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A METHODOLOGY FOR IMPACT AND RISK ASSESSMENT IN INTEGRATED ENVIRONMENTAL MANAGEMENT

Michael N. Moore

United Nations Industrial Development Organization (UNIDO), Vienna International Centre, PO Box 300, A-1400 Vienna, Austria, & Centre for Coastal & Marine Sciences, Plymouth Marine Laboratory (CCMS-PML), Plymouth PL1 3DH, UK

Abstract

Most of the Earth's living resources are found in specific geographical locations such as the global coastal environment and the catchment basins of large river systems. Furthermore, a large proportion of the world's population lives in close proximity to these regions and is frequently dependent upon it for either part or much of its food supply and industrial raw materials. The consequence of this situation is that much of the waste, both industrial and domestic, and various other types of habitat destruction generated by the human population, occurs in those areas that are of greatest biological and economic significance. The overall problem is, how to develop effective procedures for environmental/ecological impact and risk assessment? One of the major difficulties in impact and risk assessment is to link harmful effects of chemical pollutants in individual animals and plants with the ecological consequences. Consequently, this obstacle has resulted in a "knowledge-gap" for those seeking to develop effective policies for sustainable use of resources and environmental protection. However, diagnostic "clinical-type" ecotoxicological tests or "biomarkers" and immunochemical tests for contaminants are now increasingly available; and there is a concerted international research effort to improve and extend this predictive capability. These ecotoxicological tools can provide information on the health-status of populations based on relatively small samples of individuals. Also, biomarkers can now be used to begin to link processes of molecular and cellular damage through to the higher levels (i.e., prognostic capability), where they can result in reduced performance and reproductive success. Research effort to meet this challenge is interdisciplinary in character, since the key questions mainly involve complex interfacial problems. These include the effects of physical chemical speciation of pollutant chemicals on uptake and toxicity and the toxicity of complex mixtures; as well as linking the impact of pollutants through the various hierarchical levels of biological organisation to ecosystem and human health. Finally, the development and use of process simulation models (i.e., "virtual" cells, organs and animals), illustrated here using an endosomal/lysosomal uptake and cell injury model, will further facilitate the development of a predictive capacity for estimating risk associated with the possibility of future environmental events.

In conclusion, an integrated environmental management strategy must be truly cross-disciplinary if an effective capability for risk assessment and prediction is to be developed in relation to resource sustainability. Areas of collaboration need to include, among others remote/satellite surveillance, risk assessment, interpretation of complex information and predictive modelling. There also needs to be increased focus on precautionary anticipation of novel environmental hazards (e.g., from Biotechnology & Molecular Nanotechnology). And last but not least, it is crucial to educate politicians, industrialists and environmental managers concerning the long-term consequences of pollution; and that increased consumer awareness of environmental problems is exerting pressure on industry to make its products "environmentally friendly" (i.e., eco-labelling), in order to maintain existing markets and to improve their penetration into new markets.

INTRODUCTION

Riverine, coastal & shelf areas are the most heavily used yet vulnerable zones of the planet. They receive a multitude of man-made inputs from land-based sources (land drainage, rivers, municipal & industrial outfalls), as well as contaminants introduced through combustion and atmospheric inputs. Consequently, this results in deterioration in water quality of groundwater, lakes, rivers, estuaries & coastal marine environments. The problem arises from a variety of reasons including:- economic failure; inadequate governance & non-enforcement of existing environmental protection laws; haphazard industrialisation and urbanisation results in runoff of polluted wastewater and contamination of land, rivers and coastal waters; poor public education and

understanding of the problems; and the strongly sectoral structure of government bodies frequently presents a barrier to integrated solutions.

River basins, deltas and estuaries are often characterised by a rich diversity of plants and animals, that are, unfortunately, often environmentally sensitive and susceptible to human interference. Consequently, this can lead to conflict over resource rights and deprive the indigenous human population of major sources of food (e.g., fish as a major source of dietary protein). However, there is now increasing awareness of the global importance of specific geographical domains, such as the coastal land-sea interface, as major resources and concern for maintaining the diversity of life on our planet. This was a major focus for Agenda 21 of the UNCED, Earth Summit Conference in Rio de Janeiro (Quarrie, 1992).

The scale of the problem is indicated by the findings of a recent economic study. These placed a value of US\$ 12.6 Trillion/year for Coastal Zones & US\$ 6.6 Trillion/year on Wetlands, Rivers & Lakes, out of a Global Total of US\$ 33.3 Trillion/year (Costanza *et al.*, 1998).

Pollutant impact on ecosystem and human health is an urgent and international issue, since there is an ever-increasing number of examples of environmental disturbance, likely to affect the biota and humans, by both natural and anthropogenic stress. Important stressors include toxic industrial chemical contaminants, increased UV-radiation, nutrient enhancement or deprivation, hypoxia, habitat disturbance and pathogen-induced disease. In fact, environmental disturbance will frequently comprise various combinations of such stresses. Furthermore, it is increasingly recognised that assessment of the impact of environmental disturbance on organisms requires understanding of stress effects throughout the hierarchy of biological organisation, from the molecular and cellular to the organism and population levels, as well as the community and ecosystem level. In the past, damage to the environment has largely been identified retrospectively and in response to acute events such as major disasters (e.g., industrial accidents like Seveso and Bhopal; and oil spills (Amoco Cadiz & Exxon Valdez) and chemical pollution of the Great Lakes). Generally, these have been measured in terms of human health impacts and visible changes resulting from the loss of particular populations or communities. However, long term and chronic exposure to environmental stress, including chemical pollutants or other anthropogenic factors, will seldom result in rapid and catastrophic change. Rather, the impact will be gradual, subtle and frequently difficult to disentangle from the process and effects of natural environmental change. This latter problem has been a major stumbling block in assessing environmental impact since such investigations began, mainly in the 1960s.

The major issues of concern include the role of "Industry" as a major source of pollution; the fact that pollution does not respect national boundaries; the loss of living resources and biodiversity; damage to human health; and support for sustainable financing and banking in order to support developing economies. The environmental objectives of sustainable industrial development include the sound management of natural resources, effective transfer of environmentally sound technologies in order to reduce, reuse and recycle waste, investment promotion for sustainable industry, environmental monitoring and control of investments for environmental industry projects.

Environmental Components for Sustainable Industrial Development need to include:-

- an effective environmental policy framework
- cleaner industrial production and pollution prevention
- environmental emission and discharge standards
- enforceable pollution control and waste management
- ecotoxicology for assessing environmental impact of pollution and overuse of resources
- environmental modelling for policy decisions
- risk assessment and risk reduction
- the integrating process with socio-economic conditions and governance issues.

