ECOTOXICOLOGY
A Hierarchical Treatment

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CHAPTER 1

Ecotoxicology as a Science

Michael C. Newman

I. ECOTOXICOLOGY ASSESSED FROM A SCIENTIFIC CONTEXT

> *Science is concerned with creating an intellectual model of the material world. Technology is concerned with procedures and tools and their general use to gain or use knowledge. Practice is concerned with how to treat individual cases. Confusing the three can be dangerous.*
>
> Slobodkin and Dykhuizen (1991)

The goal of science is to organize and classify knowledge based on explanatory principles (Nagel, 1961). It follows that the goal of ecotoxicology as a science is the organization of knowledge about the fate and effects of toxicants in ecosystems based on explanatory principles (Newman, 1995). The consistency of this goal with the definition of ecotoxicology originally given by Truhaut (1977) and more recent definitions (e.g., Cairns and Mount, 1990; Jørgensen, 1990) imparts a comforting unanimity during our initial efforts to describe this emerging scientific discipline. Unfortunately, this appearance of consistency passes quickly when this goal is used to judge present activities in ecotoxicology. Inconsistencies arise from the complex interweaving of various scientific, technological, and practical goals within this socially obligated endeavor.

What are these various goals? The goal given above suffices for scientific ecotoxicology. However, the technological objective of ecotoxicology is development and effective application of tools and procedures to acquire a better understanding of toxicant fate and effects in ecosystems. Practical ecotoxicology applies available knowledge, tools, and procedures to specific problems. For justifiable reasons, most present efforts address crucial issues in technological

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and practical ecotoxicology. Taken together, the predominance of technological and practical motivations imparts a distinctly nonscientific structure to the field. Consequently, a contradiction emerges: the accepted (scientific) goal of the field is inconsistent with the activities of most ecotoxicologists. In the resulting confusion, standard methods essential in practical ecotoxicology may be timidly applied to scientific questions, despite the availability of more appropriate methodologies and the absence of any regulatory requirement for using the standard methods. An individual's proficiency may be gauged more from his or her rote application of such methods and regulations than from scientific creativity and problem-solving skills.

Although the confusion is lessened by recognizing the distinct goals of scientific, technological, and practical ecotoxicology, the imbalance in relative effort remains. Scientific ecotoxicology frequently comes as an afterthought as the immediate and crucial technological and practical goals are addressed. Unfortunately, the long-term vitality of the field depends upon the growth of knowledge based on explanatory principles. Students are not routinely trained to effectively address ecotoxicological questions in a scientific manner. After defining ecotoxicology as a scientific discipline, mentors teach by example that technical acumen is more important than circumspective development of hypotheses and formal testing through the falsification process. Students of ecotoxicology are instructed extensively in techniques, specific qualities of important toxicants, and important regulatory practices, while problem solving skills and inferential methods are quietly neglected. At present, measurement is taught as intrinsically valuable, a characteristic of "unnatural science" that Medawar (1982) calls *idola quantitatis*. This process perpetuates itself as students so taught move on to work in the field, assess proposals, and mentor new students. At present, most innovation in ecotoxicology diffuses in from other fields such as chemistry, ecology, epidemiology, statistics, and mammalian toxicology. A degree of cross-fertilization of ideas occurs among all fields but, lamentably, the ability to generate, clearly state, and test novel concepts remains underdeveloped in ecotoxicology.

II. ECOTOXICOLOGY AND THE QUALITIES OF A SCIENTIFIC DISCIPLINE

> [A balance of faculties] *should be cultivated in scientific research. Imaginativeness and a critical temper are both necessary at all times, but neither is sufficient. The most imaginative scientists are by no means the most effective; at their worst, uncensored, they are cranks. Nor are the most critical minded. The man notorious for his dismissive criticisms, strenuous in the pursuit of error, is often unproductive, as if he had scared himself out of his own wits ...*
>
> Medawar (1982)

