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Environmental fate and exposure models: advances and challenges in 21st century chemical risk assessment

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Environmental fate and exposure models are a powerful means to integrate information on chemicals, their partitioning and degradation behaviour, the environmental scenario and the emissions in order to compile a picture of chemical distribution and fluxes in the multimedia environment. A 1995 pioneering book, resulting from a series of workshops among model developers and users, reported the main advantages and identified needs for research in the field of multimedia fate models. Considerable efforts were devoted to their improvement in the past 25 years and many aspects were refined; notably the inclusion of nanomaterials among the modelled substances, the development of models at different spatial and temporal scales, the estimation of chemical properties and emission data, the incorporation of additional environmental media and processes, the integration of sensitivity and uncertainty analysis in the simulations. However, some challenging issues remain and require research efforts and attention: the need of methods to estimate partition coefficients for polar and ionizable chemical in the environment, a better description of bioavailability in different environments as well as the requirement of injecting more ecological realism in exposure predictions to account for the diversity of ecosystem structures and functions in risk assessment. Finally, to transfer new scientific developments into the realm of regulatory risk assessment, we propose the formation of expert groups that compare, discuss and recommend model modifications and updates and help develop practical tools for risk assessment.

Environmental significance

Multimedia environmental fate models are regularly employed in the risk assessment of chemicals. They historically evolved from simple approaches to more refined and integrated modeling tools, often provided as part of a tiered strategy. Much work has been devoted to improving various aspects at the process and environmental description levels, but some issues need further research and model development, such as the capability to properly simulate the behaviour of polar and ionizable chemicals in the environment, the bioavailability of chemicals in aquatic and terrestrial environments, and variability in time and space to account for more ecological relevance. At the same time, it is important to avoid "paralysis by analysis" and develop practical tools for regulatory risk assessment that are fit for purpose. We propose the formation of expert groups to address this task.

1. Introduction: evolution and current status of fate and exposure modeling

Assessing the environmental fate and exposure of chemicals used in commerce is a challenging but critical part of assessing the risks associated with their production, use and release. Environmental fate and exposure models play an important role in the chemical assessment process, and when coupled with monitoring data, can provide reliable information about the exposure of humans and the environment to chemicals.[1]

Over the last three decades, the development and application of environmental fate models has been facilitated by a repeating pattern of co-operation between model developers and users in *ad hoc* working groups. In 1994, workshops were organized by the Society of Environmental Toxicology and Chemistry (SETAC) at Leuven, Belgium (April, 1994) and later at Denver, Colorado (November, 1994). These two workshops brought together 30 model users and developers to discuss the application of environmental fate and exposure models; to evaluate their performance; to provide guidance on their use; and to make recommendations on how the models could be improved to

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broaden their acceptability and encourage their use.[2] Seven years later, an OECD/UNEP Workshop was organized in Ottawa, Canada (October, 2001), to assess the utility of multimedia fate models for estimating overall environmental persistence and long-range transport of chemicals in the context of assessing potential persistent organic pollutants (POPs) and/or persistent, biaccumulative and toxic substances (PBTs). The Ottawa workshop marked the beginning of a period of activity by a working group of model developers and users (the OECD Expert Group on Multimedia Modeling) that led to the publication of a model comparison study,[3] recommendations for assessing persistence and long-range transport with models[4] and a consensus model, the OECD Overall Persistence and Long-range Transport Modeling Tool (The OECD Tool[5]). In 2013 a working group jointly organized by the three Scientific committees of the European Commission, DG SANCO (SCHER, SCHENIR, SCCS),[6] published the scientific opinion "Addressing the New Challenges for Risk Assessment" in which a number of opportunities to improve exposure models to increase their ecological realism and predictive ability for the growing number of chemical classes on the market were identified. Some of the fate and exposure assessment challenges from the scientific opinion were reported by Di Guardo and Hermens.[7]

Most recently, the European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) organized a workshop on environmental fate and exposure models in Brussels, Belgium (May, 2017). Following the format of previous workshops, the ECETOC workshop brought together users and developers of environmental fate models. At this workshop, industry scientists and regulators who conduct chemical hazard assessments using PBT criteria, and risk assessments for industrial chemicals, pharmaceuticals, biocides and agricultural chemicals, came together to review current standards of practice in exposure modeling and to identify key challenges for addressing 21st century needs in chemical hazard and risk assessment. The authors of this review article have been active in many of the workshops summarized above, and all participated at the recent ECETOC workshop. This review article summarizes key observations from the workshop, with a particular emphasis on how advances in environmental fate models over the last 20 years have addressed the challenges identified in the 1994 workshops, and to identify the primary needs to further advance the models.

