ECOLOGICAL RISK ASSESSMENT OF ENVIRONMENTAL STRESS

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Keywords: Ecological assessment, SimpleBox, SimpleTreat, species sensitivity distribution (SSD), biodegradation, bioavailability, environmental quality criteria (EQCs), PICT (pollution induced community tolerance), PAF (potentially affected fraction of species), pT methodology, indicator, toxic stress, ecosystem, desiccation, acidification, eutrophication, multi-stress, compartments, ecotoxic, risk assessment, risk evaluation, IQ-Tox, microbial indicator, multi-stress analysis, multi-stress modelling, life support functions (LSF), biological indicator for soil quality (BISQ)

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Summary

This section describes a toolbox of models and decision support systems that is maintained and developed at the Laboratory for Ecotoxicology of the National Institute of Public Health and the Environment to assess the fate of environmental pollutants and the potential and actual risk of such compounds for ecosystems in relation to other environmental stresses. This toolbox is applied to support the governments of The Netherlands and the European Union.

It comprises models (SimpleBox and SimpleTreat) to assess the fate of pollutants in the environment and in waste water treatment plants, respectively, based on emission data and knowledge on physical and chemical characteristics of pollutants and the environment. Both fate models are comprised in EUSES, the decision support system (DSS) of the European Union for the Evaluation of Substances.

Dependent on physico-chemical characteristics of contaminants, the environment and the specific organisms, organisms may, or may not, be exposed to a specific chemical, and this chemical may have an effect. The research that is being done on this bioavailability concept of compounds, and its impact is described here.
The concept used to assess exposure to, and effects of pollutants, is based on the determination of species sensitivity distributions (SSDs), derived from laboratory toxicity tests. Therewith environmental quality criteria can be, and are, derived. On the other hand this approach is applied to determine the fraction of organisms in ecosystems that is being exposed to concentrations of contaminants that exceed certain ecotoxicological criteria, based on knowledge of concentration and bioavailability of contaminants (PAF, Potentially Affected Fraction). The technique is being improved to assess potential effects, not only of single compounds, but also of mixtures.

To validate the approach the pT methodology has been developed, to determine total toxicity of known and unknown mixtures of contaminants in surface waters.

Environmental quality criteria for environmental pollution are derived from laboratory toxicity tests. We use several tools to validate the criteria, e.g. the PICT (Pollution Induced Community Tolerance) approach, in which adaptation of field communities to contaminants is determined, showing that the organisms indeed have experienced the presence of contaminants, and that they exert certain effects.

Based on a triad approach a DSS is being developed to assess effects of contaminants on specific sites, and to determine the necessity to take certain management measures to facilitate a certain use of the site, taking chemical, ecological and ecotoxicological data about the site into consideration.

Besides environmental contamination with pollutants there are other stresses on ecosystems, such as desiccation, eutrophication, acidification, climate change, certain types of management (e.g. agriculture). The relation between these stresses and the relative contribution of different stresses to the total environmental impact is

investigated using statistical techniques, and in the development of a biological indicator for soil quality, a food web based indicator based on monitoring data of the soil fauna in relation to data on contamination and management of land. It is one of the possible tools that can be applied also to assess the sustainability of land use.

Finally some results are shown of an Integral Analysis Method where of the relative contribution of different environmental stresses on the impact measure "decrease of the possibility of the occurrence of groups of species" (vascular plants, butterflies, birds and mammals) is determined.

1. Methodologies for Ecological Assessments

Ecological risk assessment seeks to assess the fate of compounds entering the environment and their risks and impacts on ecosystems. To do this, models and indicators are developed to assess the integral effects of toxic compounds and other types of environmental stresses in natural conditions. Ecological risk assessment also needs decision support systems for risk management (i.e. site specific risk assessment and ecosystem health assessment).

A variety of techniques is used to assess ecological risk, and “classical” measures of ecosystem performance and life support systems are especially important. The following techniques are detailed:

1. Using the specific models SimpleBox and SimpleTreat, the fate of contaminants entering the environment is assessed based on information about emissions and the chemical, physical and biological (biodegradation) characteristics of the compounds. Bioavailability considerations also allow for the exposure of biota to pollutants to be assessed.

