Ecological Applications, 7(4), 1997, pp. 1099–1102

THE ROLE OF MESOCOSM STUDIES IN ECOLOGICAL RISK ANALYSIS

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Abstract. Mesocosms have been primarily used as research tools for the evaluation of the fate and effects of xenobiotic chemicals at the population, community, and ecosystem levels of biological organization. This paper provides suggestions for future applications of mesocosm research. Attention should be given to the configuration of mesocosm parameters to explicitly study regional questions of ecological interest. The initial physical, chemical, and biological conditions within mesocosms should be considered as factors shaping the final results of experiments. Certain fundamental questions such as the ecological inertia and resilience of systems with different initial ecological properties should be addressed. Researchers should develop closer working relationships with mathematical modelers in linking computer models to the outcomes of mesocosm studies. Mesocosm tests, linked with models, could enable managers and regulators to forecast the regional consequences of chemicals released into the environment.

Key words: ecological inertia; ecological resilience; ecosystem structure and vulnerability; fate and effects models; indirect effects of xenobiotics; mesocosm experiments; pesticides; resource management, regional framework; risk analysis.

INTRODUCTION

The assessment of the risk of xenobiotic chemicals to aquatic resources has evolved to include an array of toxicity, fate, and exposure studies conducted under both laboratory and field conditions. Within the requirements of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), the U.S. Environmental Protection Agency (EPA) currently requires a laboratory toxicity data set for selected target species in addition to a limited set of nontarget species expected to be exposed as a result of the proposed use-pattern (Urban and Cook 1986, Jenkins et al. 1989). Even less data are required for nonpesticide chemicals of industry and commerce, which are regulated under the Toxic Substances Control Act (TSCA) (Bedford 1984).

Regulatory data for both TSCA and FIFRA have traditionally been generated using standardized testing procedures involving single species. However, in 1988 EPA made a major decision to require additional simulated aquatic field studies FIFRA (Touart 1988, Touart and Slimak 1989). This requirement was rescinded in 1992 (Anonymous 1992), which effectively eliminated regulatory studies of the indirect or secondary effects of pesticides on nontarget organisms. The EPA apparently rescinded the field-testing requirement because it was perceived that the studies were not providing data beyond that which were already provided by existing laboratory tests. However, this opinion remains controversial among ecotoxicologists, and has led to reconsideration of the role that experimental mesocosm studies should play in risk assessment and other applications of applied ecology (Taylor 1994).

MESOCOSMS AND THE ASSESSMENT OF XENOBIOTICS

Ecological risk analysis can be succinctly defined as "the process of defining and determining the probability of environmental threats and the impact they are able to cause" (paraphrased from Suter [1993:3; see also Bartell et al. [1992] and EPA [1992]). Although there is some difference in terminology in the designation of microcosms and mesocosms, in practice ecotoxicologists have defined mesocosms as outdoor semicontrolled ecosystems such as experimental ponds and streams whose physical dimensions and basic water chemistry are known and controlled. Mesocosms characteristically include both natural species assemblages (e.g., invertebrates, algae, and macrophytes) in addition to structured populations of vertebrates such as fish. These experimental systems are subject to the vicissitudes of regional weather, natural recolonization, interspecific interactions, disease, and other factors. Aquatic mesocosms can be viewed as part of an experimental continuum from single-species laboratory tests; to microcosms, which are small (<1 m^3) indoor or outdoor experimental ecosystems composed of axe-

Manuscript received 17 January 1996; revised 4 March 1997; accepted 31 March 1997. For reprints of this Invited Feature, see footnote 1, p. 1083.

nic (controlled) or natural biological assembledges; to larger (>1 m^3) semi-controlled ecosystems (i.e., mesocosms) such as littoral corrals, in situ bags or limnocorrals, streams, or ponds (Odum 1984, LaPoint et al. 1988).

