Ecology: From Individuals to Collectives

A Physicist's Perspective on Ecology

Vishwesha Guttal

Common people and even scientists think of ecology as a discipline that exclusively studies wildlife and topics related to environmental pollution. My friends both within and outside the scientific community are often baffled when they hear that I am a physicist doing research in ecology. The aim of this series of articles is to emphasize the less known fact that theory and mathematics have been central to ecology since the inception of this relatively young scientific field. In this first article, I will talk about the following three points. First, I will discuss how the emphasis of the basic science of ecology is much broader than its applied aspects involving the conservation of natural ecosystems. Second, I will discuss a fundamental parallel between statistical physics and ecology that arises because both disciplines emphasize macroscopic systems (e.g., magnetic materials in physics or flocks of birds in ecology) as collectives of interacting units that are more than the sum of their constituents. What makes them fascinating is that interactions at small scales typically give rise to unexpected properties at larger scales. Finally, I will discuss how ecology offers a new and rich set of challenges to mathematically trained scientists because of variations among biological organisms and the role of natural selection in shaping ecological systems, both of which have no parallels in the physical sciences.

Vishwesha Guttal studies and teaches theoretical ecology and evolution at the Centre for Ecological Sciences, IISc, Bengaluru. He is a theoretical physicist by training and his current research interests are in tipping points in ecology, self-organization in ecological systems including pattern formation in vegetation, and collective behaviour in animal societies and evolutionary theory. He is also interested in developing interactive teaching methods to teach mathematics, physics and ecology to students of various age groups, from primary school children to college students and the general public.

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Ecology, evolution, conservation, statistical physics, mathematics, mathematical ecology.

Introduction

As I begin this series, I am reminded of an article published by Amitabh Joshi, an evolutionary biologist, in

Resonance nearly a decade ago. He noted that people associate evolution with fossils, and genetics with DNA [1]; however, he looks at neither fossils nor DNA, but he does carry out research in the area of evolutionary genetics. This often baffles his audience. My case is no different. The first layperson to be baffled is my own father, a retired agriculture officer, when he asks what are you physicists trying to do with ecosystems?! Of course, other lay persons and surprisingly even professional scientists are equally confused and bewildered when they learn that I am a physicist trying to study ecology and evolution, not by going into the field but often with pen, paper and computers!

Is ecology only about classifying plants and animals into different families, or studying wildlife, or is it all about agriculture, pollution and environmental conservation?

There are at least three different reasons for this confusion. The first stems from a general lack of understanding of what constitutes ecology. Is ecology only about classifying plants and animals into different families, or studying wildlife, or is it all about agriculture, pollution and environmental conservation? The second concerns why a theoretical physicist such as myself, or an applied mathematician, might be interested in research in ecology when they must concern themselves with physical laws of particles, properties of materials, and of course, sending rockets to the moon and Mars! A third reason for confusion is prevalent among ecologists themselves, when they fail to distinguish the roles of statistical and mathematical models in ecology.

The aim of this series of articles is to demonstrate how simple mathematical models can offer fundamental insights into ecological systems and processes. In this article, I will discuss the differences between the basic science of ecology and its applied aspects of conservation and mitigation of environmental degradation. I then argue that ecology offers fertile ground for fascinating and challenging questions for theoretical physicists and/or mathematically trained persons. I will continue the discussion of mathematical and statistical models in the next article.

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Ecology and Conservation

Historically, many ecologists have been closely involved in conservation and have championed the cause of environmental conservation. However, ecology is to environmental conservation as physics is to engineering. We know that physicists such as Newton or Einstein spent their lives discovering fundamental laws governing physical matter. Engineers, on the other hand, use those laws to invent new devices and tools that include the laptop that I am using to type this article, or to build rockets that take man-made satellites, or even humans, to the moon or Mars!

The relationship between ecology and conservation of wildlife is analogous to the relationship between physics and technology. Ecologists aim to discover fundamental principles of interaction within and between organisms, such as different plants and animals, that make up complex ecosystems such as forests, grasslands, lakes, marine systems and so on. Environmental scientists and conservationists use those principles to develop sustainable management tools to preserve our ecosystems. Below, I provide two examples, one from population biology and the other from studies on animal movement, to illustrate basic and applied aspects of ecology.

