature as Newton's Laws, it is much more complex because equation (3), when solved, does not display the same additive nature. Although equation (1) is linear, (3) is nonlinear, with the first admitting only a single equilibrium and the second solutions including an equilibrium, oscillations, and chaos when expressed in discrete form. The continuous form of (3) produces a single stable equilibrium. The interpretation of the results then depends on how the system is represented. For physical laws we are not given a choice in how to represent the dynamics, thus leading to an outcome with wildly divergent results.

As a law of ecology, the logistic equation suffers from some of the same problems as Malthusian growth, as well as from of its own unique issues. First, as a universal factual truth, the logistic, like Malthusian growth, fails to have much empirical support. In fact, Hall (1988) points out that no dataset for wild populations can be shown to fit a logistic any better than a simple linear model.

Logistic growth does not support counterfactuals well largely because there are numerous formulations of single population dynamics, such as the Beverton-Holt and Ricker equations, that can all produce equilibrium dynamics comparable to the logistic, but with different functional forms. Turchin (2001) attempts to account for the problem with the logistic by reframing the law of population self-limitation as a foundational principle, which states that a population must have an upper bound. However, by removing the mechanism for self-limitation, it is unclear that this principle is not simply reduced to stating that no two physical objects can fill exactly the same space at the same time. This is not a principle of biology but a definition of what it means to be an extended object. It is obvious that all organisms in a finite habitat must have a maximal population size. This is not a biological reality per se, but a physical one, and it obviates Malthusian growth for temporal universality.

Other Laws, Other Problems

Although only two proposed laws are discussed here, others include the law of consumer-resource oscillations (Turchin 2001; Berryman 2003), Kleiber Allometry and other allometric relationships (Colyvan and Ginzburg 2003; Ginzburg and Colyvan 2004), stable age distributions (Murray 1979), and Liebig's law of the minimum (Berryman 2003). In general, these proposed laws suffer from the same criticisms directed toward the two laws discussed in this paper. Several are logically derived mathematical statements without strong empirical support. The allometric laws are notable due to the substantial growth in the metabolic theory of ecology that relates to these kinds of statements. Although there is empirical support for some of these allometric relationships, there are a number of critiques of the results that indicate that considering them laws would be premature. The critiques suggest that the relationships fail to meet the conditions of universality and necessity (see Brown et al. 2004 for a discussion of the current state of allometric relationships and Clarke 2004, 2006; Cyr and Walker 2004; Glazier 2005; Nee et al. 2005; and Niven and Scharlemann 2005 for criticisms of the approach).

Why Is Ecology Different?

Does ecology have laws or is it different in some fundamental way from other sciences? We may yet find laws with all the same robustness and predictability that occur in other disciplines, but it is also acknowledged that ecology is different than other sciences on some very fundamental levels.

That biology, and especially ecology, is different from other sciences is not a new idea, and several reasons for these differences are frequently stated. Ecological processes are historical, with past contingencies influencing the current state. The units of study in ecology, whether they are communities, populations, or individuals, do not conform to a Platonic ideal: any variation in a measurement of electrons is due to measurement error, while variation in population-level traits is a combination of measurement error and phenotypic variation occurring within the population. In ecology, there is no such thing as an ideal rabbit. As Brown (1997) points out, ecology requires both a reductionist and holist approach to understanding. Brown further argues that the reductionist approach is limiting the science, and I would argue that the current quest for Newtonian-like laws is a manifestation of the reductionist approach. Ecology fundamentally explores the dynamics among objects, and isolating the objects removes them from that which we are studying.

