January 2004

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DOI: 10.1007/s00267-004-0261-0

Using Wildlife as Receptor Species: A Landscape Approach to Ecological Risk Assessment

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ABSTRACT / To assist risk assessors at the Department of Energy's Savannah River Site (SRS), a Geographic Information System (GIS) application was developed to provide relevant information about specific receptor species of resident wildlife that can be used for ecological risk assessment. Information was obtained from an extensive literature review of publications and reports on vertebrate- and contaminant-related research since 1954 and linked to a GIS. Although this GIS is a useful tool for risk assessors because the data quality is high, it does not describe the species' site-wide spatial distribution or life history, which may be crucial when developing a risk assessment. Specific receptor species on the SRS were modeled to provide an estimate of an overall distribution (probability of being in an area). Each model is a stand-alone tool consisting of algorithms independent of the GIS data layers to which it is applied and therefore is dynamic and will respond to changes such as habitat disturbances and natural succession. This paper describes this modeling process and demonstrates how these resource selection models can then be used to produce spatially explicit exposure estimates. This approach is a template for other large federal facilities to establish a framework for site-specific risk assessments that use wildlife species as endpoints.

Understanding historical and current ecosystem patterns, processes, and functions allows ecological modelers to try to predict future conditions. This approach is now taken in ecological assessments and adaptive resource management. Predicting future conditions requires that ecosystem modelers consider different scales of ecological organization and complexity and use these components to determine what the limits of predictability may be. Protocols specific to ecological assessments should be properly designed to consider the host of parameters necessary so a modeling approach can be taken to attempt to predict ecosystem pattern and process for complex systems. Because there are many types of ecological assessments, their scope and nature commonly differ based on the goals, disciplines, and audiences involved and are further constrained by legislation, funding, and time. In the United States, most ecological assessments focus on regulatory decision-making or land management planning (Jensen and Bourgeron 2001).

Ecological risk assessment (ERA) is a specific category of ecological assessment designed to meet Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)/Resource Conservation and Recovery Act (RCRA) regulatory mandates. According to the U.S. Environmental Protection Agency (EPA), an ERA evaluates the potential adverse effects that human activities have on the flora and fauna that define an ecosystem (USEPA 1997). The risk assessment process provides a way to develop, organize, and present scientific information in a format that is relevant to environmental decisions. When conducted for a particular geographic location, the ERA process can be used to identify vulnerable and valued resources, prioritize data collection, and link human activities with their potential effects. Risk assessment results provide a

KEY WORDS: Ecological risk assessment; Endpoint; Exposure; GIS; Receptor species; Spatially explicit models; Wildlife

Published online October 26, 2004.

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common framework for comparing different management options, thus enabling decision makers and the public to make better-informed decisions about the management of ecological resources (http://www.epa.gov/ncea/ecologic.htm). The ERA uses available toxicological and ecological information to estimate the occurrence of a specified undesired ecological event or endpoint. The type of endpoints targeted for investigation depends on the objectives and the constraints imposed upon the risk assessment process (Newman and Strojan 1998) based on various stakeholders; therefore, multiple endpoints at different scales may be necessary.

ERA on large federal government facilities such as the Department of Energy's (DOE) Savannah River Site (SRS) is conducted in accordance with the policies and practices specified by the EPA (USEPA 1997). ERA activities on the SRS have primarily focused on the behavior of radionuclides and metals in the environment due to their widespread distribution and bioavailablity. In the early 1990s, the DOE realized that Geographic Information Processing (GIP) technologies such as remote sensing, spatial databases, and spatially explicit models could be extremely useful in the risk assessment process, allowing a landscape-level approach. Concurrently, there was a great interest in focusing on the use of wildlife as receptor species for mechanisms of contaminant accumulation, transport, redistribution, and as ecological endpoints. This landscape approach emphasizes the foundations and principles of animal habitat relationships and the interaction between spatial patterns and ecological processes with particular attention to (1) spatial relationships among wildlife and their habitats, (2) spatial and temporal interactions, and (3) influences of spatial heterogeneity on biotic and abiotic processes. In this framework, the term "landscape" is defined as the landforms of a spatially heterogeneous region and its associated habitats at scales of hectares to many square kilometers (Turner and Gardner 1990).

Until recently, the landscape approach was rarely used in the ERA when using wildlife endpoint species. That is, contaminant exposure assessments took neither the spatial distribution of the pollutant nor the movements of the individual species within the landscape into account. Rather, fact gathering remained biased toward lower levels of ecological organization, despite the acknowledged need and relevance associated with information about effects at higher levels, e.g., effects upon higher trophic levels or populations at the landscape level (Taub 1989, Cairns 1993, Kendall and Smith 2003). Methods are rapidly changing because of the recognition that if a site is spatially heterogeneous with respect to either contamination or wildlife use, models must be modified to include the dynamics imposed by those spatial factors (Sample and Suter 1994). This paper describes the landscape approach that has been developed for the DOE's risk assessment activities on the SRS. Although these efforts are focused on the ecosystem processes and remediation issues concerning the SRS, this approach is suggested as a template for other large facilities to establish frameworks for site-specific risk assessments that use wildlife species as endpoints.