Environmental fate models provide a framework to assemble a quantitative and mechanistic description of the sources of chemicals to the environment, and the pathways they follow en-route to their ultimate degradation or irreversible sequestration. Fate models can be integrated with, or loosely-coupled to, multi-pathway exposure models that describe the transfer of chemicals from the environment into the food and water ingested by humans, and water and soil that directly contacts the human skin.[8] Models are currently heavily relied upon to assess chemical hazard, exposure and risk, and to formulate chemical management strategies. But models did not always occupy such a strong position as scientific and policy support tools.

One of the main outputs of the modeling workshops that were held in the 1990s was a report by Cowan *et al.*[2] that identified a number of research areas that required attention in order to strengthen the utility of models as scientific and decision-support tools. Cowan *et al.*[2] recognized that the models were powerful conceptual tools capable of characterizing and quantifying the sources, environmental pathways, and exposure routes for chemicals used in commerce. And, they recognized the importance of identifying and quantifying the uncertainty and variability associated with a model's description of these processes. The following five key areas were identified as requiring attention by Cowan *et al.*[2] in 1995:

(1) Clear classification of chemicals that are within the domain of applicability of models; chemical properties and degradation half-lives and their variability with temperature; emission data, including background environmental concentrations;

(2) Model algorithms and parameterization to increase the fidelity of the model's descriptions of the real environment within the bulk compartments of air, water, soil and sediment that were generally included in models at the time, and to extend the models to describe additional compartments such as vegetation and ice/snow; additionally, the need to develop data sets to describe inter-media transfer coefficients in a variety of environmental scenarios; among the other areas to improve were sub-models for chemical fate in soil and sediments as well as waste-water treatment models, and bioaccumulation and food chain models.

(3) Model comparison exercises to enhance reliability and credibility, especially in model documentation;

(4) Sensitivity and uncertainty analysis to provide confidence intervals to support hazard and risk-based decisions and to identify key areas for further research and model development;

(5) Establishment of a set of guidelines for good modeling practice in scientific and decision-support applications of models, with a particular attention to the model validation issues and the comparison of predicted to measured results.

Model developers have invested considerable resources to address these areas since the publication of Cowan *et al.*[2] in 1995. Moreover, they have expanded the scope and applicability of fate and exposure models in several other dimensions that go beyond these recommendations. Areas where there have been notable developments include:

- Development of models with a range of spatial and temporal resolutions that can be used in concert with field data to rationalize chemical concentrations and estimate the rates of emissions or key fate processes at different spatio-temporal scales;
- Inclusion of transformation products in model scenarios;
- Scenario analysis to investigate the influence of climate variability and climate change on exposure to environmental contaminants;
- Development of fate and exposure models for engineered nanoparticles and for mercury;
- Adaptation of the principles from chemical fate and exposure models to pharmacokinetic models and application to human biomonitoring data.

Here we review the progress made in these areas, discuss the mechanistic foundations of fate and exposure models, and identify open questions and needs for strengthening future model development and application. We first provide a summary of progress in different areas and then highlight selected topics of particular interest.

2. Progress in fate and exposure model development since the mid-1990s

The areas of fate and exposure modeling where progress has been made range from chemical property data needed as model inputs to model parameterization and design, types of scenarios that can be handled by the models, model evaluation by comparison to field data, sensitivity and uncertainty analysis, and more.