Wimsatt (1997) cogently defines aggregativity and emergence as traits of a system. Aggregative systems meet four conditions: 1) the system remains invariant for specific properties with the intersubstitution of parts, 2) system property maintains qualitative similarity with the addition or subtraction of parts, 3) the system is unchanged when the parts are reaggregated, and 4) the system exhibits no cooperative or inhibitory relations among the parts. Wimsatt argues that aggregative systems have robust laws (for example, the laws of conservation in physics). Systems with emergent properties are those which are not aggregative. Thus, the properties emerge from the state of the system and not from the general structure of the system. It is clear that ecological systems are not wholly aggregative and are emergent, otherwise, communities would be interchangeable and invasive species would be of little concern. It is important to note that emergent systems are resistant to strict reductionist methodologies for study. This has strong implications for the scientific laws of emergent systems. Physical laws (for instance, those that address the forces acting on bodies) are easily decomposable and, as such, are amenable to the reductionist approach. Proposed laws of ecology that are structured only as aggregative properties are, thus, likely to fail to provide strong explanatory power for understanding the complex phenomena in ecology.

WHAT IS TO BE DONE?

Philosophers argue for different ways to consider the structure of ecology. Elsasser (1981) argues that biological systems do not lend themselves to "mathematical" laws and suggests a more set theoretical notion of organization. By organizing the complexity of biology into heterogeneous classes, Elsasser posits that biology has effectively emergent properties and that, although the laws of physics and chemistry obviously apply, they are insufficient to fully explain biology. Elsasser's sets are similar in concept to Wittgenstein's "family resemblance" for kinds that cannot be reduced to single properties.

Mitchell (2004) argues for an integrative pluralism with respect to a philosophical structure of sciences and, in particular, biology. Avoiding the pitfalls of uncritical anarchy (i.e., allowing all propositions to stand) and of isolationism, in which science is discretized into different levels, Mitchell proposes three types of integration: 1) mechanical rules, which fit the physical sciences well as they are structured on linear, aggregative systems (sensu Wimsatt); 2) local theoretical unification, which addresses a smaller part of a system while, at the same time, recognizing that it represents part of a more complex whole and may offer predictions in a "roughly additive" way; 3) explanatory, concrete integration, which addresses the complexity of single systems in detail, acknowledging that the results are not likely to be "global and algorithmic." Mitchell (2002) also argues against the use of *ceteris paribus* laws for biology as they are mechanical rules but with the complexity swept under the rug, as it were, and they imply that a simple causal relationship is at the heart of the dynamics.

O'Hara (2005) acknowledges that ecology does not have causal laws, but does not consider this to be a serious roadblock. The fact that there are no generalities does not imply that there cannot be predictive successes. O'Hara also argues that there may be generalities in ecology, but they do not meet the standard of the definition of scientific law. O'Hara suggests that ecology may be better served by correlative laws, since these are not exceptionless. However, it is unclear whether correlative implies causal when *ceteris paribus* conditions are added. The notion of correlative laws being those descriptions that consist of observed regularities seems to be an attempt to admit a class of "fuzzy laws" into the philosophy of science.

CONCLUSIONS

There is no clear evidence that ecology cannot produce scientific laws, but proposed laws for ecology fall short of the task. Relying on these proposed laws as the underpinnings of the science will handicap ecology and limit its usefulness to society. Imagine if Newton's laws of motion provided no predictive results in real world applications. Engineering development of many technologies would have been reduced to a lengthy process of trial and error. Without laws for ecology, applied ecological sciences (such as restoration ecology and conservation biology) approach problems with the hypothetico-deductive method, rather than with an engineering-like method of applying known laws to novel systems.

The two specific laws discussed, Malthusian growth and the logistic equation, were developed based on logical principles and have tenuous connections to data. Although self-consistent and precise, the *ceteris paribus* conditions of the laws so restrict their applicability as to remove them from consideration as toolsfor predicting the behavior of natural populations.

Ecology is an important science that is involved with the human condition. It is critical to have society correctly understand that, as a science, ecology can produce results that can inform policy makers and managers to make better decisions. Holding up "laws" that fail to meet the criteria for being a scientific law will not engender a level of confidence in the results of ecological science in general.

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