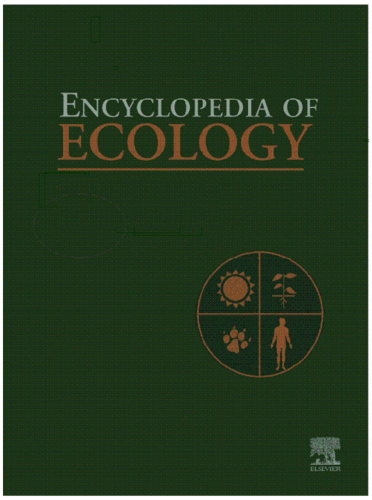

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Ecotoxicology: The History and Present Directions

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Introduction

Ecotoxicology is the science of contaminants in the biosphere and their effects on constituents of the biosphere, including humans. (The inclusion here of effects to humans in the purview of ecotoxicology is consistent with the original definition of Truhaut but atypical of recent definitions.) The impetus for this new science was the need to understand and make decisions about environmental contaminants. From the close of World War II and into the 1960s, several pollution events occurred with consequences universally acknowledged to be unacceptable. These watershed events included population crashes of raptor and piscivorous bird species due to DDT effects on reproduction, widespread water pollution, and epidemics of mercury (Minamata disease) and cadmium (Itai–Itai disease) poisoning. Expertise for dealing with such issues became essential to society and several practical sciences coalesced into the nascent science of ecotoxicology.

Ecotoxicology is a synthetic science that combines causal explanations (paradigms) and information from many sciences, particularly biogeochemistry, ecology, and mammalian, aquatic, and wildlife toxicology. The integration of paradigms and data from these disciplines is presently incomplete. Chief among remaining challenges is establishment of congruency among theories and data emerging from different levels of biological organization. Because ecotoxicology is an applied science, ecotoxicologists take on different roles that are also not fully integrated. Some ecotoxicologists are concerned chiefly with scientific goals, that is, organizing facts around explanatory principles. Others focus on the technical goals, that is, developing and applying tools to generate high-quality information about ecotoxicological phenomena. Still others focus closely on resolving specific, practical problems such as assessing ecological risk due to a chemical exposure or the effectiveness of a proposed remediation action. Associated activities overlap but are presently performed inconsistently in many instances. For example, the ecotoxicity tests applied today focus on effects to individual organisms, but predictions of consequences to populations and communities are a very high priority for ecotoxicologists. A major theme in ecotoxicology today is finding the best way of achieving scientific, technical, and practical goals while organizing a congruent body of knowledge around rigorously tested explanations.

Some general trends exist in ecotoxicology relative to different levels of the biological hierarchy (Figure 1). Causes of lower-level phenomena such as biomolecular effects tend to be easiest to identify and relate to immediately adjacent levels such as to cells or tissues (top panel of Figure 1). Techniques for study of lower-level effects often have the advantage of documenting quicker responses than those occurring at higher levels (middle panel of Figure 1). Unfortunately, the ecological relevance of change at the lowest levels is more ambiguous than that for higher-level changes. This creates a dilemma for ecotoxicologists attempting to develop better technologies. The ecotoxicologist tries to avoid measuring precisely the wrong effect or imprecisely the right effect. Another trend is that lower-level effects tend to be used proactively and those at higher levels are applied reactively by ecotoxicologists trying to solve specific problems (bottom panel of Figure 1). Lower-level effects tend to be more tractable than those at the higher levels.

Scientific activities of ecotoxicologists rely on conventional methods although conventions vary among scientists focused at different levels of organization. Controlled experiments tend to be practiced more during studies of