Chemical properties, specific model parameters

Chemical property data are essential as model inputs. Since the publication of the property data handbooks by Mackay *et al.*,[9] property data for many organic chemicals have been critically evaluated, missing data have been estimated with improved chemical property estimation methods, and sets of recommended best estimates have been published for several classes of environmentally important chemicals (*e.g.*, PCBs,[9,10] HCHs,[11] PAHs,[12] PFASs,[13] siloxanes,[14] chlorinated paraffins[15] and chlorinated dioxins and furans,[16] and complex mixtures of halogenated organics[17]). Polyparameter linear-free energy relationships (ppLFER)[18] have been established to estimate partition coefficients for a range of environmental media for which partitioning cannot be related to the octanol–water partition coefficient (K_{OW}) (*e.g.*, ice/snow,[19] mineral surfaces,[20–22] aerosols[23–25] and polymers and biopolymers[26]). A great deal of effort has also been invested in expanding the applicability domain of models to better assess the environmental fate and bioaccumulation of polar and ionizable organic chemicals.[27–30] Lastly, model parameters describing environmental mass-transfer processes have been critically reviewed and updated.[31]

Emission data

Two complementary approaches have been employed to estimate the emission source strength of chemicals used in technical applications and consumer products. The first is the bottom-up approach that was pioneered by Breivik *et al.*[32–34] to estimate the emissions of PCBs globally, and applied by Diamond and colleagues[35–37] for the city of Toronto. Other bottom-up emission inventories have been compiled by Wang *et al.*[38] for PFCAs, by Glüge *et al.*[39] for chlorinated paraffins, Li *et al.*[40] for α-HCH, and by Zhang and Tao for 16 PAHs.[41] The second approach is the back-calculation of emissions from measured concentration data by inverse modeling,[14,42–47] which is discussed in more detail below.

Expanding the scope and applicability of the models

A key contribution in this area is the definition of a variety of metrics of exposure-related environmental and human exposure hazard that can be calculated with fate and exposure models. These include metrics of persistence and long-range transport potential that reflect a chemical's tendency to be widely distributed, to form long-lived reservoirs in the environment, and to lead to the formation of persistent transformation products.[5,48–58] Models have also been applied to map the remoteness of locations in the global environment from sources of chemical pollution,[59,60] see Fig. 1. Metrics of environmental risk and human exposure potential for chemicals have been derived within the framework of fate and exposure models.[61–65]

Multimedia models of the 1990s included bulk compartments for air, water, soil, and sediment. Several additional environmental compartments, sub-compartments and processes have been incorporated into fate and exposure models, including terrestrial and aquatic vegetation,[66–79] DOC in terrestrial and aquatic systems,[76,80,81] ice and snow,[82–84] different types of aerosols,[85] mountainous regions,[86,87] and the effect of intermittent rain.[88–90]

The fundamental concept underlying all fate and exposure models is the integration of chemical transport, transfer and degradation processes into mass balance equations for the chemical investigated. This concept of setting up multi-media mass-balances is generally valid and goes beyond the most common type of models that have been developed and applied

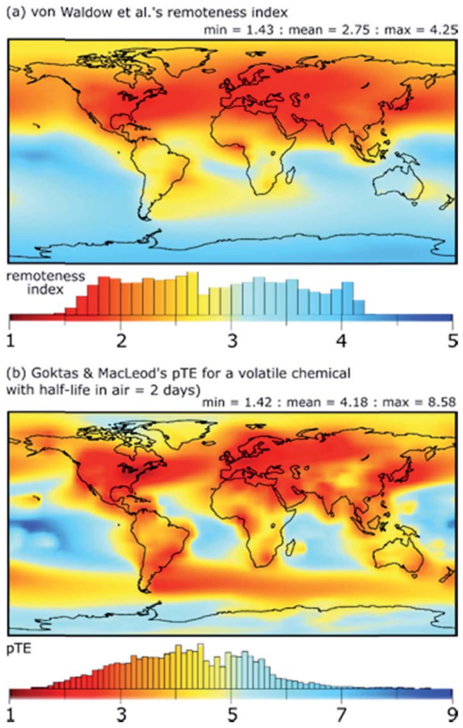

Fig. 1 (a) Remoteness index calculated by von Waldow *et al.*[59] using an atmospheric transport model (chemical independent), and (b) the negative log of transfer efficiency (pTE) of a volatile chemical calculated by Goktas & MacLeod[60] using the BETR Global multimedia transport model. Higher values of remoteness index and pTE indicate locations on the Earth that are more remote from emissions of chemicals to air that occur in proportion to the intensity of night-time light observed from space. Histograms illustrate the area distribution of different values of remoteness index or pTE.

to non-ionizing, often long-lived, organic chemicals. For example, mass-balance models have been developed for nanoparticles[91–98] and recently for microplastic.[99]

