

Introduction to
ECOTOXICOLOGY

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Preface

Ecotoxicology is becoming more prominent in the curricula of wildlife, biology and environmental science departments in universities and colleges. This book is a response to that development and addresses some of the aspects which have become more significant over recent years such as ecological risk assessment and biomarkers. However, it takes a broad view of the subject ranging from the chemical and biochemical level to ecosystems and management.

The book is aimed principally at undergraduate students who have completed basic courses in biology and chemistry. These students could be in areas such as biology, ecology, wildlife management, environmental sciences, toxicology, chemical engineering, civil engineering, sanitation engineering and other similar disciplines. The book will also prove useful to consultants, civil servants and other people involved in water quality evaluation, waste engineering, environmental impact assessment, biological conservation, toxic chemical management and so on.

Ecotoxicology has had a relatively short gestation period. The gathering of information regarding chemicals in the environment first commenced during the 1950s with the development of sensitive techniques for the analysis of chemical residues in natural systems. A picture gradually emerged during the 1960s of the widespread but low concentrations of pesticides in birds, fish and other organisms. The book *Silent Spring* by Rachel Carson (1962) attributed a variety of deleterious effects to these persistent agricultural chemicals. This stimulated a major research effort into the effects of chemicals in natural ecosystems which continues to the present day.

The evaluation of these chemicals in natural systems has posed a set of problems not previously encountered in investigations of toxic chemicals. Prior to this period toxicology was principally concerned with lethal or therapeutic doses of substances for mammals or pest organisms with special relevance to human situations. On the other hand the chemicals in the environment belong to relatively persistent chemical groups, usually occur in extremely low concentrations and in many situations do not have immediate lethal or therapeutic effects; and the organisms of concern belong to many different biotic groups apart from mammals and pests. It has become apparent that a new approach is needed to understand chemicals in the environment. This has led to the development of 'ecotoxicology' which essentially provides a broad conceptual framework for evaluating chemicals in the environment.

The use of the term ecotoxicology has not yet found universal agreement. Some see it as the evaluation of the toxicity of chemicals to organisms in natural systems. In this book ecotoxicology has been taken to mean the study

of the pathways of exposure, uptake and effects of chemical agents on organisms, populations, communities and ecosystems.

Many people assisted us in the preparation of this book. The original concept was suggested by Simon Rallison and developed by Ian Sherman of Blackwell Science. The preparation of the final complex manuscript was capably carried out by Rahesh Garib. To all of these people we are extremely grateful.

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1: The Ecotoxicology Concept: An Introduction

The essence of toxicology: a multidisciplinary approach

The term 'ecotoxicology' was first coined in 1969 by Professor R. Truhaut, who defined it as a science describing the toxic effects of various agents on living organisms, especially on populations and communities within ecosystems. The essence of ecotoxicology lies in two main areas: a study of the environment, with origins in the science of *ecology*; and a study of the interactions of toxic chemicals with individual living organisms—the science of *toxicology*. Humans have always interacted with their environment, relying upon it for a source of building materials, clothing, sustenance, etc. Toxicology has also played an important part in human history. For example, poisoned arrows have long been used to kill animals for food (a tradition continuing today in certain remote African and South American tribes). There are numerous other examples of toxicology in practice: from water pipes contaminated with lead in ancient Rome to the more modern horrors of the gas chambers during the Holocaust of World War II, the release of radioactive material at Chernobyl and the ever-present threats of chemical warfare in many parts of the globe.

Truhaut's definition of ecotoxicology has been followed by several others. Importantly, recent definitions have included two aspects that dominate modern approaches to the subject. The first of these includes the notion that hazards to living organisms from toxic chemicals can be investigated through the use of survey data; in other words, a *retrospective* approach, which assesses the levels of toxic chemicals in the environment and uses this information to determine their potential past, present and future impacts. In essence, this takes the form of a 'historical environmental perspective'—looking at a situation which *has* occurred, and linking the cause (i.e. the chemicals) with effect (i.e. the response of the living organism to these chemicals). The second aspect, in contrast, seeks to *predict* the impact of chemicals through *prospective* studies. This involves the use of specific tests which allow scientists to assess the *likely impact* of single chemicals or mixtures such as complex effluents and industrial and municipal wastes.