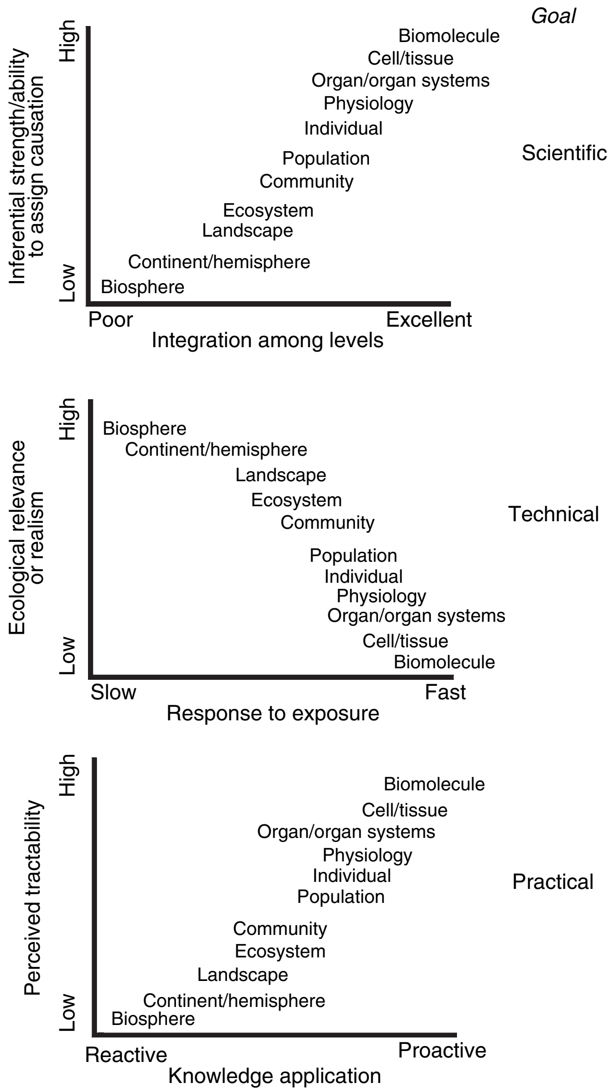

Figure 1 Qualities of ecotoxicological knowledge based on the three goals to which it is applied and the biological levels for which it is generated.

lower-level effects such as biochemical shifts; whereas, higher-level effect studies rely more on observation and natural experiments such as accidental toxic releases. Regardless of the manner in which insight is obtained, the scientific intent is to organize facts around rigorously tested paradigms. Some ecotoxicologists work to produce more precise or detailed information around existing paradigms while others work to rigorously test existing paradigms or to propose novel ones. Both of these activities are essential to the growth of ecotoxicology as a science.

Activities to develop new or enhance existing technologies produce tools with which to understand contaminant fate and effects in the biosphere. Ecotoxicological technologists develop analytical instruments, procedures for studying regional impact, and specific tools for documenting exposure or effects. As examples, biomarkers are continually developed and improved so effects from the biochemical to individual levels can be documented. Biomarkers (cellular, tissue, body fluid, physiological, or biochemical changes in individuals) are also useful for documenting effect or exposure even in the absence of any discernible adverse effect. Also important at higher levels of organization are biomonitors, changes in organisms or groups of organisms used to infer adverse impact of contaminant exposure. Qualities valued in ecotoxicological technologies are biomarker or biomonitor effectiveness (including low cost and ease of application), precision, accuracy, appropriate sensitivity, consistency, and capacity to generate clear results.

The goal of practical ecotoxicology is the use of existing science and technology to document or solve specific problems such as remediating harm done by a chemical spill. Much of practical ecotoxicology is currently done within the ecological risk assessment (ERA) framework (Figure 2). ERAs can be retroactive, predictive, or comparative. A retroactive ERA estimates the risk from an existing situation such as a contaminated site, whereas a predictive ERA predicts the same for a future situation such as the proposed licensing of a new agrochemical. A comparative risk assessment might be done if the risks of two or more alternative actions are to be contrasted during environmental decision making. Regardless of the kind of ERA, the best available science is applied to formulate the problem, that is, define plausible consequences of exposure. The best available science and

