Title
Global Ecotoxicology: Science and Management

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Publication Date
1993

LBL-33216
UC-000

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT
DIVISION

To be published as a chapter in *Industrial Ecology*,
R. Socolow, Ed,.Cambridge University Press,
Cambridge, UK, 1993

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ENERGY & ENVIRONMENT
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Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-33216
UC-000

Global Ecotoxicology: Management and Science

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March 1993

This work was supported by the NIEHS Superfund Basic Research Program, University of California Berkeley Program Project (NIH P42 ES04705-03), through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. This work was also partially supported by the Pew Charitable Trusts.

I. INTRODUCTION

It is well known that toxic substances have the potential to harm ecological systems. However, the role of such substances as agents of global, rather than regional, change is poorly understood. Do toxic substances (and the practices that introduce them) simply cause a patchwork of regional insults, or do they harm the biosphere in ways that have profound global implications? Are subtle global impacts more important than acute but localized ones? Are the effects of toxic substances significant in comparison to effects attributable to other agents of global change? Significantly, these questions cannot be answered in depth until advancements are made in the science of ecotoxicology.

This paper examines the most critical scientific barriers to answering the questions posed above. First, characteristics of global pollution problems are defined. Second, scientific questions that are vital for an understanding of both global and regional pollution problems are discussed and interlinkages described. Finally, priorities for global ecotoxicology are proposed. Examples are taken primarily from the field of aquatic toxicology, and an emphasis is placed on the effects of contaminants rather than their fate in ecosystems.

For over two decades, scientists in the United States and much of the world have focused primarily on local and regional pollution assessment and control. Largely it has been found that point-source inputs and acute effects of environmental pollution are relatively easy to study and are amenable to technological control (Stumm, 1986). However, it has also been recognized that evaluation and control of low, sublethal levels of environmental pollution emanating from diffuse sources is a far more difficult task --a true curse upon the scientists and engineers that helped to solve so many pollution problems of the 1970s. What now awaits the solution of even more complex global issues? This paper forwards the proposal that the key scientific barriers to more sophisticated regional ecotoxicological assessments are largely the same as those confronting the newer area of global ecotoxicology. This viewpoint is significant, because it leads to the formulation of research priorities in global ecotoxicology, and because it suggests that many key problems are truly at the frontiers of science.

II. SPATIOTEMPORAL CHARACTERISTICS OF GLOBAL POLLUTION

What are the key characteristics of global environmental pollution, and how should they be classified? One approach is to classify global pollution problems according to spatial and temporal characteristics. For example, localized acute emissions are quite distinct from diffuse, low-level emissions. Below, I have identified four key characteristics of global pollution problems based on this spatio-temporal approach (Figure 1).

Characteristic 1: Global pollution can be partially characterized as a patchwork of regional acute and chronic effects. Examples of significant regional activities are numerous in the developed and developing world. Activities introducing such pollution fall into obvious categories such as mining, oil development and processing, agriculture, pulp and paper production, municipal sewage disposal, industrial hazardous waste disposal, and numerous direct and indirect effects of urbanization, especially urban runoff. The litany of current concerns worldwide can be characterized by such diverse topics as widespread mercury contamination of the Amazon Basin as a consequence of gold processing (Malm et al., 1990; Martinelli et al., 1990), acute pesticide poisoning in Central America (Whelan, 1988), fisheries impacts attributable to the Exxon Valdez oil spill in Alaska, and degradation of near coastal waters of the East Asian Seas by untreated sewage (Gomez, 1988). These topics represent only the breadth of the types of problems, but they do not adequately represent the temporal and spatial distribution of such insults on a global level. The magnitude of exposure as well as the frequency and duration of exposure may vary dramatically at any given site, as may the severity of impact (Figure 1).

Significantly, there is apparently no global assessment of regional impacts of pollution by toxic substances. Such an assessment would ideally characterize the nature of the activity causing toxic substances to be introduced, the distribution of the substances or of toxic effects, the duration of the exposure, and relevant information on the biological resources of the receptor site. This information, of course, is rarely all available; and consequently, it is questionable whether meaningful ecological risk assessments can be performed using data of a lesser assessment. Would such an assessment, if commissioned, simply become a list of fish kills around the world? This topic bears further consideration. An understanding of the degree and extent of acute insults worldwide is necessary to determine whether acute and regional insults confer greater harm to the global environment than do effects that may be more widespread, but occurring at a lower level. It must also be seriously considered whether toxic substances even cause detrimental effects that are as significant as other agents of global change such as tropical deforestation, war, eutrophication, international water development, soil erosion, or potentially, global warming.

