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Review

Ecotoxicology and macroecology – Time for integration

Mikhail A. Beketov*, Matthias Liess

UFZ – Helmholtz Centre for Environmental Research, Permoserstrasse 15, D 04318 Leipzig, Germany

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A B S T R A C T

Despite considerable progress in ecotoxicology, it has become clear that this discipline cannot answer its central questions, such as, "What are the effects of toxicants on biodiversity?" and "How the ecosystem functions and services are affected by the toxicants?". We argue that if such questions are to be answered, a paradigm shift is needed. The current bottom-up approach of ecotoxicology that implies the use of small-scale experiments to predict effects on the entire ecosystems and landscapes should be merged with a top-down macroecological approach that is directly focused on ecological effects at large spatial scales and consider ecological systems as integral entities. Analysis of the existing methods in ecotoxicology, ecology, and environmental chemistry shows that such integration is currently possible. Therefore, we conclude that to tackle the current pressing challenges, ecotoxicology has to progress using both the bottom-up and top-down approaches, similar to digging a tunnel from both ends at once.

The essence of the ocean cannot be seen in a drop of seawater
Kurt Tucholsky, 1925

1. The central questions in ecotoxicology remains to be answered

Currently ecotoxicology represents a distinct scientific field that investigates impact of chemical contaminants on the environment at the molecular, physiological, individual, and ecological levels. This discipline is characterized by rapid progress and many remarkable achievements. However, a strategically critical issue is now becoming apparent, as to whether we have really solved the deep, chronic, and relevant problems regarding contaminants. The answer, if taken seriously, is discouraging. The ultimate aim of ecotoxicology is to determine and predict the effects of contaminants in real-world systems at large spatial scales (e.g. Newman and Unger, 2003). However, our capacity to elucidate and predict such effects remains severely limited. For example, with respect to four areas of active investigation and discussion in ecotoxicology, the following central questions have not been answered so far:

- What effects do agricultural pesticides have on biodiversity and ecosystem goods and services? What is the impact of modern compounds that are currently used in normal practice (i.e. not due to accidents and violation of the application norms)?
- What is the contribution of chemical toxicants to the degradation of coral reefs like the Australian Great Barrier Reef?
- What are the effects of pharmaceuticals on biological communities, ecosystems, and their functions, goods, and services?
- What are the large-scale effects of oil spills on marine and coastal ecosystems?

In our opinion, these different examples illustrate a single general problem; namely, the lack of current capacity to assess and predict the effects of toxicants on real-world ecosystems at large spatial scales. In this situation, decisions in the risk assessment are made under conditions of deep uncertainty. As a result, the protective standards that are prescribed are either over- or under-protective, which in turn leads to economic inefficiency or environmental hazards, respectively. Furthermore, attempts to manage landscapes efficiently, to implement conservation measures, and to place an economic value on ecological impacts, are impaired deeply.

The major cause of this central problem is that ecotoxicology and ecological risk assessment are based almost exclusively on a single paradigm, namely, a bottom-up approach that implies the use of toxicity tests carried out at the (sub)organism level (Box 1) and also, to a lesser degree, experiments on simple artificial ecosystems whose purpose is to predict the effects of contaminants on real-world ecosystems and entire landscapes. Even the most advanced current initiatives, such as REACH or the new "EU directive concerning the placing of plant protection products on the market", do not base their predictive methods on the empirical

* Corresponding author.
E-mail address: mikhail.beketov@ufz.de (M.A. Beketov).

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Box 1. **Glossary**

Organism- and sub-organism-level toxicity test systems – the systems designed to investigate effects of chemicals on individual organisms or their components (e.g. cells) and employing organism-level (e.g. survival, growth, body size, and individual fecundity) or sub-organism-level endpoints (e.g. gene expression, endocrine disruptions, and reactions of biomarkers).

Bottom-up approach – in ecology, an approach that seeks to develop understanding of ecological systems through studying the components of these systems. In this approach, patterns, processes, and mechanisms elucidated at small scales are used to describe and predict large-scale systems and processes (Gaston and Blackburn, 2000).

Top-down approach – in ecology, an approach that seeks to develop understanding of ecological systems by investigating the properties of such systems in their entirety. The main rationale for this approach is based on the fact that complex systems, such as biological communities and ecosystems, may exhibit properties that arise from the interaction of their constituent parts, and therefore are poorly predictable from the knowledge about these parts considered separately (Gaston and Blackburn, 2000).

