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An Approach to Predict Risks to Wildlife Populations from Mercury and Other Stressors

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Abstract. Ecological risk assessments for mercury (Hg) require measured and modeled information on exposure and effects. While most of this special issue focuses on the former, i.e., distribution and fate of Hg within aquatic food webs, this paper describes an approach to predict the effects of dietary methylmercury (CH_3Hg) on populations of piscivorous birds. To demonstrate this approach, the U.S. Environmental Protection Agency's National Health and Environmental Effects Research Laboratory (U.S. EPA NHEERL) is working cooperatively with environmental and conservation organizations to develop models to predict CH_3Hg effects on populations of the common loon, *Gavia immer*. Specifically, a biologically-based toxicokinetic model is being used to extrapolate CH_3Hg effects on the reproduction of a tested bird species, the American kestrel (*Falco sparverius*), to the loon. Population models are being used to incorporate stressor effects on survival and reproduction into projections of loon population effects. Finally, habitat and spatially-explicit population models are being used to project results spatially, assess the relative importance of CH_3Hg and non-chemical stressors, and produce testable predictions of the effects of biologically-available Hg on loon populations. This stepwise process provides an integrated approach to estimate the impact on wildlife populations of regulations that limit atmospherically-distributed Hg, and to develop risk-based population-level regulatory criteria.

Keywords: wildlife populations; mercury effects; ecological risk assessment; land use changes; environmental protection–conservation partnerships

Introduction

The Clean Water Act (CWA) provides the legislative mandate under which the U.S. Environmental Protection Agency's (EPA's) Office of Water is charged with restoring and maintaining the chemical, physical, and biological integrity of the Nation's waters. To fulfill this mandate, the EPA develops criteria used in setting standards for various pollutants, and intended to protect designated uses of the Nation's aquatic resources. Within the EPA's Office of Research and Development

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(ORD), the National Health and Environmental Effects Research Laboratory (NHEERL) has developed a strategy (U.S. EPA 2005) and implementation plan (U.S. EPA, 2002) for ecological research to support criteria development for aquatic species and aquatic-dependent wildlife. Much of this research focuses on stressors that have been recognized for their potential and actual impacts on aquatic ecosystems (e.g., U.S. EPA, 1998a, 2005, 2002; NOAA, 1999). Two of these high priority stressors are toxic chemicals and habitat alteration.

Minimizing the ecological risks of chemical contaminants has been an important goal for the EPA, resulting in development of water quality criteria designed to protect against adverse effects on aquatic organisms (e.g., U.S. EPA, 1991, 1994, 1995). These chemical-specific criteria have had an enormous impact on the Agency's ability to manage toxic chemical inputs to aquatic systems. Until recently however, the procedures used to develop water quality criteria have been based on a relatively narrow conceptual framework that limits their application to some classes of compounds. Specifically, these procedures do not recognize dietary uptake as a potential route of exposure or account for the tendency of some compounds to bioaccumulate and biomagnify in aquatic food webs. Recognizing these deficiencies, EPA developed prototypical methods to calculate criterion values for persistent, bioaccumulative and toxic chemicals consumed by piscivorous wildlife, and published criterion values for mercury, TCDD, PCBs, and DDT/DDE in the Great Lakes Water Quality Initiative (U.S. EPA, 1995). These same methods were used subsequently to calculate mercury criterion values for piscivorous birds and mammals in the EPA's Mercury Study Report to Congress (U.S. EPA, 1997).

The mandates of the Clean Water Act also dictate the need to develop processes for ecological protection that account for greater biological and environmental complexity and realism, e.g., to protect populations and communities (e.g., Beyer and Heinz, 2000). In addition, the EPA is being asked increasingly to participate in interagency species protection and conservation efforts where the importance of habitat quality to wildlife populations has long been recognized. Thus, the EPA is required to address concerns related to toxic chemicals and habitat alteration in the context of wildlife risk assessment and criteria development. This need resulted in the development of NHEERL's Wildlife Research Strategy (U.S. EPA, 2005), which prioritizes research to advance ecological risk assessment in three areas: (a) extrapolating toxicity across species, (b) predicting population dynamics in spatially-explicit contexts, and (c) assessing relative risks of chemical and non-chemical stressors.

