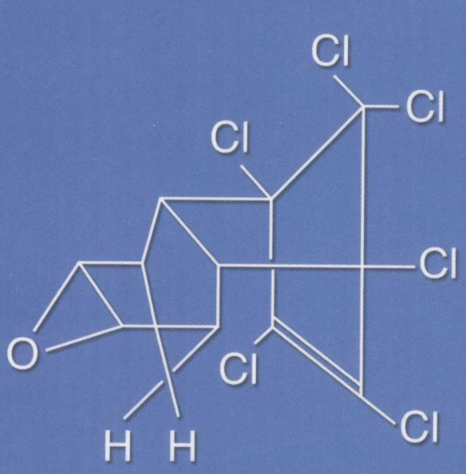
Fourth Edition



PRINCIPLES OF ECOTOXICOLOGY

C.H. Walker, R.M. Sibly, S.P. Hopkin, D.B. Peakall

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Fourth Edition

PRINCIPLES OF ECOTOXICOLOGY

This fourth edition is dedicated to the memory of

Dr. Steve Hopkin (1956–2006)

who made key contributions to the first two editions.

Preface to Fourth Edition

Since publication of the first edition of *Principles of Ecotoxicology*, both David Peakall and Steve Hopkin have died—serious losses to the international scientific community. Both made key contributions to the first two editions. The last edition was dedicated to the memory of David; we dedicate this edition to the memory of Steve.

The origins of this book lie in the MSc course titled "Ecotoxicology of Natural Populations," first taught at Reading in 1991. Ecotoxicology was then emerging as a distinct subject of interdisciplinary character. The structure of the course reflected this characteristic and was taught by people of widely differing backgrounds ranging from chemistry and biochemistry to population genetics and ecology. Combining the different disciplines in an integrated way was something of a challenge.

The experience of teaching the course persuaded the authors of the need for a textbook that would deal with the basic principles of such a wide-ranging subject. The intention has been to approach ecotoxicology in a broad interdisciplinary way, cutting across traditional subject boundaries. However, the nature of the text is bound to reflect the experiences and interests of the authors.

Since publication of the first edition, important advances occurred in some areas of ecotoxicology and progress was disappointingly slow in others, reflecting the high costs of certain types of research and the difficulty of obtaining support for some areas of study that do not represent the highest priorities of funding agencies. The objective of this fourth edition has been to bring the text up to date and strengthen the treatments of certain topics that we believe are very important now. We have continued to follow our original purpose—emphasizing principles rather than practice. Other works that describe testing protocols and modern statistical techniques for analyzing data from ecotoxicological studies are cited in the text and on lists of further reading at the end of each chapter. Throughout the book, small changes and additions have been made and a new final chapter has been added to discuss prospects for the future development of ecotoxicology.

A theme running through this new edition is how the concepts discussed may contribute to improved methods of environmental risk assessment. To what extent will it be possible to adopt a more mechanistic approach to risk assessment using biomarker assays or comprehensive simulations of animal populations in realistically modelled landscapes? How feasible is it to use results from tests whose endpoints are not toxicity data for laboratory species but changes in populations, communities, or ecosystems? Protocols for ecotoxicity testing are currently subject to much debate and touch not only on scientific issues but on ethical, economic, and political ones as well. In recent years, the suffering of laboratory animals caused by toxicity testing has become an important issue in Western countries.

In producing this fourth edition the authors gratefully acknowledge the feedback, help, and advice from many users of the book, especially Dr. Peter Hodson, Dr. Russ McClain, Dr. Erik Muller, Dr. Marinus L. Otte, Dr. William E. Robinson, and Dr. Denise M. Woodward.

Colin Walker and Richard Sibly

Acknowledgments

Many people have contributed to this book in many ways. Although we cannot acknowledge them all, we would specifically like to mention our MSc students who contributed much in discussion and feedback, and Amanda Callaghan, Peter Calow, Peter Dyte, Mark Fellowes, Valery Forbes, Glen Fox, Andy Hart, Graham Holloway, Tom Hutchinson, Paul Jepson, Laurent Lagadic, Alan McCaffery, Mark Macnair, Steve Maund, Pavel Migula, Diane Nacci, Miroslav Nakonieczny, Ian Newton, Demetris Savva, Ken Simkiss, Nick Sotherton, Nico van Straalen, Pernille Thorbek, Chris Topping, Charles Tyler, Paule Vasseur, and George Warner.