Mesocosm research in the past has been directed primarily at four aspects of the assessment of xenobiotics: (1) estimations of the fate of the chemical, including volatilization, compartmentalization, and degradation (Robinson-Wilson and Boyle 1983, Heinis and Knuth 1992; (2) assessment of the primary, direct effects on a variety of organisms at the individual, population, and community levels of biological organization (Boyle 1985, Fairchild et al. 1992, Heimbach et al. 1992); (3) validation of mathematical models of fate (Park et al. 1982) and effects (Park 1990); and (4) determination of the secondary and tertiary indirect effects of biological restructuring on ecosystem structure and function (Eaton et al. 1982, Fairchild et al. 1992).

The first two areas have been adequately explored in the literature and have become standard areas of analysis in mesocosm experiments. Although mesocosm studies have analyzed the effects of xenobiotics at the population, community, and ecosystem levels of organization, too often these results have been interpreted as if they were consummate ends in themselves. They have not been used to their fullest potential in asking questions in a regional context. Broader ecological questions have largely been ignored.

Prospectus on the Future of Mesocosm Research

We outline here an agenda for mesocosm research that will address areas necessary for more comprehensive ecological risk analysis. Our primary goal is to place ecological risk analysis in the broader context of regional management of natural resources, which is a central theme of applied ecology. In the language of risk assessment, we form a corollary to our previous definition of ecological risk analysis by asking "What is the probability and expected magnitude of the secondary and tertiary effects of exposure to xenobiotics in ecosystems with different characteristics reflective of regional ecological conditions?"

This question parallels other efforts to explore approaches for managing resources withina regional framework (EPA 1989, Hunsaker et al. 1990, Grahm et al. 1991) including risk analysis of water resources. Mesocosms are a valuable tool that can be used in a systematic exploration of the influence of regional factors in ecological restructuring of aquatic ecosystems due to secondary and tertiary effects of toxic xenobiotics. This is perhaps the area least examined in mesocosm studies to date. Mesocosms studies can be designed to include critical ecological variables such as site-specific water-quality conditions, endemic flora and fauna, and various strengths and complexities of ecological interactions.

Additional studies should continue to be directed at the validation of models of chemical fate in mesocosms given different sets of ecosystem properties (Eaton et al. 1982). Factors that need to be considered in the assessment of the fate of xenobiotics include physical differences such as solar radiation, temperature, transparency of the water; chemical differences such as level of critical inorganic nutrients, pH, and buffering capacity; and biological differences such as standing crop of macrophytes, levels of planktonic organic carbon, and rates of metabolic activity (Fairchild et al. 1984, Boyle and Robinson-Wilson 1985, McCarthy and Bartell 1988). Differences in these ecological conditions occur regionally, and are expected to produce differences in the results of mesocosm experiments as well as model outputs.

Toxic effects of xenobiotics are also affected by physical factors such as temperature, pH, alkalinity, and hardness (Schindler et al. 1985, Mayer and Ellersieck 1986). Biological factors such as the age, physical condition, and phylogenetic origin of the target species (e.g., algae, crustaceans, and fishes) as well as the species within these groups will determine the differential sensitivity to various contaminants with varying modes of action (Mayer and Ellersieck 1986).

Indirect responses within ecosystems are strongly affected by variations in trophic structure (e.g., number of layers), nature of interactions, and interaction strength (Carpenter et al. 1985, Vanni and Findlay 1990, Deutch et al. 1992, Power and Marks 1992), Strong 1992. Indirect responses may be further exacerbated depending on the specific trophic layer that is targeted, such as the effects of herbicides on primary producers (Dewey 1986, Lampert et al. 1989) or the effects of insecticides on consumers (Fairchild et al. 1992, Boyle et al. 1996).

Thus, the effects of toxic chemicals are under the influence of a complex number of factors that vary regionally according to climate, geology, soils, landform, and resident biological communities. Future mesocosm experiments could be structured to address the ecological effects and management of toxic chemicals in a regional framework. Even aquatic ecosystems within regions vary according to level of inorganic nutrients and primary production (e.g., oligotrophic to eutrophic), physical structure (e.g., monomictic, dimictic, or polymictic), basic water chemistry (e.g., alkalinity and acid neutralizing capacity), and trophic structure (e.g., three or four-layer ecosystems) (Strong 1992). These factors may have profound effects on the structural and functional attributes of the entire system (Carpenter et al. 1985, Vanni and Findlay 1990, Power and Marks 1992).