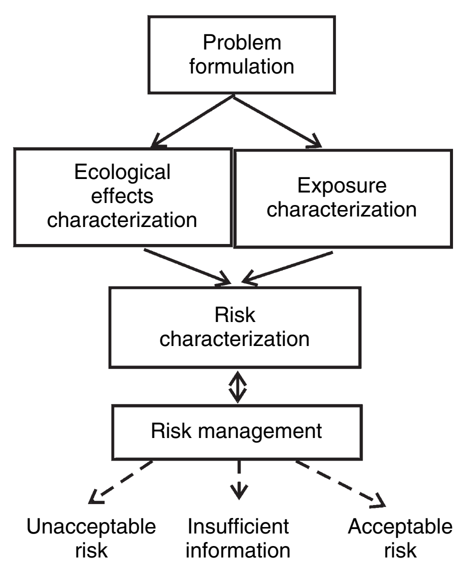

Figure 2 The ecological risk assessment paradigm including problem formulation, exposure characterization, ecological effects characterization, and risk characterization. This paradigm was derived from that developed by the National Academy of Science.

technologies are applied next for ecological effects and exposure characterizations. A computer model might predict movement of the contamination or the contaminant concentration might be measured in the relevant media. The best information is gathered to relate the contaminant concentrations to possible effects to valued ecological entities. All of this information is combined in the last stage of ERA to produce a risk statement. This information is shared with risk managers who decide on the most appropriate action. This decision might also mandate a remediation which would draw on ecotoxicological science and technologies.

Scales of Study

Ecotoxicological subject matter spans a wide range of biological levels (**Figure 1**). Levels drawing heavily on classic toxicology extend from the biomolecular to the individual. Some population issues addressed by ecotoxicologists also benefit from the work of human epidemiologists. Associated themes and information at these levels of organization could be described as autecotoxicology, just as similar subjects in ecology are classified as autecology. Issues associated with higher levels would then be issues of synecotoxicology: considerable biogeochemical and ecological knowledge are applied in synecotoxicological studies. A brief sampling of major autecotoxicological and synecotoxicological research themes is provided below.

Biomolecule

Information from the biomolecular level of organization is key to elucidating molecular mechanisms of toxicity, differences in sensitivity among individuals, and adaptation of populations to contamination. Understanding the molecular mode of toxic action also helps to predict how toxicant mixtures might affect exposed individuals. From a technological vantage, biochemical shifts are frequently used as evidence of toxicant exposure or effect.

Perhaps the best illustration would be the biomolecular shifts involved in phase I and II reactions of organic contaminants. The levels of associated biomolecules can quickly increase during exposure. Type I reactions are mediated by enzymes that catalyze contaminant hydrolysis, reduction, or oxidation, producing more reactive metabolites. The metabolites might be more readily eliminated from the cell or participate in phase II detoxification reactions. The best-studied phase I system is cytochrome P-450 monooxygenase which transforms contaminants such as polycyclic aromatic hydrocarbons (PAHs), chlorinated hydrocarbons, polychlorinated biphenyls (PCBs), hydrocarbons, dioxins, and dibenzofurans. Although phase I transformations are intended to facilitate detoxification, some transformed contaminants are more toxic than the parent compounds or might be carcinogenetic. Phase II enzymes facilitate conjugation, that is, the addition of endogenous groups to contaminants or phase I metabolites which make the compounds more water soluble and readily eliminated.

Other biomolecules provide mechanistic insight and a foundation for biomarker technologies. Elevated concentrations of metallothioneins, cysteine-rich proteins that bind and sequester metals, are often employed as evidence of metal exposure. Also commonly used as biomarkers are stress proteins, proteins induced by chemical stressors that function to reduce protein damage (proteotoxicity). The recent surge in genetic technologies provides another suite of biomarkers. Changes in DNA, RNA, protein products, and cellular metabolites are used separately or together to reveal mechanisms of response or damage, and to document effects at the molecular level.