A class of organic chemicals of emerging concern are the ionizable organic substances. Given that the process descriptions of most of the current multi-media environmental fate models were derived from the well-established understanding of partitioning and mass transfer of neutral organic chemicals, expanding the domain of applicability of the models to address ionizable organics represents an important development. Unit world mass balance for ionizing chemicals using activity *in lieu* of fugacity have been presented.[100,101] The multimedia activity model for ionizable (MAMI) organic chemicals has recently been modified in the development of a multimedia chemical fate model for China (SESAMe), designed using the nested structure of SimpleBox.[102,103] The SimpleTreat model 4.0 [104] has been updated to include improved handling of ionizable organics, thus providing a tool for estimating chemical fate and behaviour in domestic sewage and activated sludge systems for down-the-drain chemicals, such as pharmaceuticals.[105]

Model evaluation by comparison to field data

Fate and exposure models can be evaluated by comparing the model results to field data. If a model can reproduce field data (collected under conditions that correspond to the assumptions and settings in the model), this strongly increases the credibility of the model and demonstrates that the model is suitable for the chemical and environmental system considered. Results from fate and exposure models have often been found to agree well with field data; this includes at the global level,[63,106–111] and at the continental level[112–115] for selected persistent organic pollutants, and also in local and regional systems, such as the cases of diuron in a small, highly dynamic tropical catchment,[116] plant protection products in agricultural catchments at different scales,[117–121] PBDEs in a Swiss lake,[122] and PCBs in the Adriatic Sea.[123]

Sensitivity and uncertainty analysis

Sensitivity and uncertainty analyses have become more and more common and are now an integral part of many fate and exposure modeling studies. MacLeod *et al.*[124] provide a practical guide to sensitivity and uncertainty analysis for fate and exposure modeling studies. In the OECD Pov and LRTP Tool the user can activate the built-in options for a sensitivity and uncertainty analysis of the results for overall persistence and long-range transport potential. Becker *et al.* (2011)[125] provide an extensive uncertainty analysis for the concentrations of endosulfan in air and seawater calculated with a global environmental fate model, and Wöhrnschimmel *et al.*[126] propagated uncertainty in chemical properties and degradation half-lives of persistent pollutants through an analysis of the effects of climate change on pollutant transport to the Arctic.

Good modeling practice

Finally, the need of incorporating good modeling practice in the development and evaluation of environmental models was proposed by Jakeman *et al.* (2006);[127] this was then specified by Buser *et al.*,[128] who set up six principles of good modeling practice in the field of fate and exposure modeling. These principles range from a specification of the goal and scope of the assessment to specifying the model used, specifying all input and all output data, conducting a sensitivity analysis so that the most influential model parameters can be identified, and specifying the limitations of the model results and the modeling exercise.

Improved modeling of bioavailability of contaminants

Bioavailability of chemicals to terrestrial and aquatic environments and more generally the ecological realism of scenario descriptions has been pointed out as a critical issue to evaluate the exposure and therefore the toxicity of hydrophobic chemicals in the environment.[7,129,130] Some models were recently published and have incorporated additional compartments and subcompartments (such as dissolved organic carbon, macrophytes, algae) to account for their influence on dynamically changing bioavailable concentrations,[76,81,131,132] as well as compartment variability in scenarios.[78,132,133]

3. Models for small spatial scales and dynamic scenarios

In the 1990s fate and exposure models had mostly been developed to describe long-lived chemicals, such as organochlorine pesticides and PCBs. Analytical chemistry techniques for such substances required large-volume samples and intensive effort in the laboratory for analysis. Thus, the temporal and spatial resolution of available measurements was low, and, due to the persistent nature of the chemicals, long time scales were needed to observe trends in concentrations. Models developed in the 1990s correspondingly described environmental conditions using long-term average conditions for temperature, rain rate, wind speed, *etc.*, and models were often applied using a steady-state assumption that represents a hypothetical conditions where emissions are balanced by removal processes.[134] In the years since the 1990s it has been increasingly recognized that environmental fate models can be more flexible if they implement more rapidly changing conditions. This is needed if the chemical considered has short degradation half-lives and/or if there are strong and rapid changes of the environmental conditions. Advances in analytical chemistry capabilities have provided more measurements at higher spatial and temporal scales to provide context for these model scenarios and to support model-measurement comparisons that enable a process-based understanding of chemical dynamics. This also made it possible to appreciate the role of temporal and spatial changes of specific compartments, such as a pond or a forest, in driving concentration changes in the main compartments *e.g.* water and air.[76,132,133,135]