A. BALANCE OF NORMAL AND INNOVATIVE SCIENCE

Now that we have defined the goal of science and related it to the goals of ecotoxicology, let's examine the means by which such a goal is reached. Kuhn (1970) identified two essential categories of scientific endeavor, normal and innovative. Scientists engaged in normal science do not intend to generate new ideas or discoveries. Instead, they abandon the large picture to their fascination with solving puzzles, regardless of their intrinsic value. The importance of normal science lies in the incremental enrichment of our breadth, depth, and precision of knowledge about established theories and paradigms (Kuhn, 1970). In contrast, innovative science involves rejection or major modification of existing paradigms, and formulation of new paradigms. Innovation occurs after normal science has accumulated sufficient detail to test established paradigms more rigorously. It follows that a balance of normal and innovative science must exist within any discipline for effective progress. For example, a preoccupation with every detail of every instance in a scientific discipline leads to the "tyranny of the particular" (Medawar, 1967). Facts accumulate faster than they can be incorporated into theory, with a consequent inefficiency in developing, organizing, and using knowledge for predictive purposes. In ecotoxicology, the necessity for standardization and the immediate need for action in specific situations, combined with the normal scientist's fascination with particulars, contributes to our present dearth of innovative science. It encourages a preoccupation with methodology, particulars, and *idola quantitatus*.

How should the science of ecotoxicology change to progress more effectively? Remarkably, most of the essential components for rapid advancement are already present. Technological and practical ecotoxicologists have already adopted quality control methods for accurate and precise measurement, a crucial requirement for rapid advancement (Newman, 1995). Normal science has flourished during the present presynthetic stage of ecotoxicology; consequently, facts are plentiful. The present movement of ecotoxicology from a predominantly descriptive discipline to a mature science requires only that the value and qualities of innovative science be taught to students both formally and by example. Possessing sufficient facts in many areas, we now need to focus more on the question, "Why is this so?"

B. THE IMPORTANCE OF STRONG INFERENCE

Advancement in the new science of ecotoxicology can be fostered in several ways. Required at this time is a stronger inferential approach, which must be perceived and taught to be as valuable as the present regulatory approach of most ecotoxicology. The writings of John Platt (1964) are particularly pertinent to this point.

Platt (1964) observed that scientific disciplines progress at very different rates and that these differences appear to arise from the value placed on systematic scientific thinking and rigorous testing of hypotheses. He referred to such systematic application of inductive inference within a field as strong inference. Problems are formally addressed using working hypotheses, alternative hypotheses, critical testing with appropriate accuracy and precision, and repetition of the testing with sequential hypotheses until only one explanation survives the falsification process, i.e., the scientific method. Rigorous testing with high risk of falsification is an essential feature of this process. Chronic application of low-risk tests in any field of study is undesirable, as belief can be falsely increased solely by frequent repetition of a theme (Popper, 1965). Platt (1964) argued simply that a sequence of a few carefully selected hypotheses, rigorously tested, will advance understanding faster than many poorly formulated or weakly tested ones. The cumulative effect within a discipline of each worker using strong inference is accelerated progress. Also critical to Platt's formulation of strong inference is the concept of multiple working hypotheses.

Chamberlin (1897) formulated the concept of multiple working hypotheses nearly a century ago yet, in reality, it is rarely practiced explicitly today. Many aspects of Chamberlin's argument are particularly germane to ecotoxicology and will be discussed in detail. In developing his arguments for multiple working hypotheses, Chamberlin described three historical phases of intellectual evolution. Initially, so little was known in most subject areas that experts were assumed capable of understanding fully any particular subject. An immediate and sufficient answer based on some general theory was given when a question was asked. Such a ruling theory provided unquestioned or weakly questioned explanation. This process of uncritical assertion of a theory (precipitate explanation) reinforces the ruling theory by repeated application alone, not by rigorous testing. Although formally discarded as untrustworthy in modern science, a tendency toward precipitate explanation still exists. It is pervasive in ecotoxicology due to technological advocacy (a reluctance to question or tendency to unobjectively support a particular technique, regulatory approach, or standard method) and a general inconsistency in adhering to a scientific context. Although the goals of technical and practical ecotoxicology justifiably encompass such unscientific behavior, the purpose of science is decidedly not to win or maintain primacy for a particular theory, idea, method, or approach (Cournand, 1977). Scientific progress in ecotoxicology continues to be hindered by precipitate explanation.