Ecotoxicology, by its very nature, must be multidisciplinary, combining the sciences of chemistry, toxicology, pharmacology, epidemiology and ecology with an understanding of the sources and fates of chemicals in the environment. To this must be welded a managerial aspect, resulting from the increasing need to regulate industrial and human activities which may possibly cause pollution. Thus, we can also enter the concepts of risk assessment and risk management into the ecotoxicological equation. These facets seek to

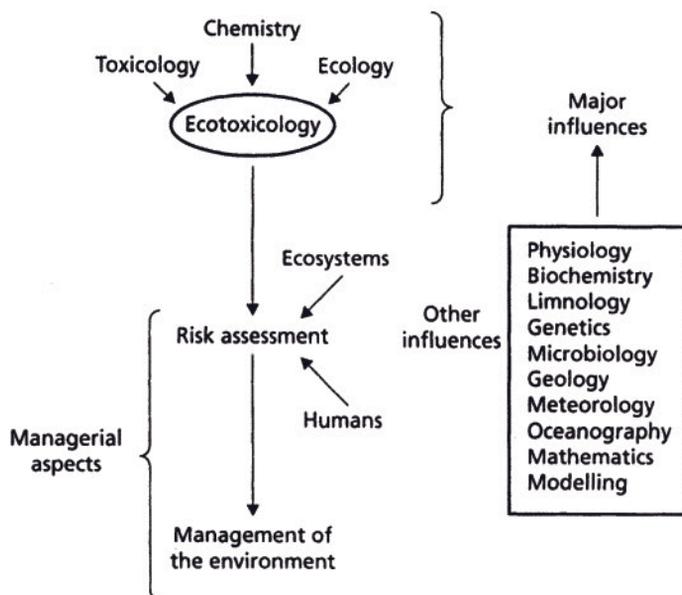


Fig. 1.1 The various components that contribute to *ecotoxicology*.

determine and assess the inputs and fates of chemicals (especially new chemicals) in the environment, and to manage the possible consequences of their introduction (Fig. 1.1).

Perhaps the best definition of ecotoxicology is that of Moriarty (1988), who suggests that the task of this science is to assess, monitor and predict the fate of foreign substances in the environment. This definition encompasses the chemical characterization of contaminants that are present in our environment; the need to monitor them in order to assess whether environmental loads are increasing or decreasing; and the need to predict their impacts through studies involving modern methods of toxicology and ecology.

A short history of the chemical age

At the present time, the number of chemicals routinely in use by human society is enormous. It is estimated that around 70 000 chemicals are commonly utilized for a wide variety of purposes in our global community, and that the rate of introduction of new substances is in the order of 200–1000 compounds per year. Indeed the manufacture of novel substances which do not occur naturally (the so-called *xenobiotics*) is a trend which has increased markedly during the present century.

All human communities throughout history have produced wastes. Such wastes included sewage, which was typically disposed of into water bodies (e.g. rivers, lakes and seas), or alternatively onto the land or in burial sites where natural degradation over time could occur. Historically, disposal in this

manner was easy and convenient, as most communities were small and centred upon a location where a ready supply of water could be accessed—for instance, close to rivers and lakes.

Such disposal may be easy when communities are relatively small in size, but as human populations grew, and larger cities were built, waste disposal became an increasingly difficult problem, leading some communities to develop rules and regulations for proper handling of the material. For instance, laws in Athens around 500 BC prevented the disposal of rubbish within the city walls. The ancient Romans built aqueducts and sewers, and took steps to prevent the disposal of rubbish in their most important waterway, the River Tiber. These Greek and Roman laws may therefore be amongst the earliest that we would now recognize as legally enforceable environmental protection regulations.

It should be noted that the vast bulk of these wastes were natural substances based upon products of the environment. We recognize today that disposal of these wastes resulted in physicochemical and microbial-induced degradation, and that the wastes generated by relatively small community sizes could be readily handled by the receiving environments.