For example, Camenzuli *et al.* (2012)[116] investigated the fate of the herbicide, diuron, in a small river catchment in Queensland, Australia. The problem in this case was that appreciable amounts of the diuron used on sugarcane and other crops in Northern Queensland were flushed into the Great

Barrier Reef lagoon by water runoff. In the lagoon, the herbicide affects, among other effects, the seaweed and thereby wildlife living on seaweed (dugongs, turtles). There is a strong seasonal change in the rain rates in Northern Queensland and the rain rates in the wet season are very high (with peaks above 200 mm per day). Camenzuli *et al.* (2012)[116] developed a model of the Tully River catchment with six compartments (agricultural soil, non-agricultural soil, seawater, sea sediment, air, water on land that is present under flooding conditions) and ran the model with very high temporal resolution (time steps on the order of seconds). This allowed them to drive the model with the highly dynamic actual rainfall data measured at a station in the Tully River catchment (Fig. 2a).

The model results of interest were the fluxes of diuron into the seawater compartment and the diuron concentrations in that compartment. Comparison with diuron concentrations measured in the lagoon shows that the model results agree well with the measured data, see Fig. 2b. The concentrations follow the seasonal rainfall trend.

In this way, the model was established as a tool that was then used to explore the effect of a diuron restriction scenario (no application of diuron in the wettest months of the year, November to April). Such a restriction would lead to a decrease in diuron concentrations in seawater by a factor of two. Overall, this case study shows that fate and exposure models are not limited to cases with "slow" processes and average environmental conditions, which is sometimes seen as a serious limitation of this type of model, but can also be set up in a way that they describe highly dynamic conditions with high accuracy.

Similarly to the diuron case, an integrated compartmental model (DynaPlus) was recently developed and used to predict the surface water contamination by pesticides used in an intensive orchard cultivation in a mountain region in Italy.[121] Mountainous regions are characterized by rapid land response to precipitation, resulting in quick runoff chemical peaks and consequent potentially high peak exposure concentrations in aquatic ecosystems receiving such runoff. The model consisted of a dynamic water network model (built upon the Dyna model[136]) and a spatially explicit terrestrial multimedia model[81,120] parametrized using specific scenario and emission data provided by the local authorities. The model incorporated an improved algorithm to calculate water runoff in steep slopes (average 30%, up to 80%) which allowed to more accurately calculate chemical runoff in these conditions. The integrated model was run for two cultivation years and results of chemical runoff from treated orchards were compared to *ad hoc* measured water concentrations for the organophosphorus insecticide chlorpyrifos in order to benchmark the model against field data. The model simulations showed that concentration peaks of chlorpyrifos in river water (Fig. 3) spanned and oscillated between 3 and 4 orders of magnitude, in the range of 0.1 to 1000 ng L^{-1}, which is well within the range of the acute EC50 for Daphnia (around 100 ng L^{-1}).[137]

Given that ecotoxicity data (such as those for Daphnia) are usually determined at constant exposure, the results of these model simulations reveal the difficulty of evaluating the effect of higher concentration peaks but shorter in time (peak exposure) in protecting aquatic ecosystems.

A dynamic model for assessing pesticide residues in fruit in comparison against EU and US maximum residue levels has recently been presented by Mendez *et al.*[138] in relation to the cultivation of bananas in Costa Rica. In addition to water, air, soil, and sediment compartments, Mendez *et al.*[138] also included a banana plant and estimated the residues of diuron, ethoprofos, and epoxiconazole. Their results demonstrate the importance of dynamic models as decision-support tool that complements ongoing efforts to assess the ecological effects of

