EXTRAPOLATING ECOLOGICAL RISKS OF IONIZING RADIATION FROM INDIVIDUALS TO POPULATIONS TO ECOSYSTEMS

L. W. Barnthouse

ChemRisk Division
McLaren-Hart Environmental Engineering

EXTRAPOLATION DES RISQUES ÉCOLOGIQUES DES RAYONNEMENTS IONISANTS SUR LES INDIVIDUS, LES POPULATIONS ET LES ÉCOSYSTÈMES

RÉSUMÉ

En matière d'écosystèmes, les méthodes de protection contre les rayonnements ionisants diffèrent énormément de celles utilisées contre les effets nocifs des produits chimiques toxiques. Conceptuellement parlant, les méthodes utilisées pour la protection environnementale contre les produits chimiques et pour l'évaluation des risques qu'ils présentent pour la santé humaine se ressemblent car elles misent sur la protection des individus les plus sensibles ou les plus exposés. Elles supposent que si les espèces ou les stades les plus sensibles ou les plus exposés sont bien protégés, les écosystèmes le seront aussi. En revanche, il existe une prémisse formelle des normes de radioprotection voulant que tous les organismes, les populations et les écosystèmes possèdent des capacités compensatrices qui leurs permettent de survivre aux variations naturelles et imprévisibles de leurs environnements. On suppose que ces capacités persistent lorsqu'il y a radioexposition. Cette philosophie a été développée il y 30 ans à l'époque où les expressions « évaluation du risque » et « gestion du risque » étaient peu utilisées. Plusieurs considèrent que l'approche d'examen d'expert utilisée pour établir les normes de radioprotection est en contradiction avec la méthode ouverte et interactive actuelle pour la réglementation des produits chimiques toxiques. Il y a beaucoup plus de données environnementales pour les radionucléides que pour les produits chimiques. Il devrait donc être possible, étant donné une compréhension du rapport dose-réaction des effets du rayonnement et des radioexpositions d'organismes individuels, de développer des méthodes qui permettront de quantifier les effets des radioexpositions sur les populations. Un système d'évaluation par niveaux et des modèles disponibles de populations pouvant être utilisés pour évaluer le risque écologique des radionucléides sont présentés.

ABSTRACT

Approaches for protecting ecosystems from ionizing radiation are quite different from those used for protecting ecosystems from adverse effects of toxic chemicals. The methods used for chemicals are conceptually similar to those used to assess risks of chemicals to human health in that they focus on the protection of the most sensitive or most highly exposed individuals. The assumption is that if sensitive or maximally exposed species and life stages are protected, then ecosystems will be protected. Radiological protection standards, on the other hand, are explicitely premised on the assumption that organisms, populations and ecosysytems all possess compensatory capabilities to allow them to survive in the face of unpredictable natural variation in their environments. These capabilities are assumed to persist in the face of at least some exposure to ionizing radiation. The prevailing approach to radiological protection was developed more than 30 years ago, at a time when the terms risk assessment and risk management were rarely used. The expert review approach used to derive radiological protection standards is widely perceived to be inconsistent with the open, participatory approach that prevails today for the regulation of toxic chemicals. The available data for environmental radionuclides vastly exceeds that available for any chemical. Therefore, given an understanding of dose-response relationships for radiation effects and exposures for individual organisms, it should be possible to develop methods for quantifying effects

of radiation on populations. A tiered assessment scheme as well as available population models that could be used for the ecological risk assessment of radionuclides is presented.

1.0 INTRODUCTION

Over the past five years explicit regulatory processes for protecting ecosystems from adverse effects of toxic chemicals have been developed in the United States, Canada, and the OECD. Although the stated intent of the regulations is to protect populations, communities, and ecosystems, most of the supporting data and assessment methods relate to individual organisms. The philosophy underlying this approach is that the limited state of knowledge concerning the ecological effects of chemicals necessitates the use of conservative assessment methods. These methods are conceptually similar to those used to assess risks of chemicals to human health in that they focus on the protection of the most sensitive or most highly exposed individuals. The operating assumption is that if sensitive or maximally exposed species and life stages are protected, then ecosystems will be protected. This philosophy has led to the development of hazard assessment schemes in which standards and criteria are based largely on data derived from single-species toxicity tests. Although it is acknowledged that density-dependence, behavioral avoidance, natural selection, and other ecological processes that cannot be captured in laboratory test systems have major influences on the responses of ecosystems to chemical exposures, these processes are not considered when criteria are established.

