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Valery E. Forbes
University of Nebraska-Lincoln, veforbes@umn.edu

Udo Hommen
Fraunhofer Institut fur Molekularbiologie und Angewandte Oekologie

Pernille Thorbek
Syngenta

Fred Heimbach
RifCon

Paul J. Van den Brink
Wageningen University

See next page for additional authors

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Short Communication

Ecological Models in Support of Regulatory Risk Assessments of Pesticides: Developing a Strategy for the Future

Valery E. Forbes,[1] Udo Hommen,[2] Pernille Thorbek,[3] Fred Heimbach,[4] Paul J. Van den Brink,[5] Jörn Wogram,[6] Hans-Hermann Thulke,[7] and Volker Grimm[7]

[1]Centre for Integrated Population Ecology, Department of Environmental, Social and Spatial Change, Roskilde University, Roskilde, Denmark; to whom correspondence may be addressed: vforbes3@unl.edu, affiliation 2012: University of Nebraska-Lincoln, Lincoln, Nebraska, USA
[2]Fraunhofer Institut fur Molekularbiologie und Angewandte Oekologie (IME), Schmallenberg, Germany
[3]Syngenta, Environmental Safety, International Research Centre, Bracknell, Berkshire, United Kingdom
[4]RifCon, Leichlingen, Germany
[5]Alterra Centre for Water and Climate, and the Aquatic Ecology and Water Quality Management Group, Wageningen University, Wageningen, Netherlands
[6]Umweltbundesamt/Federal Environment Agency, Department IV 1.3, Plant Protection Products, Dessau, Germany
[7]Helmholtz Centre for Environmental Research (UFZ), Department of Ecological Modelling, Leipzig, Germany

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ABSTRACT

This brief communication reports on the main findings of the LEMTOX workshop, held from September 9 to 12, 2007, at the Helmholtz Centre for Environmental Research (UFZ) in Leipzig, Germany. The workshop brought together a diverse group of stakeholders from academia, regulatory authorities, contract research organizations, and industry, representing Europe, the United States, and Asia, to discuss the role of ecological modeling in risk assessments of pesticides, particularly under the European regulatory framework. The following questions were addressed: What are the potential benefits of using ecological models in pesticide registration and risk assessment? What obstacles prevent ecological modeling from being used routinely in regulatory submissions? What actions are needed to overcome the identified obstacles? What recommendations should be made to ensure good modeling practice in this context? The workshop focused exclusively on population models, and discussion was focused on those categories of population models that link effects on individuals (e.g., survival, growth, reproduction, behavior) to effects on population dynamics. The workshop participants concluded that the overall benefits of ecological modeling are that it could bring more ecology into ecological risk assessment, and it could provide an excellent tool for exploring the importance of, and interactions among, ecological complexities. However, there are a number of challenges that need to be overcome before such models will receive wide acceptance for pesticide risk assessment, despite having been used extensively in other contexts (e.g., conservation biology). The need for guidance on Good Modeling Practice (on model development, analysis, interpretation, evaluation, documentation, and communication), as well as the need for case studies that can be used to explore the added value of ecological models for risk assessment, were identified as top priorities. Assessing recovery potential of exposed nontarget species and clarifying the ecological relevance of standard laboratory test results are two areas for which ecological modeling may be able to provide considerable benefits.

Keywords: Extrapolation, Individual-based models, Pesticide registration, Population modeling, Recovery

INTRODUCTION

Effects of pesticides on populations of nontarget organisms depend not only on exposure and sensitivity to the toxicant but also on life-history characteristics, population structure, population density, interactions with other species, and—if recovery via recolonization is considered—species mobility and landscape structure (Liess et al. 2005; Schäfer et al. 2007). Ecological modeling can be a powerful tool for exploring the importance of, and interactions among, suchfactors and for predicting effects of pesticides on populations of nontarget species. Whereas ecological modeling has the potential to be implemented into pesticide risk assessment and regulation, its use has, so far, been minimal. This is despite the wide range of models that is suitable for ecological risk assessments and that such models are used widely in conservation biology (e.g., Frank et al. 2002) and in other types of ecological management (Barnthouse et al. 2008). In contrast to the absence of models used in assessing likely effects of pesticides, modeling is used routinely to predict pesticide fate and exposure to increase the realism, relevance, and robustness of exposure assessments (FOCUS 2001; Barnthouse et al. 2008). Ecological modelers certainly can learn a lot from how fate modeling got established, but there are also important differences. Fate models describe physical processes, which are based on established physical models that rely on well-understood and widely accepted principles. In ecology, there is no established model based on first principles, and there is more debate on the underlying theory. Moreover, the entities and interactions to be represented in ecological models—individual organisms and their behavior—are more variable, contingent, and complex than the building blocks of physical systems.