The project described here demonstrates a process for the development of risk-based wildlife criteria, and is focused on the effects of dietary methylmercury (CH_3Hg) on the common loon, *Gavia immer*. Concerns about the ecological effects of Hg are supported by reports of wildlife tissue CH_3Hg concentrations exceeding levels associated with adverse effects in controlled studies, and some evidence of reduced productivity in certain piscivorous birds (U.S. EPA, 1997). The loon was selected because it is a relatively well-studied wildlife species (e.g., McIntyre and Barr, 1997; Evers, 2001), and a potentially vulnerable obligate piscivore, whose summer breeding range encompasses areas potentially impacted by atmospheric pollutants (U.S. EPA, 1997). In addition to Hg effects, other atmospherically-deposited industrial pollutants, point source contaminants and land-use changes have altered biotic and abiotic characteristics of habitats that support loons and other wildlife species. The methods used in this study integrate effects of toxic chemicals and co-occurring stressors, including habitat alteration and loss, into an assessment of population-level effects. This project demonstrates a model for the development of risk-based criteria to protect wildlife populations from persistent, bioaccumulative and toxic chemicals. The specific focus of this project complements research on the bioaccumulation of Hg as advanced by North Eastern Research Cooperative (NERC, e.g., Evers and Clair, 2005) and other researchers, providing scientific support to develop and evaluate regulations that limit the environmental distribution of atmospherically-deposited pollutants.

Approach

Ecological risk assessment (ERA, U.S. EPA, 1998b) procedures provide the general framework for scientific components to support broadly protective criteria and site-specific guidelines (Fig. 1). NHEERL's research focuses on methods to assess population-level ecological effects, which complements research relating to environmental stressor exposures in the analysis phase of the assessment.

Conceptual framework

NHEERL's Wildlife Research Strategy (WRS, U.S. EPA, 2005) provides a research framework and conceptual model describing stepwise, integrated methods that comprise a generic approach to assess risks from multiple stressors to spatially-structured populations of wildlife (Fig. 2). Research is prioritized to advance ecological risk assessment focusing on methods and models to extrapolate biological effects across species (including those species for which data are limited), and predict landscape-level population effects for species with various life histories. The conceptual model describes four critical steps to predict how the distribution and magnitude of anthropogenic stressors will affect wildlife populations (Fig. 2). The first step involves the spatial and temporal characterization of stressors (e.g., contaminants, habitat alteration) that may adversely impact the wildlife population of concern. Quantitative chemical dose–response relationships and habitat–response relationships at the individual level are developed in step two (e.g., stressor relationships to fecundity and survival). In step three, these demographic rates are used in population models to generate outputs describing population growth rates or other appropriate population-level attributes. Spatially-explicit models are used in step four to describe cumulative population dynamics across the landscape and assess relative effects due to chemical exposure as well as other forms of habitat disturbance. Using this process, it is possible to make projections about how wildlife populations may be impacted by many stressors, including toxic chemicals, which result directly or indirectly from human activities.

While steps described in the WRS provide general guidelines for population-level risk assessment, the level of accuracy and realism appropriate for each step varies with the needs of the assessment and management goals. For example when applied in the context of a site-specific risk assessment, these models can be applied to real landscapes by interfacing with geographical information systems (GIS). For more generalized regional or national-level assessments, simulated (or constructed) landscapes can be used that mimic the general characteristics of the ecosystems of concern.

Research focus

Consistent with the application of the conceptual model, specific components or steps of this research project include (1) characterizing the distribution of bioavailable mercury, as well as natural and anthropogenic factors affecting habitat quality for loons; (2) defining response relationships for mercury and habitat quality on relevant life history stages for loons where data are available, or via interspecies extrapolations as necessary; (3) predicting effects on loon populations from individual-level effects using a stage-based demographic model; (4) projecting population dynamics across a specific, heterogeneous landscape using spatially-explicit models.

A general objective of this project is to provide methods that permit analyses at varying spatial scales of biological and regulatory relevance, ranging from local areas within states to entire breeding ranges that can span international boundaries. However, the project is focused initially on a data-rich geographic area, New Hampshire (NH), through collaborations with the New Hampshire Loon Preservation Committee (NH LPC), and Biodiversity Research Institute (BRI), and other partners in environmental protection and conservation. Examples of current and planned research activities follow.