Approaches to protecting ecosystems from ionizing radiation, as summarized in a recent International Atomic Energy Agency Report (IAEA 1992) are quite different. Radiological protection standards are explicitly premised on the assumption that organisms, populations, and ecosystems all possess compensatory capabilities that allow them to survive in the face of unpredictable natural variations in their environments. These capabilities are assumed to permit biological systems to persist in the face of at least some exposure to ionizing radiation above and beyond the natural background level. Moreover, radiological standards explicitly incorporate an assumption that impacts on a few individual organisms are permissible, provided that the integrity of the population or community as a whole is maintained (IAEA 1992). In the past, there have been no standard test systems or hazard assessment protocols for regulation of radionuclides in the environment. Instead, scientific panels have derived dose limits based on evaluation of laboratory experiments, field experiments, and monitoring studies.

The prevailing approach to radiological protection was developed more than 30 years ago, at a time when the use of the term "risk assessment" and "risk management" were rarely used outside the insurance business. No convincing evidence has been brought forward that current radiological protection standards are inadequately protective, however, the "expert review" approach used to derive the standards is widely perceived to be inconsistent with the open, participatory regulatory philosophy that prevails today.

Can the radiological assessment process be recast in the form that is similar to the chemical risk assessment process? The existing information base concerning biological effects of ionizing radiation suggest that such a reformulation is possible. Moreover, it appears feasible to take radiological risk assessment a step beyond current approaches to ecological risk assessment of chemicals by explicitly considering risks to populations rather than individual organisms. Accomplishing this task would involve (1) evaluating experimental data concerning dose-response relationships for sensitive life-stages of aquatic and terrestrial biota under both laboratory and field conditions, and (2) utilizing recently-developed methodologies for extrapolating individual-level data to population and community responses.

2.0 THE DATA

The IAEA (1992) report evaluates a wide array of information on the biological effects of ionizing radiation, including:

- Molecular and cellular changes such as chromosomal aberrations and DNA damage,
- Induction of tumors or other benign or malignant lesions analogous to those that occur in humans,
- Reductions in the rates of growth of exposed organisms,
- Reproduction effects, including sterility, reduction in fecundity, and occurrence of developmental abnormalities or reduction in viability of offspring,
- Reduced seed germination in plants,
- Mortality, including both acute lethality and long-term reduction in life-span,
- Experimental field studies in which natural ecosystems have been exposed to radiation under controlled conditions, and
- Monitoring studies, in which measurements of radiation exposures and effects have been made following accidental releases.

Early studies focused on acute effects of high-levels of radiation, where lethality is the endpoint of concern. Beginning in the late 1950s, field-scale studies employing long-term, low-level exposures were initiated. Some of these involved long-term monitoring at sites contaminated with radioactive waste (e.g., Blaylock 1965, Cooley 1973). Others involved experimental irradiation of natural ecosystems (e.g., the experiments described by Woodwell and Whittaker 1968). Experimental field studies involve much more natural conditions than are possible in controlled laboratory experiments. The full array of natural biota are potentially available for study, although in practice data on birds and large, mobile animals are difficult to collect. For plants, soil-dwelling invertebrates, and small mammals population-level effects can be directly observed. Highly accurate dosimetry is possible, at least for external exposures. True ecosystem-level effects, notably changes in plant in animal community composition caused by reduced abundance of sensitive plant species, have been directly observed. A few sites have been studied continuously studied for nearly four decades. Laboratory and experimental field studies together have provided information regarding the relative sensitivity of different taxonomic groups and have generally shown that natural populations in a wide variety of settings appeared unaffected at dose rates much higher than are considered acceptable for human exposure.

More recently, information has become available from biological monitoring studies conducted at sites of major radionuclide releases in the former Soviet Union, including Chernobyl, Mayak, and Chelyabinsk. Levels of contamination observed these sites greatly exceed those observed in North America and western Europe and are high enough that obvious ecological effects were observed at the most heavily contaminated locations. Data collected at these sites, although subject to a variety of methodological problems, have confirmed generalizations derived from previously-published studies (J. R. Trabalka, personal communication).