In this context, UNIDO provides knowledge-based expertise on environmental policy, cleaner production, waste management and pollution control, through its service modules, in order to achieve sustainability. It also provides expert diagnostic and predictive software to link existing models with industrial information and knowledge of the environment. In addition, UNIDO supports the development and use of indicators, which show effectiveness in moving towards sustainable development, that link environmental, social and economic measures.

Environmental Stress can be caused by a number of factors including:- natural forces such as sea level rise, climate change and soil erosion; poorly planned development, such as haphazard urbanisation and industrialisation; depletion of resources through over-fishing, deforestation and poor use of agricultural land; unregulated discharges of municipal sewage and industrial waste; and illegal practices, such as disposal of dangerous toxic wastes.

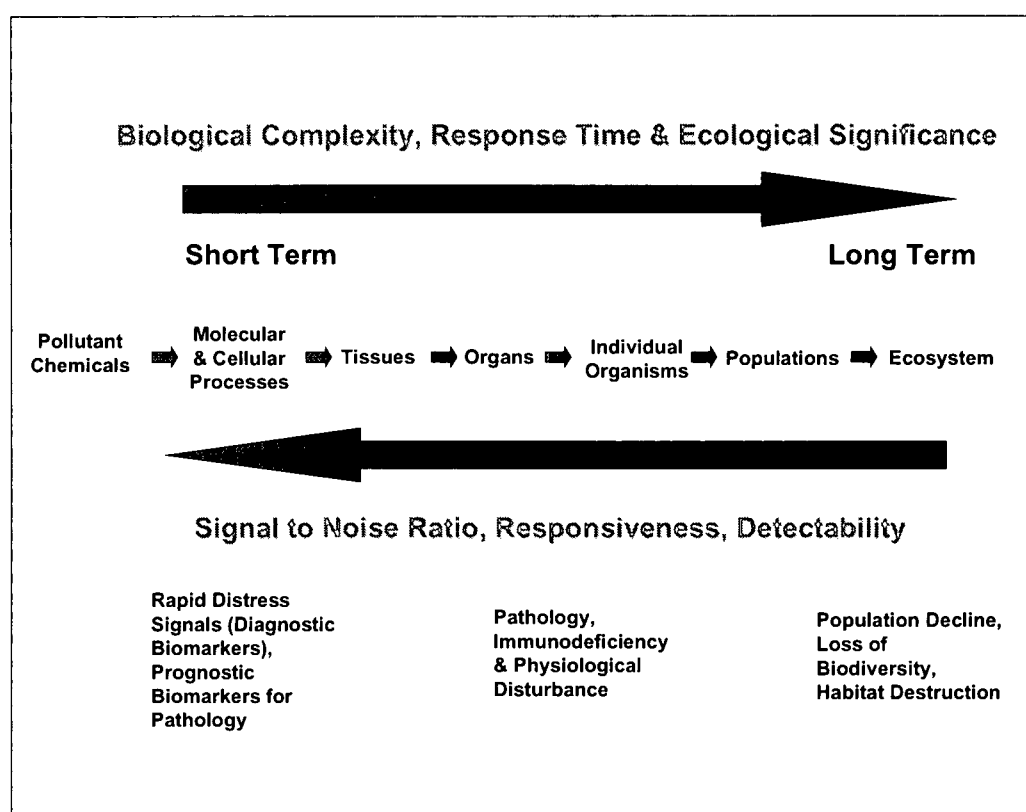


Fig. 1. Diagrammatic representation of the relationship between environmental distress signal detectability and ecological relevance (Bayne *et al.*, 1985; Moore & Simpson, 1992; Moore *et al.*, 1994; Moore, 2000).

While it is clearly recognised that stress-induced changes at the population / community / ecosystem / human health levels of biological organisation are the ultimate concern, they are generally too complex and far removed from the causative events to be of much use in developing tools for the early detection and prediction of the consequences of environmental stress (Fig. 1; Depledge *et al.*, 1993). Rapid resolution of this link to health is essential if environmental management is to have a sound scientific basis for the regulation of the release of toxic substances, nutrients and habitat disturbance. The basis of such regulation, where it exists at present, is often at best sketchy with a heavy reliance on empirical observations and laboratory based toxicity tests using organisms that have limited relevance to the real environmental context.

A probable solution to this problem lies in the effective detection of "**distress signals**" at the molecular and cellular levels of organisation and linking these latter to the higher level consequences (Fig. 1; Bayne *et al.*, 1985; Depledge *et al.*, 1993; Moore, 1990; Moore and Simpson, 1992). It is only at these lower levels that we will have the reasonable expectation of developing a reasonable basis of mechanistic understanding of how different environmental conditions can modulate organismal function, which in turn will ultimately help in linking causality with predictability of response. This is in part due to our ability to make certain generalisations about biological organisation and function at the molecular and cellular level which rapidly disappear as we ascend the hierarchical ladder. Hence, distress signals at the molecular, cellular and physiological levels of organisation should be capable of providing "early warning prognostic biomarkers (molecular, cellular, physiological and behavioural)" of reduced performance, impending pathology and damage to health (Depledge *et al.*, 1993; Hinton and Lauren, 1990; McCarthy and Shugart, 1990). In fact, there is a direct analogy here with the use of clinical tests (biomarkers) in human and veterinary medicine (Moore and Simpson, 1992).

The derivation of potential prognostic tests for "distress signals" will only arise out of an understanding of the mechanistic basis of the cellular and physiological processes that contribute to uptake, biotransformation, molecular damage and cell injury, impairment of protective systems and, ultimately, to degenerative change and the consequences for reproduction and survival (Moore, 1990; Moore *et al.*, 1994; Fig. 2). For this way forward to be fully effective it requires an integrated multi-tiered approach combining both reductionist and synthesisist components. The tools to implement this are now becoming increasingly available.

Briefly, these include mechanisms of pollutant uptake, biotransformation and radical generation, molecular damage and consequent cell injury, as well as antioxidant protection and repair. These in turn need to be linked with cellular and physiological processes of vesicular transport of proteins, protein turnover, and interactions of the nervous and endocrine systems with effective immune defence function. At the higher organisational levels, differential sensitivity needs to be assessed according to individual genotype, life-history stage, and natural seasonal changes in physiological and/or reproductive status. Finally, this information then needs to be used to develop process simulation models of the type increasingly used in quantitative cell biology and cellular bioengineering (Biganzoli *et al.*, 1998; DÜchting *et al.*, 1996; Koo, 1999; Lauffenburger & Linderman, 1993; Noble *et al.*, 1999). Mathematical simulation models can provide insights into the links between molecular properties and cell and organ behaviour; and the predictive power of such models can be harnessed to develop tools for risk assessment of toxic chemicals.