Characteristic 2: Global pollution can be partially characterized by low-level but widespread increases in the occurrence of (or background concentrations of) numerous toxic substances. The distribution of toxic substances in waterways of the world has been monitored in international programs such as the Global Mussel Watch Program (Risebrough, 1989). Nevertheless, our understanding of the fate, fluxes, and effects of low-level environmental pollution is not sufficient to make predictions of the potential for broadscale detrimental ecological effects. There are, however, regional examples that document that sublethal effects of environmental pollution can have significant impacts on organisms in marine ecosystems. One of the most remarkable examples includes the decline of brown pelican (*Pelecanus occidentalis*) populations in California. This decline was attributed to the accumulation of DDT in body fat or egg lipids of the birds; elevated DDT concentrations caused egg shell thinning which resulted in unhatched eggs being crushed by the weight of incubating adults. At the same time, at the same sites in California, an approximately 25%

increase in the incidence of premature births of California sea lion (*Zalophus californianus*) pups was also attributed to elevated organochlorine residues (Risebrough, 1989).

Nriagu (e.g. 1988, 1990) has trumpeted concern regarding the potential detrimental effects of global increases in emissions of trace metals. As trace metal concentrations in aquatic ecosystems approach toxic thresholds for many organisms (e.g. Patin, 1985), the potential for widescale impacts related to elevated trace metal concentrations is a serious issue.

Spatial and temporal characteristics of widespread, low-level increases in toxic substances are quite different from those that characterize regional pollution problems (Figure 1). Because the spatial distribution of contaminants is widespread, inputs which are episodic or localized are dampened and diluted. Therefore, by definition, the duration of exposures should be relatively long and the frequency of exposures relatively constant. These exposure characteristics tend to produce more subtle biological effects, if any at all. Such effects could be manifested at the organism, population or ecosystem level. To elucidate subtle biological effects, the newest developments in ecotoxicology must be considered. In particular, sophisticated techniques for assessing sublethal effects must be developed and coupled with state-of-the-art exposure assessment. Significant efforts must also be made to determine strategies for the implementation of existing techniques.

Characteristic 3: A unique aspect of global pollution is the occurrence of increasing UV-B attributable to the effects of CFCs on stratospheric ozone. Many of the challenges related to assessing the effects of low-level increases in UV-B are similar to those described for low-level increases in toxic substances, but there are also some significant differences. First, the study of UV effects is unique, because the mechanisms of solar UV action on living cells are reasonably well characterized (Jagger, 1985). The mechanisms include a broad spectrum of DNA damage (formation of pyrimidine dimers, single strand breaks and DNA to protein crosslinks) as well as effects on biological membranes. Designing programs to assess and monitor these selected mechanisms is a different task than is doing so for mixtures of contaminants for which mechanisms of effect may vary or may not be known. There is the possibility that, if mechanistic approaches are used, the effects of UV-B can be distinguished from other potentially confounding factors. This opportunity to establish cause and effect relationships is somewhat unique within global ecotoxicology.

The spatio-temporal scale of the global UV problem is also unique (Figure 1). Predictions of levels of ozone depletion in the Antarctic and in temperate latitudes are rapidly changing. However, estimates of ozone depletion up to 50% during the Antarctic spring and of 3 to 8% at selected seasons in temperate latitudes are now widely supported (Blumthaler and Ambach, 1990; Solomon, 1990; Stamnes et al., 1992). These phenomena have seasonal patterns which have been thoroughly described (e.g. Solomon, 1990). Although it is not known how quickly ozone depleting chemicals will be phased out worldwide, recent predictions are that the problem of ozone depletion is certainly a major concern for at least 50-100 years (Hammitt et al., 1987; Manzer, 1990). The exposure characteristics of the

UV-B problem are also different from those broadly described for chemical contaminants, because there is no concern about bioaccumulation, and because there is no need to predict fate and fluxes from varied media.