Molecular and ionic qualities of contaminants also influence the nature of exposure. An organism's exposure to the same amount of a contaminant under different conditions can result in different realized doses and consequences. For example, the free ion form of a dissolved metal is considered the most bioactive. Metals dissolved in water form complexes with ligands such as dissolved inorganic anions and natural organic compounds. Depending on the ionic composition of the waters, the same amount of dissolved metal will result in different concentrations of free ion and, consequently, concentrations of bioactive metal. Similarly, some organic contaminants are weak acids. If ingested with food, the capacity of such contaminants to pass through the gut wall and cause harm is dependent on the amount of unionized compound present. Unionized compounds are generally more amenable to passage across the gut wall than ionized compounds. Under different pH conditions, different amounts of such a weak acid would be unionized as can be easily estimated with the Henderson–Hasselbalch relationship:

$$f_{\text{unionized}} = \frac{1}{1 + 10^{\mathrm{p}K_\mathrm{a} - \mathrm{pH}}}$$

where $f_{\text{unionized}}$ is the fraction of the compound present that is unionized, and $\mathrm{pK_a}$ the $-\log_{10}$ of the compound's ionization constant (K_a). Exploring the influence of molecular factors like the two just described is an active area of exposure research in ecotoxicology today.

Cells and Tissues

Toxicant-induced changes in cells and tissues are useful biomarkers. Some changes reflect a cell's failure to remain viable in the presence of toxicants and others reflect partially successful attempts to maintain homeostasis. For example, histological examination of the liver from an exposed organism might reveal many dead (necrotic) cells. In the same tissues, inflammation might be occurring in an attempt to isolate, remove, and replace damaged cells. Both necrosis and inflammation are common biomarkers. Other changes such as the cellular accumulation of damaged biomolecules or cells modified to cope with toxicant damage are also good histological biomarkers.

Cancer is a cellular response to carcinogen exposure that is carefully studied by ecotoxicologists. Several ecological studies have demonstrated the role of environmental toxicants on cancer etiology. For example, Puget Sound English sole (*Parophrys vetulus*) taken from sites with elevated sediment contamination showed high prevalence of liver cancers. Another case of elevated cancer prevalence (27% of dead adults) involved beluga whales (*Delpinapterus leucas*) inhabiting a contaminated reach of the St. Lawrence estuary.

Exposure studies at this level focus on the routes of contaminant movement into and out of cells, and differences in accumulation in various tissues. Generally, contaminant movement into and out of cells involves (1) simple diffusion across the membrane lipid bilayer or through an ion channel, (2) facilitated diffusion involving a carrier protein, (3) active transport, or (4) endocytosis. Some of these routes are designed for other purposes such as ATPase active transport of cations but facilitate movement of contaminants such as cadmium. Other mechanisms are more specific. For example, the multixenobiotic resistance (MXR) mechanism specifically removes moderately hydrophobic, planar contaminants from the cell.

Organ and Organ Systems

Toxicant effect on organs and organ systems is another major theme in classical toxicology that also has a role in ecotoxicology. Organs can be targets of toxicant effects as in the case of the liver cancer mentioned above or can be routes of toxicant entry into the body as in the case of the integument, breathing organs, and digestive tract.

Contaminant effects on organs and organ systems are diverse. Pyrethoid pesticides modify essential ion exchange across amphibian skin. Fish gills are changed by exposure to low pH or high metal concentrations in such a way that normal ion and gas exchange are altered. Some contaminants (teratogens) can cause abnormal organ development. For example, fish embryos develop cardiovascular abnormalities if exposed to high concentrations of PAH. Still other toxicants compromise immunological competency, increasing susceptibility to infection or infestation. These examples represent only a few of the possible organ or organ system effects of contaminants on nonhuman species.

An issue attracting considerable attention at the moment is the ability of some environmental contaminants to modify endocrine functions such as those essential for sexual development and viability, or optimal metabolic activity. For example, the presence of the antifouling paint constituent, tributyltin, caused pervasive imposex (imposition of male features such as a penis or vas deferens on females) in whelk populations along the English and Northeast Pacific coasts. Contaminants that act as estrogen include DDT and its replacement, methoxychlor, nonylphenol from surfactant and detergent synthesis, and synthetic hormones from birth control pills that enter waterways from sewage treatment plants. Still other endocrine modifiers such as ammonium perchlorate from military munitions disrupt thyroid function.