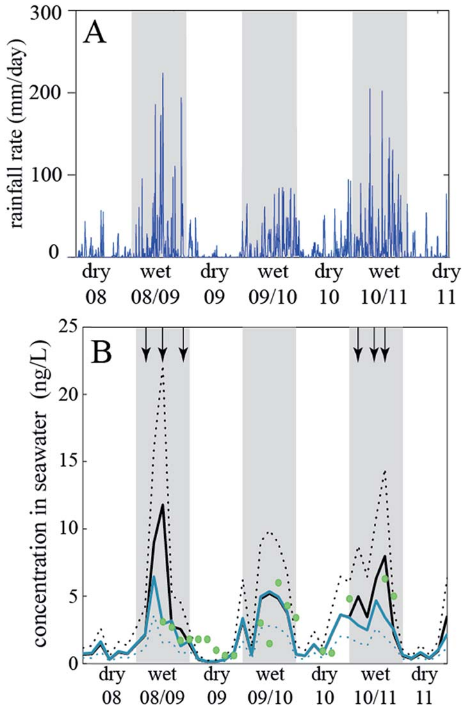

Fig. 2 (A) Rainfall data from the Tully River catchment, Queensland, Australia, and (B) diuron concentrations measured in the Great Barrier Reef lagoon (dots) and calculated with the fate and exposure model (lines) by Camenzuli *et al.* (2012)[116]. Reprinted from The Science of the Total Environment, 440, L. Camenzuli *et al.*, Describing the environmental fate of diuron in a tropical river catchment, pp. 178–185, Copyright (2012), with permission from Elsevier.

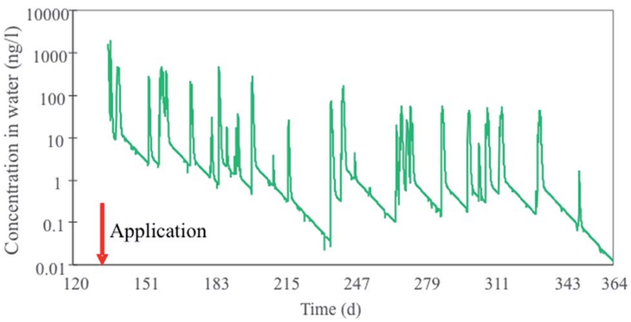

Fig. 3 Peaks of chlorpyrifos concentrations in a mountain river (Novella) in Italy in 2012 calculated with the DynaPlus model of Morselli *et al.* (2018).[121]

exposure to chemical mixtures and transient pulses. For instance, such models can be helpful in minimizing the occurrence of pesticide pulses, by providing a decision-making tool with respect to the timing of pesticide applications.

4. Day-night cycling of SVOCs in boundary layer air

As sampling and analytical capabilities improved for atmospheric micropollutants, measurements of persistent semi-volatile pollutants with temporal resolution of several hours became more widely available in the 2000s. In 2007, MacLeod *et al.*[139] developed a dynamic multimedia model that included variable atmospheric boundary layer height, temperature, hydroxyl radical concentrations and windspeed. They collected measurement data from six studies that reported concentrations of semi-volatile organic chemicals in air over consecutive 24 hour cycles, and demonstrated that in all cases the model could explain the drivers of day-night variability of concentrations in terms of variable process rates. Their analysis with the dynamic mass balance model identified four controlling factors that determine the day-night variability of concentrations of persistent semi-volatile chemicals in air: (1) source characteristics, (2) temperature dependent air-surface partitioning, (3) atmospheric mixing height and stability, and (4) hydroxyl radical concentration.

The insights from the 2007 modeling study informed the design of day-night measurement campaigns that were designed specifically to determine the rate of emissions of air pollutants from diffuse sources in urban areas. Several of these studies were carried out in Zurich, Switzerland to measure emission rates of PCBs,[42,140] PBDEs,[43,44] perfluoro alkyl substances,[47] cyclic siloxanes,[141] and PCDD/Fs.[140] The recent quantification of ongoing PCB emissions in Zurich led the Swiss Federal Office for the Environment to re-open the question of PCB emission sources and to commission the set-up of a current and comprehensive PCB emission inventory for Switzerland.[142]

Mass balance models applied in conjunction with day-night measurement campaign data have demonstrated the potential to infer process rates for hydroxyl radical degradation of PCBs,[139] for a more physically-based description of the air compartments in fugacity models, introducing hourly variable PBL (planetary boundary layer) compartment[81,143,144] and for reversible air-vegetation exchange of PCBs, PBDEs and chlordane.[42,145] Studies of this type provide the opportunity to evaluate the process descriptions provided by mass balance models in a relatively controlled situation, which helps to identify weaknesses in the models that can be improved, and ultimately improve model performance and reliability in applications at all spatio-temporal scales.