We have made every effort to contact authors and/or copyright holders of works reprinted in *Principles of Ecotoxicology*. This has not been possible in all cases, and we will welcome correspondence from individuals and companies we have been unable to trace.

Authors

Steve Hopkin died in 2006. He was a zoologist who worked on electron microscopy and x-ray analysis for his Ph.D. and later investigated the effects of metals on soil ecology at the University of Bristol. During his time at University of Reading, his teaching and research focused on the roles of essential and nonessential metals in the biology of soil invertebrates.

The late **David Peakall** studied chemistry and commenced his research as a physical chemist. He moved into biochemistry and finally into environmental toxicology. The last move was in keeping with his long-standing interest and active involvement in ornithology. During the last fifteen years of his scientific career, he was chief of the wildlife toxicology division of the Canadian Wildlife Service where he played a major role in studies of the Great Lakes.

Richard Sibly applied a degree in mathematics first in animal behavior and then more widely in ecology, including studies of the population effects of environmental chemicals. His recent work has focused on the new metabolic theory of ecology and developing and using agent-based models (ABMs) in population ecology and environmental risk assessment.

Colin Walker originally qualified as an agricultural chemist. He was responsible for chemical and biochemical studies of environmental pollutants at the Monk's Wood Experimental Station during the mid-1960s when certain effects of organochlorine insecticides were established. This work led to restrictions on the use of cyclodienes and DDT. He subsequently joined the University of Reading where he taught and conducted research on the molecular basis of toxicity with particular reference to ecotoxicology. Now retired, he is currently affiliated with the Department of Biosciences at the University of Exeter where he teaches a course in ecotoxicology.

Introduction

The term *ecotoxicology* was introduced by Truhaut in 1969 and was derived from the words *ecology* and *toxicology.* The introduction of the new term reflected a growing concern about the effects of environmental chemicals on species other than humans. It identified an area of study concerned with the harmful effects of chemicals (toxicology) within the context of ecology. Until now environmental toxicology focused mainly on the harmful effects of environmental chemicals on humans, e.g., the effects of smoke on urban communities. However, environmental toxicology in its widest sense encompasses the effects of chemicals on ecosystems as well. Thus ecotoxicology is a discipline within the wider field of environmental toxicology (see Calow, 1994). In the present text, it is defined as the study of harmful effects of chemicals upon ecosystems and includes effects on individuals and consequent effects at the levels of population and above.

Despite this definition, much early work described as ecotoxicology related little to ecology or toxicology. It was concerned with the detection and determination of chemicals in samples of animals and plants. Seldom could the analytical results be related to effects on individual organisms, let alone effects on populations or communities. Analytical techniques such as gas chromatography, thin layer chromatography, and atomic absorption facilitated the detection of very low concentrations of chemicals in biota. Establishing the biological significance of the results was a more difficult matter! One of the main themes of this text is the problem of progressing from the measurement of concentrations of environmental chemicals to establishing their effects at the levels of the individual, the population, and the community.

New disciplines frequently present problems of terminology, and ecotoxicology is no exception. Several important ecotoxicology terms are used inconsistently in the literature. Their use in the present text will now be explained. Both pollutants and environmental contaminants are chemicals that exist at levels judged to be above those that would normally occur in any component of the environment. This immediately raises the question of what is to be considered normal. For most man-made organic chemicals such as pesticides, the situation is simple—any detectable level is abnormal because the compounds did not exist in the environment until humans released them. Conversely, chemicals such as metals, sulfur dioxide, nitrogen oxides, polycyclic aromatic hydrocarbons (PAHs), and methyl mercury occur naturally and existed in the environment before humans appeared. The variations in concentrations of these chemicals from place to place and from time to time make it difficult to judge their normal ranges.