For species that feed or hunt in groups, a certain minimum population size is required for them to form groups and forage socially. If the population falls below the minimum size, it may go extinct due to the reduced ability of individuals to survive on their own. This principle is now popularly known as Allee effect.

An ecologist by name Warder Allee made an interesting discovery in the first half of the 20th century. He showed that, for species that feed or hunt in groups, a certain minimum population size is required for them to form groups and forage socially. If the population falls below the minimum size, it may go extinct due to the reduced ability of individuals to survive on their own. This principle is now popularly known as Allee effect. How is such a basic principle useful to a forest manager? We commonly hear news about reintroduction of a species into forest patches where they had originally lived. If such species live and feed in groups, the manager may need to account for the Allee effect for his/her species of interest, and introduce a certain minimum population size as part of the restoration plan. Otherwise, individuals will not be able to form groups that are essential for their survival. Therefore, a restoration plan that did not account for this could result in failure.

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Let me provide another example. I am always intrigued by how animals move to search for food in forests where the information on resources is uncertain? Do they have memory of previously visited places? Perhaps the most extraordinary of these is the phenomenon of long distance migration where birds, mammals and insects often cover significant parts of the globe. To answer questions related to animal movement, which arise out of sheer curiosity to understand the animal world, ecologists put radio collars on elephants, tigers, or birds to track their trajectories using satellite-based GPS and related technologies. Using data from these tracking methods, we can assess their movement patterns, preferred habitats, and resolve questions about how they search for resources and navigate over continental scales. Although these studies on animal movement may initially have arisen without any application in mind, they offer important clues to questions in conservation such as the minimum space required by organisms, or how migration may be affected by fragmentation of landscapes. Knowledge of feeding and breeding areas, and the migratory routes that animals use, is necessary to design reserve protected areas of appropriate sizes, and corridors that connect them so that the disruption of the natural behaviour of organisms is minimized.

In a nutshell, a primary goal of ecological research is to understand the fascinating patterns in the interacting world of plants and animals. This is not to say that the relevance of these research questions to applied aspects of conservation is not important. Indeed, many basic ecological questions arise based on a need for application to conservation. However, applied research is only a small subset of all ecological research.

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Rich Parallels Between Physics and Ecology: Emphasis on Collectives

Let me now move to the next point of confusion for my curious audience. Why would a theoretical physicist or a mathematically trained scientist be interested in ecological research? At the outset, the focus of these two fields looks worlds apart.

To begin with, consider this fairly straightforward parallel: physicists study the basic constituents of matter, such as electrons and protons and their properties (e.g., charge, mass). Ecologists, likewise, look at individual organisms (plants and animals of different species) as basic units of ecological systems and study their properties such as behaviour and physiology. This analogy, however, is somewhat superficial because such comparisons can be made between any two fields. However, neither physicists nor ecologists confine their studies to the properties of individual entities. They investigate how these basic units interact with one another; for example, while physicists would study interactions between electrons and electrons, electrons and protons, etc., ecologists study interactions between organisms of the same and different species. A focus on such basic interactions forms a fundamental pursuit of both sciences.

The deepest connection between physics and ecology, however, arises from the following; in both disciplines, there is a strong emphasis on understanding the collective behaviour of interacting units. Physicists try to understand commonly observed phases of matter such as solids, liquids, gases, or of magnetic materials. As an example, physicists study how these properties of magnets (such as attraction between opposite poles) arise because of the properties of tiny invisible spinning electrons that interact with one another.

Likewise, ecologists investigate distribution of species in space, such as species–area relationships that determine how the number of species scale with increasing area.