In the present phase of intellectual evolution, ruling theories have been replaced by the familiar working hypothesis. Facts are gathered and tests are formulated to falsify the working hypothesis. A working hypothesis should have no favored status except that accrued after surviving repetitive and rigorous testing. Chamberlin argued that many applications of the working hypothesis concept retain elements of precipitate explanation. There is a tendency to give favored status to the central working hypothesis and to consider alternate hypotheses as secondary. Loehle (1987) refers to this tendency to "confirm one's theory, or to not seek out or use disconfirming evidence" as confirmation bias. Chamberlin suggested that the method of multiple working hypotheses can be used to lessen confirmation bias. With this method, equal amounts of effort are spent in testing all reasonable hypotheses simultaneously. The method of multiple working hypotheses also avoids the tendency to stop testing when a single cause is found and to ignore the possibility of additional causes. Consideration of multiple causes is particularly important in ecology and ecotoxicology (Hilborn and Stearns, 1982). Indeed, Quinn and Dunham (1983) point out that the numerous interactive effects in ecological systems must be incorporated into this process. An awareness of interactions must be used to supplement the steps just described and to temper conclusions drawn from hypothesis testing when applying strong inference to ecological questions.

C. THEORY MATURATION AND STRENGTH OF INFERENCE

With the goals and general qualities of modern scientific inquiry summarized, we can address theory maturation within scientific disciplines. The process of theory maturation gives explanation to transitions and contrasting attitudes seen in ecotoxicology today.

Symptomatic of the present evolution of ecology, and specifically ecotoxicology, are the contrasting views regarding the applicability of the classic hypothetico-deductive method. Quinn and Dunham (1983) reject this method and the associated strong inference concept with the remarkable statement that the logic of ecology (and evolution) is different from that of traditional science. Hilborn and Stearns (1982) also reject strong inference and identify ecological science as unique. Slobodkin and Dykhuizen (1991) also urge caution in applying traditional scientific methods to ecotoxicology. In contrast, Cairns (1990) argues that too many of our present practices in ecotoxicology are driven by the history of the field, not their scientific soundness. He advocates rejection of many of our present paradigms and adherence to a more rigorous falsification process (Cairns, 1992). The present author strongly supports Cairns's argument.

Is ecology (and ecotoxicology) unique as a science or can traditional scientific methods be applied profitably to ecotoxicology? A brief discussion of the maturation process exhibited by scientific disciplines will reveal the partial truths in these contrasting views. All sciences pass through a period in which facts accumulate faster than they can be assimilated into theory (Medawar, 1967). Accrual of facts and description is paramount in these early stages, and rigorous falsification is less pertinent. This descriptive stage may end after an uncomfortable transition period characterized by a continued, but now unjustifiable, preoccupation with detail (i.e., tyranny of the particular). Eventually, a mature and healthy science emerges in which normal and innovative scientists work together to carefully examine facts and test hypotheses. If a particular hypothesis withstands the rigors of strong inference, it is incorporated into a unifying set of theories and paradigms.

The contrasting views described above suggest that ecotoxicology is making that confused, yet exciting, transition to a mature scientific discipline. As rightfully suggested (Hilborn and Stearns, 1982; Quinn and Dunham, 1983; Slobodkin and Dykhuizen, 1991), such a deficiency of facts and basic understanding of phenomena existed until recently that insistence on rigorous falsification would have led to premature rejection of many correct theories. Insufficient information was available to formulate concise and discriminating hypotheses, and interpretation of test results would have remained superficial. Loehle (1987) cautions against such dogmatic falsification. Hinderance of progress by dogmatic falsification is exaggerated by the surprising, yet pervasive, resistance of most practicing scientists to innovation (Barber, 1961). The rejections of strong inference described above appear to be aimed at dogmatic or inappropriate falsification. Fact accrual and description remain the most valuable means of advancing our knowledge in several areas of ecology and ecotoxicology. However, there are many more areas in which the tyranny of the particular exists and, as argued by Cairns and the present author, strong inference is essential for further advancement. Without strong inference, progress is hindered by precipitate explanation, *idola quantitatis,* confirmation bias, technical advocacy, and theory tenacity (a resistance to discard a theory, belief, or framework during problem solving despite evidence to the contrary [Loehle, 1987]). Consequently, ecotoxicology remains ripe for pathological science, i.e., science practiced with excess loss of objectivity (Hall, 1989; Rousseau, 1992).