2. In the Species Sensitivity Distribution (SSD) approach, bioavailability data and toxicity data are integrated into statistical models in order to predict toxic effects on ecosystems. Environmental quality criteria (EQCs) are derived based on SSDs; and SSDs are also used to predict the toxic stress of mixtures of toxic chemicals upon ecosystems. To validate the SSD-methodology, indicators are being developed to measure ecological effects of the presence of toxicants in field (as opposed to laboratory) situations (PICT, Pollution Induced Community Tolerance). Furthermore, an indicator to validate the PAF (potentially affected fraction of species) concept in aquatic ecosystems is the pT methodology, in which toxic compounds are extracted from water and the undefined mixture is tested in laboratory toxicity tests. This indicator is being applied to monitor the spatial and temporal variation in total toxicity of Dutch surface waters. For soil, pT methodologies are still under development.

3. Besides toxic stress, ecosystems face other stresses, such as desiccation, acidification and eutrophication as well. Using non-linear multiple regression techniques, the combined effects of these stresses are being analysed, resulting in an estimate of the relative contribution of different kinds of stress on species in ecosystems. For terrestrial plants the MOVE model, originally developed to estimate

the effects of eutrophication, acidification and desiccation, was adapted to incorporate toxic stress. Similar models are under development for aquatic and soil organisms. This approach yields insight into what the best investments toward risk mitigation efforts would be for an optimal reduction of national or regional environmental stress effects. Eventually, to assess the ecological effects of pollutants in multi-stress field situations, indicators will be developed that can be used to validate the environmental quality criteria and to assess the ecological quality of natural systems.

4. These methodologies provide tools and decision support systems to assess the ecological effects of environmental stress based on knowledge of the concentration or strength of stressors in the field. The utility of these tools has been validated primarily in the Netherlands, but they can be used anywhere in the world to assess the extent of ecological damage without having to perform direct ecological field observations. This approach is useful as a first stage for damage assessment or for local and regional assessments and scenario analyses.

2. Assessment of the Concentration and Fate of Toxicants in the Environment

2.1 Simplebox

SimpleBox is a multi-media environmental model that can be used to calculate the fate and concentration of chemicals in a given environment if the emission of the chemical is known. By defining the characteristics of the environment, it may be used to calculate the concentration in a region, country or continent. In SimpleBox, homogeneous boxes represent the various environmental compartments (air, water and soil, see also description further). SimpleBox is a generic model, but it can also be customised to represent specific environmental situations. Transfer and transformation of substances are treated as first-order processes. Boxes in SimpleBox represent environmental compartments (see below). The concentration of a chemical in each box is affected by processes that cause mass flows of the chemical to and from the box. The chemical can be an INPUT coming from outside the system into a box, an OUTPUT leaving a box, or a product entering or leaving a box by means of transport to and from other boxes.