An enormous change resulted from the *Industrial Revolution*—a turning point for modern society in terms of ecotoxicological studies. In the late 18th century, human culture in many countries changed radically, shifting from a rural base towards an increasingly industrialized civilization. A demographic shift in population also occurred: large numbers of rural people shifted to the cities and industrial centres, where jobs, money and a more comfortable lifestyle were available. A greater supply of fuels, the result of more intensive mining activities, fired the factories: coal, generating steam power, combined with newly developed machines to speed production. The first recognizable ecotoxicological problems at this time were the result of intensive industrial activity in confined areas. Rural areas were rapidly converted to industrial centres, as factories were placed near to sources of fuel. Coal usage—the principal form of energy driving the industrial revolution—produced localized and regional problems of atmospheric contamination. A London doctor, Percival Pott, noted the high incidence of occupationally-induced cancer of the scrotum among chimney sweeps, many of whom crawled up through chimneys to do their job. He believed that this was the result of exposure to soot or, more precisely, a group of chemical compounds produced as a result of the combustion of fossil fuels—the polycyclic aromatic hydrocarbons, or PAHs.

In the early 1900s, another change was to take place which would eventually limit the use of coal to fewer industries. A new fuel—petroleum—was found and a whole new industry created, not only for its extraction and refining, but also for finding new ways to utilize this material and the new substances which could be formed from it. The 20th century rapidly became the age of oil. Indeed, most industries are dependent upon a form of petroleum-based substance for some or all of their activities.

The introduction of the motor car and petroleum-based fuels had other repercussions. As engines were refined, so too petrol was further improved. Antiknock fuels, containing lead, were first introduced in the 1920s, and produced widespread contamination of urban areas and localities near major traffic arteries throughout the rest of the century.

Another highly significant change was quietly taking place—a revolution in agriculture—to cope with the increasing population size. The development of fertilizers was perhaps the critical step which drove agricultural production forward. The important breakthrough—the manufacture of nitrogenous fertilizers from atmospheric nitrogen was developed by Fritz Haber in Germany with factories operating by 1913. With the widespread use of fertilizers began a ‘chemical’ age in agriculture, whereby poorer soils could be more effectively utilized for agriculture, large crop yields could be gained year after year, and plentiful supplies would allow exports to countries unable to produce sufficient in their own right. The net result was an increased human survival and a leap in population growth.

Throughout the first half of the 20th century, chemistry was the driving scientific force, creating a myriad of new compounds which would be used for industry, agriculture and military purposes, and in homes and workplaces throughout the world.

A second group of chemicals which have ultimately had a major effect on human life, health and survival have been the biocidal agents, including pesticides and herbicides. These substances have been the ‘magic bullets’ against agents such as insects and weeds which harm or destroy crops or are the transmitters of diseases to humans and animals. Many of these compounds are synthetic chemicals: in other words, they do not occur naturally in nature, but have been synthesized by man. The introduction, in the latter days of World War II, of DDT to combat the mosquito-borne disease malaria is a classic case of pesticide use (see Box 1.1). Following World War II, agricultural practice

Box 1.1: The DDT story

Dichlorodiphenyltrichloroethane, more commonly known as DDT, became a household name as a pesticide and a saviour against a wide range of insect pests. Although it was not introduced until the latter days of World War II, DDT was first synthesized by the German chemist Othmar Zeidler in 1874. However, its power as a pesticide was not recognized until 1939, after which its use became widespread.

The first widespread use of DDT was by the military during World War II. Diseases such as malaria and dengue fever could thus be controlled simply by the application of the ‘magic dust’. DDT has been credited with controlling typhus in Naples during 1943 and the eradication of malaria in Italy and

continued

Box 1.1 *continued*

Sardinia during 1945, and was widely used in the Pacific theatres of war to control insect pests. The advantages of DDT seemed obvious: it appeared to be nontoxic to humans who liberally dusted it on their skin and clothing; it was long lasting when applied to the environment; and above all it was effective. But the side-effects were soon to be seen in certain quarters.