Controversy exists as to whether detrimental effects of increasing solar UV have already been documented in natural ecosystems. However, strong evidence has recently been presented that UV-B inhibition of photosynthesis is occurring in Antarctic phytoplankton communities during the spring ozone depletion (Smith et al., 1992). These recent findings highlight the need for rapid action to evaluate potential ecological impacts and to develop global monitoring strategies.

Characteristic 4: Global pollution problems have unique ecological boundaries. The "ecological boundaries" of global pollution problems are as important as are the spatial boundaries. It is possible to define ecological parameters and life history traits that may result in regionalized pollution problems having global significance. In addition, critical habitats should be identified for protection; critical habitats could include such areas as wetlands and migratory corridors (major rivers and important habitat on flyways). For example, riverine habitat destruction rendered by hydroelectric development has already taught us many lessons that should be directly translated to pollution research. Hydroelectric dams have decimated fisheries in many parts of the world, largely because one acute action at a single spot can deter migration and spawning of fish throughout the system. It is not implausible that acute environmental pollution in one area along a river could create "chemical dams" that would result in similar impacts throughout the system. Foe and coworkers[1] have documented stretches of toxicity dozens of miles long (using acute toxicity tests on indicator species) in the Sacramento and San Joaquin Rivers in California that are attributable to agricultural chemicals. It is not yet known whether these toxic events have created "chemical dams" for the already depleted salmon and striped bass populations, but this possibility is under investigation.

An additional consideration includes the potential impact of regional pollution problems on rare and declining species (Lubchenco et al. 1991). Although numerous factors may contribute to loss of biological diversity worldwide, the relative significance of pollution, as a factor in declining biological diversity, has not been systematically evaluated. Citations abound referring to the potential threat of toxic substances on biological diversity, but hard evidence is lacking. As was implied above, pollution may cause direct toxic effects on the species of interest or indirect effects on its prey and competitors. In addition, pollution may cause altered genetic diversity in exposed populations (Bishop and Cook, 1981). Gillespie and Guttman (1989) have used starch gel electrophoresis to document decreases in genetic diversity of selected organisms following exposure to toxic substances. Such findings raise

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[1] Data presented in reports to the Central Valley Regional Water Quality Control Board, Sacramento, California.

concern that populations with low genetic plasticity (such as rare and declining species) may be particularly vulnerable to the effects of toxic substances.

III. SCIENTIFIC PRIORITIES

Today, assessments of the effects of toxic substances are widely invoked in management decisions about the integrity of ecosystems; yet, research is needed to develop more sensitive and robust techniques. For aquatic ecosystems, effluent toxicity assessments typically rely on the use of short-term toxicity tests to predict the effects of mixed wastes as well as analytical chemical analyses to evaluate compliance with water quality objectives[2] (Bascietto et al. 1990; Cairns and Mount, 1990; Anderson et al., 1991). Managers do not have reliable techniques to predict many types of sublethal effects[3] of environmental contamination; the assessment of sublethal effects in complex media such as soil and sediment is a particularly thorny problem. The latter problem is crucial to better management of Superfund site cleanups and dredged materials disposal operations. Managers also lack tools to assess the significance of bioaccumulation of toxic substances on the health of fish and wildlife. Such problems, and the overarching need for a better understanding of the population and ecosystem-level effects of pollution, are common barriers to improved assessments at the local, regional, and global levels.

Below are described four key research topics that are central to a better understanding of regional and global pollution problems. For each topic, I briefly describe the significance of the question to various aspects of global change research, the components of the question, and progress to date in research on the topic. Because this paper focuses on responses to xenobiotic substances, I have not taken examples from the literature on acid rain; although this area of environmental management represents one of the best examples of the potential importance of research and monitoring in regulatory decisionmaking on both global and regional scales.

ASSESSING SUBLETHAL EFFECTS

The potential impacts of global pollution problems must be evaluated considering both the lethal and sublethal effects of toxic substances. The oldest rationale for this statement is

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[2] Water quality objectives are protection levels that are based on toxicity test results. Consequently, they are an estimate of levels that are protective of aquatic life. They are not technology-based standards.