Progress

Characterizing the distribution of mercury and anthropogenic factors affecting habitat quality

Limited availability and broad diversity of data on the spatial and temporal distribution of Hg,

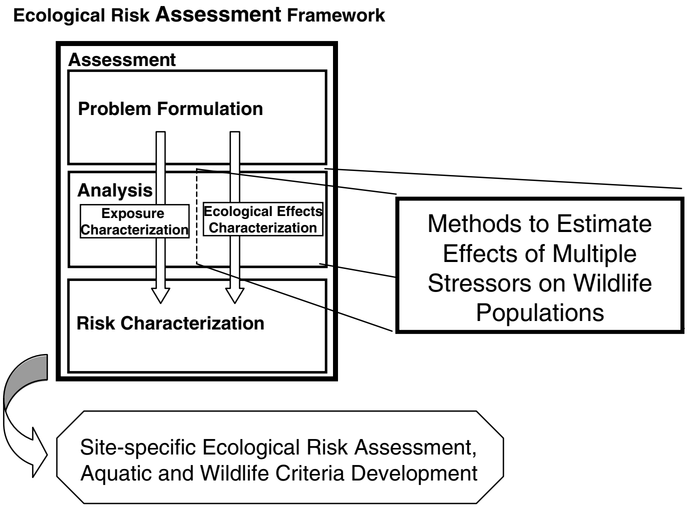


Figure 1. Ecological risk assessment procedures provide the general framework for scientific components to support the development of broadly protective criteria and site-specific guidelines (U.S. EPA 1998a, b), while EPA's National Health and Environmental Effects Research Laboratory's Wildlife Research focuses on the development of methods to characterize ecological effects (inset box) which complement research characterizing exposures to environmental stressors (in the Analysis phase).

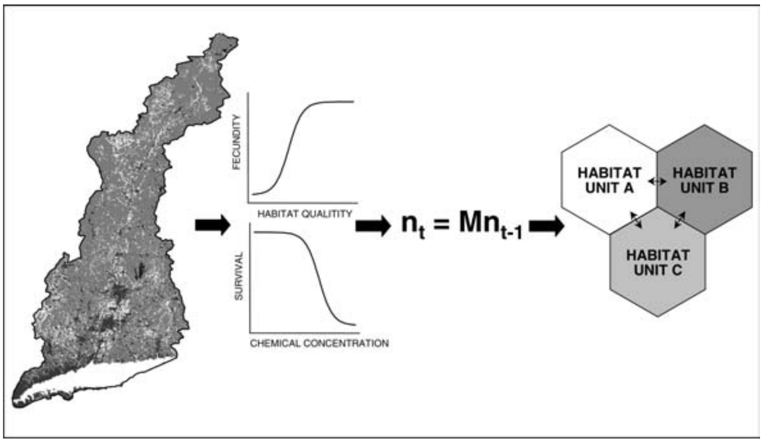


Figure 2. EPA's National Health and Environmental Effects Research Laboratory's Wildlife Research Strategy (U.S. EPA 2005) provides a model and plan for the development of integrated research methods that comprise a generic approach for the assessment of risks from multiple stressors to spatially-structured populations of wildlife. Components or steps of this process (from left to right) include: landscape characterization, characterization of stressor–response relationships, population modeling approaches, and spatial integration.

environmental characteristics, and anthropogenic factors, presents a significant challenge to understanding the ecological effects of Hg contamination in northeastern North America. To address this issue in part, some of these data have been synthesized and organized into a public data system (http://www.epa.gov/aed/html/wildlife/index.html). This data system is based on one developed for EPA's Environmental Monitoring and Assessment Program (EMAP), modified according to input from potential contributors and users, including the U.S. Geological Survey (U.S. GS), the Canadian Wildlife Service, New York and New England state departments of environmental protection, management, and conservation, Tufts University School of Veterinary Medicine, and private loon conservation groups from New England and New York. The system contains a central database and linkages to other relevant sites to provide a distributed network of information useful to researchers and policy makers. Information related to mercury and habitat loss includes watershed and lake characteristics, water and sediment chemistry, fish contaminant data, and a limited set of data on loon contamination and productivity.