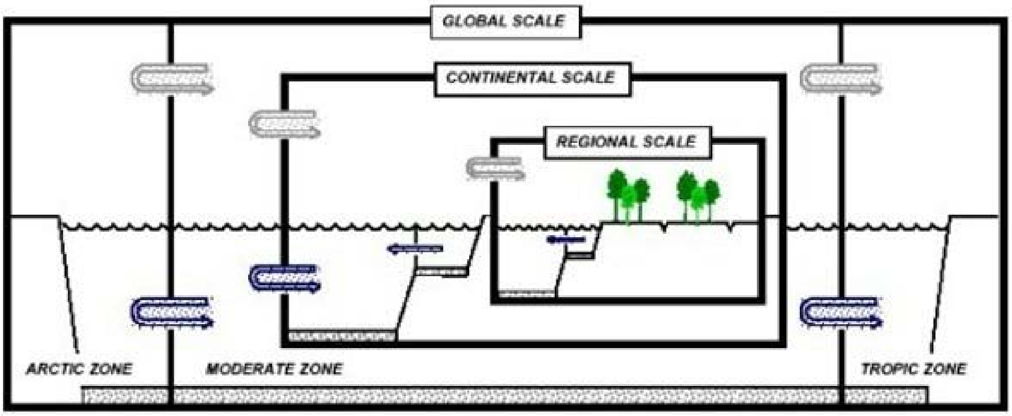

Figure 1. SimpleBox 2.0 model

If mathematical expressions that relate the mass flows to the chemical concentrations are available, the set of mass balance equations (there is one for each box) can be solved and the chemical concentrations in each of the boxes can be computed.

The SimpleBox model consists of different spatial scales: a regional scale, a continental scale and a global scale. The global scale consists of three parts that reflect the arctic, moderate and tropic geographic zones (Figure 1). The default settings of the regional and continental scale of the model are set to match the EU procedures for the evaluation of substances. In this case, the regional scale is represented as a densely populated Western European region. The continental scale is a copy of the regional scale with adjusted parameters to represent the whole European region. The global scales are added to serve as background for the continental and regional scales.

Compartments: The regional and continental environments that are modelled consist of ten homogeneous environmental compartments: air, two separate water compartments, sediments, three separate soil compartments, and vegetation on natural and agricultural soil. The global scales consist of 4 homogeneous compartments: air, water, sediment and soil. The atmospheric phases gas, rain, and aerosol and the terrestrial phases solids, water, air and roots are considered to be in a state of thermodynamic equilibrium at all times.

The aquatic phases (water, suspended particles, and biota) are treated as a bulk compartments (this means that in the overall description of these compartments it has been taken into account that it consists of water, suspended solids and sediment, but these constituents are not described separately) and are also considered to be in thermodynamic equilibrium. The water compartments represent a fresh-water (lakes, rivers, etc.) and seawater compartments.

The soil compartments can be used to define different geographic areas, different soil types or different soil uses. In SimpleBox, the soil compartments stand for natural, agricultural and industrial/urban-use soil. Vegetation is situated on natural soil and agricultural soil on the regional and continental scale, with different parameter settings for each vegetation compartment.

Two important applications of the SimpleBox model in environmental policy are its incorporation by the European Union in the DSS EUSES (Decision Support System of the European Union System for the Evaluation of Substances) and its use in the Netherlands in the evaluation of the coherence of independently derived environmental quality criteria for air, water and soil. The latter use, also called “intercompartmental evaluation of risk limits,” should preclude soil EQC (Ecological Quality Criteria, see further on) from threatening water systems (i.e. through runoff).

2.2 The SimpleTreat Model

SimpleTreat 3.0 is a model that predicts the distribution and the elimination of chemicals by sewage treatment plants (STP), and it is also useful for a generic exposure assessment resulting from STP operations. The accuracy of such an exposure assessment, in particular for the water compartment in urban regions, is largely determined by the accuracy with which the chemical fate in STP can be predicted.

In the SimpleTreat model, chemical transport and transformation processes cover a wide range of compound properties and scenarios. Emission of substances via sludge production may account for the presence or absence of the primary sedimentation technique, which is the separation of sludge solids in raw wastewater from the liquid phase prior to the biological treatment.

Many chemicals that are used domestically, commercially, and industrially, including non-agricultural pesticides, are discharged to sewer systems. In urban regions, most of these sewer systems are connected to STP, so SimpleTreat can be applied to estimate the relative emission of a chemical from a STP to the various environmental compartments. For a readily biodegradable chemical, the amount of a chemical eliminated due to biodegradation is also calculated. All processes that determine the fate of a chemical are assumed to be linear, which means that they occur at a rate that is proportional to the concentration of the chemical in the various media in which the chemical resides. The SimpleTreat model is also incorporated into the EUSES decision support system.