Research effort to meet this challenge must be interdisciplinary in character, since the key questions mainly involve interfacial problems. These questions include the effect of physico-chemical speciation on uptake and toxicity, the toxicity of complex mixtures (Howard, 1997; Kanzawa *et al.*, 1997), and linking the impact of pollutants at the various hierarchical levels of biological organisation from the supra-molecular and cellular to the population and ecological community (Figs. 1 & 2).

Major aims include the development of conceptual frameworks based on a mechanistic understanding of contaminant geochemistry and uptake, metabolic biotransformation, toxicity and impact within the biological organisational hierarchy. Large scale tasks include predicting the toxicity of contaminant mixtures (Howard, 1997); and modelling environmental pollution and impact as a complex adaptive system, which will encompass contaminant geochemistry, biochemical toxicology, cellular pathology, ecological consequences and human risk (Fig. 2; Moore, 2000).

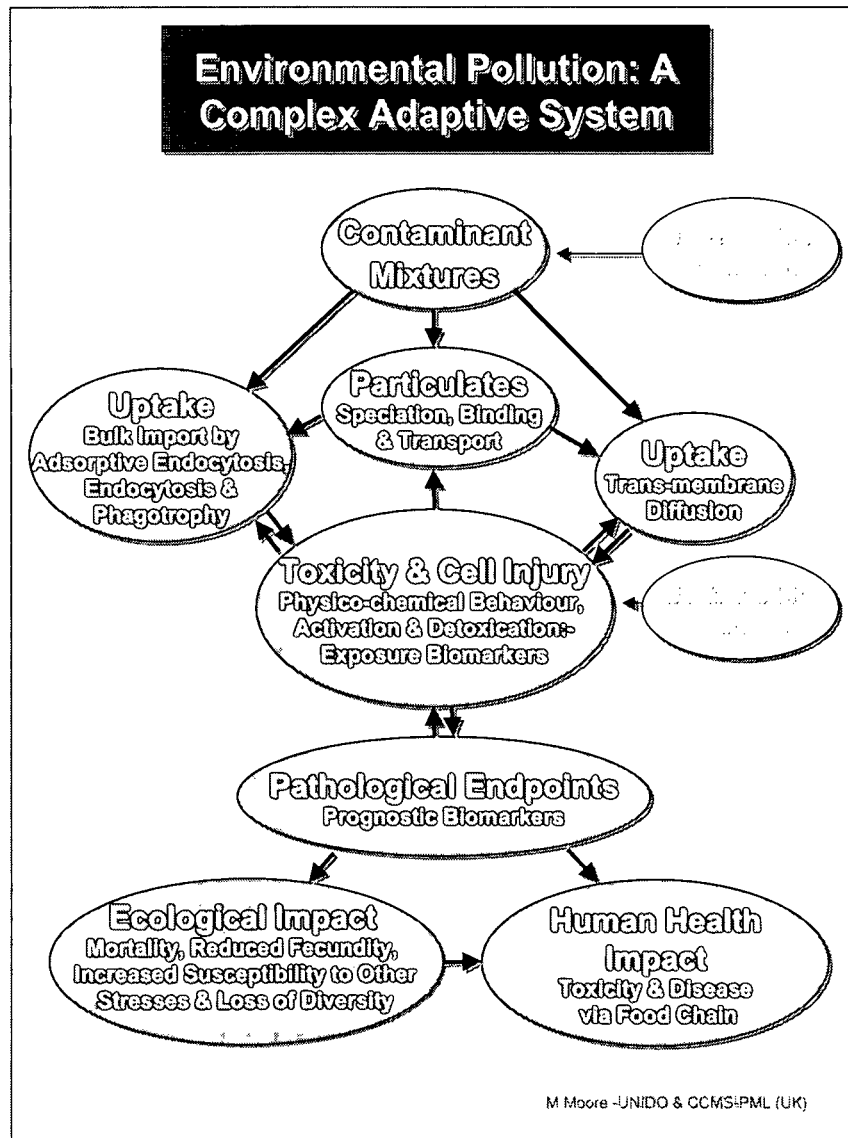


Fig. 2. A conceptual framework showing the interconnectedness of environmental pollutant-related processes and their harmful effects as components of a Complex Adaptive System (taken from Moore, 2000).

Finally, the major challenges for ecotoxicologists and environmental scientists are to aim for “real mechanistic understanding”, which must also include the linkages between levels of organization in the biological hierarchy. This is essential if the question of biocomplexity is to be effectively addressed through the development of computational simulation models, based on multiple molecular interactions (Schaff *et al.*, 1997). These cellular models must be capable of experimental validation, which should also include genetic manipulation of key processes. Visualisation of cellular processes *in silico* will facilitate the identification of complex subcellular strategies for adaptation to altered environmental conditions.

ENVIRONMENTAL RISK & INTEGRATED ENVIRONMENTAL MANAGEMENT

First, we must consider what is at risk in the coastal zone: clearly these are land use and environmental resources, such as water and fisheries; biodiversity and environmental quality; environmental and human health (in some countries, such as Ghana, up to 70% of the health costs are directly related to environmental causes); and finally aesthetics, which can be particularly important in relation to the tourist industry.

The acceptability of risk in Integrated Environmental Management is not an issue for scientific research alone. It involves economic, social and political issues, which all need to be integrated in order to develop prognostic risk models. There are also important economic components that are directly related to the value of the resources to be protected and the costs of increasing safety margins.

We can forecast and reduce Environmental Risks through the implementation of innovative environmental monitoring and surveillance techniques to understand the extent of the problems (new rapid low cost immunochemical tests for contaminants, health tests (biomarkers) for animals, plants and humans, satellite monitoring). These require supporting research into understanding physical, chemical, biological and ecological processes. We also need to develop decision support (expert) systems to link existing models with our experience and knowledge of the environment; as well as to develop and use indicators of sustainability to show effectiveness in moving towards sustainable development, where there is a need to link environmental, social and economic measures.

The Objectives of Integrated Environmental Management (IEM) are as follows:

- prevent, reduce and control degradation of the total environment thereby maintaining and improving its life support and productivity capacities
- develop and increase the potential of living resources to meet human nutritional needs, as well as social, economic and development goals
- promote the integrated management and sustainable development of terrestrial, freshwater and coastal marine environments.

IEM holistically assesses the changing states of ecosystems based on information from five operational modules:-

- 1) ecosystem productivity;
- 2) water, fisheries, agricultural and forestry resources;
- 3) pollution and health (ecosystem & human);
- 4) socio-economic conditions;
- 5) and governance protocols.