Efforts to integrate data from disparate sources include unifying naming conventions and units (e.g., flushing rate versus retention time), assembling and (in some cases) creating metadata, and clarifying quality assurance codes. Initial data have been obtained through national programs such as EPA's EMAP, as well as regional and state-sponsored environmental monitoring programs. Spatially-explicit data on the abundance and distribution of loons is being acquired from government environmental agencies, avian conservation groups, and an EPA Science To Achieve Results (STAR) cooperative agreement (EPA STAR R82-9085), which is investigating risks to loons in the midwestern North America.

These data, in combination with those assembled by NERC, are being used to characterize distributions throughout the study area of bioavailable Hg, co-occurring stressors (i.e., acidification), and land uses associated with loon habitat. In addition to displays, these distributions are contributing to the development and testing of habitat and spatial models correlating loon abundance and productivity with natural and anthropogenic factors, including measured and modeled concentrations of fish CH_3Hg.

Defining response relationships for mercury and habitat quality

Effects of CH_3Hg on birds

Controlled exposures to dietary CH_3Hg using a surrogate test species, the American kestrel (*Falco sparverius*), are being conducted via interagency agreement between EPA and U.S. GS (Patuxent Wildlife Research Center). The primary focus of this effort is to develop dose–response relationships for reproductive endpoints relevant to the population modeling effort. This focus was selected because avian reproduction may be sensitive toxicologically (e.g., Barr 1986) and important demographically (see subsequent section). In spring 2004, pairs of kestrels were fed one of a series of dietary concentrations of CH_3Hg and allowed to nest and raise chicks to fledging. Tissue concentrations of Hg (e.g., liver, kidney, blood, feathers, eggs) were measured across dietary treatments at various exposure durations. Preliminary results indicate that Hg concentrations are highly correlated among tissue types and that concentrations increase in a dose-dependent manner over time. These data will be used to develop a physiologically-based toxicokinetic model for CH_3Hg in birds that describes uptake and distribution of CH_3Hg in tissues in relation to dietary exposure. For example, existing literature suggests that birds eliminate CH_3Hg primarily by deposition into developing feathers. Feather replacement and growth patterns differ substantially among bird species. A model that accounts for this and other important kinetic processes can be used to extrapolate effects information from a tested to an untested species using CH_3Hg concentrations in specific tissues as the dose metric. The outcome of this research will be a dose-response model relating CH_3Hg exposure and reproduction in the kestrel, and a toxicokinetic model, which together are being used to extrapolate dietary CH_3Hg effects from the kestrel to untested avian species, including the loon. These predicted responses will be used to influence vital rates, and develop projections of loon population responses to ingestion of Hg-contaminated prey (see projecting stressor effects).

To complement these direct measurement and modeling efforts, pathological analyses are being conducted using tissues from the Patuxent caged kestrel studies. Analyses of pathological endpoints from these controlled studies could become useful for the diagnosis of CH_3Hg intoxication in wild birds, which could serve as a basis for characterizing spatial patterns of CH_3Hg-related mortality or predicting CH_3Hg sensitivity in diverse avian species. However, additional research and validation will be required to realize these benefits.

Effects of habitat quality on loons

Loon-specific habitat models are being developed to assess the relative importance of natural and anthropogenic landscape features in defining and predicting loon distribution and abundance at the local, watershed and bioregional scales. For example, lake-specific habitat models suggest that lake morphometry (e.g., perimeter, area, depth, elevation), water quality, and shoreline vegetation, as well as human activities (e.g., housing development and boat usage) may contribute importantly at the local scale. At the next geographic scale, models are used to evaluate the importance of watershed-level variables such as the configuration of lakes. Finally, historical satellite imagery is being used to incorporate land use changes over adjacent/connecting watersheds into bioregional habitat models. Collaboration with the NH LPC and other conservation partners provides an opportunity to develop multi-scale habitat models for this area based on their collection of information on the distribution and productivity of loons in recent decades.