2.3 Bioavailability of Chemicals

A main characteristic of soil ecosystems is their heterogeneity. In addition, there is an enormous variance of both the numbers and biodiversity of organisms in the ecosystem and the numbers of physico-chemical soil properties that directly or indirectly affect specific species within a given ecosystem. Toxic effects will occur as a consequence of a number of external (outside organisms) and internal (within organisms) transport processes of chemical compounds. In their turn, these processes depend on a large number of species and soil type dependent factors.

The response of specific soil dwelling organisms to soil heterogeneity and to soil composition in terms of physico-chemical soil properties is still insufficiently understood to allow for accurate prediction of adverse effects of pollutants on soil ecosystems. Furthermore, the differences in the bioavailability of chemicals among soil ecosystems are not taken into account sufficiently in ecological risk assessment.

Recently, a conceptual framework based upon the concept of toxicological bioavailability as defined by Hamelink *et al.* (1994) was developed for the implementation of metal bioavailability in ecological risk assessment. The concept of toxicological bioavailability assumes that adverse effects will take place only when the concentration of a pollutant within an organism has exceeded a metal- and species-specific critical level, a level that the organism can handle (the so-called critical body burden). Although examples exist in which the concept of toxicological bioavailability is invalidated, research within our laboratory seeks to unravel the component processes of bioavailability and to quantify the impact of soil-related properties on differences in bioavailabilities of chemicals among ecosystems. Although this approach has been described for metal bioavailability, it is also applicable to the bioavailability of other compounds. As shown in Figure 2, three main processes may be distinguished: chemical bioavailability, environmental bioavailability, and toxicological bioavailability.

The concept of chemical bioavailability is not, in its present form, suitable for inclusion in ecological risk assessment schemes. Its essential feature is that it will enable the prediction of adverse chemical effects on soil organisms and plants on the basis of a limited number of soil and pore water properties and on a limited number of metal pools. Metals are present in ecosystems in different forms: dissolved, adsorbed, complexed, reduced, oxidised and chemically bound. Depending on the analytical procedure used for measuring metal concentrations, a different fraction of the total amount of metal present is determined. The result of one type of analysis is called a "metal pool."

A metal pool gives an indication of how a metal is present in the soil. Proper inclusion of bioavailability in ecological risk assessment requires toxicity data that is based upon truly bioavailable metal pools (the fraction of a metal that may interact with an organism, depending on the organism, the metal, and the soil properties). Thus the impact of soil properties on metal uptake and metal toxicity is taken implicitly into account. This will allow for the proper extrapolation, for instance, of laboratory-derived toxicity data to the toxic effects that will occur under field conditions. Further research in the area of metal bioavailability is aimed at substantiating and validating the methods that allow for this type of extrapolation.

2.4 Chemical Availability of Metals for Uptake by Soil Dwelling Organisms

Soil-related processes that affect metal partitioning over the various soil constituents govern chemical availability, so only physico-chemical properties need to be considered. The (physico-chemical) availability of metals is shown schematically in Figure 2 by means of (equilibrium) partitioning of a metal over the soil solid phase (the soil fraction remaining after drying the soil) and the pore water (water present between the soil particles) (Figure 2, left). As shown, metal partitioning is, in principle, dependent upon a large number of soil properties (though pH is often the most important parameter). An empirical approach was followed to quantify the impact of soil properties on metal availability, and models were developed that enable the quantitative prediction of metal partitioning in soils with widely varying soil properties.

2.5 Environmental Bioavailability

Organism-specific chemical transport processes (accumulation and elimination) play a central role in environmental bioavailability. A dynamic equilibrium will be established between the content of pollutants in the soil that is available for uptake by a specific species and the *levels* within this organism, which depend upon both external and internal (organism-specific) factors. This dynamic equilibrium is a consequence of pollutant partitioning within the soil and is dependent on the organism-specific uptake routes of pollutants (i.e. via pore water, soil ingestion, or food consumption).