5. Environmental fate models as decision-support tools

Applying environmental fate models in decision-making requires that the models are understood by stakeholders, credible and that their reliability has been assessed. For multimedia models, the three key elements are: (i) the models themselves, *i.e.* the process descriptions and their mechanistic basis, and the model parameterization; (ii) the chemical property data used as model input; and (iii) the emission data, including their temporal and spatial resolution, used as model input.

Importantly, the three elements are independent of one another, which means that each of them may introduce a certain type and degree of error into the model results, but also that errors from these different elements can be traced separately, which makes it easier to constrain the source of error. The first element, process descriptions and model parameterization, strongly relies on the general laws of nature such as the law of the conservation of mass, the law of mass action, and the laws of chemical kinetics and diffusion, as well as empirical data reflecting the environmental conditions assumed in the model. Nevertheless, in setting up a model there is always, to some extent, room for choices to be made by the model developer. The effect of this variability in model setups can be assessed by model–model comparisons. An extensive model comparison was performed for multimedia fate models used to determine the overall persistence (Pov) and long-range transport potential (LRTP) of organic chemicals.[3]

The other two elements, chemical property data and emission data, often introduce greater error than the choice of model or details of the model setup. Chemical property data available in data bases and compilations often show surprisingly high variability and uncertainty; they need to be selected carefully and are ideally checked for their internal consistency, *e.g.* the octanol–air partition coefficient (K_{oa}) needs to be equal to the ratio of K_{ow} and the air–water partition coefficient, K_{aw}.[146,147] Emission data are often the most uncertain and incomplete element,[148] as discussed above.

Even when the property and emission data are selected carefully, there will be some remaining uncertainty that has to be accepted. For both, property and emission data, it is then advisable to determine a confidence factor or uncertainty range and to propagate this range through the model, for example by means of Monte-Carlo simulation or by applying the rules of error propagation.[124]

One environmental fate model that was developed explicitly for decision making purposes is the OECD Pov and LRTP Estimation Tool.[5] Before the actual tool was created, nine different models for Pov and LRTP calculations were evaluated and compared in much detail.[3] Also a set of well-characterized reference chemicals that define the scales of Pov and LRTP was introduced.[4] Once the validity of the underlying concepts was established and the scope and purpose of the model within a decision-making context were defined, the specific setup of the tool, *i.e.* the format of the data input and display of results, the model algorithm, options for uncertainty analysis, and the software environment, was defined.[5] Because the tool is based on a robust and common software environment (MS Excel for both Windows and Macintosh computers), is easy to use (reliable and robust handling of incorrect input), offers all results in both a graphical and numerical format, and is available free of charge from a trusted organization (OECD), it was quickly adopted by its users in government, research and industry. Since then, it has been used regularly for the evaluation of possible persistent organic pollutants in the context of the Stockholm Convention.

6. Outlook for improving the application of models within regulatory frameworks

This paper has summarized research conducted in the last three decades that addressed the needs identified by Cowan *et al.*[2] and that evolved in the various workshops that have been held since then. Improvements in characterizing and quantifying physicochemical properties and emission estimates and refinements in model formulation and parameterization have led to better comparability between model results and monitoring data, which in turn imparts greater confidence to the use of models within regulatory chemical risk assessment. Overall, there has been considerable progress in model development, model transparency and model reliability. However, in the context of regulatory risk assessment it is important to strike a balance between increasing model complexity and diversity driven by scientific progress, on the one hand, and the need for models that are practical and relatively easy to use, on the other hand. Ongoing scientific development and the presence of open scientific questions must not reduce the availability of practical tools for regulatory risk assessment out of "paralysis by analysis". Therefore, there is a continuous need for the translation of new scientific insights into the sphere of – often simplified – modeling tools suitable for regulatory risk assessment.

This translation process is a task in itself and requires time and resources. Participants from the 2017 ECETOC workshop expressed frustration regarding the lack of advances in environmental fate and exposure models that are included within the tools used for regulatory purposes. For instance, as described above, substantial progress has been made in expanding the applicability domain of the models with respect to both chemical and environmental properties. However, the European Union System for the Evaluation of Substances (EUSES), which is used for assessing exposure of general chemicals and biocides regulated under REACH, has not been updated to reflect advances in research, with the most recent update (EUSES 2.1.1) parameterized according to algorithms and assumptions described in the 2003 EU Technical Guidance Document.[149] There is clearly a need to improve the pace at which advances in research are implemented within regulatory tools. However the process of evaluating new modeling approaches and adopting them into regulatory tools must be conducted in an open and transparent manner that facilitates building consensus among key stakeholders from industry, NGOs, government, and academia who are actively engaged in the development and use of environmental fate and exposure models.