[3] The types of sublethal effects assessed vary widely. Responses may include growth, development, reproduction, histopathologic alterations, DNA damage or enzyme and cellular responses.

perhaps the best one-- that dead animals do not herald an impending problem--they tell us a serious problem has already occurred. Ideally, we should be able to detect the "disease" before the patient is dead. In addition, diseased or even dead animals are not immediately apparent in the environment. This is particularly true of the early lifestages of many organisms. Thus, many losses may go undetected, and natural phenomena modify the population-level consequences of such occurences.

Sublethal effects assessments are frequently more sensitive than are assessments of lethality. Unfortunately, a major failure of ecotoxicology in the past two decades has been the inability of researchers to determine the ecological significance of these sensitive techniques or to describe the potential utility of such responses as early warning signals. Even if some responses may not be appropriate triggers for regulatory action, early warning signals may help to prioritize pollution problems. The potential ecological significance of any given technique may vary dramatically depending on where it fits within a spectrum encompassing strictly compensatory responses to noncompensatory responses that reflect "disease".

There is an urgent need to determine the hazards of low-level exposures to toxic substances and UV and to develop appropriate applications for existing sensitive assessment tools. These problems can only be addressed by further focused and prioritized research into the sublethal effects of contaminants and their potential ecological significance. This area of ecotoxicology is significant in both global and regional studies (Figure 2).

As a more specific example, it is well understood that solar UV causes many types of DNA alterations (Peak and Peak, 1985). Some alterations are likely to result in changes in reproductive success and carcinogenesis in natural populations (Anderson and Harrison, 1990a). In addition, because solar UV is mutagenic (Jagger, 1985), long term genetic changes in populations could occur, and these changes could probably be distinguished mechanistically (e.g. techniques of Cariello et al., 1990) from those attributable to other environmental contaminants. How can accurate hazard assessments be based on short-term tests that may barely span one generation and do not assess relevant sublethal changes? How can we ignore the fact that other widely distributed classes of toxic substances such as polycyclic aromatic hydrocarbons (PAH), aromatic amines, ionizing radiation, and some pesticides cause similar types of genetic effects?

In general terms, sublethal effects research is comprised of two broad components. One component involves the development of early life history and lifecycle tests in indicator organisms. The second and burgeoning component is the development of biomarkers[4] to evaluate effects of and exposure to toxic substances.

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[4] This term most commonly refers to biochemical, physiological or histopathologic indicators of either effects of or exposure to toxic substances.

Early lifestage and lifecycle tests have been widely developed and standardized using fish, amphibia, and aquatic invertebrates (e.g. Birge et al., 1985; DeGraeve et al., 1985; Bantle et al., 1989). They typically assess developmental abnormalities, growth and reproductive success in organisms exposed over either long time periods (60-90 days) or an entire lifecycle. Many such tests require only minor amounts of further research and validation before they can be applied to the decisionmaking process (e.g. Anderson and Harrison, 1990b). The short-term effluent toxicity tests that have become so widely used in managing aquatic ecosystems (USEPA, 1985a,b; Anderson et al., 1991) are the shortest and simplest incarnations of the early lifestage tests. Although this area of research has recently received less attention than the popular topic of biomarkers, further research in this area is warranted. Growth, reproduction and development are more clearly recognized as detrimental effects than are many biomarker responses. The key disadvantages of this type of test are that the long-term assays are not easily applied to field monitoring and that mechanisms of effect are not elucidated.

Biomarkers of sublethal effect have been researched for two decades; although they have only recently attained a very high profile. The pitch of research has heightened as a critical mass of data have been attained (catalogued in Huggett et al., 1992) and as decisonmakers have come to an understanding that the tools they have to assess pollution effects are not adequate. To some extent, research in this area has also been accelerated by the development of new technologies such as monoclonal antibody technology and advances molecular genetic techniques.