These modules link science-based information to socio-economic benefits for countries sharing boundaries for international waters; and are used in an integrated interdisciplinary mode to address the consequences of ecosystem change (e.g., GEF-Large Marine Ecosystem Projects).

The methodology of IEM brings together elements for dealing with the complex interactions of the many demands placed on the environment. The methods are implemented through training, technology transfer and capacity building, that are firmly grounded on strategic science-based assessments and monitoring and linked to standard internationally agreed QA protocols.

Programme components for Integrated Environmental Management should include:-

- biogeochemical and physical processes
- bioavailability of toxic chemical pollutants, uptake into plants, fish and animals and the subsequent transfer to humans through the food chain

- ecotoxicology and environmental impact of pollution and overuse of resources (e.g., land, water, rivers, forests and fisheries)
- models for integrated environmental management
- human health risks
- risk assessment - a cross-disciplinary issue
- the integrating process for environmental data and predictions, together with economic and social aspects.

BIOAVAILABILITY AND UPTAKE OF CONTAMINANTS

The uptake and accumulation of organic micropollutants and metals by aquatic organisms is governed by their physical chemical speciation. Lipophilic pollutants are largely associated with particulates and colloidal organic carbon (Murdoch *et al.*, 1994; Smedes, 1994; Readman *et al.*, 1984). It is becoming increasingly clear, however, that the mechanisms of binding vary from that simply described by the traditional K_d . In considering bioavailability and uptake, this factor needs to be addressed. In addition, it is probable that contaminant entry into cells is directly related to the extracellular and intracellular behaviour of particulates/colloids with adsorbed chemicals (Fig. 3; Moore & Willows, 1998).

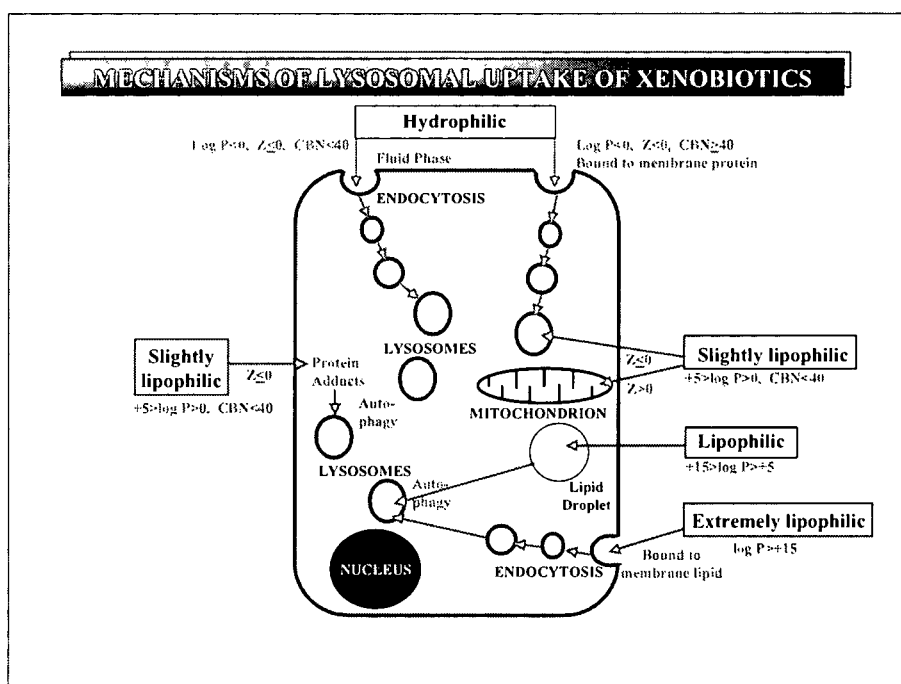


Fig. 3. Diagrammatic representation of the various routes of uptake (diffusion and endocytotic) of contaminant xenobiotic chemicals into the cell that result in their accumulation in the lysosomal compartment, based on their physical chemical characteristics (Rashid & Horobin, 1990; Rashid *et al.*, 1991; Moore *et al.*, 1996).

Contaminants are seldom present as a single chemical and usually comprise a complex mixture (Howard, 1997; Kanzawa *et al.*, 1997). Uptake of xenobiotics from such mixtures is poorly understood and questions of whether components of the mixture influence the uptake and biotransformation of other components have not been seriously addressed (Kortenkamp & Altenburger, 1998). Uptake is often viewed as taking place from solution with the contaminant crossing cellular membranes by diffusion (Moore & Willows, 1998). However, as stated above,

most contaminant chemicals are bound to particulates and so, are seldom in true solution (Smedes, 1994; Moore & Willows, 1998; Readman *et al.*, 1984). This is probably of considerable importance in explaining the known compartmentation of many micropollutants and metals within cells and tissues of plants and animals, so it is essential that an appropriate mechanistic understanding of the intracellular transport processes, intracellular chemistry and associated biotransformations is developed in the future (Moore, 2000; Moore & Willows, 1998). This type of knowledge is essential if we are going to be able to attempt to predict the kinds of organisms at risk and, also, whether particular life stages are more vulnerable than others.