Exposure studies at this level of biological organization emphasize target organs. Some organs or organ systems are more prone to toxicant impacts due to their intimate contact with environmental media, location relative to blood circulation, or specific function. For example, the gills of aquatic organisms are often target organs for dissolved contaminants because of their intimate contact with the surrounding water. The liver or analogous organs in invertebrates are often sites of harmful effects because of their prominent detoxification function, that is, the liver cancer noted above in English sole was caused by contaminant activation during phase I reactions in the liver.

Whole Organism

Effects to individuals are used to make inferences about contaminant impacts on individual fitness, and indirectly, on populations and communities. The most commonly measured qualities are mortality, development, growth, reproduction, behavior, physiology, and bioenergetics.

Lethal effects are measured under different exposure scenarios. They might be measured during acute (4 days or shorter) or chronic (longer than 10% of an individual's lifespan) exposures. They might also be measured for contaminant exposure via different media such as water, air, food, and sediment. Most are studied in the laboratory in such a manner that physical, chemical, and biological factors influencing response to exposure are controlled. Therefore, mortality predicted for a particular exposure concentration might not completely define the mortality that would occur in the field where exposed individuals must successfully forage, compete with individuals of other species, avoid predators, and interact with individuals of the same species in order to remain alive.

Exposure studies that involve whole organisms emphasize bioaccumulation, the net accumulation of contaminant in an organism from water, air, or solid phases of its environment. Mathematical bioaccumulation models range from simple ones such as the one compartment model shown below to multicompartment, pharmacokinetic models:

$$C_t = C_{\text{Source}} \frac{k_u}{k_e} \left[1 - e^{-k_e t}\right]$$

where C_t is the concentration in the organism at time, t, C_{Source} is the concentration in the source, k_u is uptake clearance, and k_e is elimination rate constant. Most studies attempt to understand and quantify the influence of extrinsic (e.g., food type containing the contaminant) and intrinsic (e.g., animal sex or size) factors on bioaccumulation.

Population

Knowledge of effects to individuals is valuable, but insufficient, for predicting population-level impacts. Consequently, a growing number of ecotoxicologists study population-level effects directly. Such studies emphasize vital rates such as birth, death, stage change, or migration rates. Demographic models based on vital rates improve our ability to project consequences such as a drop in the population growth rate or increase in local population extinction risk.

Some population studies treat the population as one in which individuals are uniformly distributed in the area of interest but others consider the population (metapopulation) to be composed of subpopulations inhabiting habitat patches of different qualities, including different levels of contamination. The differences in vital rates, including exchange rates among patches, are used to project contaminant exposure consequences. With metapopulation models, effect manifestation at a distance from a contaminated patch can be explored: a population member can be exposed in one patch yet the effects might manifest in an uncontaminated patch after migration.

Community

Community ecotoxicology explores the consequences of contaminant exposure of and movement of contaminants within ecological communities. The majority of such studies are field studies either addressing scientific questions or applying knowledge to assess risk or define remediation action for a contaminated system. Like the biomarkers applied at lower levels of biological organization, bioindicators are applied by community ecotoxicologists. Bioindicators might be particularly sensitive species whose absence suggests an adverse impact. A community metric such as species richness, evenness, or diversity might also be used as an indicator of an adverse exposure consequence. Any study in which biological systems are applied to assess the structural and functional integrity of ecosystems is referred to as a biomonitoring study.

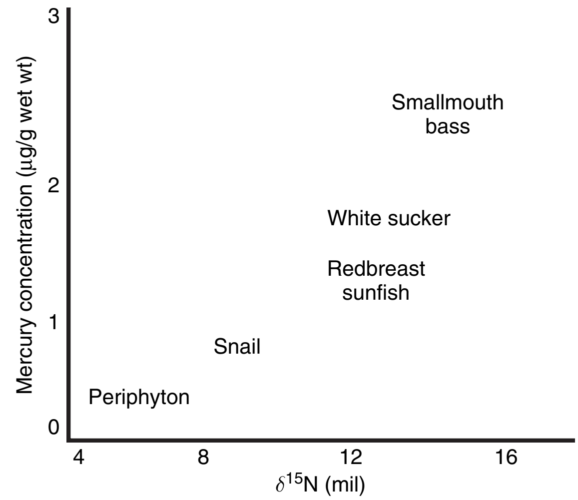

Figure 3 Mercury biomagnification in the South River (Waynesboro, Virginia, USA) illustrated with periphyton, a grazing snail (*Leptoxis carinata*), two intermediate fish species (redbreast sunfish, *Lepomis auritus* and white sucker, *Catostomus commersoni*), and a top predator species (smallmouth bass, *Micropterus dolomieu*). Author's unpublished data.