The development of the OECD Tool demonstrated how bringing an expert group of modelers together can result in successful development and adoption of a regulatory modeling tool. Another example of an expert group building consensus about the application of exposure modeling within a regulatory context is the Forum for Co-ordination of pesticide fate models and their Use (FOCUS). FOCUS was an initiative of the European Commission, with the objective to harmonize the predicted environmental concentrations (PECs) of active substances of plant protection products (PPP) in the framework of the EU Directive 91/414/EEC. It provided a platform for close co-operation of expert groups of scientists drawn from regulatory agencies, academia, and industry under the auspices of the Commission's DG SANTE.

We propose that the creation of expert groups that follow the approaches provided by FOCUS and the OECD Tool is a fundamental element for achieving consensus among stakeholders to update and improve models used in regulatory exposure assessment. Multi-stakeholder expert groups provide a forum for communication and education about developments and application of environmental fate and exposure models. When the groups are tasked with a clear objective, they can work in a focused manner to define the attributes of a fate and exposure model that is "fit for purpose" to confront a regulatory question. Tools used at lower tiers of assessment will likely address questions that differ from tools used at higher tiers of assessment. Consequently, separate expert groups may be needed to confront related questions, or a single expert group might be tasked to develop a tiered set of models that address the problem at several levels of complexity. Ideally, an active and collaborative expert group that represents all key stakeholders should be able to define the tools, assumptions, and acceptable level of uncertainty associated with the various assessment tiers that might be required in a regulatory context. The work of these groups would include model comparison exercises, and critical evaluation of assumptions and limitations of models with the ultimate goal of providing recommendations for the application of existing models, or purpose-built new software for conducting exposure assessments that reflects scientific consensus among stakeholders.

We acknowledge that creating multi-stakeholder expert groups that are tasked to agree on how to best update regulatory tools used for chemical risk assessment is not likely to be a trivial exercise. It will require commitments of time and money from the stakeholders to be successful. In the specific case of EUSES, the process could build on the foundation provided by the list of high-priority corrections, improvements, and extensions that was published by van de Meent *et al.*,[150] the key observations published in the 2013 EU scientific opinion,[6] and the recommendations of the 2017 ECETOC workshop participants.[151]

A high priority for improving exposure models used in regulatory assessments is the need to expand the chemical applicability domain. The rapid development of target and non-target analytical chemistry techniques based on LC/MS over the last decades has made measurement and monitoring of environmental contaminants that are ionisable organic chemicals, including halogenated organic acids and chemicals used in pharmaceuticals and personal care products, an important area of environmental chemistry. Attention placed on these chemicals by their detection in the environment has been a key driver for drawing regulatory attention. Particularly at lower screening and prioritization tiers of assessment, regulatory models are currently not capable of handling these chemicals in a reliable manner, and a lack of reliable property estimation methods for such chemicals further hinders screening level assessments.

Many regulatory models are also not appropriate for describing measurement data collected at high temporal resolution (*e.g.* hours). The 2013 Scientific Opinion[6] expressed a need for criteria and protocols for obtaining and comparing chemical monitoring data, especially for evaluating the fate of chemical mixtures, including metabolites. Such data should be collected and assembled in databases that can be used for model development, validation and benchmarking to support developing and calibrating higher temporal resolution models that could eventually be applied with confidence within a regulatory context.

In the absence of reliable property data and regulatory models that are appropriate for interpreting monitoring data and placing the data in the context of the environmental fate, transport and exposure of chemicals, measurements documenting the occurrence of pollutants place pressure on regulatory authorities to infer potential risks without a quantitative framework.[152] Recent experiences with cyclic volatile methyl siloxanes,[153,154] and the public policy debate about regulation of microplastics in consumer products[155,156] illustrate the confusion this situation can create. It is therefore vital that chemical property measurement and estimation methods, and environmental fate and exposure modeling, continue to advance and evolve to support rational management decisions for the 21st century's environmental contaminants of concern.

Conflicts of interest

There are no conflicts of interest to declare.

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