Preliminary results for a local habitat model for the state of New Hampshire developed using binomial logistic regression analyses suggest that loons here tend to occupy larger, deeper lakes with islands and/or extensively convoluted shorelines, located near lakes occupied by other loons (Table 1). This loon habitat suitability model was developed using a subset of monitored Loon presence/absence field data at 586 lakes in NH collected by the NH LPC from 1980 to 2002, and GIS-derived measures of habitat. The remaining data were set aside to test model predictions. The classification table (Table 2) provides a measure of predicted and observed values of loon presence and absence based on the fitted habitat suitability model. Predictions of whether a given lake belongs to the "loon-present" or "loon-absent" group were made by using a threshold to dichotomize the continuous output of a classifier function (e.g., lake area, perimeter, distance to loon lake). Selection of the threshold or cut-off value was based on balancing correct predictions for both presence and absence of loons. The overall accuracy for this preliminary model was 80% correct for predicting the presence and absence of loons.

To improve predictive power, subsequent models will assess the value of additional lake-scale data from the NH Department of Environmental Services' lake monitoring program, such as fish Hg content, lake chemistry, and fish species composition. Human disturbance indices for each lake, such as building densities and boating recreational activity, are being developed using GIS data and population census data along lakeshores and surrounding nest site locations. In addition, remotely sensed images and GIS are being used to describe land-use changes over time, and develop and test watershed and bioregional habitat models for this region. Specifically, a pilot study performed with satellite imagery and NH GRANIT land cover GIS data from two subregions of NH demonstrated differential change in

Table 1. Logistic regression habitat model results

Step	Variable	χ-Square score	*p*-Value
1	Minimum dist to lake with Loon	46.912	< 0.0001
2	Lake elevation	31.305	< 0.0001
3	Ratio (perim/sqrt(area))	25.231	< 0.0001
4	Perimeter (excluding islands)	23.447	< 0.0001
5	Lake area (excluding islands)	12.975	0.0003
6	Number of islands/lake	6.961	0.0083

Table 2. Classification table for loon habitat model using LPC 1980–2002 data

	Predicted loon presence (1)	Predicted loon absence (0)	% Correct
Observed loon presence (1)	153	33	82.3
Observed loon absence (0)	83	316	79.2
Cut-off value 0.3		Overall accuracy	80.2%

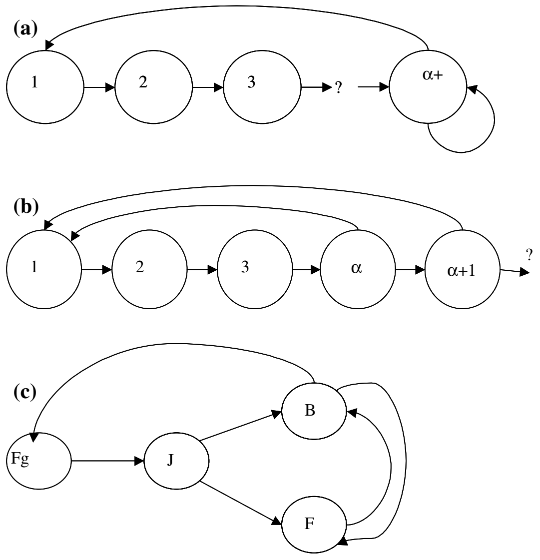
land use land cover rates over a 10 year period (1990–1999). Areas within these sub-regions that were converted to urban use between 1990 and 1999 were identified. A more comprehensive spatial (encompassing all lakes where loons have been observed) and temporal (1970s through 2004) change detection model is being developed to determine if changes in land cover are related to changes in the spatial distribution of loons over time.

Similarly, habitat models are being developed that describe relationships between habitat quality and loon fitness. For example, lake-level habitat models quantify differential reproductive performance of loon pairs and groups of pairs across a multivariate gradient of habitat (e.g., including varying habitat associated with CH_3Hg in loon prey). Analyses of loon productivity/habitat relationships are being used to infer source and sink habitat through spatial population modeling techniques (see fourth activity). Furthermore as illustrated in the conceptual model (Fig. 2), habitat model output is being integrated into population demographic models (third activity) through the integration of habitat quality relationships with demographically (e.g., chick survival) and stressor-sensitive (e.g., nesting success) life stages.