Exposure within communities is often explored in the context of contaminant trophic transfer. Depending on its properties, a contaminant can increase (biomagnify), decrease (trophic dilution), or not change in concentration with progression through a food web. Contaminants such as methylmercury or persistent organic pollutants (POPs) such as DDT biomagnify. Biomagnification can lead to adverse consequences to higher trophic level species such as the raptors and piscivorous birds mentioned above. Studies of food webs including omnivorous members require a measure of trophic status for species. A convenient measure of trophic status is provided by the nitrogen isotopic fractionation that occurs with each trophic exchange: the amount of heavy (^{15}N) nitrogen increases in tissues relative to light (^{14}N) nitrogen with each trophic exchange. The $\delta\,^{15}$N is the conventional metric for expressing relative N isotopic abundances:

$$\delta^{15}\text{N} = 1000\left[\frac{[^{15}\text{N}_{\text{Species } i}]/[^{14}\text{N}_{\text{Species } i}]}{[^{15}\text{N}_{\text{Air}}]/[^{14}\text{N}_{\text{Air}}]} - 1\right]$$

Graphs (e.g., Figure 3) or quantitative models of contaminant concentration in species within the subject community versus $\delta\,^{15}$N facilitates prediction of contaminant movement in communities.

Ecosystems

Ecosystem-level studies vary widely in their spatial and temporal scales. Often ecosystem modeling techniques are applied to an easily definable ecosystem such as a contaminated lake or watershed. Fate and movement of

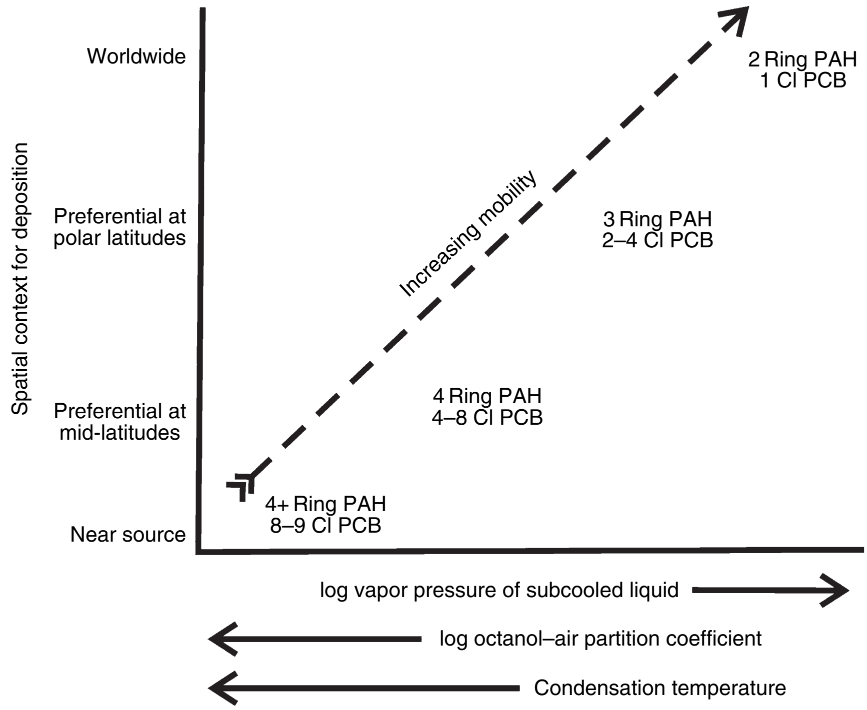

Figure 4 Global movement of a POP is determined by several qualities including its (subcooled liquid) vapor pressure and condensation temperature which, together, determine its tendency to move into and remain in the atmosphere. A more volatile compound will be transported more by atmosphere movement than one that is less volatile. Its condensation temperature influences the latitudinal limits to which it might move. The octanol–air partition coefficient is also important because it reflects the POP's tendency to remain associated with the solid and liquid phases of the Earth versus the atmosphere. Here, polycyclic aromatic hydrocarbons (PAHs) with different numbers of aromatic rings and polychlorinated biphenyls (PCBs) with different numbers of chloride atoms are used to illustrate trends for global deposition of POP. This biospheric process is called global distillation.

