Genetic Information and Ecosystem Health: Arguments for the Application of Chaos Theory to Identify Boundary Conditions for Ecosystem Management

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To meet the demands for goods and services of an exponentially growing human population, global ecosystems will come under increasing human management. The hallmark of successful ecosystem management will be long-term ecosystem stability. Ecosystems and the genetic information and processes which underlie interactions of organisms with the environment in populations and communities exhibit behaviors which have nonlinear characteristics. Nonlinear mathematical formulations describing deterministic chaos have been used successfully to model such systems in physics, chemistry, economics, physiology, and epidemiology. This approach can be extended to ecotoxicology and can be used to investigate how changes in genetic information determine the behavior of populations and communities. This article seeks to provide the arguments for such an approach and to give initial direction to the search for the boundary conditions within which lies ecosystem stability. The identification of a theoretical framework for ecotoxicology and the parameters which drive the underlying model is a critical component in the formulation of a prioritized research agenda and appropriate ecosystem management policy and regulation. — Environ Health Perspect 102(Suppl 12):71–74 (1994)

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Introduction

Exponential human population growth and the concomitant demands for goods and services have brought humans face to face with the failure of the Industrial Age position towards the environment. The Industrial Age management position defined success solely in terms of how much could be extracted from the environment and assumed that landscapes, ecosystems, communities, and populations all had an effectively infinite ability to recover for the sustained benefit of humans. With ever more powerful human technology, it is now apparent that the human ability to effect larger and larger changes of energy and material throughput in ecosystems in shorter and shorter time swamps the capacity of ecosystems to adapt to change and leads to the destabilization of ecosystems, communities, and populations. The challenge of the 21st century will be the creation of management systems that will maintain ecosystem cycles and community and population dynamics, while meeting the needs of human populations by factoring in all ecosystem needs and relationships.

Two conceptual tasks stand between us and the goal of sustainability. First, humans must reassess their material and energy needs, including population growth, with the realization that there is no ‘free lunch’, environmentally or economically. This area is receiving increased scrutiny (1–3) and will not be discussed here. The second task is the development of technology which can supply goods and services with minimal ecosystem, community, and population destabilization. This will require the evaluation of current technologies to determine environmental effects and, for those older technologies identified as unacceptable, the invention of new technologies designed specifically to avoid impacts of a destabilizing nature.

In the Industrial Age, the criteria for acceptability rested in a technology’s ability to serve a human need without a deleterious impact on humans. Indeed the first cracks in the Industrial Age paradigm came as a result of our increased awareness of the deleterious effects of chemicals on human health, giving rise to the field of toxicologic research. Although its mandate was human health, toxicologic experiments provided much of the reductionist argument for correlating observations of community and population fluctuations with chemical contaminants in the environment. Hence, the field of ecotoxicology was born.

The concerns of ecotoxicology are the negative impacts of chemical compounds and ions on organisms. Historically, ecotoxicology evolved out of studies of the negative impact of chemical compounds on human health, and hence ecotoxicology exists within the greater conceptual sphere of environmental health. It must be noted that an intense debate centers on the use of the term “health” as it pertains to the environment. The debate contrasts the position of Costanza and colleagues (4) and those of Sutter and colleagues (5) who oppose the concept on a number of grounds, especially focused on the implications of the “health” model for regulation. This debate is not rhetorical. As Bateson (6) has conceptualized and Sutter (5) has articulated in a specific application to ecotoxicology, contextual bias due to language can all too frequently lead to logical errors. In this, ecotoxicology is not immune and would be well served by a critical reexamination of the implications of the health metaphor and its appropriateness within the ecology/environmental context.

The focus of this conference is the role genetic investigations could play in ecotoxicology. This focus gives us the opportunity to limit discussion in two ways. First, the perturbations in which we are interested are the measurable effects of chemical
compounds on DNA; the frequency of genetic alleles in the population; and the genetic structure of populations, including changes in mutation rates. The second limitation constrains us to discuss how these specific genetic changes perturb ecosystems, communities, and populations to cause impacts and, potentially, destabilization.