Both laboratory and field approaches suffer from limitations similar to those that affects studies of the fate and effects of toxic chemicals. The species tested in the laboratory have, for the most part, been selected because of ease of handling or relevance to human health research. Rodents, beagles, chickens, and *Drosophila* have been the most common animals studied. For plants, most laboratory research on radiation effects has been performed using seeds and seedlings. Techniques employed for both external and internal dosimetry in early experimental studies were much less accurate than are those used today. Moreover, test systems were much less standardized than those now employed in environmental toxicology (especially aquatic toxicology) so that results of different studies are more difficult to compare. Like the laboratory studies, the field studies are subject to a variety of important limitations. Almost all experimental studies, and in particular experimental studies in which doses are high enough to produce detectable biological effects, have been limited to acute external exposures. A small number of field experiments have involved direct application of isotopes to plants or soils; dose rates for these experiments have been below biological effects thresholds so that the results are useful primarily for estimating transfer coefficients. For practical reasons, experimental studies have emphasized effects on sedentary species, especially plants. Monitoring studies are subject to additional uncertainties relating to the high spatial heterogeneity of radionuclide deposition rates and, in most cases, high uncertainty concerning the actual doses received by exposed organisms.

Radiation dosimetry presents some significant technical challenges in comparison to chemical exposure assessments, because the appropriate unit of received dose is the energy received from absorption of an α, β, or γ particle. The tissue receiving the dose may not be the tissue of origin of the atom whose decay produced the absorbed particle. Radiation biologist must account for both the internal dose (primarily α and β particles) originating from atoms deposited within the organism and the external dose (primarily γ particles) originating from atoms in solution, on the soil or sediment surface, or on the surface of the organism itself. Models for dose assessment in both aquatic and terrestrial ecosystems are available (IAEA 1979, NRC of Canada 1983, Whicker and Kirchner 1987). However, the accuracy of these models is difficult to confirm, especially for internal doses.

Despite these qualifications, it should be clear that the available data for environmental radionuclides vastly exceeds that available for any chemical. Given an understanding of dose-response relationships and exposures for indiviual organisms, it should be possible to develop methods for quantifying effects on populations.

3.0 MODELS

Barnthouse et al. (1986) argued that existing theories of population response to stress were adequate to support development of quantitative ecological risk assessment methods for chemicals. The principal modeling approach available at that time was the age/stage-based approach exemplified by the age-structured models long-used by fisheries biologists. In fisheries management, these models are used to estimate changes in abundance, population structure, and likelihood of decline resulting from different rates of mortality due to fishing. Such models can readily be used to translate information on effects on age-specific survival and reproduction caused by chemicals to effects on populations, accounting explicitly for environmental variation, life-history variation, and density-dependence (Barnthouse et al. 1990). Since 1986 the theoretical basis and range of applications of population models has significantly advanced because of the needs of conservation biologists to manage small clusters of populations in fragmented habitats. Concurrently, the unprecedent increase in the power and accessibility of computers and geographic information systems (GIS) has permitted the development of modeling approaches that would have been impossible to implement a decade ago.

3.1 Individual-based models

Individual-based models are models that characterize the dynamics of populations in terms of the physiological, behavioral, or other relevant properties of the individual organisms. The "core" of an individual-based population model is a model of the organism, including its physiology, behavior, reproduction, spatial location, or any other relevant property. For some simple models, the population-level consequences of individual properties can be generated analytically. For more complex organisms or realistic environmental scenarios, these properties are calculated by numerical simulation: a fixed number of individuals are simulated day-by-day or week-by-week and quantities such as abundance, spatial distribution, or probability of extinction are generated by tabulating the numbers and distributions of organisms. The most relevant published examples of individual-based models involve forest composition (Huston and Smith 1987, Shugart 1984, Dale and Gardner 1987) or fish (Beyer and Laurence 1980, DeAngelis et al. 1991, Madenjian and Carpenter 1991, Rose and Cowan 1993). More recently, models that simulate the behavior and distribution of animals moving over a complex landscape have been developed (Loza et al. 1992, Liu 1993).

3.2 Metapopulation models

As discussed by Hanski and Gilpin (1991), a metapopulation can be defined as a "set of populations which interact via individuals moving among populations." Many metapopulation models, including complex ones involving interacting species (e.g., hosts and parasitoids, predators and prey, plants and herbivores) have been developed for use in biological pest control studies (Murdoch et al. 1985). Many recent applications are in conservation biology, most notably in studies of the Northern spotted owl (Lande 1987, Lamberson et al., 1994) and other endangered species (Lindenmayer and Lacy 1995). The principal problem addressed using these models is the influence of habitat size, immigration, emigration, and environmental variability on the persistence of rare species with fragmented spatial distributions.