For all these reasons, from September 9 to 12, 2007, the LEMTOX workshop was held at the Helmholtz Centre for Environmental Research (UFZ) in Leipzig, Germany, to bring together 35 experts from academia, regulatory authorities, contract research organizations, and industry, representing Europe, the United States, and Asia, to discuss the role of ecological modeling in risk assessments of pesticides, particularly under the European regulatory framework (EC 1997). Although the workshop intentionally focused on pesticide risk assessment under European legislation, many of the issues raised, regarding challenges and opportunities for the use of models in risk assessment, are of general relevance for other chemical groups and other legislative frameworks. A detailed report of this workshop is provided in Thorbek et al. (2008). The following specific questions were addressed: What are the potential benefits of using ecological models in pesticide registration and risk assessment? What obstacles prevent ecological modeling from being used routinely in regulatory submissions? What actions are needed to overcome the identified obstacles? What recommendations should be made to ensure good modeling practice in this context?

Participants addressed the above questions through a series of keynote lectures, breakout sessions, and plenary follow-up discussions. Although there was overall agreement that ecological models have the potential to offer many benefits for pesticide risk assessment, it was recognized that case studies are needed that can be used to compare traditional risk assessments with those produced with the aid of modeling to determine whether, and what, added value models can contribute for specific risk-assessment questions. A need also exists to develop guidance to assist regulators and industry in choosing the right models for particular situations, in employing the models consistently, and in interpreting model outputs confidently. The workshop focused exclusively on population models and did not consider ecosystem models, food web models, or bioaccumulation models. This was done partly to limit the scope of the discussions and partly because the population level is the lowest ecological level (i.e., above the level of individual organisms) of concern for risk assessment (EC 2002). Discussion was focused on those categories of population models that link effects on individuals (e.g., survival, growth, reproduction, behavior) to effects on population dynamics. In particular, we were interested in exploring whether, and in which situations, models could improve the ecological interpretation of pesticide effects measured in standard toxicity tests and mesocosm studies. Several keynote presentations demonstrated how matrix models (Stark 2008), epidemiological models (Thulke and Grimm 2008), simple individual-based modes (Van den Brink 2008), and complex individual-based models (Topping et al. 2008) could add value to risk assessments.

BENEFITS OF ECOLOGICAL MODELING

Ecological models are already used to support management decisions and to assess environmental risks in many other fields. For example, in conservation biology, population models are used to project population growth rates, to assess extinction risk, and to rank management options as well as their cost effectiveness (Grimm et al. 2004; Drechsler et al. 2007). In forestry, individual-based models are used both to manage temperate forests on small scales in great detail (Pretzsch et al. 2002) and to develop sustainable logging regimes for tropical forests (Huth and Tietjen 2007). In wildlife epidemiology, spatially explicit population models are used to compare vaccination strategies and to predict immunization levels required to eradicate disease, such as rabies (Eisinger and Thulke 2008). These models are currently used for control legislation (Thulke and Grimm 2008).

In principle, therefore, ecological models could be used for decision support in pesticide risk assessment as well. Here, the aim of ecological risk assessment is to directly address effects on populations of nontarget species, not only on individuals. Classical scientific methods—observation and experiments—are often not sufficient to study ecological systems because they are too large, too complex, too variable, and develop too slowly. Experiments are also often not possible for ethical reasons. Thus, models that assess or predict likely impacts on population-level attributes are necessary. The workshop focused on benefits and obstacles associated with various types of population models, ranging from simple differential equation models (Grimm et al. 2008) to matrix models (Caswell 2001) to more detailed individual-based models (DeAngelis and Mooij 2005; Grimm and Railsback 2005). Whereas matrix models have a long history of use and are easy to construct and understand, they make a number of unrealistic assumptions (e.g., that all individuals within an age or stage class are identical and that vital rates are time invariant) and are, therefore, more useful for projection (i.e., what would happen given certain hypotheses if we extrapolate from current vital rates [Caswell 2001] rather than prediction [i.e., what would happen if we extrapolate from current processes affecting vital rates; Caswell 2001]). In contrast, it is possible to develop individual-based models that realistically capture spatiotemporal complexities of landscape structure, management activities, and animal ecology (e.g., Topping et al. 2003), but such models require a great deal of effort and expertise to construct, can be cumbersome to run, and are a challenge to validate.