The distinction sometimes made between pollutants and contaminants raises further difficulties. In the wider literature, the term pollutant implies that the chemical in question causes environmental harm. A contaminant is a chemical present at levels above those that might be judged normal and may or may not have caused environmental damage. In this text, examples of environmental chemicals have been chosen that are widely regarded as pollutants. They have been shown to have caused environmental harm or clearly exhibit the potential to do so at environmentally realistic levels.

By contrast, the contaminant term implies that a chemical is not necessarily harmful at environmentally realistic levels. The difficulties with this distinction are threefold. The first is the general toxicological principle that toxicity is related to dose (Chapter 5). Thus a compound may answer to the description of pollutant in one situation but not in another—a problem mentioned earlier. The second issue is the lack of general agreement about what constitutes environmental harm or damage. Some scientists regard deleterious biochemical changes in an individual organism as harmful; others reserve the term for declines in populations. Third, the effects of measured levels of chemicals in living organisms or in their environments are seldom known, but the term pollutant is applied to them. Judgment of this issue is made more difficult by the possibility of potentiation of toxicity when organisms are exposed to mixtures of environmental chemicals. To minimize these terminology, problems of "pollutant" will refer to environmental chemicals that exceed normal background levels and can cause harm. It would be attractive to reserve the term for particular chemicals in situations in which they have been shown to cause harm, but because problems of measurement, this usage would be too restrictive. Harm encompasses the biochemical or physiological changes that adversely affect individual organisms' birth, growth, or mortality rates. Such changes would necessarily produce population declines if other processes (e.g., density dependence) did not compensate (Chapter 12).

Whether a contaminant is a pollutant therefore depends on its level in the environment, on the organism considered, and whether the organism is harmed. Thus a compound may answer to the description of pollutant for one organism but not for another. Because of the problems in demonstrating harmful effects in the field, the terms pollutant and contaminant will, to a large extent, be used synonymously because it can seldom be said that contaminants have no potential to cause environmental harm in any situation. We will use environmental chemical to describe any chemical that occurs in the environment without judging whether it should be regarded as a pollutant or as a contaminant.

Another word that has been used inconsistently in the literature is the term biomarker. Here, biomarkers are defined as biological responses to environmental chemicals at the individual level or below, demonstrating departure from normal status. Biomarker responses may be at the molecular, cellular, or whole-organism level. Some workers would regard population responses (changes in number or gene frequency) as biomarkers. However, as the latter tend to be much longer term than the former, it may be unwise to use the same term for both. In the present text, the term biomarker will be restricted to biological responses at the level of the whole organism or below. An important thing to emphasize about biomarkers is that they represent measurements of effects, which can be related to the presence of particular levels of environmental chemicals; they provide a means of interpreting environmental levels of pollutants in biological terms.

Finally, the organic pollutants considered in this text are examples of xenobiotics (foreign compounds). They play no part in the normal biochemistry of living organisms. Xenobiotics will be discussed in Chapter 5.

Although ecotoxicology is a relatively new discipline, it is worth emphasizing that chemical warfare has been waged in the natural environment since early in the evolutionary history of Planet Earth. Both plants and animals produce chemical weapons. Plants produce metabolites that are toxic to animals that graze upon them. In turn, animals developed enzyme systems (e.g., forms of cytochrome P450) that can metabolize and thereby detoxify such compounds. This phenomenon has been called a co-evolutionary arms race (Harborne, 1993).

It is worth recalling that a number of naturally occurring compounds exert insecticidal actions and this property has been harnessed commercially by marketing these compounds as insecticides—or using them as models for the development of novel insecticides. Examples include natural pyrethrins and nicotine, both of which have been used as insecticides and as models for novel commercially developed insecticides. Conversely, the detoxifying enzymes present in insects can protect against commercially developed insecticides. Indeed, the continued and indiscriminate use of insecticides leads to the emergence of resistant strains of insects via a process that might be described as unnatural selection. Whichever term is used, the study of the molecular basis of the development of resistance provides a superb example of the operation of the principle of natural selection—a phenomenon of great interest to Darwinians.