3.3 Spatially-explicit models

Spatially-explicit models are models that incorporate realistic features of landscape structure. These representations can range from idealized arrangements of "patches" of suitable and unsuitable habitat to vegetation maps generated by GIS (Pulliam et al. 1992, Liu 1993, Turner et al. 1994). These models can be thought of as extensions of the metapopulation and individual-based modeling concepts to complex spatial environments. If desired, each organism can be assigned a specific location, and explicit rules for determining the behavior of an organism as a function of local environmental characteristics can be defined. As with other individual-based models, a spatially-explicit model simulates population dynamics by simulating the behavior (including reproduction and death) of the individual organisms. Environmental transport models can be used to generate spatial patterns of contaminant distributions. For example, given an estimated pattern of radionuclide release, a specific dose rate could be assigned to any location. Such models would be ideally suited to site-specific assessments in which detailed information about the structure of a specific environment of interest can be developed and for which highly specific predictions of potential risks are required.

4.0 USES IN TIERED RISK ASSESSMENT SCHEMES

All chemical regulatory schemes involve tiered testing and assessment. As an example, for many years the U. S. Environmental Protection Agency's Office of Pesticide Programs has employed a tiered approach to pesticide registration (Urban and Cook 1986). In the first tier, estimates of standard toxicity test endpoints such as LC_{50}s and LD_{50}s are compared directly to "Estimated Environmental Concentrations" (EECs) derived from standardized surface-water runoff models. Depending on the results of this comparison, more extensive testing or implementation of risk management measures might be required. Analogous procedures are used in the regulation of toxic chemicals (Zeeman and Gilford 1993).

These screening approaches could easily be extended to include age/stage-based models that could account for the influences of specific levels of mortality and reproduction on organisms with different life-history types and distributional patterns. Long-lived species with low reproductive rates are often especially vulnerable to changes in survival or reproduction. Models that predict responses of such species to adverse effects of radionuclide exposure could be estimated. Barnthouse et al. (1990) provided an example, comparing the short-lived menhaden to the long-lived striped bass. Criteria could be set based on an "acceptable" level of population impact (1%, 5%, etc.).

Demonstrating that operating facilities comply with criteria is another important regulatory problem for which population models might be applicable. Currently, the approach used for this purpose is to compare measured activity rates from monitoring programs to generic protection standards. If such standards are replaced by a more site-specific approach directed at protecting sensitive species or habitats that may be present, then spatially-explicit models might be used to perform site-specific risk assessments. Commercially-available GIS systems not only can provide maps of habitat or soil type, they also can be linked to hydrologic simulation models or radionuclide fate/transport models. Estimated dose rates could be calculated at any point in the vicinity of a facility, both for routine operating conditions and for hypothetical accidental release scenarios. Doses to all individuals in a local population could be calculated, accounting for the location of each tree, nesting territory, etc., with respect to the facility.

5.0 RESEARCH AND DEVELOPMENT NEEDS

Quantitative risk assessment of any kind require the development of dose-response relationships for ecologically relevant responses such as growth and reproduction. Standard test endpoints such as No-Observed-Effects Levels (NOELs) provide no information concerning the the significance of exposures greater than the NOEL. Molecular and cellular-level responses such as chromosome aberrations cannot be clearly extrapolated to organism-level effects. It is not clear at this point whether any actual research is needed to develop dose-response relationships. Although the existing data on biological effects of ionizing radiation have been reviewed many times, all past reviews have been directed at establishing a numerical standard. A re-evaluation focused on those studies that provide dose-response information would be a necessary prerequisite to the development of population-level risk assessment methods.

Improved dosimetric models may also be needed. For fish and other aquatic biota, the methods recommended by IAEA (1979) and the National Research Council of Canada (1983) provide an adequate starting point. Similar guidance does not exist for terrestrial biota.

If implented, the approach outlined above would provide more realistic and defensible risk assessments than either the current radiological protection approach (i.e., a fixed dose per day, supported only by expert judgement), or an alternative based (like current chemical hazard assessments) on risks to individual organisms.

6.0 DISCUSSION

There were no questions to Dr. Barnthouse following his platform presentation.

7.0 REFERENCES

Barnthouse, L.W., R. V. O'Neill, S. M. Bartell, and G. W. Suter II. 1986. Population and ecosystem theory in ecological risk assessment. pp. 82-96 IN: T.M. Poston and R. Purdy (eds.), *Aquatic Toxicology and Environmental Fate: Ninth Volume*, ASTM STP 921, American Society for Testing and Materials, Philadelphia, Pennsylvania.

Barnthouse, L.W., G. W. Suter, II, and A. E. Rosen. 1990. Risks of Toxic Contaminants to Exploited Fish Population: Influence of Life History, Data Uncertainty, and Exploitation Intensity. *Environmental Toxicology and Chemistry* 9:297-311.