Environmental bioavailability is envisaged by means of toxicokinetic uptake characteristics, *which are* the chemical uptake rate constant, k_1, and the organism's internal equilibrium level, C(eq), and the rate of elimination of toxicants is of importance. Similarly to the approach followed to quantify metal availability, an empirical approach was followed to quantify the impact of soil properties on the environmental bioavailability of metals. Models were developed that may be used to calculate internal steady-state metal levels within a number of soil organisms. In addition to metals, the accumulation of organic chemicals in earthworms has also been studied to help determine their environmental bioavailability.

2.6 Toxicological Bioavailability

Internal (re)distribution processes govern the toxicological bioavailability concept, which includes the transport of chemicals to specific targets for toxic substances, the possible inert storage of metals in specific organs, and the additional detoxification mechanisms (right-hand side, Figure 2). Until now, only limited attention has been paid to the toxicological aspect of the bioavailability concept.

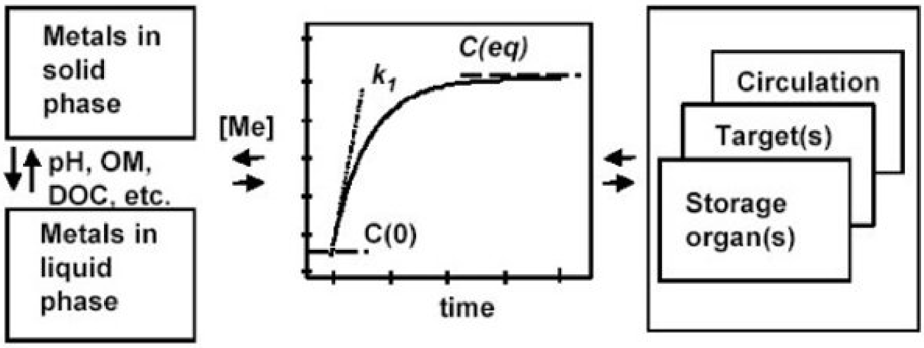

Figure 2. Schematic Representation of the Underlying Processes of the Bioavailability Concept

2.7 Bioavailability and Biodegradation

In principle, the bioavailability concept developed for metals also holds for organic contaminants and environmental bioavailability especially influences the biodegradation of organic compounds by bacteria.

In general, bacteria degrade organic compounds that have been taken up in their cells, and to be able to take up these compounds they have to dissolve (enter the aquatic phase as a single molecule), or desorb (detach from the solid phase of soil) therefore, hydrophobic and sorbed (attached to soil particles) pollutants such as polycyclic aromatic hydrocarbons are poorly degradable because bacteria do not take them up.

Based on laboratory experiments, a model has been developed to predict the biodegradation rate as a function of the desorption and dissolution rates of organic compounds. Often the extracellular (outside bacteria) *transport* processes of the organic compounds, especially of hydrophobic organic compounds, and not the capacities of the degrading organisms, limit the rate of biodegradation.

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Biographical Sketches

Dr Anton Breure is head of the department of Data analysis, Risk assessment and Modeling of the Laboratory. Trained in chemistry and microbial ecology he works on the development of models and indicators to quantify effects of contamination and other human impacts on the composition and functioning of ecosystems and on the bioavailability and biodegradation of organic pollutants.

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He (co-) authored 40 papers in refereed journals, 9 chapters in scientific books, 25 scientific reports and co-edited 1 book.

Tjalling Jager is currently working at the Free University in Amsterdam, the Netherlands, at the department of Theoretical Biology. He holds an M.Sc. in biology, also from this University. After graduating, he worked 9 years at the Laboratory for Ecological Risk Assessment of the National Institute of Public Health and the Environment (RIVM) in Bilthoven on the development and analysis of support systems for chemical risk assessment. Furthermore, he is particularly interested in the mathematical aspects of chemical accumulation and toxic effects on soil organisms. He got his Ph.D. in 2003. He has authored over 20 peer-reviewed papers, several book chapters and was editor of several risk assessment systems.