Irrespective of these differences among model types, ecological modeling aims to bring more ecology into ecological risk assessment, and it provides an excellent tool for exploring the importance of ecological complexities (such as temporal and spatial variability in environmental conditions and in the ecological attributes of populations or in interacting species) on risks to populations. Ecological models can be linked to exposure models, or they can use the time series produced by exposure models as forcing functions, and at least some of the models (e.g., individual-based models) can directly integrate exposure and effects more realistically than standard approaches currently used in pesticide registration (Topping et al. 2005; Van den Brink et al. 2007).

Ecological modeling could benefit the pesticide authorization process in getting more use out of the data collected (i.e., extrapolation) and in facilitating substitution of high-risk substances by comparing compounds with different types of toxicities, modes of action (e.g., reproductive toxicant vs acute mortality), or fate profiles. Even though not yet implemented in the approval process of active substances within the European Union, a substitution approach is part of a current proposal by the European Commission regarding the amendment of the European Union pesticide legislation (Commission of the European Communities 2008). In addition, models could be used to explore the impacts of different risk-management strategies (e.g., buffer or no-spray zones). They could also provide a valuable tool for optimizing study designs, for example, by identifying particularly vulnerable life-cycle types, comparing likely impacts of different exposure scenarios, quantifying important sources of uncertainty and knowledge gaps for which additional data are needed, identifying the most important drivers of population-level impacts, and assessing the scale, frequency, and duration of postregistration monitoring that might be needed. Ecological modeling may also help to reduce animal testing because it should be able to help focus testing on only the highest risk scenarios (e.g., leading to the need for fewer and more optimally designed field or mesocosm tests). Once data have been collected, ecological models can provide a quantitative basis for interpreting the data; they can help to determine the likelihood that toxicological responses of individuals will have measurable impacts on population size and structure; and they could aid in cost–benefit analysis by providing common metrics for expression of ecological effects and economic impacts.

Extrapolation from collected laboratory or field data to impacts of ecological concern is a major challenge for ecological risk assessment, and an area where the application of ecological modeling can provide a substantial improvement over standard regulatory approaches (Forbes et al. 2008). Even simple matrix models, that integrate toxicological responses on survival, reproduction, and development, are a major step forward for extrapolating standard toxicity test results to population-level effects. For example, assessing the relative sensitivity of species to chemicals on the basis of their population growth rate (or other population-level attribute), rather than on the basis of individual survival or reproduction, is a more ecologically robust approach that incorporates differences in life cycle and that integrates impacts on different life-history traits. Forbes and Calow (1999) demonstrated that population growth rate was less than or equally sensitive to the most toxicant-sensitive life-history trait for a wide range of invertebrates and toxicants. However, the most toxicant-sensitive traits are difficult to predict a priori, and thus, one may either overestimate or underestimate effects on population growth rate from single individual-level traits. Using simple matrix models and standard test species' life cycles, Forbes et al. (2001) showed that the same effect on juvenile mortality can have vastly different effects on population growth rate depending on life cycle. Stark et al. (2004) showed that different species exposed to the same levels of stress (mortality, reductions in the number of viable offspring, or a combination of both of these effects) do not react the same over time periods in which reproduction can occur.

A particularly important challenge for pesticide risk assessment is in assessing the likelihood of, and time needed for, recovery of nontarget populations following pesticide application. Today, mesocosm systems are the most common tool for assessing recovery of aquatic species. Unfortunately, such systems are typically isolated from the surrounding environment, they lack a landscape dimension, and their time span may be too short to allow recovery of some species to be assessed adequately (Van den Brink et al. 2007). Applying ecological models to mesocosm data could provide a better assessment of recovery potential (Traas et al. 2004) and could explore potential consequences of multigenerational effects. The models could also be used to extrapolate from short-lived, rapidly reproducing laboratory test species to longer-lived, more slowly reproducing species in the field; to extrapolate effects and recovery across different environmental conditions (e.g., climate, habitat type) and exposure scenarios; and to explore the likely effectiveness of different risk-mitigation strategies. More sophisticated models, which incorporate spatiotemporal variability in landscape structure and organism behavior, could be used to perform virtual experiments at scales that would not otherwise be feasible to test.

