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Can ecology help genomics: the genome as ecosystem?

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Abstract

Ecologists study the rules that govern processes influencing the distribution and abundance of organisms, particularly with respect to the interactions of organisms with their biotic and abiotic environments. Over the past decades, using a combination of sophisticated mathematical models and rigorous experiments, ecologists have made considerable progress in understanding the complex web of interactions that constitute an ecosystem. The field of genomics runs on a path parallel to ecology. Like ecology, genomicists seek to understand how each gene in the genome interacts with every other gene and how each gene interacts with multiple, environmental factors. Gene networks connect genes as complex as the 'webs' that connect the species in an ecosystem. In fact, genes exist in an ecosystem we call the genome. The genome as ecosystem is more than a metaphor – it serves as the conceptual foundation for an interdisciplinary approach to the study of complex systems characteristic of both genomics and ecology. Through the infusion of genomics into ecology and ecology into genomics both fields will gain fresh insight into the outstanding major questions of their disciplines.

Introduction

Genomics has been described as the ultimate integrative discipline, crossing the full spectrum of the biological sciences. Without doubt, genomics is a multidisciplinary pursuit, combining primarily molecular biology and computer science. The genomics era has also brought a renewed interest in systems biology, conceptually a broader multidisciplinary endeavor, and said to bring together biology, chemistry, computer science, engineering, mathematics, and physics (Ideker et al., 2001; Kitano, 2002; Hood & Galas, 2003). Absent in these lists of the 21st century's new biology is a mention of the field of ecology, the scientific study of the processes influencing the distribution and abundance of organisms, particularly with respect to the interactions of organisms with their biotic and abiotic environments.

This absence is surprising – surprising because both ecologists and genomicists ask similar questions, their respective disciplines have developed along similar intellectual trajectories and share basic epistemological approaches. In many ways, the genome and the ecosystem are parallel constructs and can be studied using similar approaches. The thesis of this paper is that including the field of ecology as part of the study of genomics will lead to advances in both disciplines.

A metaphor

Imagine the Serengeti plain of east Africa: grasses, shrubs, and trees extend over the landscape; giraffe, elephants, and antelope graze over the grasslands; lions, leopards, and hyena hunt and scavenge; vultures, flies, and fungi linger over carrion. Over the past millennium, natural historians

have discovered and described these, and many other, individual species of plants, animals and microbes. Ecologists stepped in over a century ago to study what an individual species *does* in its environment, its 'autoecology'. In other words, we now know how a giraffe manages to live in the Serengeti. In the past century, through a combination of manipulative experiments and mathematical theory, ecologists have made great strides in understanding interactions between individual species (e.g., Wilbur, 1987; Morin, 1999). As a result, to a large degree, we now know how giraffes interact with trees, with other giraffes, with other herbivores, with predators, and even with dung beetles (Jankielsohn et al., 2000): a fairly complex network of interactions.

However, the challenge of ecology is not to understand only the giraffe's role in the Serengeti ecosystem: a complete ecological understanding of the Serengeti would require that we understand the rules regulating how *each* and *every* species in the ecosystem, from bacteria to lions, interacts with every other species and how each species interacts with multiple environmental factors. Needless to say, this is a complicated problem. It is made more complicated by the fact that complex systems are rarely the sum of their parts: emergent properties lead to nonlinearities. Considering the complexity of the problem, ecologists have made astonishing inroads into understanding the natural world, although some remain skeptical (e.g., O'Connor, 2000). Keep the metaphor of the giraffe in the Serengeti in mind as we consider how examination of another 'species' – the gene in its genomic ecosystem – may further accelerate breakthroughs in ecology and genomics.

The metaphor extended: the genome as ecosystem

Although the pace of intellectual development has been much more rapid in genomics, the parallels to the development of ecology are unmistakable. Like those legions of systematists identifying the individual species in the ecosystem, geneticists made a cottage industry of identifying single genes until the advent of whole-genome sequencing (and bench geneticists continue to make remarkable progress in carefully reconciling predicted genes with actual ones). In many ways, genomicists reintroduced natural history to biology, albeit a molecular natural history, eschewing hypothesis-driven research and proclaiming a new phase of 'discovery-based' inquiry (Ideker et al., 2001) with the argument that the field needed to accumulate the basic information upon which hypotheses could later be based.

Like ecologists in the Serengeti, the mainstay of many modern molecular geneticists is attempting to understand the function, the autoecology, of each gene. For many pathways, we know how genes interact with other genes, like we know how giraffes interact with other giraffes or other animals. Molecular geneticists have long understood how genes interact with the environment. Genes live in an ecosystem like animals live in their ecosystem, and although the tools used to study genes and giraffes are clearly different, the broad intellectual approaches to understanding genes and giraffes are not so different.

However, like ecology, the ultimate challenge of genomics is to understand how each gene in the genome interacts with every other gene (epistasis) and how each gene interacts with multiple, environmental factors. Gene networks are just as complex as the 'web' that connects all the species in an ecosystem (Tong et al., 2004). Again, understanding that degree of complexity is a complicated, multidimensional problem. What emergent properties will arise from the complexities of the genome? Will understanding the function of every gene ever allow us to predict complex phenotypes? How pervasive are epigenetic effects (e.g., Waddington, 1942)?

If we see the genome as an ecosystem where genes live, how much more progress will genomicists make in understanding that ecosystem than ecologists have made in understanding their ecosystems? Regardless of the answer to that question, ecology and genomics do have enough to offer one another that the two disciplines may reach their common goal with a healthy interchange of ideas.

What can ecology and genomics offer each other?

Certainly molecular geneticists have offered ecologists a myriad of tools to understand ecology and in many ways those tools have revolutionized ecology. However, what does ecology offer genomics? The most important thing ecology can offer genomics is experience in simply thinking about, and being trained in thinking about, complex interactions. Most often, this training is