Dr. Dik van de Meent is an environmental chemist and serves as a senior scientist in projects on environmental risk assessment of chemicals. His main interests are fate and effects modeling of toxic chemicals. He has contributed to this field by developing the multi-media fate model SimpleBox. His mission at RIVM is to quantify the contribution of toxic chemicals to multistress effects on biodiversity. He holds an engineering degree in organic geochemistry and a doctoral degree in environmental science, both from Delft University, The Netherlands. Prior to joining RIVM, he worked as a postdoctoral fellow at UC Berkeley. During his present employment, he worked as visiting scientist at the US EPA Environmental research Lab in Athens, Georgia, and at the Institute of Environmental Systems Research of the University of Osnabrück in Germany.

An active member of the Society of Environmental Toxicology and Chemistry (SETAC), he participates in international activities in chemical risk assessment, and serves on organizing committees of professional activities in his field. Van de Meent has (co) authored over 50 technical and scientific contributions to journals and books, and as many contributions to internal RIVM reports. He regularly presents his findings on international scientific meetings.

Dr. Christian Mulder holds a Bachelor in Geological Sciences and a Master in Natural Sciences from the First University of Rome "La Sapienza" (Italy). Then, he focused his research at the Laboratory for Palaeobotany and Palynology on the role of plants as monitor, motor and moderator of environmental changes in research on the desertification in southern Europe. His research on the interplay between landscape-ecology and climatology resulted in an Italian National D.Phil. in vegetation science/geobiology. In 1996 he moved to the Laboratory of Botanical Palaeoecology of the University Utrecht, the Netherlands, where he focused on various ecological themes as disturbance ecology, resilience and ecosystem stability of terrestrial biomes across southern Africa, like the Kalahari and the subarid Okavango wetlands. He performed research on peat and lignine geochemistry of Greek coal mines, working as botanist together with the geology departments of Utrecht, Rome, and Athens on the interplay between inland fans and local vegetation on both historical and geological time-scales, up to statistical and ecological improvements in global change modeling. In 2000 he became Senior Scientist for ecotoxicological modeling at the Laboratory for Ecological Risk Assessment. His aim remains the improvement of diagnostic and prognostic parameters in ecological modeling to be used in stress factor studies. He is currently working to infer dynamic processes occurring within the soil food web of Dutch agricultural landscapes.

Dr. Willie Peijnenburg is an environmental chemist, whose research interests include: the implementation of bioavailability of heavy metals in risk assessment procedures, the development and application of quantitative structure-activity relationships (QSARs) for the estimation of physical-chemical properties and transformation rates of chemical substances in the environment, and the study of biotic and abiotic transformation processes of chemical substances in natural ecosystems. He completed his Ph.D. study in 1988 at the Eindhoven University of Technology. The topic of this research was on mechanisms of photochemically induced sigmatropic shifts. Currently, he is a senior staff member of the Laboratory and in addition he is editor Environmental Chemistry of the Journal 'Environmental Toxicology and Chemistry', editor-in-Chief of the 'Journal of Soils and Sediments', and editor of the 'Bulletin Chemical Society Ethiopia' and "Environmental Pollution". He has authored over 70 technical papers and reports, including editing a book on predictive methods for biodegradation.

Dr Leo Posthuma is currently Research Staff Member and he is involved in the development, testing and validation of methods for ecological risk assessment. He studied biology and received a Ph.D. in ecology and ecotoxicology at the Vrije Universiteit, Amsterdam, the Netherlands. He has authored and co-authored over 75 open literature publications, reports and book chapters, and has acted as book co-editor and book editor. His research experience has included phytopathological studies, studies on the evolutionary ecology and population genetics of contaminant adaptation of exposed soil arthropod populations, on community tolerance evolution, on the bioavailability of toxic compounds for terrestrial organisms, on joint effects of compound mixtures, and stability and resilience of soil ecosystems.

Dr. Michiel Rutgers is senior scientist and member of the staff of the Laboratory for Ecological Risk Assessment. Evolved from the disciplines of microbial physiology, biochemistry, and thermodynamic modeling of microbial growth, his contributions to the field of ecotoxicology comprise the analysis of autochthonous microbial communities in disturbed, reference and pristine soils. The aim of his work is to develop tools for site-specific ecological risk assessment of contamination and other environmental stresses, and to develop indicators for soil quality and ecosystem health.