DDT was used extremely effectively in the control of malaria throughout Asia by the World Health Organization in the period following World War II. But, in Malaysia, an interesting phenomenon occurred. The thatched roofs of villages where DDT had been sprayed collapsed, and the local cats died. How could this be so?

We now know the reasons. Apart from the vector of malaria (a mosquito), DDT also killed a wide range of other insects. These included a wasp that usually fed upon moth larvae in the thatched roofs of the villages. The wasps were more sensitive to DDT than the moth larvae, so the wasps died and, with the lack of a natural predator, the larvae flourished. The larvae fed upon the thatch, and the roofs collapsed.

By the 1960s, DDT use was widespread in agricultural practice, and an enormous amount of the substance was used annually to control insect pests. Birds eating insects accumulated large amounts of DDT in their bodies, and died or failed to reproduce as a result. The household use of DDT added to this; DDT was an effective mothproofener within the home, and an effective pesticide in the garden. Although DDT was undoubtedly a success in controlling such diseases as malaria, its widespread and uncontrolled use was increasingly seen as a problem. Ecotoxicological studies detailed its presence in populations of living organisms worldwide. DDT was discovered in living organisms from the Arctic to the Antarctic: it was suddenly a problem on a global basis. The problem was exacerbated by the realization that DDT caused eggshell thinning in many species of birds, leading to ineffective hatching and loss of populations. The ecotoxicological writing was on the wall.

In 1971, the USA banned the use of DDT for most purposes. It was replaced with a variety of other pesticides, but the damage was done. Although DDT was effective, its overuse had led to global environmental contamination. Its era of massive use was over.

If nothing else, the DDT story is a case history which illustrates the dangers of indiscriminate usage of substances. In the same manner that many antibiotics have become ineffective against disease, indiscriminate use of DDT has caused global problems beyond our initial imagination. The sheer fact that DDT was a persistent chemical in the environment—i.e. it did not degrade rapidly—was an added factor in the chain of events which has led us to realize that use of such compounds needs to be strictly controlled, and that effectiveness over long periods alone is not a formula for the continued health of the environment. DDT certainly sparked the 'Age of Pesticide Use', but the end result has been a sobering experience.

became almost as dependent upon biocidal agents as it was on the use of fertilizers. An enormous range of new compounds was introduced, often when previously used compounds became ineffective due to the development of resistance amongst target organisms. Many compounds were designed not only to kill organisms, but to stay active in the environment for extended periods, thus lowering the costs involved in their usage. Still other compounds were designed to be 'broad spectrum'—killing more than one pest at a time (often, unfortunately, including 'nontarget' species).

The period since the end of World War II has seen a rapid development in technology, communications and transport, a vast widening of the usage of various chemicals and a huge demand for the raw materials from which they are derived. The use of various metals for technology has also increased substantially, and previously rarely utilized metals, including mercury and cadmium, have been used in increasing quantities, often with toxicologically significant side-effects for the environment and for human populations. Mercury is an excellent case in point (see Box 1.2).

Box 1.2: The mercury story

Minamata disease has become a catch-phrase in the annals of trace metal contamination. The disease was first recognized in Japan, in the vicinity of Minamata Bay, in the mid-1950s.

In this area, a factory manufacturing acetaldehyde discharged its wastes into the Bay. The wastes included mercury in various forms. Certainly, some methyl mercury was discharged in the waste stream, although this form of the metal can also be formed from the element mercury itself in the environment through the action of microorganisms. Huge amounts of mercury were discharged into Minamata Bay—estimated at some 600 tonnes between 1932 and 1970.

Within the Bay, methyl mercury was accumulated by living organisms. This form of mercury is lipophilic (i.e. fat soluble), and easily accumulated from the water column by the fatty tissues of living organisms. The early problems noticed in the area related to the local organisms—birds failed to fly in the correct manner, and various reports had them dropping from the sky into the sea for unknown reasons. Some organisms within Minamata Bay died, whilst others suffered changes in behaviour, leading local children to be able to catch octopus with their hands. In addition, other unusual phenomena were reported: cats died, often in convulsions.