The most common classes of biomarkers (Huggett et al., 1992) are DNA alterations, metabolic product indicators, immunologic responses, histopathologic measurements, and enzyme and protein synthesis responses. These types of indicators hold enormous potential for evaluating low-level effects of global pollution *in situ*, for determining their potential cause, for discerning long term or latent effects using short-term indicators, and for examining the effects of specific toxic agents. In addition, these techniques can be excellent indicators of exposure to rapidly metabolized toxic substances that do not bioaccumulate. Although the ultimate promise of such techniques is enormous, they have only been suggested for use in a limited number of decisionmaking applications (e.g. Landner, 1988; Anderson and Harrison, 1990b); and broadly speaking, there is limited consensus as to which techniques are most useful. The level of development of the techniques varies widely. Strengths and weaknesses of any given test are dependant upon sensitivity, specificity, inherent variability, applicablity to field conditions, ecological relevance, methodologic utility and other considerations.

McCarthy (1990) has recently concluded that improved integration and prioritization of biomarker research is crucial for its full promise to be realized. The prioritization of further research on the application of biomarkers is a task beyond the scope of this document, but a few simplifying principles should be discussed. Given the status of current biomarker research, it is crucial to emphasize research that will lead to:

- Indicators of effect that are more sensitive than more overt responses but which can be linked to significant detrimental effects

- Indicators which are applicable to reliable field detection of the effects of or exposure to a wide range of chemicals. This ideal trait of "something that will detect everything" will never be realized, but limited batteries of tests with broad applicability and low inherent variability are a potential reality.

- Indicators which are applicable to the field monitoring of effects of and exposure to specific chemicals with high specificity in target organs (such as specific DNA adducts or cDNA probes to P450 enzymes). These could be very useful in monitoring biologically effective doses and exposures in complex media when single contaminants or classes of contaminants are of particular concern.

- Indicators which will aid in determining basic mechanisms of effect. If monitoring programs are to be prioritized, specific mechanisms could be targeted for chemicals of concern. This avoids the application of inappropriate biomarker techniques and the potential risks of false negatives.

Significantly, the evaluation of genotoxic responses fulfills many of these criteria. Biological dosimeters of effective doses, such as specific DNA adducts, are being developed, sensitive reponses are being linked to ecologically significant endpoints such as reproduction (Liguori and Landolt, 1985; Anderson et al., 1990; Anderson and Harrison, 1990a) and carcinogenesis (reviewed in Shugart et al., 1992), and numerous techniques are being adapted from the human health literature (e.g. Hose and Puffer, 1983; Shugart, 1988; Singh et al., 1988) that are useful in evaluating mechanisms of effect. In addition, field validations of selected techniques have been performed (Long and Markel, 1992). Finally, the potential for using molecular genetic techniques to evaluate specific mechanisms of effect (e.g. Cariello et al., 1990) may enable researchers to "fingerprint" the spectrum of DNA damage produced by classes of contaminants.

UNDERSTANDING MECHANISMS OF TOLERANCE AND ADAPTATION

Animal populations may be altered by mutations that confer tolerance to toxic substances. Although this topic has only been treated critically in a limited number of ecotoxicological studies (Bishop and Cook, 1981), it may have unique significance in global ecotoxicology (Figure 2). This is because the widespread, long term, and low-level constant exposures that typify global pollution problems are more likely to produce stable population changes than are the intermittent or localized exposures that typify regional pollution problems.

Bishop and Cook (1981) have provided a general synthesis of this topic. They summarize key examples on insecticide resistance, industrial melanism, and the tolerance of higher plants to selected toxic materials. Shugart et al. (1992) have also recognized the need for further work on genetic adaption attributable to pollutant exposure, and they suggest that modern molecular techniques used in evolutionary genetics be applied to this problem.

Globally, metals are mobilized into the air and water at rates that are greatly accelerated by human activity (e.g. Nriagu and Pacyna, 1988; Nriagu, 1990). We do not know at what point narrow differences between natural (and sometimes essential) levels and toxic levels of heavy metals will have eroded too far. Tolerance to metals has been evaluated in numerous aquatic organisms (Luoma, 1977; Kuwabara and Leland, 1986). However, as gradual increases occur in the concentrations of trace metals in aquatic ecosystems, it becomes increasingly difficult to determine how control sites and control organisms should be selected for experiments on adaptation. It is posssible that for some organisms, no true controls exist. The limits of genetic adaptation and their relation to thresholds of toxicity should be fully explored.