contaminants are then modeled by computer or measured in extensive sampling programs. Larger-scale studies are required for contaminants amenable to wide spatial dispersion via atmospheric transport such as mercury from coal power plants or contaminants used widely by society such as atrazine, an herbicide applied in the North American Corn Belt. Often geographical information system (GIS) and remote sensing technologies are essential in these types of studies. In still other instances, a global perspective is required to adequately grasp the ecotoxicological consequences of contaminants. Current global issues are ozone depletion in the stratosphere due to chlorofluorcarbon (CFC) release, global warming due to greenhouse gas emissions, and global movement of persistent organic pollutants (Figure 4). More and more frequently, large-scale issues are emerging as critical ones in ecotoxicology.

Current Trends in Ecotoxicology

A working knowledge of the movement and effects of environmental contaminants is recognized worldwide as essential to maintaining an acceptable quality to life. Ecotoxicology has emerged as the applied science that addresses the central issues of contaminants in the biosphere. Major challenges in this young science include the following: (1) the integration of causal explanations and knowledge arising at different levels of biological organization into a coherent whole; (2) integration of scientific, technical, and practical goals of ecotoxicologists; and (3) consideration of ecotoxicological issues at increasingly wider spatial and longer temporal scales.

See also: Bioaccumulation; Biogeochemical Approaches to Environmental Risk Assessment; Biomagnification; Ecological Risk Assessment; Metapopulation Models.

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Edaphic Factor

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Introduction

This article describes the important roles geology and soil conditions play in the ecology and evolution of plant species and their associated biota. We seek to: (1) describe the edaphic factor as a life force responsible for generating and maintaining unique species assemblages and (2) emphasize the importance of conserving habitats with extreme edaphic conditions because of their biological diversity. First, we describe the edaphic factor: its definition and role in shaping the biotic world. Then we review our current knowledge of the ecology of unusual geologies, focusing on studies performed within and across biotic kingdoms. Further, we examine the process of plant evolution on extreme geologies, an area that has generated much interest among evolutionary biologists in the last few decades. Finally, we cover the applied ecology and conservation of plants and other biota restricted to unique geologies.

The Edaphic Factor: Its Role in Shaping the Biotic World

Ecologists have long noted the importance of geology in the global and regional distribution of organisms. Life, ranging from macro- to microscopic, exists on and within a mosaic of geologies that vary across both space and time. The contributions of geologic phenomena to maintaining and generating biotic diversity are twofold. First, large-scale geologic events (e.g., continental drift and rising of mountains) create discontinuous or patchy landscapes. Second, within this patchwork of landscapes, parental geologic materials such as igneous, metamorphic, or sedimentary rocks can become exposed, leading to the development of soils differing in chemical and physical characteristics. This creates opportunities for colonization and differentiation of species. The edaphic factor pertains to physical, chemical, and biological properties of soil resulting from these geologic phenomena. Discontinuities in the edaphic factor have contributed to the intriguing patterns of diversity we see in the biotic world. Edaphology is a branch of soil science that studies the influences of soils on organisms, especially plants. It includes agrology, the study of human uses of soils for agriculture, as well as how the features of soils affect human land use decisions.

According to soil ecologist Hans Jenny, soils owe their distinct characteristics to five interacting factors: climate, organisms, topography, parental rock, and time. If all but one factor (e.g., parental rock) remain unchanged, then variation in a soil body can be attributed to that one factor. Botanists have long recognized that the distribution, habit, and composition of vegetation are greatly