D. MODEL MATURATION

Just as theory maturation has yet to occur fully in ecotoxicology, there has been an epiphenomenal delay in model maturation. Models in any quantitative science function as either exploratory tools, redescriptions, or generative representations (Taylor, 1989). An exploratory tool is formulated to highlight behaviors of the system of interest. For example, the logistic growth model may be used to explore possible behaviors of populations, although it is understood that the model does not accurately reflect the behavior of any specific population. The one-compartment, first-order bioaccumulation model is often used as an exploratory tool in ecotoxicology.

A redescription simply summarizes observations and permits limited prediction under the assumption that the modeled pattern will be repeated. Many examples of this type of model occur in ecotoxicology. A response surface model generated with a polynomial is a redescription model. As implemented in ecotoxicology today, the probit model for toxic response is a redescription of data. A redescription makes the transition to a generative representation if "the model captures the necessary and sufficient conditions to explain the phenomenon observed [so that] we can make confident predictions for situations not yet observed" (Taylor, 1989). Many quantitative structure-activity relationships (QSAR) are presently making this transition from redescription to generative representations.

As our understanding increases, more ecotoxicological models must make the transition from redescriptions to generative representations. For example, the empirical relationship between metal toxicity and water hardness should be replaced by models quantitatively linking metal speciation to toxic action. Another example is the empirical incorporation of a temporal dimension to toxicity data by plotting some endpoint value (e.g., LC50) against time to estimate an incipient lethal level. This approach should be replaced by methods such as those described in Chapter 8. Obviously, model maturation is slowed by legal or regulatory adherence to any specific redescription model. Finally, more effective use must be made of exploratory tools. For example, very few ecotoxicologists have taken advantage of optimal foraging theory, despite a rich literature surrounding it, (e.g., Stephens and Krebs, 1986), the notable exception being papers by Atchison and Sandheinrich (Atchison et al., 1987; Sandheinrich and Atchison, 1990; Chapter 11 of this book). With the transition to a mature science, the emphasis on redescription will be replaced by an emphasis on explanatory principles. Hopefully, the result will be that arrested development at the redescription stage will be remedied and a more effective use of exploratory models will occur.

III. THE EMERGENCE OF ECOTOXICOLOGY AS A SCIENCE

Well, there are two kinds of biologists, those who are looking to see if there is one thing that can be understood, and those who keep saying it is very complicated and that nothing can be understood ... You must study the simplest system you think has the properties you are interested in.

Cy Levinthal as quoted in Platt (1964)

Ecotoxicology is making the transition to a mature science. Whether this occurs quickly or slowly depends on our collective openness to change, dissatisfaction with mediocrity, and sense of urgency regarding current environmental issues. The distinct goals and activites of practical, technological, and scientific ecotoxicologists must be understood and valued during the transition. As scientific ecotoxicologists, it is time to abandon the false paradigm that "ecological systems are too complex to permit any useful level of prediction." This hobbling belief permeates much of ecotoxicology today and prolongs the tyranny of the particular (Newman, 1995). Although true in early stages of our science and still true in some areas of ecotoxicology, this false paradigm is now invoked more to avoid rigor and allow business to comfortably continue as usual. With its rejection, emphasis can be placed on paradigms that function as touchstones, not talismans. In addition to descriptive, analytical, and regulatory training, it is important that students develop strong problem-solving skills and a reflexive tendency to insist on knowing, "Why is this so?".

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