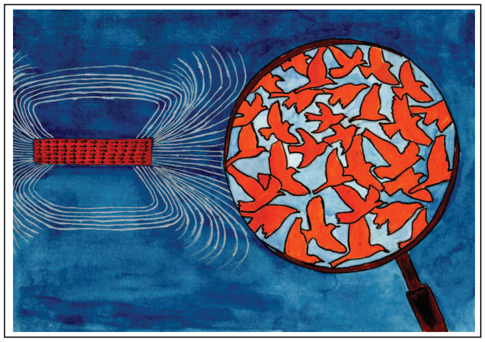

Figure 1. An illustration caputuring parallels between a magnet as a collection of interacting spins and a flock as a collection of interesting birds on flight.
Illustration: Suneha Mohanty

At smaller scales, behavioural ecologists might look at a flock of starlings to investigate their fascinating group maneuvers and synchronicity in flight, moving as if they have a collective consciousness. In both of these examples, like in the example of physics, ecologists investigate these macroscopic properties as a consequence of interactions among their constituents. A purist might find it hard to buy my analogy, but research over the last two decades shows that we can learn a lot about flocking birds and their movement by thinking of them as locally interacting electronic spins (which are typically stuck on a lattice) but in motion. Put simply, flocks might be thought of as flying magnets!

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It is not just in the type of questions that there is commonality between physics and ecology. P W Anderson, a Nobel laureate in Physics, eloquently wrote in his article in 1972, 'More is different', arguing that a detailed understanding of constituents does not necessarily guarantee an ability to derive collective properties of systems. This is because collectives are more than the sum of their constituent parts with new sets of fundamental laws arising at higher levels of organization. These laws can only be understood when such systems are studied as collectives. This is the basic principle on which both physicists (especially statistical physicists) and ecologists find common ground [3], despite the appearance of their focus being very different. In fact, the term 'emergent properties', implying collective properties arising from fine-scale interactions, made its way from ecology and evolutionary biology to physics [4].

Rich Gets Richer

Physicists like me would obviously be excited to find that the theories, tools and principles of physical sciences in which we were initially trained can shed light on fundamental ecological questions. Well, are the parallels between physics and ecology so perfect that we can just borrow results from physics, and apply them to ecology? Clearly, the answer is no.

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Ecological systems are substantially more complicated than physical systems. Physical particles such as electrons are all identical to one another whereas individual units of study in ecology, e.g., even organisms of the same species, show considerable variability in their characteristics. These cannot always be dismissed as mere additional detail. Whereas starling flocks may indeed be thought of as collections of moving electronic spins that interact with neighbors to align with each other, recent research shows that swarms of locusts are best explained because of their cannibalistic tendencies. Such differences can be extremely important from a biological perspective.

Apart from such details, biological organisms are subjected to a 'force', namely, Darwinian forces of natural selection due to differential reproductive ability of individuals. In simple terms, the dynamics of ecological systems are played out in a theatre with an underlying constraint of the 'survival of the fittest'. There is no counterpart of individual fitness and natural selection in physics; an electron remains an electron with any number of interactions (ignoring high energy scenarios which are not relevant for our discussion) and its interactions with other particles remains the same.

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For a willing physicist, not only does ecology offer interesting parallels to physics, but it is also serendipitously a fertile ground for fundamentally new and mathematically challenging questions on evolving heterogeneous individuals, their interactions and resultant emergent properties of their collectives. A lifetime hardly seems sufficient to understand the various fascinating possibilities arising out of such complex systems.

Concluding Remarks

In this article, I have tried to provide an informal perspective on ecology to address an audience who wants to know what ecology is, and why a theoretical physicist would want to study ecology. In summary, I have argued that ecology is a basic science with rich parallels to studies in physics, especially statistical physics where the focus is on understanding emergent properties of collective phenomena of large numbers of interacting constituents. If the constituents are physical particles, we are in the realm of statistical physics. If we replace them with biological organisms, we are studying ecology. Of course, the inherent variation and biological evolution that operates on living organisms make ecology rich with profound and challenging questions. In addition, the principles we derive from these basic questions can offer us insights and tools for better management of ecosystems.

Ecology is a basic science with rich parallels to studies in physics, especially statistical physics where the focus is on understanding emergent properties of collective phenomena of large numbers of interacting constituents.

In the next article, I will give specific examples to show how mathematical theories of simple ecological systems can offer predictions and unusual insights into the dynamics of ecological systems. I will also discuss the distinct roles that mathematics and statistics play in ecological studies.

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Address for Correspondence
Vishwesha Guttal
Centre for Ecological Sciences
Indian Institute of Science
Bangalluru 560 012, India.
Email:
vishwesha.guttal@gmail.com

Suggested Reading

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