**Impacts versus Effects**

Pollution and contaminated environments offer the opportunity to evaluate ecosystem, community, and population responses to perturbations resulting from current chemical technology. For clarity, two levels of responses to a perturbation can be defined: effects and impacts. "Effects" are measurable responses in the DNA, its higher order structure, or the frequency of alleles with each organism or within a population. These effects may or may not result in measurable changes in ecosystem function or community or population dynamics. Klekowski (7) notes that genetic changes, such as chromosomal aberrations in meristematic cells of angiosperm plants, have been measured in response to PCBs and can be lethal to these cells. However, these changes may have no impact on the whole plant because the multicellular nature of the apical bud and the developmental patterns of the bud can accommodate loss of meristematic cells through replacement. The case is totally different in lower plants such as ferns in which the meristem consists of only one cell, which, if lost, will terminate further development of the fern apical meristem and lead to premature death of the plant. This observation speaks to the idea that the translation of effects into impacts occurs when effects change the behavior of an organism or a population of organisms with other organisms or with the abiotic environment, such as changing the plant's developmental pathway as in the case above.

"Impacts" are measurable responses to perturbations which are manifested at the level of ecosystem processes or community or population interactions. For the majority of perturbations, impacts will range in size over orders of magnitude. It is obvious that human existence, at whatever technological level, will have effects, some of which will result in impacts. From the perspective of societal needs vis à vis environmental regulation and policy, the focus of research needs to be the subset of impacts whose probability to result in destabilization of ecosystems, communities, and populations is high. Although we may regret specific impacts, destabilization is what threatens future human existence. For progress to be made in the recreation of technology with minimal potential for ecological system destabilization, the challenge rests in determining the criteria which will identify the subset of destabilizing impacts and how such impacts effect the processes which effect stability. In other words, what is needed are the predictive criteria for ecosystem, community, and population destabilization.

**Theoretical Framework**

At present, ecotoxicology lacks a theoretical framework which identifies and organizes the parameters affecting system dynamics. As the proceedings of this conference clearly show, a large amount of substantive data is being collected on the genetic impacts of a number of chemical contaminants on an ever widening diversity of organisms and environments. What is repeatedly lamented is the lack of a theoretical framework which could distinguish between random fluctuation and system fluctuation driven by process. Such a predictive model is critical for two reasons. First, it is required to prioritize research studies by identifying which parameters drive system processes at the different levels of ecologic scale, landscape, ecosystem, community, and population. Second, predictive capability is a fundamental requirement for policy. Without prediction, regulation is meaningless and systematic prevention of deleterious effects is impossible. Two approaches can be taken to develop models for observational data: first, models developed for other systems can be evaluated for their application to ecotoxicologic data; and second, new models can be developed from mechanistic understanding of the parameters believed to result in system behavior. Both approaches are available to ecotoxicology.

The problems of ecotoxicologists are similar to those of epidemiologists. In the latter case the study of impacts of pathologic agents on host organism populations is the problem to be modeled. The traditional approach to modeling such data has been spectral analysis (8). Using this approach, the conclusion drawn from a number of studies is that fluctuation of disease incidence in populations is stochastic and is not predictable. In recent years, however, a new type of mathematical analysis has been used successfully to reveal underlying deterministic behavior in apparently random systems in physics and chemistry, such as turbulent flow and dissipative systems (9). Driven by the success of the new mathematical formulation, applications have begun to surface in a number of fields, including epidemiology (10,11) and ecology (12–14).

**Application of Chaotic Models**

Based on these approaches, ecotoxicologic population data over generations can be analyzed to determine if the impacts of chemical toxins on populations fall into the category of deterministic chaos (11), as some epidemiologic data do, or if this model is not appropriate. If the results of these modeling efforts show evidence for chaotic system behavior, then the challenge becomes to determine the underlying parameters which drive these chaotic systems. More specifically, within the framework of genetics, the question becomes one of determining what role changes in genetic structure or information play in determining the behavior of the chaotic systems as applied to ecotoxicology.

Kauffman (15) has recently presented a theoretical treatise which attempts to model adaptation, evolution, coevolution, and organism development based on the mathematics of deterministic chaos. He presents the NK Model and its modifications as a theoretical framework upon which to organize evolution and coevolution of populations and communities with our understanding of the statistical interactions of genes, alleles, and loci in fitness landscapes. This model makes specific predictions about how gene locus number, allelic number and frequency, the number of intra- and interspecies, epistatic interactions, mutation rates, and the number of species will interact to settle into stable states, oscillations, or unpredictable (chaotic) patterns. However, to quote Kauffman (15), "The applicability to real coevolving systems is untested." The opportunity exists for ecotoxicologists to test this model for its ability to predict community and population responses to chemical compounds as they specifically impact the genetic information within these ecologic assemblies.