Beyer, J. E., and G. C. Laurence. 1980. A stochastic model of larval fish growth. *Ecological Modelling* 8:109-132

Blaylock, B. G. 1965. Chromosomal aberrations in a natural population of *Chironomus tentans* exposed to chronic low-level radiation. *Evolution* 19:421-433.

Cooley, J. L. 1973. Effects of chronic environmental radiation on a natural population of the snail *Physa heterostropha*. *Radiation Research* 54:130-141.

Dale., V. I., and R. H. Gardner 1987. Assessing regional impacts of growth declines using a forest succession model. *Journal of Environmental Management* 24:83-93.

DeAngelis, D. L. L. Godbout, and B. J. Shuter. 1991. An individual-based approach to predicting density-dependent compensation in smallmouth bass populations. *Ecological Modelling* 57:91-115.

Hanski, I. and M. Gilpin. 1991. Metapopulation dynamics: a brief history and conceptual domain. *Biological Journal of the Linnaean Society* 42:3-16.

Huston, M. A., and T. M. Smith. 1987. Plant succession: life history and competition. *American Naturalist* 130:168-198.

International Atomic Energy Agency (IAEA) 1979. Methodology for assessing impacts of radioactivity on aquatic ecosystems. Technical Report Series No. 190, IAEA, Vienna, Austria.

International Atomic Energy Agency (IAEA). 1992. Effects of ionizing radiation on plants and animals at levels implied by current radiation protection standards. Technical Report Series No. 332. IAEA, Vienna, Austria.

Lamberson, R. H., R. McKelvey, B. R. Noon, and C. Voss., 1994. Reserve design for territorial species: the effects of patch size and spacing on the viability of the northern spotted owl. *Conservation Biology* 8:185-195.

Lande, R. 1987. Extinction thresholds in demographic models of terrestrial populations. *American Naturalist* 130:624-635.

Lindenmayer, D. B., and R. C. Lacy. 1995. Metapopulation viability of Leadbeater's possum, *Gymnobelideus leadbeateri*, in fragmented old-growth forests. *Ecological Applications* 5:164-182.

Liu, J. 1993. An introduction to ECOLECON: a spatially-explicit model for ECOLogical ECONomics of species conservation in complex forest landscapes. *Ecological Modelling* 70:63-87.

Loza, H. J., W. E. Grant ,J. W. Stuth, and T. D. A. Forbes. 1992. Physiologically based landscape use model for large herbivores. *Ecological Modeling* 61:227-252

Madenjian, C. P., and S. R. Carpenter. 1991. Individual-based model for growth of young-of-the-year walleye: a piece of the recruitment puzzle. *Ecological Applications* 1:268-278.

Murdoch, W. W., J. Chessson, and P. Chesson. 1985. Biological control in theory and practice. *American Naturalist* 125:344-366.

National Research Council of Canada. 1983. Radioactivity in the Canadian aquatic environment. Rep. NRCC-19250. Ottawa. Canada.

Pulliam, H. R., J. B. Dunning, Jr., and J. Liu. 1992. Population dynamics in complex landscapes: a case study. *Ecological Applications* 2:165-167.

Rose, K. P., and J. H. Cowan Jr. 1993. Individual-based model of young-of-the-year striped bass population dynamics. I. Model description and baseline simulations. *Transactions of the American Fisheries Society* 122:415-438

Shugart, H. H. 1984. *A Theory of Forest Dynamics*. Springer-Verlag, New York.

Turner, M. G., Y. Wu, W. H. Romme, L. L. Wallace ,and A. Brenkert. 1994. Simulating winter interactions among ungulates, vegetation, and fire in northern Yellowstone Park. *Ecological Applications* 4:472-496.

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

Whicker, F. W., and T. B. Kirchner.1987 PATHWAY: a dynamic food-chain model to predict radionuclide ingestion after fallout deposition. *Heatlh Physics* 52:171-729.

Woodwell, G. M., and R. H. Whittaker. 1968. Effects of chronic gamma irradiation on plant communities. *Quarterly Review of Biology* 43:42-86

Zeeman, M. and J. Gilford. Ecological hazard evaluation and risk assessment under EPA's Toxic Substances Control Act (TSCA): an introduction. 1993. pp. 7-21 IN Landis, W. G., J. S. Hughes and M. A. Lewis (eds) *Environmental Toxicology and Risk Assessment*, ASTM STP 1179, American Society for Testing and Materials, Philadelphia, Pennsylvania.