Extrapolating stressor effects to loon populations

Model construction

Demographic models are being used to integrate effects of stressors throughout the life cycle, and also to evaluate how changes in specific life stages (from stressors or management strategies) may affect overall population dynamics. Models of varying complexity are being evaluated. Most simply, loon life history can be represented as an age-structured matrix model (Fig. 3a). While this model assumes a fixed age at first reproduction (α), often around 6 years of age, common loons can breed as early as age four. This complexity can be incorporated as a breeding propensity term within specific age classes (Fig. 3b), or as separate pathways in a stage-based model with separate breeder and floater classes (Fig. 3c). Another approach, periodic matrix modeling, permits a focus on seasonal components of loon life history. Whereas an annual period does not account explicitly for summer (breeding habitat), migration or wintering mortalities, periodic models (Fig. 3d) can incorporate separate matrix models for each season to maximize available information and provide flexibility in assessing complex life-cycle risks.



(d)

$$n_{t+1} = A_{\text{winter}} A_{\text{nesting}} A_{\text{incub}} A_{\text{rearing}} n_t$$

Figure 3. Four loon life cycle models that vary in their treatment of life history complexities. (a) Age-structured model with fixed age at first reproduction (α). (b) Age-structured model with age-specific breeding propensity. (c) Stage-structured model emphasizing breeder-floater dynamics. (d) Periodic model where each "A" symbolizes a seasonal matrix and n is a population vector.

Although models that explicitly represent life history complexities or seasonal dynamics (i.e., periodic models) may ultimately provide greatest flexibility for risk analysis, initial efforts with current data necessitate a simpler approach. Existing knowledge of loon natural history, including data from the NH LPC and Wisconsin Department of Natural Resources (M. Meyer, personal communication), suggests the construction of an age-based matrix model with a one year projection interval, a birth-pulse life history, a post-breeding census and four or fewer age classes. An important consideration in this model is that NH loons migrate southward and eastward during their first fall and are not seen typically on the breeding grounds until their third spring. Because of this behavior and the difficulty of aging after-hatch-year birds, annual survivorship during these first three years of life cannot be estimated from band re-sightings on the breeding grounds. A parsimonious model would therefore use a single juvenile stage, but concern about stressor effects on these early stages may justify a model with three juvenile age classes. Currently, this approach is only enabled by theory-based assumptions about pre-adult survivorship (e.g., constant survival during the first 3 years of life). Since each of these early years contains differing amounts of migration, survival is likely to vary in ways that may be partially resolved by juvenile banding efforts (W. Piper, personal communication) and research on the wintering grounds.

Preliminary matrix models using available data and some simplifying assumptions suggest that NH loon population per capita growth rate is in the vicinity of 1.0 (i.e., neither growing nor declining). However as analyses proceed, stochastic parameter variation will be incorporated to produce more reliable estimates of long-term population growth. Also, as commonly seen in long-lived vertebrates, adult survival is the parameter to which estimated population growth is most sensitive. Caution is warranted in interpretation of these estimates since the model currently ignores the spatial density dependence that is likely to occur in this highly territorial species. Efforts are underway currently to examine these relationships between population density and demography.

Projecting stressor effects

Model simulation exercises are being used to project CH_3Hg effects on loon populations. Specifically, extrapolations from studies using the American kestrel (see Section Approach) are being used to modify the fecundity component of the matrix population model. For example, if dietary CH_3Hg reduced hatching or fledging success by 20%, the predicted reduction in annual population growth would be on the order of a few percent (under the assumptions of the simple 4×4 age-based model described above). Since stochastic processes also impose an element of population-level risk (Lande et al. 2003), natural and stressor-related variance in reproduction and spatial variation in chemical exposure are being incorporated into these models. Also, demographic data are being evaluated for loons indigenous to different geographic areas and subject to varying levels of Hg exposure, providing a statistical basis for assessing Hg effects on wild loons and any regional differences among populations (M. Mitro, personal communication). As described in the next section, demographic models are being developed for loons ranging over large spatial areas as well as geographically-defined sub-populations and then included in spatially-explicit projections of population dynamics (see Section Summary and challenges).