The NK Model describes the behavior of systems made up of discrete members (N) which interact with each other (K). This model has been extended to community and population levels with the addition of environmental interactions (C) and ranges of the number of species (S). Discussion of the structure and special cases of this model are fully developed by Kauffman (15) and are beyond the scope.
of this commentary. However, a basic observation of this treatment is that fitness landscapes which are too smooth or too rugged relative to the magnitude of interactions among individuals will not allow adaptation; instead they produce chaotic appearance of phenotype or freeze phenotypes into poor fitness compromises for interacting individuals. It is only within the modest window between chaotic behavior and frozen phenotypes that enough organized interaction and unpredictable individual behavior exist to optimize the systems ability to adapt to perturbations.

The NK Model is Kauffman's approach to defining the fitness landscape with particular attention to relationships and couplings of landscape features, the number of coevolving members, and the overall structure of the system in terms which can be tested. The concept of fields of interaction is not new and has been developed in genetics as fitness landscapes (16) and in ecology as field theory (17,18). What is the focus of increased interest is the idea that the fitness landscape and fields of influence may be best modeled by nonlinear, chaotic functions.

The NK Model (15) suggests that a number of experiments within the scope of genetic effects in ecotoxicology research would produce data which could be used to test the NK Model. For example, mutation rate is one parameter which drives the NK Model. Consider the appearance of a mutant phenotype within a population which resulted from a change in DNA structure caused by exposure to a chemical compound. In terms of the model, this event could change the number of epistatic interactions of the genetic locus (before mutation) or could result in a change of the number of interactions of the individual organism and others in its environment. This corresponds to changes in the K value of the model, which in turn will change the fitness landscape for the organism and may or may not change the balance of stable, interactive states from more fluid margins.

**Model Testing**

Experiments which determined the dose response of mutation rate as a function of a particular chemical contaminant within a particular species would be of use in testing the model. Extension of these studies to classes of chemical contaminants would generalize model testing accordingly; e.g., one specific PCB vs the class of PCBs, and to groupings of species, e.g., angiosperm vs gymnosperm plants, vertebrates vs nonvertebrates, fish vs rodents, and within and across environmental types, e.g., within temperate hardwood forest vs softwood forest communities. The number of interactions (K) among the discrete members at any scaling level—e.g., genes, individual genotypes within a species population, or individuals between species within a community—also drives the model and for smaller values of K, stable fitness peaks organize in the fitness landscape. Estimating epistatic interactions of genes is quite difficult; however, crude estimates may be possible (19). Determining the value of K at the ecosystem, community, and population levels has major emphasis in ecologic research (20). Allen and Hoekstra (20) have attempted to restructure ecology along intellectual lines similar to those of Kauffman in their application of nonlinear modeling to ecologic systems. These authors have noted that the specificity of connections in the ecologic landscape, the change in the specificity, the number and the cycling times of connections can be destabilizing events for ecosystems (20).

The second task that lies ahead is to integrate science findings into policy, regulation, and the reinvention of technology. Society's need for rules of conduct vis à vis their interactions with the environment is increasingly pressing onto the reluctant scientific community the responsibility of regulatory decision making. It is no longer enough to know how something works in the closed, isolated, and simple laboratory system; scientists are continually asked to predict how individual perturbations will impact the open and complex ecologic systems in which people live.

Scientific information continually adds to the database from which technological solutions to societal problems arise. The formulation of these solutions crosses the line from science and enters the realm of technological development, engineering, and management. It is here that mechanistic data become of premier importance. It is through the understanding of mechanism that intervention strategies, either in the form of fixing what isn't working or preventing unwanted anticipated outcomes, can be devised. As stated earlier, an intrinsic position of the "health" paradigm is intervention in the form of reversal of undesirable condition. However, the time and spatial scales of ecosystems, communities, and populations make apparent that intervention, in the medical sense, is not viable. Within the environmental scale, management for stability will be within the context of preventing destabilizing impacts. In ecotoxicology, the need for mechanistic data lies in understanding the characteristics of chemical toxins which lead to destabilizing impacts. Armed with this theoretical understanding, new technologies can then be invented which will minimally destabilize ecosystems, communities, and populations. Clearly the value of any subset of mechanistic studies cannot be evaluated relative to ecosystem management at present because a theoretical framework capable of predicting the relative destabilizing effects of impacts is not in hand.

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