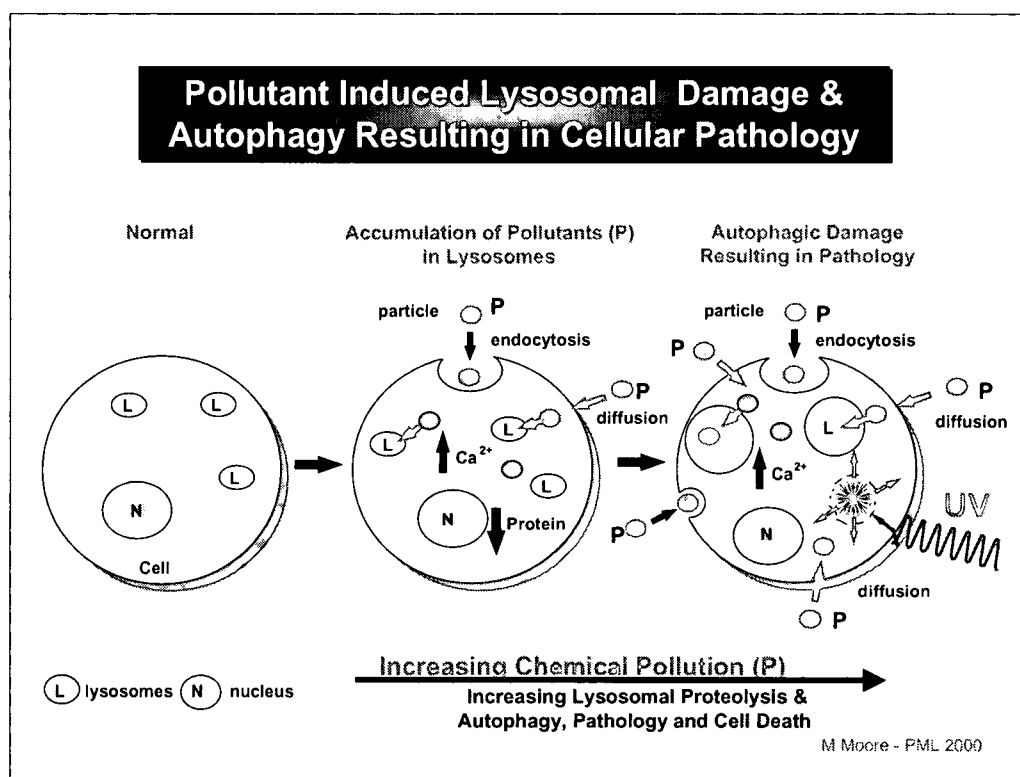


Fig. 4 Diagrammatical representation of the processes of cellular uptake of xenobiotics; their lysosomal accumulation and harmful effects, including induced lysosomal proteolysis, augmented autophagy and the interactive effects of UV radiation in cell injury (Benchimol, 1999; Bonifaciano & Weissman, 1998; Calle *et al.*, 1999; Franke, 1990; Halliwell, 1997; Hawkins & Day, 1999; Hein *et al.*, 1990; Hutchins *et al.*, 1999; Luzikov, 1999; Moore, 1990, 1991, 2000; Moore & Willows, 1998; Moore *et al.*, 1994, 1996, 1997; Mortimore & Poso, 1987; Rashid *et al.*, 1991; Seglen, 1997; Thevenod & Friedmann, 1999; Viarengo *et al.*, 1994; Winston *et al.*, 1996).

There is also a clear need for new rapid analytical methods for routine application, such as the use of immunochemical detection of organic micropollutants (Aga & Thurman, 1997; Sherry, 1997). Clinical chemists have utilised immunoassay (IA) techniques to detect and quantify proteins, hormones, and drugs for decades. The most common version of environmental IA is called ELISA (Enzyme Linked Immunosorbent Assay; Aga & Thurman, 1997). ELISA is an immunoassay method that uses antibodies and enzyme conjugates to detect and quantify target compounds, otherwise known as compounds of interest (COIs), in field samples. Therefore, with appropriate calibration, IA can be used for rapid low cost pollutant determination in soil, sediment, water and body fluids (Aga & Thurman, 1997; Sherry, 1997).

In studies of bioavailability, there has only been very limited use of modelling procedures to simulate intracellular behaviour of pollutants. Here, process simulation modelling will be particularly important in helping to define the problems and in developing hypotheses in this highly complex area. One such preliminary mathematical model has been developed that defines the component processes in endocytosis, lysosomal compartmentation, toxicity and pathology (Figs. 3 & 4; Moore & Willows, 1998). This model focuses on ligand-binding sites associated with endocytosed particulates and the role of the endosomal-lysosomal system in pollutant uptake, toxicity and cell injury (Cheung *et al.*, 1998; Hauton *et al.*, 1998; Lowe *et al.*, 1995; Moore *et al.*, 1994, 1996 & 1997; Rashid *et al.*, 1991; Ringwood *et al.*, 1998; Svendsen & Weeks, 1995; Wedderburn *et al.*, 1998; and Figs. 3 & 4). This model has provided a conceptual framework for pollutant uptake and biotransformation, lysosomal accumulation, protein degradation, cellular autophagy and cell injury, as well as excretion of pollutants and bioavailability. It also highlights key hypotheses for experimental testing and validation of the model (Moore & Willows, 1998).

BIOMARKERS OF EXPOSURE & EFFECT

Ecosystem Risk can be assessed using "Clinical-type Health Tests" or Biomarkers: these often simple and rapid tests are frequently based on molecular and cellular reactions that help to identify exposure to pollutants, their harmful effects and the causative processes involved.

Understanding the molecular mechanisms by which the cells of animals and plants protect themselves against pollutants is necessary for predicting the impact of such chemicals on ecosystems, and for designing tests (biomarkers) that can be used to monitor the health of the environment and its biota (Depledge *et al.*, 1993; Moore & Simpson, 1992). This will necessitate characterising the membrane protein pumps of the multidrug resistance system that directly remove xenobiotics from cells (MDR/MXR), as well as biotransformation processes by which the enzymes of cells either detoxify pollutants to harmless, excretable products, or activate them to more toxic forms (Kurelec & Pivcevic, 1991; Minier & Moore, 1997; Stegeman & Lech, 1991).

Many natural and pollutant organic xenobiotics are detoxified by biotransformation enzymes of phase I and II metabolism (Stegeman & Lech, 1991). Of central importance in the former is the multi-gene, multi-functional cytochrome P450 (CYP450) family of inducible isoenzymes of which particular forms (e.g., CYP1A) can activate xenobiotics to form covalent adducts with nucleic acid and protein (Livingstone, 1991). Interacting with xenobiotic metabolism are pro-oxidant and antioxidant processes involving the production of oxyradicals and their removal by antioxidant defences (Livingstone, 1993; Livingstone *et al.*, 1990; Winston *et al.*, 1996). Oxyradical production can be increased by interaction with transition metals (Fe, Cu, Cr, Ni, Co, Va) and redox cycling organics (nitroaromatics, quinones), and also by induction of particular components of the biotransformation system, causing oxidative damage to cellular constituents (Mason, 1990; Premereur *et al.*, 1986). The consequences of xenobiotic activation and enhanced oxyradical production include impaired cellular function, cancer and certain disease processes. Aspects of the defences may be integrated at the gene level, *viz.* enzymes of the mammalian [Ah]-gene battery, including CYP1A and the antioxidant enzymes DT-diaphorase (DTD) and aldehyde dehydrogenase (ALDH), can be co-induced by organic xenobiotics (Nebert *et al.*, 1990).

Cellular reactions to chemical pollutants can provide early-warning distress signals of injurious change in plants and animals (Bannasch *et al.*, 1989; Hinton & Lauren, 1990; Köhler, 1989; Köhler *et al.*, 1992; Moore *et al.*, 1994; Moore *et al.*, 1999). Such reactions will be of particular use if they can be shown to be precursors of pathology, since this will relate directly to the risk potential (Figs. 4 & 5). Cellular changes are used as indicators of toxic impact in testing new chemical products in laboratory rodents, and have also been increasingly used in environmental assessment of toxic risk. A further advantage of using cellular reactions is that isolated cells can be exposed to chemicals or complex mixtures of toxicants *in vitro*, which facilitates rapid testing of many samples. Additionally, at a time when the general public is becoming aware and alarmed at

animal suffering in the name of science an *in vitro* approach requires the sacrifice of very few animals (Lowe *et al.*, 1992; Moore, 1992; Moore *et al.*, 1994). Once disaggregated, a tissue biopsy or sample of body fluids (coelomic or blood cells) or eggs can provide sufficient cells to undertake many exposure experiments in the knowledge that genetic heterogeneity has been removed as a confounding factor; which is in sharp contrast to traditional *in vivo* exposure studies where it is necessary to treat different animals with a compound.