Projecting loon population dynamics across landscapes of varying scales

Spatially-explicit population models (SEPMs) provide tools well-suited to assessing the emergent, collective effects of multiple interacting stressors (Landis, 2002). Because stressors and other drivers of population dynamics are heterogeneously distributed over space, the risks posed to a species when its key habitat overlaps significantly with regions of high stressor levels may be underestimated. Similarly, risks may be underestimated by assessment methods that consider only the average conditions in a given region. Two available SEPM platforms were selected for application to this project: RAMAS-GIS (Akçakaya, 2002) is a metapopulation model, and PATCH (Program to Assist in Tracking Critical Habitat: Schumaker, 1998) is an individual-based population model. While both are suited for describing occupancy rates and source-sink dynamics at varying spatial and temporal scales, their data needs and outputs differ (Walters, 2001; Richards et al., 2002).

The application of SEPMs for assessing the effects of multiple stressors on loon populations entails integrating components of the research project, as illustrated in the conceptual model (Fig. 2), and incorporating other information relevant to loon ecology. Specifically, output from the habitat models (Section Approach) are being used to determine which lakes are preferentially occupied by loons, and thereby estimate spatially-distributed measures of loon productivity (i.e., inferring population sources and sinks). Previously described (spatially non-explicit) population and habitat models also provide components of the demography for geographic sub-populations. An-

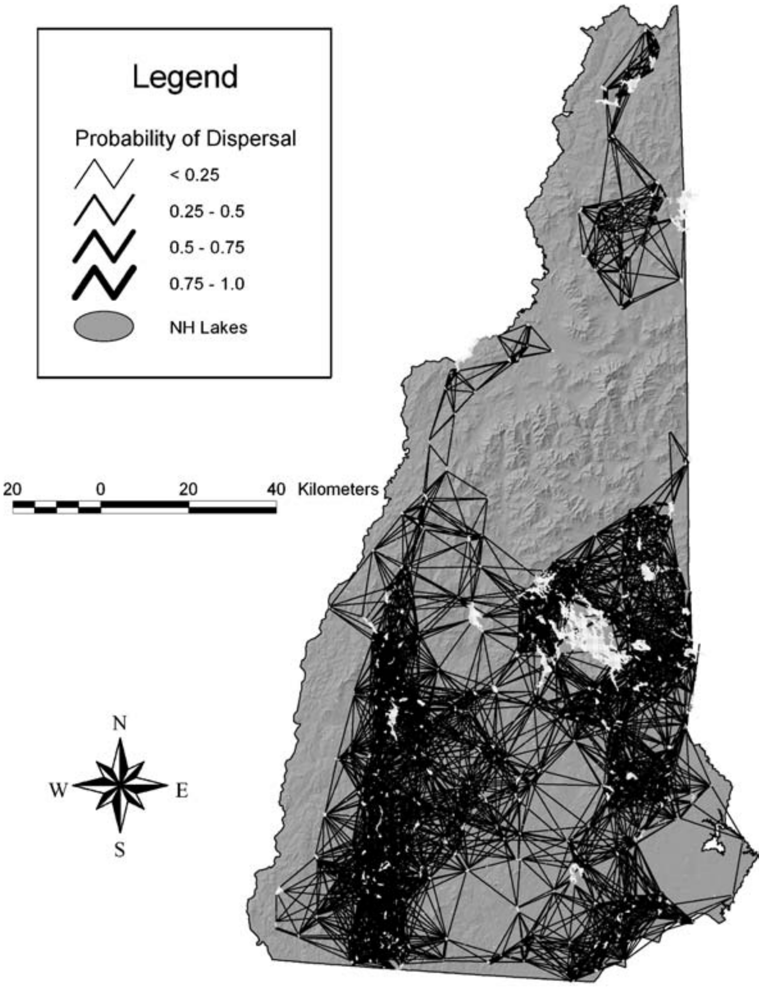


Figure 4. Preliminary prediction of the spatial distribution of loon populations in New Hampshire, USA. Probability of dispersal among lakes is shown as solid lines of increasing weights.

other parameter required for these models is dispersal, which has been estimated for some loon populations (Piper et al., 1997; Evers, 2001).