ASSESSING THE SIGNIFICANCE OF AN ELEVATED CONTAMINANT TISSUE CONCENTRATION ON THE HEALTH OF AN ORGANISM

One of the most frequently assessed parameters in pollution studies is the tissue concentration of toxic substances in varied organisms. Despite the widespread quantitation of tissue concentrations, such measurements usually only contribute to an understanding of the spatial and temporal variation of toxic substances in specific tissues of specific organisms. Only rarely, are sufficient laboratory studies conducted to correlate elevated tissue concentrations with detrimental effects on an organism. This is a significant problem in both aquatic toxicology (Cairns and Mount, 1990) and wildlife toxicology (Hoffmann et al., 1990), because there is a widespread need to predict and assess how much chemical in specific tissues of an animal is too much. Currently, then, managers generally lack sufficient information to develop criteria for fish and wildlife protection for bioaccumulative substances. Further laboratory research is needed to link elevated tissue concentrations to detrimental biological effects for specific substances. Research is also needed to link biomarker responses to elevated tissue concentrations for bioaccumulative substances.

Determination of the biological significance of an elevated tissue concentration is an urgent problem in regional assessments today (Figure 2), and the problem has been more widely recognized following recent incidents. At the Kesterson Reservoir in California, field observations of deformed birds were linked to trace metals, particularly selenium, that had leached from subsurface agricultural drainwater (Ohlendorf, 1986a,b). Previous testing of Kesterson waters, using standard bioassay tests, revealed no deleterious effects. In global ecotoxicology, there will be a similar urgent need to assess the significance of low-level, widespread increases of toxic substances in diverse organisms and tissues. It is essential that we learn to predict responses before deleterious changes occur. The only area of global ecotoxicology that will not be significantly affected by this problem is the study of solar UV effects (Figure 2).

Research into the overt detrimental effects of elevated tissue concentrations will progress as toxic substances are prioritized for global and regional assessment; however, a more concerted effort is needed to accelerate the linkages between these studies and research on biomarkers. Biomarkers should be incorporated into laboratory studies of more overt effects, such as developmental abnormalities and decreased growth, to aid in elucidating potential mechanisms of effect for selected substances and to validate the use of selected biomarkers for field monitoring. Of course, for many rapidly metabolized substances, correlations between tissue concentration and detrimental effect are not expected. Similarly, such relationships for toxic heavy metals are known to be complex because of the detoxification action attributable to metal binding proteins.

ASSESSING EFFECTS IN COMPLEX MEDIA

The difficulty of determining detrimental effects of toxic substances in complex media is a problem that impacts both global and regional assessments (Figure 2), and it overlaps with many aspects of sublethal effects research. On a regional level, there are needs to predict the bioavailability and potential effects of toxic substances in soils and sediments at hazardous waste (Anderson, 1992) and dredge disposal sites. This information is needed to make accurate predictions of the hazards associated with specific cleanup procedures, to determine appropriate disposal options for excavated wastes, and to determine targets for remediation activities ("How clean is clean"). Unfortunately, even simple toxicity test techniques may be frought with variability and interferences when applied to soils and sediments. Positive interferences are attributable to such factors as sulfides in anaerobic sediments and variations in sediment grain sizes. Selection of reference soils and sediments can also be a severe problem for many sites. Some reliable acute toxicity tests do exist, but many fewer tests assess sublethal responses (Burton, 1991).

In global ecotoxicology (with the exception of solar UV effects), there will also be a need to evaluate effects of toxic substances in complex media such as soil and sediment. Whether a substance is deposited by atmospheric distribution or ocean circulation, aquatic sediments are an important sink for contaminants. How can decisionmakers determine the effects of low-level but widespread increases of toxic substances on sediment and soil communities? This can only be accomplished if there are adequate methods to detect the sublethal effects and bioavailability of contaminants in complex media. Both early lifestage tests and biomarker responses are needed. Although field comparisons of such responses have been made at a limited number of sites (Chapman et al., 1992; Long and Markel, 1992), the relative utility of various techniques has not been thoroughly characterized.

The complex exposure scenarios occurring in sediment and soil make it an extremely complex task to develop critiera for sediment and soil protection. Nevertheless, there are numerous regulatory efforts to establish sediment and soil quality criteria. These criteria would be numerical limits for specific chemicals that would indicate "safe" exposure levels. Alternatively, integrated chemical monitoring and toxicity criteria could be applied to regulation (e.g. Ginn and Pasotorok, 1992; Southerland et al. 1992). Research in predicting the bioavailability of sediment-sorbed chemicals (summarized in Knezovich et al., 1987) is essential for regulatory efforts to result in meaningful improvements in water quality. Although such research is widely pursued and incorporated into management, it remains the source of extensive controversy.