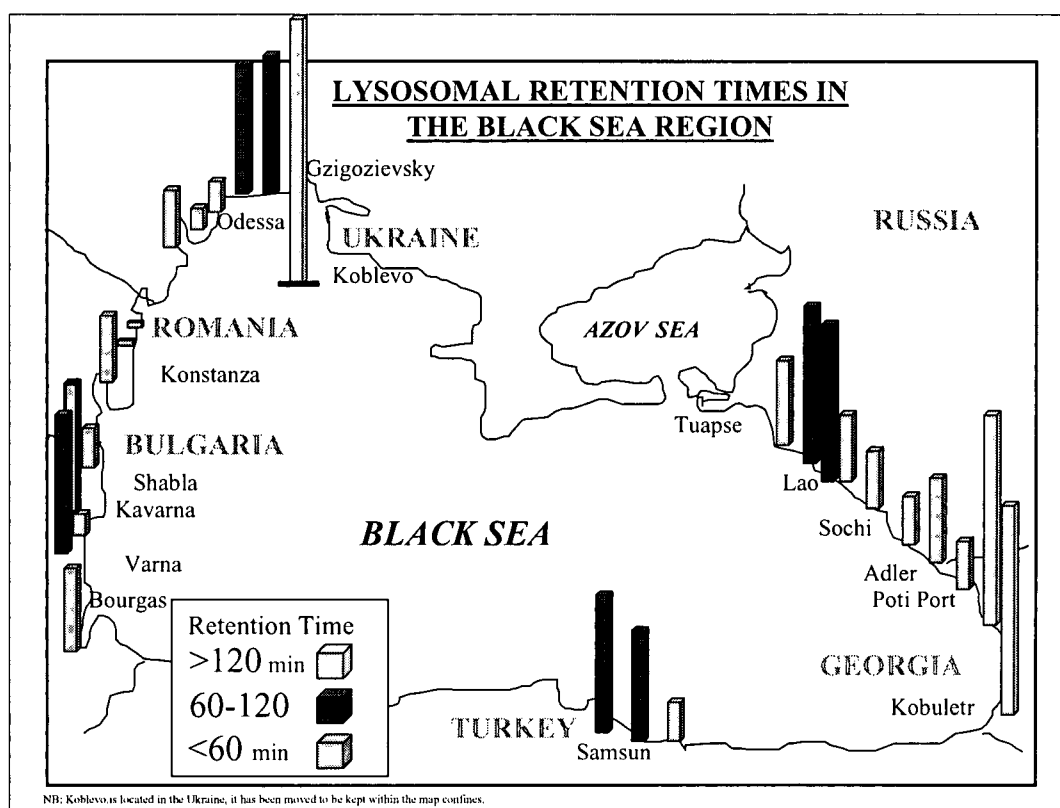


Fig. 5. Lysosomal dye retention times for the IOC-UNESCO Black Sea Mussel Watch: retention values of less than 60 minutes indicate severely impaired health (Moore *et al.*, 1999).

An attainable objective is the development of a holistic approach to environmental toxicological pathology (Fig. 2). Biomarkers are also needed which will accurately indicate the health status of the organism (Fig. 5; Lowe *et al.*, 1995; Moore, 2000). As such, this will require an integration of different tools, including molecular and cellular toxicology (including greater use of available cell lines), quantitative structure-activity relationships (QSARs), modelling the processes of cell injury and linking the models to data from flow cytometry and multiparameter fluorescent imaging of cells, coupled with cellular and tissue pathology (De Biasio *et al.*, 1987; Lowe *et al.*, 1992; Moore, 1992; Moore & Willows, 1998; Rashid *et al.*, 1991).

ECOLOGICAL RELEVANCE & RISK ASSESSMENT

A key aim of environmental science is to derive robust, practical and relatively low cost procedures for assessing risk to the health of the biosphere and to use this capability to predict the likely consequences of exposure to potentially harmful toxic pollutants. Until relatively recently, risk assessment procedures have been oriented towards protecting human health. Now,

it is widely acknowledged that such procedures must also ensure that complex biotic communities in natural ecosystems are protected if the quality of the environment in which we live is to be maintained. Environmental risk assessments are currently based on a suite of information derived from studies on the physical chemical characteristics of compounds (the QSAR approach), and from laboratory-based toxicity tests (Depledge *et al.*, 1993; Rashid *et al.*, 1991). Although these procedures constitute a low cost, pragmatic means of ranking the toxicity of potentially hazardous chemicals, they do not directly evaluate the sublethal toxicity, or other adverse effects (e.g., disturbance of ecological relationships) on organisms exposed to complex mixtures of pollutants in the highly fluctuating conditions that prevail in the environment (Howard, 1997; Kanzawa *et al.*, 1997; Kortenkamp & Altenburger, 1998).

There is therefore, a priority requirement to implement the use of robust but simple, easy to learn, cost-effective test systems that can identify early diagnostic changes in biota, that can be linked to ecologically relevant endpoints. These latter must be capable of facilitating a predictive ranking of the condition of particular ecosystems, thus highlighting environmental situations where a more detailed analysis is justified (Depledge *et al.*, 1993; Moore, 1990; Moore & Simpson, 1992; and Fig. 6).

Environmental toxicologists have also to try to anticipate the potential impacts of novel products and unwanted by-products of industry (Moore *et al.*, 1997). This includes future developments in the chemical and pharmaceutical industries as well as industries using biotechnology and the anticipated arrival of a new "molecular nanotechnology" industry (Drexler, 1992; Gross, 1999; Perrin, 1997). Harmful products are likely to include: new targeted drugs and pesticides, particularly those for use in concert with genetically modified crops; natural pesticides resulting from gene transfer into crops; and novel pathogens used for biological control (Darmency, 1994; Dunwell & Paul, 1990; Perrin, 1997).

The exponential increase in published papers in the area of nanotechnology since 1990 is a strong indicator that shortly there will be a new industry based on engineering molecules for multiple applications (Drexler, 1994; Gross, 1999). Without strong international controls on such production there could be serious environmental risks, since it is likely that the first practical developments towards nanotechnological application will rely on modified biological molecules and assemblages (Gross, 1999; Kitov *et al.*, 2000). The purpose here is primarily to raise awareness of developments and possible environmental risks in the field of nanotechnology, since it is still in the research phase.