Preliminary modeling efforts have integrated estimates of localized demography and habitat quality with a probabilistic model of loon dispersal. Specifically, relevant geographic characteristics, such as lake size and shape, and estimates of loon dispersal behavior (i.e., assuming dispersal probability is inversely proportional to distance, with a maximum distance = 20 km) were integrated using RAMAS-GIS to predict landscape connectivity of NH loons (Fig. 4). Connectivity determines the degree to which individuals at a given geographic location impact neighboring populations, and are in turn impacted by individuals and conditions at other locations (With et al., 1997; Wiegand et al., 1999; Richards et al., 2002). Predictions from this model suggest a division between northern and southern metapopulations that roughly coincides with the ridges of the White Mountains, and is an emergent feature of interactions between loon ecology and physiography of NH. Efforts to characterize loon populations genetically (McMillan et al., 2004) may provide support to the predicted spatial structure. Subsequent activities will include predictions incorporating potential impacts to loon population dynamics of varying levels of CH_3Hg in loon prey and habitat alteration.

By integrating patterns of available habitat and its usage, demographic trends, and dispersal abilities, the SEPMs being developed provide an estimate of the interactive effects of the organism's biological characteristics and heterogeneous stressor levels across the landscape on the spatial distribution and abundance of loons. Hotspots in the landscape, geographic locations at which populations may be most strongly impacted, may be identified via SEPM predictions, and regulatory, management or data-collection activities may then be concentrated at these locations. Furthermore, the models specifically highlight the means by which stressors, which may be significantly isolated in their geographic extent, can collectively impact wildlife populations beyond the spatial range of direct exposure effects.

Summary and challenges

The overall objective for the project described here is to provide the U.S. EPA, States, and other environmental protection and conservation organizations with scientifically defensible methods that support ecological risk assessments for wildlife. These methods will improve characterization of risks to individuals (including those from species of special concern), predictions of population level effects from individual-level data, and evaluations of risk to wildlife populations due to multiple stressors at several spatial scales. This is an ambitious, multi-disciplinary and multi-organizational project, and many technical challenges remain. Notable among these are needs for:

- Additional data, data management, quality assurance and quality control procedures to facilitate development of accessible databases directly supporting the Loon/Hg demonstration project, and describing status and trends for other avian and wildlife species. Partnerships with other government and non-government organizations support this need and provide access to essential data.
- Data and models to develop avian stressor–response relationships relating Hg exposure to biological effects, and habitat suitability as it affects key demographic rates. For example, the relative toxicological sensitivities of avian life stages are poorly understood, and recent data suggest that even moderate levels of maternally-delivered CH_3Hg may critically impact loon embryonic development (K. Kenow, Personal communication). Methods also are needed to integrate stressor–response relationships involving different stressors in biologically realistic ways.
- Areas of future research likely to improve the non-spatial component of loon population modeling include abundance of non-breeding adults, age at first breeding, longevity, and resolution of annual survivorship in the juvenile stages. Understanding of density dependence of population dynamics and the elements of risk imposed by stochastic processes are also critical steps in the risk assessment process.
- Due to the apparent sensitivity of loon populations to adult survivorship, winter mortality such as that suspected to result from fisheries by-catch, warrants further attention. An important consideration here is the possibility that any spatial variation in population growth observed on the breeding grounds may be partially driven by as of yet unmeasured differences in winter mortality factors among these populations.
- Refined estimates of loon dispersal behavior are necessary to assess more accurately the connectivity among spatially disjunct populations, and hence the likelihood of loons (re)colonizing specific geographic locations.

Finally, while improved predictions of wildlife population effects from bioaccumulated CH_3Hg provide an important component for risk estimation, better predictions of the relationship between atmospherically-deposited Hg and bioaccumulated CH_3Hg are needed to predict the degree of ecological protection afforded by regulations that limit the environmental distribution of Hg. The NERC (see this volume) provides an essential contribution in their efforts to improve current understanding of the complex processes that regulate the transformation and biological incorporation of Hg. Furthermore, private avian conservation organizations such as the NH LPC and BRI provide invaluable resources to support and test methods aimed at fostering the protection of birds and other wildlife.

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