During the 1960s, the local people also became ill. The disease appeared to affect the central nervous system, resulting in convulsions, excessive salivation and staggering. Some people, including newly born children, died—often in horrible circumstances.

continued

Box 1.2 continued

The cause of these strange events was eventually tracked to the mercury discharges into Minamata Bay, and more specifically to the accumulation of methyl mercury within the bodies of people eating food from the Bay. As an interesting side-effect, it was seen that pregnant women suffered less than others, although their newborn children suffered from neurological disorders, such as palsy and retardation, since some of the mercury was passed onto these children.

The phenomenon of bioaccumulation was producing these effects. Methyl mercury passed through the local food chains, accumulating in high concentrations in fish, birds and the organisms which fed upon them—cats and humans. Unlike the DDT case (see Box 1.1), mercury had entered the environment through a deliberate discharge of industrial waste. But the overall effects were the same—bioaccumulation, leading ultimately to the death of living organisms.

Apart from biocidal agents and various metals, many new compounds have been extensively used for various industrial purposes. For instance, the polychlorinated biphenyls (PCBs), which were used principally as dielectric (insulating) fluids in the electrical industry, were first introduced in 1929. The chlorofluorocarbons (CFCs), so widely used in refrigeration and air-conditioning, were introduced just shortly after. In addition, plastics of various kinds have been enormously used by man. It was only many years after the introduction of these compounds that environmental problems caused by their use and careless disposal were first recognized. Since the 1960s, many other substances have been similarly acknowledged as environmental pollutants. It was in 1962 that Rachael Carson published her influential book *Silent Spring*, detailing to the general public for the first time the unintended effects of widespread chemical usage (especially pesticides) on wildlife.

Waste and its sources

Rachael Carson's book, *Silent Spring*, proved a revelation and in the next two decades, a myriad of chemicals were revealed to be present in the environment at what were possibly toxic levels. The scientific search for these chemicals revealed that pesticides, herbicides and a wide variety of industrial chemicals (including the trace metals and such substances as PCBs) were almost ubiquitously distributed throughout the globe.

A number of factors were highlighted by this search. Firstly, poor *waste management* and poor *waste disposal practices* were the key factors in the spread of potentially toxic compounds in the environment. Secondly, *deliberate* and *unintentional* releases of various compounds were differentiated as sources.



Fig. 1.2 US Environmental Protection Agency estimates and locations of facilities producing hazardous wastes in 1981.

Waste disposal practices in the early part of the 20th century were mostly at a very basic level. Although a number of large cities had sewage treatment facilities, many areas still resorted to practices of disposal into rivers, lakes or oceans, onto the land, or into pits dug in the ground, with very little (if any) treatment prior to disposal.

However, the realization that toxic wastes could contaminate the environment changed these practices, and governments increasingly legislated for enhanced and vastly improved disposal practices. These became increasingly sophisticated. Sewage disposal methods needed to eliminate potentially pathogenic bacteria and excessive nutrients from entering and contaminating the environment; rubbish disposal practices were required to take into account the need to separate waste streams, in order to extract materials that could be recycled and reused, as well as to dispose safely of materials that were nonreusable or potentially toxic.

In the early 1980s, the US Environmental Protection Agency (USEPA) undertook wide-ranging surveys to estimate the number of facilities producing toxic wastes (see Fig. 1.2) and the sites of the worst toxic waste dumps were identified as those places where potentially dangerous materials had been dumped in quantities deemed to be potentially harmful.

Landfilling—the practice of placing waste materials in a pit dug in the soil and covering it with earth—was, and still remains one of the key methods for

the disposal of wastes, including toxic wastes. But a number of problems have been experienced with landfilling. Amongst the most notorious cases is that of Love Canal in Niagara Falls, New York, USA, where wastes in a landfill leached out into the basements of houses built later on the site, not only causing neurological and reproductive problems, but also being implicated in carcinogenesis (i.e. the causation of cancer). Cases such as this have resulted in a considerable tightening of legislation related to the disposal of wastes in landfills, including measures for the separation of wastes prior to disposal (to prevent chemical reactions occurring after burial), and addressing the need for adequate design and operational criteria for the dump sites themselves.