These considerations extend beyond the responses to chemical weapons produced by animals and plants during the so-called co-evolutionary arms race. Other naturally occurring chemicals including methyl mercury, methyl arsenical compounds, polycyclic aromatic hydrocarbons, and certain heavy metals exert selective pressures on living organisms. These chemicals originate from the weathering of rocks, natural events such as volcanic activity, and the metabolic actions of microorganisms. Thus, ecotoxicology can be viewed against the background of the effects of a wide range of naturally occurring toxic compounds acting on living organisms during the course of evolution.

Approach and Organization of This Book

An exciting feature of ecotoxicology is that it represents a molecules-to-ecosystems approach that relates to the genes-to-physiologies approach originally identified by Clarke (1975) and extensively developed in North America in the 1980s (Feder et al., 1987). Moreover, it analyzes experimental manipulations on the largest of scales (although the experiments were not designed as such). Thus metal pollution, acid rain, and the applications of pesticides have affected whole ecosystems, sometimes with dramatic consequences for their populations. In ecotoxicology, the ecosystem response is studied at all levels. Initially (Figure 0.1), the molecular structures of pollutants and their properties and environmental fate are considered (Section I of this book).

Ecophysiologists generally analyze the impact of pollutants on an organism's growth rates, birth rates, and death rates; indeed, as explained above, pollutants can adversely affect these vital rates. This makes it desirable to understand how adverse effects on vital rates have implications for populations (Chapters 12 and 13). Consequently it is, in principle, possible to evaluate pollutants quantitatively in terms of their population effects. This emphasis on vital rates as crucial intervening variables, linking physiological effects to population effects, is a particular feature of this book. The approach is continued in Chapter 13 to consider whether and how quickly resistant genes increase in populations. The rate at which resistant genes increase is measured by the population growth rate of the population of resistant genes. The population growth rate of resistant genes is a measure of their Darwinian fitness. Although this is not the conventional population-genetic measure of fitness, it is particularly useful in ecotoxicology because it (alone) shows explicitly how the fitness of resistant genes depends on the effects those genes have on their carriers. To summarize, the approach taken in this book allows linkage to be made between the different levels of organization shown in Figure 1, from molecules to physiologies to populations, right through to ecosystems. This is the underlying basis for the biomarker strategy, which seeks to measure sequences of responses to pollutants from the molecular level to the level of ecosystems (Chapters 10, 15, and 16). The use of biomarkers in biomonitoring is described in Chapter 11. These four chapters are placed at the end of their respective sections of the book. They represent the practical realization of theoretical aspects described in earlier chapters.

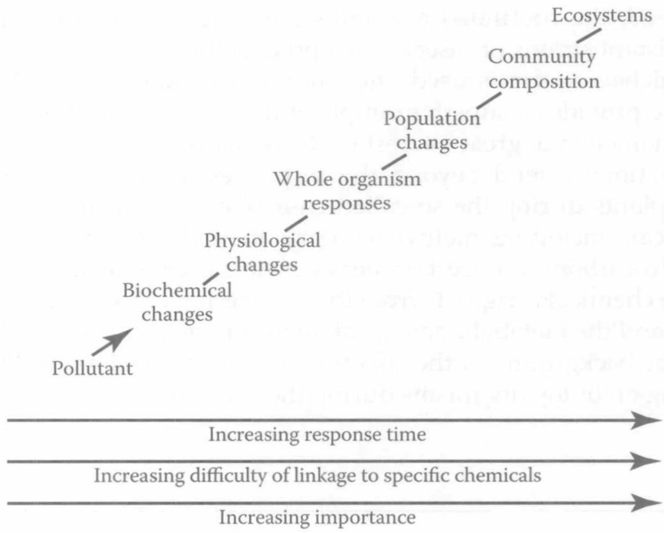

FIGURE 0.1
Schematic relationship of linkages between responses at different organizational levels.

The text is divided into three parts. Section I describes major classes of organic and inorganic pollutants, their entry into the environment, and their movement, storage, and transformation within the environment. Thus, this part bears a certain resemblance to toxicokinetics in classic toxicology which deals with the uptake, distribution, metabolism, and excretion of xenobiotics by living organisms (Chapter 5). The difference is in complexity. Ecotoxicology deals with movements of pollutants in air, water, soils, and sediments and through food chains, with chemical transformation and biotransformation.