OBSTACLES PREVENTING USE OF MODELS IN PESTICIDE RISK ASSESSMENT

Despite the many potential benefits that ecological modeling has to offer, there are a number of challenges that need to be overcome before such models will receive wide acceptance for risk assessment. The most important challenge may be to convince risk assessors and other stakeholders that using ecological models can result in substantially better risk assessments than those that have been performed using current practice. Addressing this challenge will require that convincing examples or case studies can be found to demonstrate the added value of models. Despite population models (especially matrix models) having proved useful for protecting threatened and endangered species (Crouse et al. 1987, Doak et al. 1994; Fujiwara and Caswell 2001; Norris and McCulloch 2003; Wilson 2003), for understanding species declines (Vonesh and De La Cruz 2002) and biological invasions (Thomson 2005), and for monitoring restoration strategies (Endels et al. 2005), they have, to date, hardly been used in pesticide risk assessment. A certain amount of skepticism exists about models in general, concerns persist that using models will make risk assessment more cumbersome and complex, and criticism suggests that guidance is lacking on model selection, use, and interpretation. A pervasive lack of confidence surrounds ecological models, which partly arises from lack of experience with them, a lack of transparency (particularly in more complex models), and examples of past poor performance of models. A lack of standardized and user-friendly software leads to concerns about programming errors (i.e., is this result real or is it a bug?) and the requirement that end users (who may not be modelers themselves) master a new user interface or programming language each time they run a new model.

So far, the academic literature presenting ecological models for pesticide risk assessment seems to be primarily focused on scientific questions and largely ignores issues relevant for real applications. In a review of about 40 models developed for pesticide risk assessment, Grimm et al. (2008) found that testing, verification, or validation were not even mentioned for more than 70% of the models and that the representation of toxicity and the quantification of risk were often simplistic and not specifically designed to provide the added value of models for real risk assessments.

Thus, a number of challenges need to be overcome before even starting the modeling process (i.e., during the problem-formulation phase of risk assessments), which include

- Defining clear questions for the modeling that are related to risk management issues (e.g., consensus on protection goals and assessment endpoints)
- Agreeing on which species or species types to model for

relevant ecosystem types (e.g., should the species of concern for modeling be real species that are determined to be representative of certain groups or should they be generic species that are created for the modeling exercise?)

- Establishing a geographic and temporal scale compatible with regulatory decision making
- Defining the degrees of generality, precision, realism, and representativeness (e.g., should we aim to capture average conditions or realistic worst-case conditions?) necessary for different risk-assessment needs (e.g., screening level vs higher tier).

A central challenge for the selection and development of ecological models is to determine how much complexity is needed in the models to capture the essential elements of risk. The models should not include more complexity than absolutely necessary to answer the questions posed to them, and at the same time, it must be demonstrated that the models are sensitive enough to show adverse effects when such would occur under field conditions. Also, communication of model inputs, outputs, assumptions, interpretation, limitations, and uncertainties is constrained by a lack of standard procedures and language. The diversity of model types, ad hoc designs, and lack of a systematic framework for ecological modeling has inhibited its acceptance as a decision-making tool (Grimm et al. 2006). The issue of validation can be a tricky one. With validation, we refer to the process of making sure that we can place confidence "in inferences about the real system that are based on model results" (Rykiel 1996, p. 230; note that Rykiel calls this "verification"). Models that are too simple can be too poor in structure to allow for validation, whereas for very complex models, validation may be possible, in principle, but can be very time-consuming. Nevertheless, specific methods for verification and validation are available, in particular for the comparison of model output to data and patterns observed in the laboratory and field at different hierarchical levels and scales (pattern oriented modeling [Grimm and Railsback 2005]). In many cases, it is not the models that are limiting but, rather, the input data necessary to parameterize them.

HOW THE OBSTACLES CAN BE OVERCOME

One of the most important take-home messages of the workshop was that guidance on good modeling practice in the context of ecological risk assessment is essential before models will be widely accepted as part of the registration process. Guidance is needed on model development, model analysis, interpretation, and evaluation, as well as documentation and communication. All of these steps need to be done as transparently as possible, so that assumptions can be challenged and confidence in modeling increased. Several sources of guidance on model harmonization and communication already exist (e.g., Pastorok et al. 2001; Grimm and Railsback 2005; Grimm et al. 2006; Akçakaya et al. 2008) but may need to be adapted to the specific needs of pesticide risk assessment (e.g., the need to integrate time-varying exposure outputs from fate models with the constant [acute or chronic] exposure concentrations used in ecotoxicological tests [Boesten et al. 2007]). Developing guidance on good modeling practice for pesticide risk assessment will require extensive dialogue among modelers, regulatory bodies, industry, and other stakeholders, and we believe should be a matter of urgency.