Concomitant with these changes have been advances in alternative methods for the disposal of wastes. Thus, methods such as high-temperature incineration, deep-well injection and immobilization of toxic wastes have been put forward. However, it must always be remembered that no one method is infallible. For instance, incineration can result in the formation of compounds more toxic than the original waste. Such is the case when PCBs and organochlorine pesticides are burnt using inefficient high-temperature incinerators—the end result is the formation of dioxins as a by-product, compounds considered to be among the most toxic of waste compounds.

Waste disposal practices also highlight the second key factor in the spread of toxic waste materials—the concepts of point and nonpoint sources, and deliberate and unintentional discharges. *Point sources* are easy to recognize: a point source is simply a site recognizable as the source of wastes (and potentially toxic materials) into the environment. Thus, a sewage outfall to a river or lake is a point source; similarly, a factory pipeline carrying liquid wastes to the coastal environment is also a point source. By definition, they are also *deliberate* sites of disposal.

Nonpoint sources are diverse, and are not easily defined in terms of a certain outlet, pipeline or source. Often, they are the result of *unintentional* disposal of wastes, or perhaps a deliberate usage has resulted in an environmental input which cannot, for one reason or another, be subsequently defined as an actual source. Rather, nonpoint sources refer to potentially toxic material which enters the environment from a variety of different inputs. For instance, in the city situation, pollutants may enter rivers and coastal waters through run-off from storm water. The storm water which enters the sea has come from all over the city, and contains contaminants from roads (e.g. petroleum hydrocarbons), gardens and parks (e.g. fertilizers and pesticides) and factories and commercial areas (e.g. various industrial chemicals, including such substances as PCBs). In such cases, the actual source of contaminants cannot be definitely pinpointed.

Development of the ecotoxicology concept

Living organisms are composed of cells, inside which complex biochemical reactions take place which form the basis of life. In the more complicated

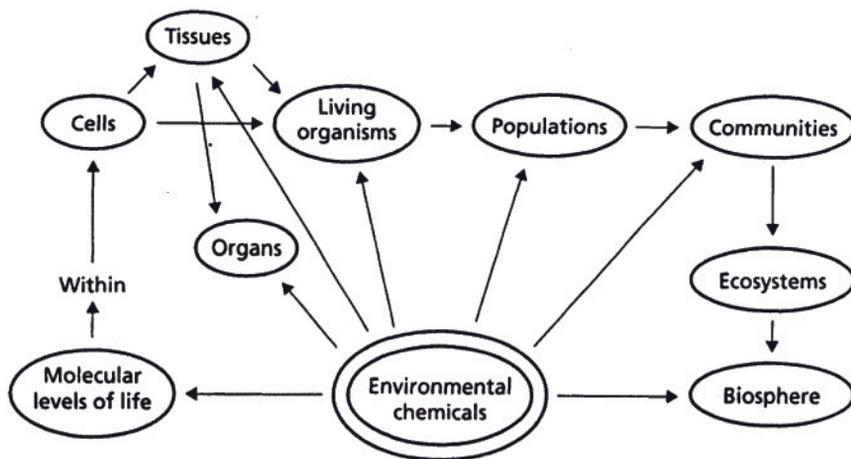


Fig. 1.3 Levels of biological organization and their interactions with environmental chemicals.

plants and animals, similar cells may be grouped together as tissues, and tissues become grouped as organs, which are committed to undertaking certain specific functions. Living organisms and the cells, tissues and organs of which they are composed require food and essential nutrients in order to grow and replicate. These materials are obtained, of course, from the environment, or by feeding on other living organisms.

Plants and animals need to reproduce, so similar species are found close to each other, forming populations. Within certain areas, populations interact with other species, forming local communities which are often based around certain physical, geographical or meteorological features (e.g. rocky shore communities; coral reef communities, etc.). At the next level of organization, communities interact with each other and their wider environment to form ecosystems, which can be defined as regional communities, which of course also interact with their physical environments (e.g. rain forest ecosystems; tundra; deserts, etc.). At the highest level of organization—the biosphere—we can consider all the organisms on the earth as a vast, global ecosystem.