The overall problem is, in essence: how to develop effective procedures for environmental/ecological impact and risk assessment? The use of biomarkers and biological effects indices has proven useful in establishing evidence of exposure to pollutant chemicals and damage to the health of sentinel organisms (Figs. 1, 2 & 5; Depledge *et al.*, 1993). This is obviously of great value in helping to establish causal relationships. However, for impact and risk assessment tools to be effective they must be capable of providing data that relates to ecologically significant processes (Depledge *et al.*, 1993; Moore *et al.*, 1994). This requires a better understanding of particular biomarkers, as they relate to health status (Figs. 2 & 5), in order to improve their interpretative value in monitoring (Fig. 6; Moore, 2000; Moore & Simpson, 1992; Moore *et al.*, 1994). Monitoring, itself, must be made more effective through rational interaction between chemists, ecotoxicologists and environmental managers: a framework for this type of interaction is outlined in Figure 6.

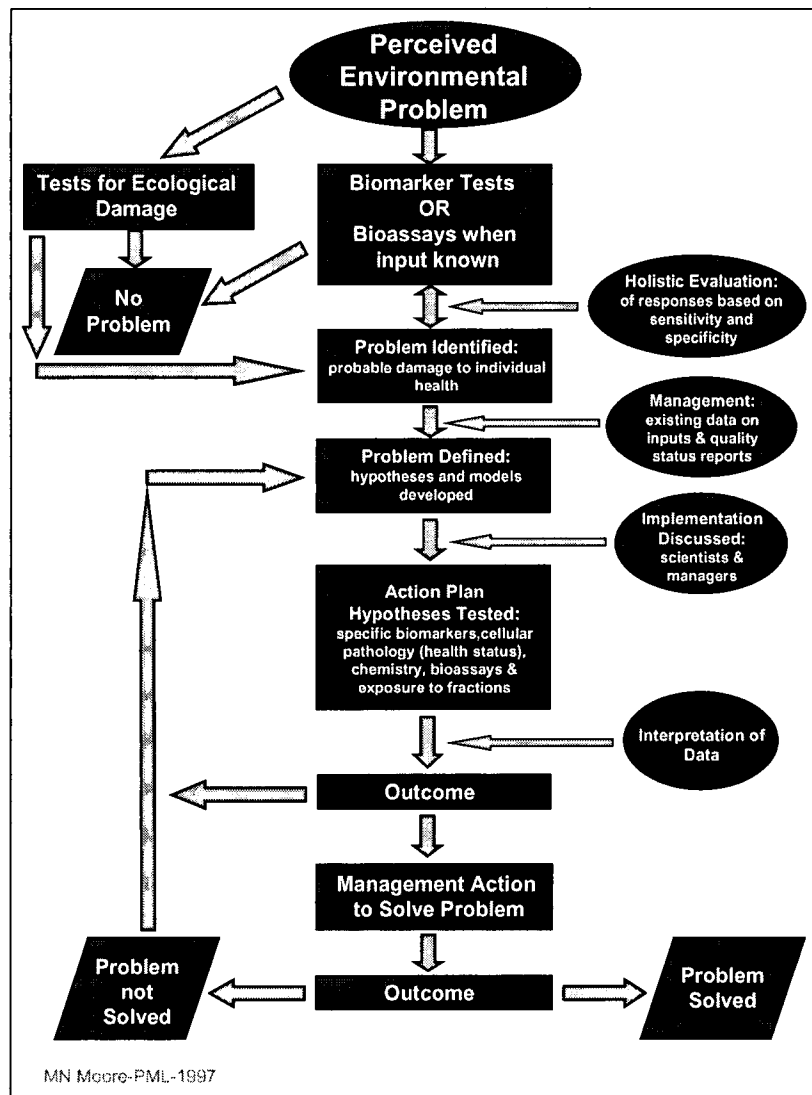


Fig. 6. Conceptual framework for an interactive monitoring programme for the assessment of environmental impact of pollutant chemicals (Adapted from the ICES-WGBEC Report, 1997 and Moore *et al.*, 2000).

In order to achieve the above aim, the science must also address the question of linkages between effects at different levels of biological organisation (Bayne & Moore, 1998; Grundy *et al.*, 1996a & b; Kauffman, 1993; Livingstone *et al.*, 2000; Moore, 2000). Establishing these linkages is essential, not only for understanding the current status of the environment, but also to provide a rational basis for prognosis for future improvement or deterioration in environmental quality (Fig. 2).

CONCLUSIONS

This broad approach to the complex problem of assessing the health of ecosystems will facilitate the validation, and further the essential new development of robust and rapid tools for assessment

(Depledge *et al.*, 1993; Ferson & Long, 1995; Moore & Simpson, 1992; Moore *et al.*, 1994). Future efforts must focus on an integrated approach to the validation of biomarkers that are prognostic for population and community endpoints (Depledge *et al.*, 1993; Moore *et al.*, 1994). As with bioavailability and uptake, exposure to pollutant mixtures must also be considered with the possibility of complex synergistic interactions resulting in emergent and novel toxicities and pathologies (Moore & Willows, 1998; Warne & Hawker, 1995). Other environmental factors such as intense visible and UV-radiation (Fig. 2) and hypoxia also need to be considered, since these are likely to be important in terms of potentially harmful interactions with contaminants (Mason, 1990). This includes xenobiotics acting as photosensitisers and the facilitation of cascades of harmful radical production on reoxygenation following a hypoxic interlude, such as that induced by eutrophication (Fig. 2).