Even though the first comprehensive studies using mesocosms were directed at fundamental questions of ecology (Hall et al. 1970), mesocosm studies by ecotoxicologists have not been fully linked to current ecological concepts nor to the broader, applied ecological questions of resource management. There has been a tendency to tacitly consider mesocosms such as outdoor ponds and artificial streams simply as containers for biological communities. Little attention has been directed either at how representative the initial conditions are to those occurring in nature, or how these initial ecological conditions shape the final results of the experiment. This has been less true for exclosures of natural systems, where the relationship with the parent ecosystem is intimate and apparent.

Recommendations

We enumerate four general recommendations for consideration in continued mesocosm experiments aimed at risk assessment for xenobiotics.

1) Develop closer links with mathematical modelers and the development of computer models. Models such as PEST and AQUATOX have benefited from validation with mesocosm studies in the past (Park et al. 1982, Park 1990). In the future the simultaneous coordination of development of models and the formation of tests and validations would improve the realism and accuracy of both activities.

2) Evaluate the significance of the initial physical, chemical, and biological conditions of mesocosms that may influence the outcome of mesocosm experiments. Attention should be given to configuring mesocosm conditions to explicitly simulate attributes that may be region-specific. This strategy not only recognizes the potential differences among mesocosm tests, but would exploit these potential difference for greater applicability to regional problems.

3) Evaluate the significance of the secondary and tertiary effects of ecological restructuring observed in mesocosm tests in a predictive framework so that managers and regulators would be better able to forecast the consequences of chemicals in the environment on a regional basis related to particular ecosystem properties. Ideally, these predictions could be made given a basic knowledge of the exposure, fate, and effects of a chemical in question. Mesocosm tests should not have to be done on every chemical registered. Results should eventually be predictable based on chemical behavior, mode of action, and regional ecosystem characteristics.

4) Determine the ecological inertia and resilience of both mesocosms and the ecosystems that they are designed to mimic (Westman 1978, Cairns and Niederlehner 1993). Moreover, establishment of methodology for evaluating the long-term sustainability of ecosystems is directly linked to maintaining their values and functions for human systems (Cairns and Niederlehner 1993).

Research results derived from these recommendations would provide information that could link both basic and applied ecology. This information should also provide a foundation for the development of ecological indicators and strategies for environmental monitoring and assessment of contaminants at the regional level.

Literature Cited

Anonymous. 1992. "EPA, OPP ecological risk data needs reduced, revamped." Pesticide and Toxic Chemical News, 24 November 1992: pp. 19–21.

Bartell, S. M., R. H. Gardner, and R. V. O'Niell. 1992. Ecological Risk Estimation. Lewis, Ann Arbor, Michigan, USA.

Bedford, B. 1984. The role of ecosystem science in USEPA's mission to regulate toxic substances. Environmental Management **8**:377–383.

Boyle, T. P. 1985. Research needs in validating and determining the predictability of laboratory data to the field. Pages 61–66 *in* R. C. Bahner and D. J. Hanson, editors. Aquatic toxicology and hazard assessment. ASTM Special Technical Publication 891. American Society for Testing and Materials, Philadelphia, Pennsylvania, USA.

Boyle, T. P., J. F. Fairchild, E. F. Robinson-Wilson, P. S. Haverland, and J. A. Lebo. 1996. Ecological restructuring in experimental aquatic mesocosms due to the application of diflubenzuron. Environmental Toxicology and Chemistry **15**:1806–14.

Boyle, T. P., and E. F. Robinson-Wilson. 1985. The effects of pentachlorophenol on lentic ecosystems with three levels of primary production. Pages 135–148 *in* A. M. Nikanorov and M. G. Valyashko, editors. Geochemistry of natural waters. Hydrometeoizdat, Leningrad, USSR.