Other current topics in sediment and soil toxicity assessment include: (1) problems associated with sample handling, (2) modelling and assessing bioaccumulation (Lee, 1992) (3) assessment of population- and community-level effects (Burton 1991; Cairns et al., 1992). All of these topics are important to producing more sophisticated regional and global assessments.

V. CONCLUSIONS AND RECOMMENDATIONS

Research priorities for global ecotoxicology must be formulated. Below are listed key recommendations for further research.

Low-level, widespread contamination by toxic substances: This is the most intractable of the problems, because extensive research is needed for the potential signifcance of low-level contamination to be determined. Nevertheless, key actions are identifiable. First, research in the four key areas discussed above should be a high priority in global ecotoxicology. Secondly, toxic substances of greatest concern should be identified based on existing data, with special emphasis on heavy metals. Third, crosscutting programs should be devised to accelerate the progress of biomarker research with respect to specific toxic substances. Combined field and laboratory programs to evaluate both methods for *in situ* monitoring and mechanisms of action of priority substances would be extremely valuable. These interdisciplinary programs would include assessments in complex media and assessments of the potential significance of elevated tissue concentrations in sentinel species. The intent of these programs would be to promote a more strategic development of the basic research agenda.

Regional effects: To better determine the magnitude, duration, and frequency of regional pollution problems, the feasibility of a global toxicity assessment should be evaluated. The feasibility analysis would first consider available information from existing international programs. Secondly, a strategic assessment should be devised. That is one that would survey selected land use categories, selected habitats, or selected industrial processes from a representation of nations. The assessment could be followed with field validation using existing water-quality based management techniques such as acute and chronic toxicity tests and analytical chemistry. Although this framework is only hypothetical, the possibilities it suggests are numerous. For example, partnerships could be developed between ecologists and toxicologists to identify critical habitats, and biomarkers could be tested in varied environments on an experimental basis. In addition, social scientists could collaborate in devising the assessment strategy.

UV-B effects: Priorities for monitoring and assessment of UV-B effects should be immediately established in a high-visibility research strategy. Many of the complexities that will slow down the pace of research on metals and chemical contaminants (complex and poorly characterized mechanisms of sublethal effects, bioaccumulation, complex media) should not inhibit the progress of UV-B research (Figure 2). Despite methodological difficulties associated with solar UV research, the UV-B problem is still a much more focused problem than the determination of the potential broadscale effects of low-level contamination by toxic substances. Consequently, the UV-B problem is more amenable to immediate "mission-oriented" solutions coupling both research and monitoring.

Ecological Boundaries: There is an urgent need for increased collaboration between ecotoxicologists and ecological theorists. If such cooperation can be attained, research could be accelerated on topics such as the effects of pollutants on global biodiversity, the frequency of identification of pollution-tolerant species and their ecological significance, the identification of key habitats (e.g. wetlands and major migratory pathways) for protection and research, the identification of life history strategies that may confer vulnerability to toxic substances, and the study of rare and declining species. I propose that well-supported requests for proposals in this area, from relevant agencies, would be the most expeditious way to promote such collaboration. Recent efforts in the ecological research community (Lubchenco et al., 1991) encouraging ecologists to be more responsive to pollution problems undoubtedly signal that the time is ripe for change.

I propose that scientists in global ecotoxicology should work toward the goal of making a first estimate of the potential significance of contaminants (and UV-B) as agents of global change within ten years. This goal may seem unambitious to some and overly ambitious to others (answers on low-level contaminants will be quite preliminary), but it is proposed as an initial step towards a clearer and more specific statement of goals and a research agenda. Although this paper has not discussed the potential institutional aspects of the proposed research, one thing is clear-- this problem will require clear goals, strategy, and partnerships.