He holds an M.Sc. (biology) and a Ph.D. (biochemistry/microbiology) from the University of Amsterdam. He was the Secretary of the Netherlands Society for Microbiology. He has authored about 40 papers, book chapters and reports.

Ton Schouten holds a M.Sc. in biology from the Free University of Amsterdam and graduated as an ecologist with a broad package of ecological disciplines (terrestrial, aquatic, and marine). After his study he specialized in the ecology of soil nematodes, and used these organisms to describe effects of soil pollution and disturbance. Later he aimed at biomonitoring and methods for assessment of (ecological) soil quality. In recent years the scope is extended to food web based monitoring of soil ecosystems in nature and arable soils. The results are used to develop applications that can be used in environmental policy and protection of soil biodiversity.

Dr. Aart Sterkenburg is the head of the Department of Exposure and Effect Assessment of the Laboratory. In recent years he has been involved in monitoring programs on the toxic pressure in Dutch surface waters, and in more integral studies as part of the 'Environmental Balance' which gives a yearly overview of the state of the Dutch environment.

Aart Sterkenburg is a chemist, carrying a Ph.D. in microbial physiology (University of Amsterdam).

Dr. Jaap Struijs is an environmental chemist who holds a Ph.D. in organic chemistry of the University of Utrecht, The Netherlands. In the past 20 years he has been working on the fate of pollutants in the environment. He is an expert on biodegradation of organic compounds and developed the model for biodegradation of organic compounds in wastewater treatment plants SimpleTreat. He also developed the extraction technique to determine total toxic stress (pT-methodology) in surface waters.

At the moment his main research interest lies in the field of Life Cycle Assessment (LCA).

Dr. Patrick van Beelen is currently Research Staff Member in the Laboratory for Ecological Risk Assessment at the Dutch National Institute of Public Health and the Environment (RIVM), Where he is involved in the development, and validation of techniques for ecological risk assessment.
He studied chemistry (M.Sc.) at the University of Leiden and holds a Ph.D. from the Roman Catholic University of Nijmegen, The Netherlands. His research included biodegradation of toxic compounds, development of microbiological techniques for ecotoxicological risk assessment, risk assessment of pesticides and genetically modified organisms.

He worked 14 months at Tyndall Air Force Base Florida on the biochemical degradation of the explosive TNT.

He is a member of the RIVM advisory group for the admission of pesticides, and a member of the European and Mediterranean Plant Protection Organization working group Environmental Risk Assessment of Plant Protection Products.

Marijke Vonk is an ecological modeler who studies ecological risk assessment of toxic stress in relation to other stresses. She participated in several projects to offer expert advice to policy makers: with a multistress analysis she predicted the influence various (policy) scenarios on biological diversity. Before starting her present job she worked as an ecological modeler at Leiden University, The Netherlands, and at an engineering firm, andsubsequently at the Laboratory for Ecotoxicology of the National Institute of Public Health and the Environment (RIVM) in Bilthoven .

She holds a M.Sc. from Wageningen University. She has several years of experience in modeling aquatic and terrestrial ecosystems and has authored a number of papers and reports on this topic.

Dick de Zwart currently is Senior Scientist at the Laboratory for Ecological Risk Assessment. He graduated from the University of Amsterdam in 1976 in aquatic ecology. He has been working in aquatic ecotoxicology since 1980. His research interests all relate to ecological effects caused by ecotoxicity, currently focusing on Species Sensitivity Distributions. As an expert in data handling and the application of complex statistical techniques (GLM and multivariate ordination) he tries to attribute effects observed in the field to different aspects of pollution. In previous years his research activities were mainly directed towards field monitoring of ecological effects caused by pollution, with a long time experience on knowledge transfer of monitoring evaluation methods to developing countries (India, Cyprus and the Slowak Republic). His research efforts resulted in a (co) authorship of about 70 reports and publications in open literature.