Cairns, J., and B. R. Niederlehner. 1993. Ecological function and resilience: neglected criteria for environmental impact assessment and ecological risk analysis. The Environmental Professional **15**:116–124.

Carpenter, S. R., J. F. Kitchell, and J. R. Hodgson. 1985. Cascading trophic interactions and lake productivity. BioScience **35**:634–639.

Deutsch, W. G., E. C. Webber, and D. R. Bayne. 1992. Effects of large mouth bass stocking rate on fish populations in aquatic mesocosms used for pesticide research. Environmental Toxicology and Chemistry **11**:5–10.

Dewey, S. L. 1986. Effects of the herbicide atrazine on aquatic insect community structure and emergence. Ecology **67**: 148–162.

Eaton, J., T. P. Boyle, G. Chapman, A. Colb, P. Donaghay, J. Gentile, J. Giesy, D. Hansen, S. Hedtke, E. Kenaga, H. Kibby, D. Mount, A. Rubin, A. Spacie, and R. Swartz. 1982. Predicting environmental effects from laboratory toxicity data. Pages 13–30 *in* J. Benforado, editor. Applicability of laboratory data to the field: research needs. U.S. Environmental Protection Agency Office of Research and Development, Washington, D.C., USA.

EPA [U.S. Environmental Protection Agency]. 1989. Regionalization as a tool for managing environmental resources. EPA/600/3-89/060. U.S. Environmental Protection Agency, Washington, D.C., USA.

———. 1992. Framework for ecological risk assessment EPA/630/R-92-001. U.S. Environmental Protection Agency, Washington, D.C., USA.

Fairchild, J. F., T. P. Boyle, E. F. Robinson-Wilson, and J. R. Jones. 1984. Effects of inorganic nutrients on microbial leaf decomposition and mitigation of chemical perturbation. Journal of Freshwater Ecology **2**:405–415.

Fairchild, J. F., T. W. LaPoint, J. L. Zajicek, M. K. Nelson, F. J. Dwyer, and P. A. Lovely. 1992. Population, community 1and ecosystem-level responses of aquatic mesocosms to pulsed doses of a pryethoid insecticide. Environmental Toxicology and Chemistry **11**:115–130.

Grahm, R. L., C. T. Hunsaker, R. V. O'Neill, and B. L Jackson. 1991. Ecological risk assessment at the regional scale. Ecological Applications **2**:196–206.

Hall, D. J., W. E. Cooper, and E. E. Werner. 1970. An experimental approach to the production of animal communities. Limnology and Oceanography **15**:839–928.

Heimbach, F., W. Pflueger, and H. T. Ratte. 1992. Use of artifical ponds for assessment of hazards to aquatic ecosystems. Environmental Toxicology and Chemistry **11**:27–34.

Heinis, J. L., and M. L. Knuth. 1992. The mixing, distribution, and persistence of esfenvalerate within littoral enclosures. Environmental Toxicology and Chemistry **11**:11–26.

Hunsaker, C. T., R. L. Grahm, G. W. Suter II, R. V. O'Neill, L. W. Barnthouse, and R. H. Gardner. 1990. Assessing ecological risk on a regional scale. Environmental Management **14**:325–332.

Jenkins, D. G., R. J. Layton, and A. L. Buikema. 1989. State of the art in aquatic ecological risk assessment. Pages 18–33 *in* J. R. Voshell, editor. Using mesocosms to assess the aquatic ecological risk of pesticides: theory and practice. Miscellaneous Publication Number 75. Entomological Society of America, Lanham, Maryland, USA.

Lampert, W., W. Fleckner, E. Pott, U. Schober, and K. Storkel. 1989. Herbicide effects on planktonic systems of different complexity. Hydrobiologia **189**:415–424.