Section II deals with the effects of pollutants on living organisms and resembles toxicodynamics in classic toxicology. The difference is again one of complexity. Toxicodynamics focuses on interactions of xenobiotics and their sites of action; ecotoxicology covers a wide range of effects on individual organisms at differing organizational levels (molecular, cellular, and whole animal). Toxicity data obtained in laboratories are used for the purposes of risk assessment. Effects of pollutants are studied in the laboratory, an approach that can lead to the development of biomarker assays (Chapter 10). The use of biomarker assays in biomonitoring is discussed in Chapter 11. The chapter also considers effects at the population level, thereby looking ahead to the final part of the text.

Section III addresses the questions of greatest interest to ecologists. What effects do pollutants have at the levels of population, community, and whole ecosystem? This takes the discussion into the disciplines of population biology and population genetics. Classic toxicology is concerned with chemical toxicity to individuals. Ecotoxicologists are interested in effects at the level of population community and whole ecosystem. Effects at the population level may be changes in numbers of individuals (Chapter 12), changes in gene frequency (as in resistance; Chapter 13), or changes in ecosystem function (e.g., soil nitifrication; Chapter 14). Effects may be sublethal (e.g., on physiology or behavior) rather than lethal. They may be indirect (e.g., decline in predator numbers because of direct chemical toxicity may lead to an increase in numbers of its prey). It is often difficult to establish effects of pollutants on natural populations. However, the development of appropriate biomarker assays can help resolve this problem.

Applications and Conclusions

The principal areas of application of ecotoxicology are the biomonitoring of environmental pollution (including the use of bioassays and biomarkers), the investigation of pollution problems, the conducting of field trials (particularly of pesticides), the study of the development of resistance and, finally, risk assessments of environmental chemicals—an area of growing importance that receives particular emphasis in this fourth edition of *Principles of Ecotoxicology*.

Risk assessment is required to establish whether novel chemicals are safe to use. In particular there is need to show they will not harm populations of non-target organisms. Current practice is largely based on laboratory testing of chemicals on a small number of organisms chosen in part for practicality (e.g., they complete their life cycles quickly in laboratory conditions) and in part as being representative of other organisms with similar lifestyles. These tests have yielded much valuable data and we refer to the results of such tests at appropriate places in the text. We do not describe in detail the methods currently in use in risk assessment, which vary to some extent between States. Our aim instead has been to provide a basis for understanding what happens to chemicals in the real world, where they go and how they ultimately degrade, and how they effect the individuals and populations that encounter them. Thus we hope our book will provide a solid foundation for all those contemplating a career in the important and interesting field of risk assessment.

A companion volume to this book covers the mechanistic aspects of ecotoxicology in greater depth and detail than this text. It is titled *Organic Pollutants; An Ecotoxicological Perspective*, 2nd Edition by C. H. Walker (2009). In the chapters that deal with individual groups of pollutants, it is structured in a similar way to the present text as shown in the following table

Divisions in This Text	Corresponding Sections in Chapters 5–12 of Organic Pollutants
Section I: Pollutants and their fates in ecosystems	Chemical properties, metabolism and environmental fate
Section II: Effects of pollutants on individual organisms	Toxicity of pollutants(s)
Section III: Effects of pollutants on populations and communities	Ecological effects

We hope that our book illustrates the truly interdisciplinary character of ecotoxicology. The study of the harmful effects of chemicals on ecosystems draws on the knowledge and skills of ecologists, physiologists, biochemists, toxicologists, chemists, meteorologists, soil scientists, and others. It is nevertheless a discipline with a distinct character. In addition to the important applied aspects that address current public concerns, it has firm roots in basic science. Chemical warfare is nearly as old as life itself and the evolution of detoxification mechanisms by animals to avoid the toxic effects of xenobiotics produced by plants is paralleled by the recent development of resistance by pests to pesticides made by humans.

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