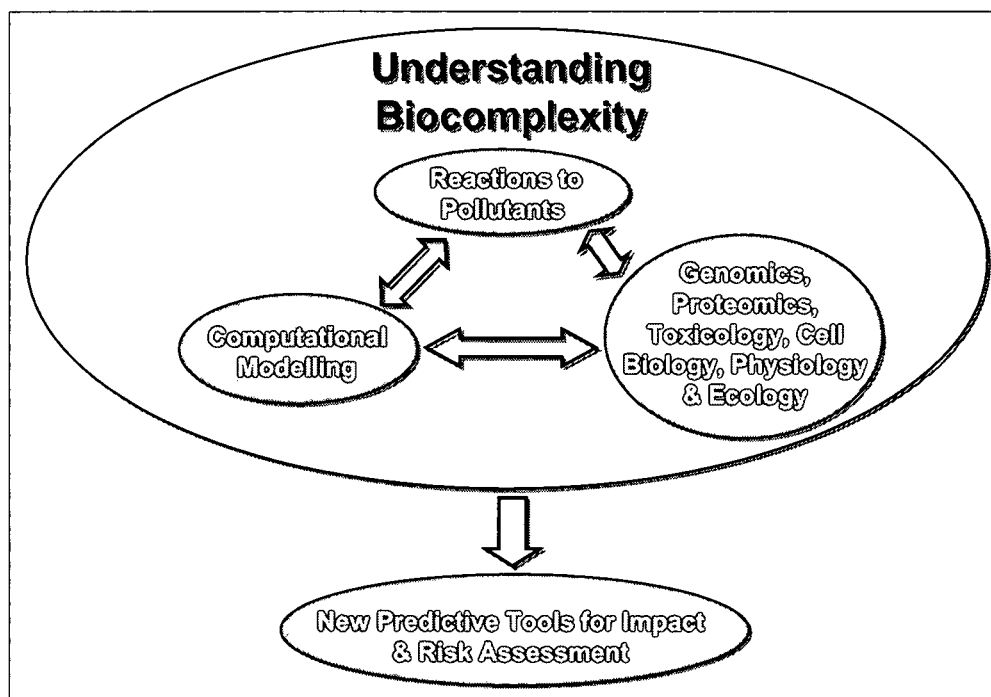


Fig. 7. Conceptual framework for developing new predictive ecotoxicological tools to address future needs for environmental impact and risk assessment (Moore, 2000).

A major reason for the development of complexity science, and its use in ecotoxicology, is to gain a realistic insight into the limits of reductionism as a very successful universal problem-solving approach (Casti, 1994; Kauffman, 1993; and Fig. 2). Complex biological and ecological processes generate counter-intuitive, seemingly acausal behaviour that is full of novelty (Howard, 1997; Kanzawa *et al.*, 1997; Kauffman, 1993). Trying to understand the behaviour of a complex adaptive (or dynamic) system, such as an organism, population, ecosystem or biogeochemical cycle, by a reductionist approach often irretrievably destroys the inherent nature of the problem (Kauffman, 1993). Recognition that a system is complex is specifically subjective, not an objective property of an isolated system. However, it can become objective, once the investigative formalism takes into account the larger system with which the target system interacts (Casti, 1994; Kauffman, 1993). In fact, complexity science is really a subset of the more general and much larger scale objective of creating a theory of models (Casti, 1994).

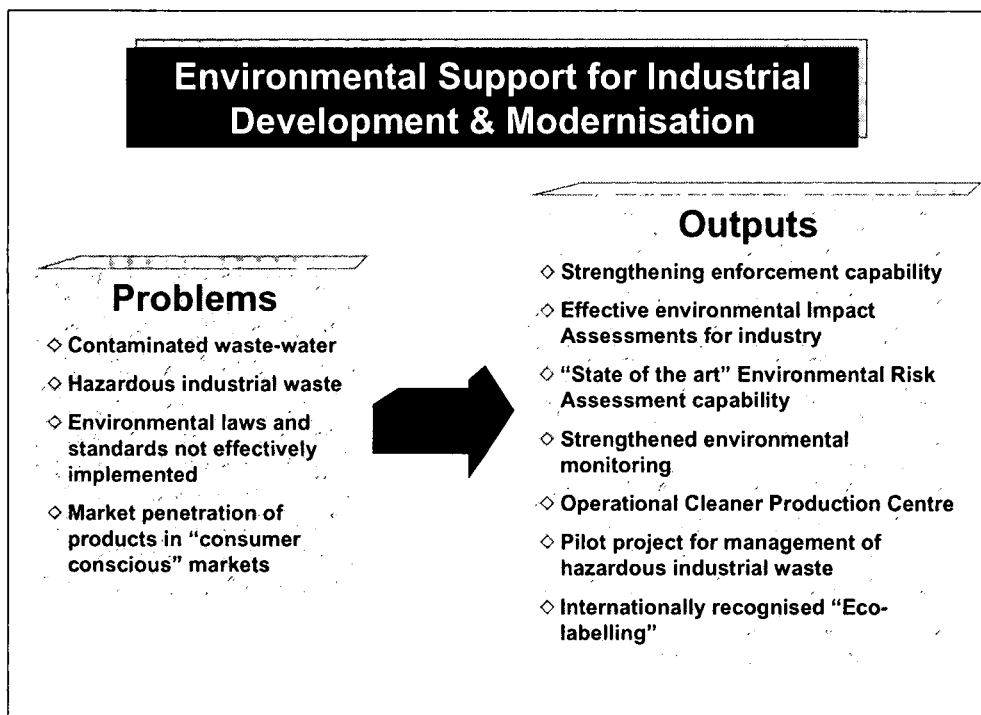


Fig. 8. Diagrammatic representation of environmental problems related to sustainable industrial development and their proposed solutions through the application of IEM.

There must also be a wider recognition that IEM and ecotoxicology/environmental toxicology is dealing with complex adaptive systems (Kauffman, 1993; Moore, 2000; and Fig. 2). Consequently, there needs to be a rapid acquisition of the new methods of "complexity science" and implementation of these into the scientific components of Integrated Environmental Management programmes (Fig. 8). Therefore, a rational way forward can be conceived, if an integrated multidisciplinary approach to the environmental impact of industrial chemical inputs is adopted as follows:

- development of conceptual frameworks and process simulation models based on an improved mechanistic understanding of contaminant uptake, biotransformation, toxicity and impact within the biological organisational hierarchy (Düchting et al., 1996; Koo, 1999; Lauffenburger & Linderman, 1993; Maddox, 1998; Moore, 2000; Moore & Willows, 1998; Noble *et al.*, 1999; Figs. 2-4 & 7);
- meet the interdisciplinary challenge of mathematically modelling processes in environmental pollution and impact as a complex adaptive system (Kauffman, 1993; Figs. 2 & 7), encompassing contaminant geochemistry, mode of uptake and intracellular behaviour, biochemical toxicology (including proteomics), cellular injury and pathology (e.g., using "virtual" organs and animals; Fig. 4), ecological consequences and human risk;
- take a broad view of the current and predicted future problems in environmental management, that incorporates both moderate reductionist and synthesisist approaches (Figs. 3, 4 & 7);
- areas of collaboration need to include, among others remote/satellite surveillance, risk assessment, interpretation of complex information and predictive modelling (Fig., 8);

- precautionary anticipation of novel environmental hazards (e.g., from Biotechnology & Molecular Nanotechnology);
- education of politicians, industrialists and environmental managers concerning the long-term consequences of pollution; and that increased consumer awareness of environmental problems is already exerting pressure on "Industry" to make its products "environmentally friendly" (i.e., eco-labelling), in order to maintain existing markets and to improve their penetration into new markets (Fig. 8).

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