LaPoint, T. W., J. F. Fairchild, E. E. Little, and S. F. Finger. 1988. Laboratory and field techniques in ecotoxicological research: strengths and limitations. Pages 240–255 *in* A. Boudou and F. Ribeyre, editors. Volume II. Aquatic toxicology: fundamental concepts and methodologies. CRC Press, Boca Raton, Florida, USA.

Mayer, F. L., and M. R. Ellersieck. 1986. Manual of acute toxicity: interpretation and data base for 410 chemicals and 66 species of freshwater animals. Resource Publication 160. Fish and Wildlife Service, United States Department of the Interior, Washington, D.C., USA.

McCarthy, J. F., and S. M. Bartell. 1988. How the trophic status of a community can alter the bioavailability and toxic effects of contaminants. Pages 3–16 *in* J. Cairns, Jr. and J. R. Pratt, editors. Functional testing of aquatic biota for estimating the hazards of chemicals. ASTM STP 988. American Society for Testing and Materials, Philadelphia, Pennsylvania, USA.

Odum, E. P. 1984. The mesocosm. BioScience **34**:558–562.

Park, R. A. 1990. AQUATOX: A modular toxic effects model for aquatic ecosystems. Final Report. EPA-026-87. U.S. Environmental Protection Agency, Corvallis, Oregon, USA.

Park, R. A., C. I. Connolly, J. R. Albanese, L. S. Clesceri, G. W. Heitzman, H. H. Herbrandson, B. H. Indyke, J. R. Loehe, S. Ross, D. D. Sharma, and W. W. Shuster. 1982. Modeling the fate of toxic organic materials in aquatic environments. EPA-600/S3-82-028. U.S. Environmental Protection Agency, Athens Georgia, USA.

Power, M. E., and J. C. Marks. 1992. Variation in the vulnerability of prey to different predators: community-level consequences. Ecology **73**:2218–2223.

Robinson-Wilson, E. F., and T. P. Boyle. 1983. The effects of increasing levels of primary production on pentachlorophenol residues in experimental pond ecosystems. Pages 239–251 *in* W. E. Bishop, R. D. Cardwell, and B. B. Hiedolph, editors. Aquatic toxicology & hazard assessment. ASTM Special Technical Publication 802. American Society of Testing and Materials, Philadelphia, Pennsylvania, USA.

Schindler, D. W., K. H. Mills, D. F. Malley, D. L. Findlay, J. A. Shearer, I. J. Davies, M. A. Turner, G. A. Linsey, and D. R. Cruikshank. 1985. Long-term ecosystem stress: the effects of years of experimental acidification on a small lake. Science **228**:1395–1401.

Strong, D. L. 1992. Are trophic cascades all wet? Differentiation and donor-control in speciose ecosystems. Ecology **73**:747–754.

Suter, G. W. 1993. Ecological risk assessment. Lewis, Ann Arbor, Michigan, USA.

Taylor, G. E., editor. 1994. Controlled environment facilities in ecology and the environmental sciences: report of a National Science Foundation workshop. Desert Research Institute, University of Nevada, Reno, Nevada, USA.

Touart, L. W. 1988. Aquatic mesocosm tests to support pesticide registrations. EPA 540/09-28-0. U.S. Environmental Protection Agency, Washington, D.C., USA.

Touart, L. W., and M. W. Slimak. 1989. Mesocosm approach for assessing the ecological risk of pesticides. Pages 33–40 *in* J. R. Voshell, editor. Using mesocosms to assess the aquatic ecological risk of pesticides: theory and practice. Miscellaneous Publication Number 75. Entomological Society of America, Lanham, Maryland, USA.

Urban, D. J., and N. J. Cook. 1986. Hazard Evaluation Division, Standard Evaluation Procedure, Ecological Risk Assessment. EPA 540/9-85-001. U.S. Environmental Protection Agency, Washington, D.C., USA.

Vanni, M. J., and D. L. Findlay. 1990. Trophic cascades and phytoplankton structure. Ecology **71**:921–937.

Westman, W. E. 1978. Measuring the inertia and resilience of ecosystems. BioScience **28**:705–710.