Thus, life operates at a range of levels: at the molecular or subcellular level within cells; at the cellular level itself and within tissues and organs; at the level of the individual organism; within populations and communities; and ultimately within ecosystems and the biosphere as illustrated in Fig. 1.3.

The major concerns of ecotoxicology are the interactions between living organisms and toxic chemicals in the environment. We can thus view ecotoxicology at various levels, and the various relationships are illustrated in Fig. 1.4. This figure will be a very important component of our future discussions, and will form the basis for the structure and content of this book.

If ecotoxicology concerns toxic substances in the environment, chemistry has a major role to play. Chemistry elucidates the nature of the chemicals

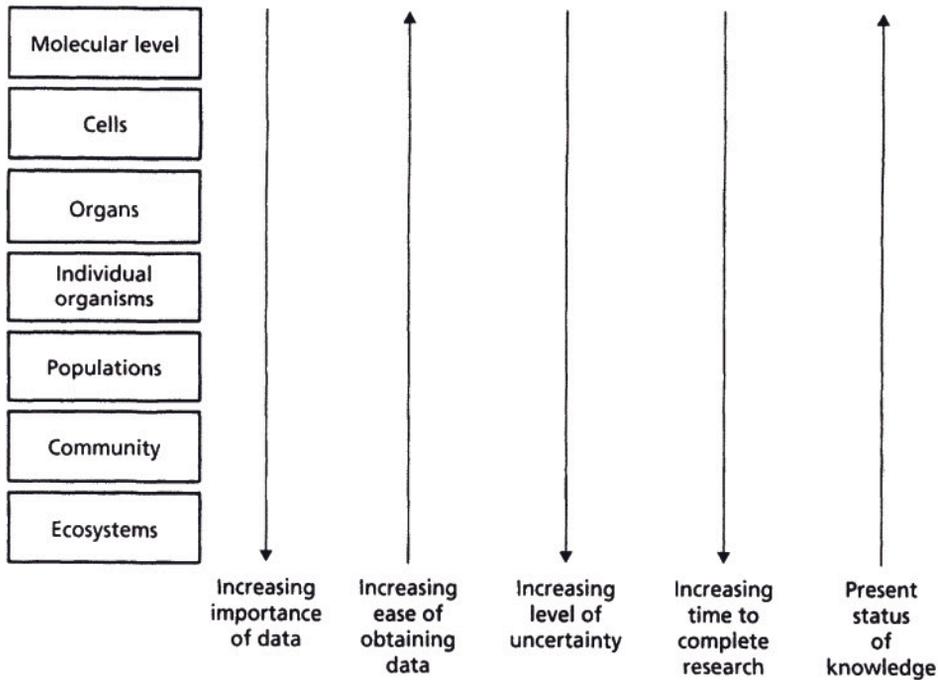


Fig. 1.4 Relationships of aspects of the science of ecotoxicology and the different levels of biological organization.

involved, and through judicious analysis of environmental samples, can aid in pinpointing the *source of contaminants*. Much information about these sources can also be gained from examining the nature of waste material being added to the environment—for example, different types of industry produce different types of wastes, and often waste materials are typical of a particular type of industry.

Chemical analysis can also provide information on the *environmental distribution* of chemicals. This requires analysis of various environmental phases so that pollutant loads in each can be estimated. *Pollutant load* information provides us with details of the bulk (or total amount) of particular pollutants entering or present within the environment, and which compartments of the environment may be at greatest risk from their effects. Thus, analysis of air, water, soil and living organisms may be required. Chemical analyses of living organisms are most important in this regard, as these data tell us how *available* a particular pollutant is to living organisms.

Not all pollutants are *biologically available*, and some pollutants accumulate in living organisms to a greater extent than others. For instance, some pollutants attach strongly onto soil and sediment particles and become effectively 'unavailable' to living organisms. Others may be biologically available, but are rapidly transformed or broken down within living organisms. Still others may be transformed in the environment, either through abiotic transformations