ACKNOWLEDGEMENTS

John Harte, Jerome Nriagu, Bruce Patton, Robert Socolow, and Valerie Thomas provided insightful comments on drafts of this paper. This work was supported by the NIEHS Superfund Basic Research Program, University of California Berkeley Program Project (NIH P42 ES04705-03), through the U.S. Department of Energy under contract No. DE-AC03-76SF00098. This work was also partially supported by the Pew Charitable Trusts.

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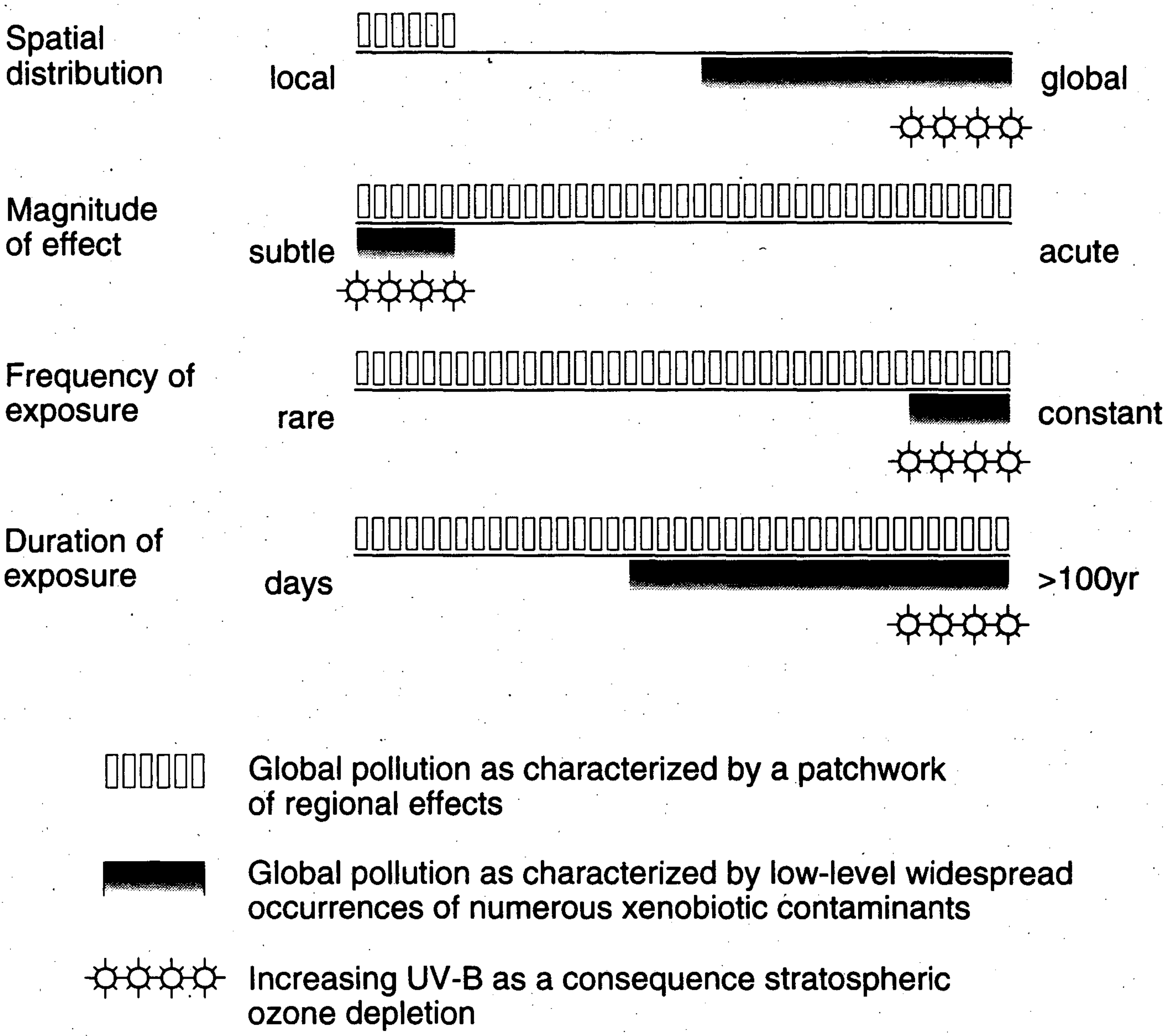

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Figure 1