Macroecology – the subfield of ecology that studies relationships between organisms and their environment at large spatial and temporal scales to characterize and explain patterns of abundance, distribution and diversity (Brown and Maurer, 1989; Brown, 1995; Gaston and Blackburn, 1999, 2000). Macroecology employs top-down holistic approach combined with correlative statistical framework, mathematical modeling, and to a much smaller degree experimental methods (Blackburn, 2004; Kerr et al., 2007).

knowledge about the effects of contaminants on real-world ecosystems and landscapes. Rather, the risk assessments are based on extrapolation from organisms to ecosystems and from small-scale systems to large-scale systems. The validity of these methods of extrapolation have been extremely rarely tested in comparison to their wide use (Geckler, 1976; Kefford et al., 2004; Liess et al., 2008), but is kept as a practical necessity, and the lack of knowledge of the effects of contaminants on ecosystems at large spatial scales is simply referred to as "uncertainty" (e.g. Walker et al., 2001; Suter, 2007).

It is not the bottom-up approach itself the cause of the problem. The approach has an important role to play. Rather, the problem results from the insufficient development of a complementary top-down approach that is focused on ecological effects at large spatial scales (Fig. 1). The bottom-up approach is an important tool that is indispensable for the investigation of many issues related to the regulation and risk assessment. However, after more than 50 years of development of ecotoxicology, it has become clear that this single tool, albeit a very good one, is insufficient to meet all the relevant challenges.

2. How ecology is solving large-scale problems

In ecology, the top-down approach, which considers large-scale systems as integrated entities, was re-established at the end of the 1980s in the form of macroecology (Brown and Maurer, 1989; Box 1). Macroecology combines the "old-school" observational approach, which had appeared before any formal science was

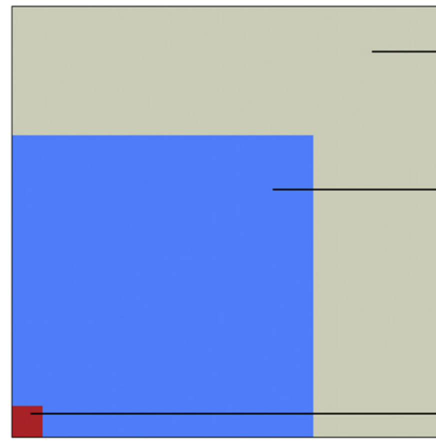

Fig. 1. Published studies that focus on pesticides and freshwater invertebrates. The three categories are as follows: (i) all studies with invertebrates including the standard ecotoxicology test organisms *Daphnia* spp., (ii) studies that do not include *Daphnia* spp., and (iii) original field studies that report comprehensive exposure analysis and link exposure to ecological effects on the local communities (i.e. community-level effects) in a system that encompasses more than one stream or river (Friberg et al., 2003; Berenzen et al., 2005; Liess and von der Ohe, 2005; Schäfer et al., 2007; Schäfer et al. 2011). Analysis is based on a search in the ISI Web of Science database (last check 25 June, 2011).

established, with novel and sophisticated statistical methods and modelling (Blackburn, 2004). The main reason that these methodologies were combined, in what may be called the "macroecological approach", was the basic inability of small-scale bottom-up studies to analyse and predict large-scale ecological patterns, similarly to the current case with ecotoxicology. The holistic top-down approach adopted by macroecology suffered from no such problems (Box 1). It enabled the discovery of regularities in large-scale patterns that only appear at large spatial scales and are stochastic and undetectable from the local perspective (Brown, 1995; Maurer, 1999; Kerr et al., 2007). This made macroecology an outstanding ecological subdiscipline.

The establishment of macroecology was accompanied by heated debates because, after decades in which the bottom-up reductionist approach predominated, many ecologists were preconditioned to believe that this was the only relevant approach to ecology and science in general (Gaston and Blackburn, 1999). However, the top-down macroecological approach has rapidly shown itself to be a credible predictive scientific practice, and, at present, macroecology is used to make large-scale (on the scale of landscapes to continents) predictions of diversity, species distribution, (meta) community structure, and other patterns (e.g. Blackburn, 2004; Kerr et al., 2007). For example, accurate predictions of the species diversity alterations induced by climate change and human population have been made and confirmed for European birds and Canadian butterflies using historical data on the climatic and biotic changes that occurred during the twentieth century (Evans and Gaston, 2005; White and Kerr, 2006, 2007).

3. What ecotoxicology can learn from macroecology

Ecotoxicology, and science in general, can learn much from this recent historical development in the field of basic ecology. To be able to tackle large-scale problems, ecotoxicology should, in a similar manner to basic ecology, develop a holistic top-down approach, which could be termed a "macroecological approach in Ecotoxicology". This approach should include the assessment of exposure to and the effects of toxicants in real-world systems