Another important outcome of the workshop was the recognition of the need for convincing case studies that demonstrate how the application of ecological modeling can add value to risk assessment and reduce both false-positives and false-negatives, compared with current practice. Validation was discussed extensively, and it is clear that procedures for validating different types of models need to be made more explicit as part of good modeling practice and demonstrated through case studies.

The process of getting ecological models into the risk assessment process would be facilitated by the development of user-friendly software with a common user interface, although such software has its own pitfalls (Grimm et al. 2004). Ideally, the models would be flexible so that they could be easily parameterized for different species, pesticide application scenarios, and habitats. Although the models themselves do not need to be simple, they need to be simple to employ for nonprogrammers. The development of training courses in ecological modeling for risk assessors and risk managers could also help to increase confidence in using models.

Thorough consideration needs to be given to the contributions that different types of ecological models can make to the risk assessment process. Requirements of precision and accuracy may change as one proceeds from lower tiers to higher tiers, with both being protective, but the former aiming to be more conservative, and the latter, more predictive. Consideration needs to be given to both exposure and effects and how precision and accuracy of one (or lack thereof) is likely to influence the other. The degree of predictability required may also depend on the species for which risk is being assessed, being greater for smaller than for larger populations (because smaller populations have a higher risk of extinction because of stochastic influences), and greater for long-lived, slowly reproducing species than for short-lived, highly fecund species (because the former will take longer to recover, which increases their extinction risk).

One of the major benefits of ecological modeling compared with mesocosm or terrestrial field studies is that it is much easier to explore the range of species-dependent, pesticide-dependent, and habitat-dependent factors that might influence the impacts of pesticides on nontarget species. Although the time and effort needed to construct the models should not be underestimated, once the models are tested and validated, it may be relatively easy to modify input parameters to ask if–then questions and to generate testable hypotheses. If the pesticide is applied in the autumn, rather than the spring, will the risk be greater? If the density of the nontarget species is higher (or lower), how will that influence risk (or recovery)? If the habitat structure (or climate) is altered in a specific way, how will that influence risk? How is the presence of other stressors likely to influence the pesticide impact? If the models, in the first instance, can be used to assess relative risks of pesticides under different application scenarios, habitat properties, and ecological conditions in virtual experiments, the use of expensive and time-consuming field trials can be focused on high-risk situations.

For two groups of vertebrates, stream fish and shorebirds, highly predictive and mechanistic models already exist that answer similar questions for other types of risk. These models are individual-based and include adaptive behavior: The stream fish models of Railsback and Harvey (2002), which predict the effects of river management; and the shorebird models of Goss-Custard et al. (2006) and Stillman and Simmons (2006), which predict, for example, the effects of tourism land reclamation on winter mortality.

CONCLUSION

It is difficult to quantify the benefits that ecological modeling could bring to pesticide risk assessment for the simple reason that we often have little idea of how precise and accurate risk assessments based on current practice are. Under European legislation, pesticide risks are estimated using a toxicity–exposure ratio and the similar hazard-quotient approach (EC 1997). Until now, most of the threshold values defined for decision-making have not been validated sufficiently with respect to the level of protection they ensure. Thus, considering the very limited monitoring that is done of agricultural areas, there is a considerable risk of overlooking inadequately conservative threshold values because all but the most obvious impacts in the field may go unnoticed. Alternatively, there is a lack of information on the number and extent of false-positives (overestimates of risk) resulting from current practice.

Complications often exist because of the presence of more than one pesticide and other confounding factors that make causal relationships between a particular pesticide and impacts on field populations difficult to establish, and both false-positives and false-negatives need to be taken into consideration if we want to make the most effective use of the resources available for crop and environmental protection. Two areas in which we expect ecological modeling to provide considerable benefits are assessing recovery potential of exposed nontarget species and clarifying the extent to which protection levels set on the basis of standard laboratory tests are adequate for protecting populations. Top priorities for the future are the development of guidance on Good Modeling Practice and the analysis of case studies that explore the added value of ecological models for risk assessment.

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