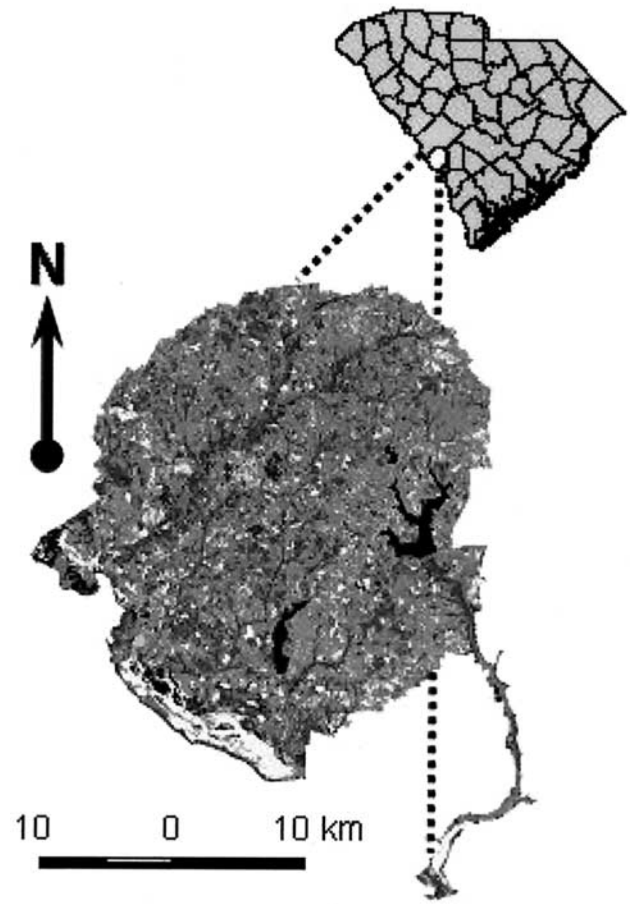

Figure 1. Habitat map of the Department of Energy's Savannah River Site based on Pinder and others (1998). This map was derived from 1997 Landsat Thematic Mapper data and classified into 32 distinct categories (see Table 1 for habitat categories and percent composition).

The Department of Energy's (DOE) Savannah River Site (SRS)

The SRS is a 778 km^2 former nuclear production and current research facility located in west-central South Carolina (33.1° N, 81.3° W; Figure 1) that was closed to public access in 1952. There have been numerous occasions when both terrestrial and aquatic SRS ecosystems have been contaminated with radionuclides, metals, and organics as well as instances where areas have been impacted by thermal effluents (White and Gaines 2000). In 1972, the entire SRS was designated as the nation's first National Environmental Research Park to provide tracts of land where the effects of human impacts upon the environment could be studied (Davis and Janecek 1997, White and Gaines 2000). Much of the suitable forested area of the SRS is managed primarily for commercial timber (pine) production by the U.S. Forest Service (USFS). Over 20% of the SRS is covered by wetlands, including bottomland hardwoods, cypress-tupelo swamp forests, creeks, streams, ponds, Carolina bays (which are natural elliptical depressions that vary in size and in the degree to which they retain water ([Ross 1987]) and two large former reactor cooling reservoirs (Table 1).

Approach

The use of endpoints in ERA must be appropriate to the spatial scale across which the risk components of interest are dispersed. On large facilities such as the SRS with broad-scale contamination, this must be done at the landscape level and can be achieved by the implementation of spatially explicit models that are calibrated using data from long-term biomonitoring of large areas (Cairns and Niederlehner 1996). The use of wildlife as endpoint species and focal receptor species for risk is a useful tool in this ERA process because species tend to be ecosystem specific and are appropriate to many spatial scales. Approaches for estimating the probability of an adverse effect of a given magnitude resulting from a human disturbance defines the ERA. These methods must be suitable to problems at multiple scales including landscape-level processes (Hunsaker and others 1990, Suter 1990, Graham and others 1991). This paper describes the four major steps taken to implement a spatially explicit modeling approach for the DOE that uses wildlife as endpoint receptor species in the ERA process for the SRS. It then gives an example of how these resource selection models have been incorporated into typical risk assessment exposure calculations.

Step I: Develop a Receptor Species List

Ecological research and data collection have been conducted on the SRS for more than 50 years and provide datasets that are large both in absolute sample size and in temporal scope, especially concerning wildlife, which can address ERA-imposed ecotoxicological problems at the landscape level. All vertebrate species inhabiting the SRS do not meet the outlined criteria for ERA activities and therefore are not ideal receptor species for risk assessment. To identify which resident species are appropriate for an ERA, a list of 70 vertebrate species (mammals, birds, amphibians, reptiles, and fish; Appendix 1) was compiled (Gaines and others 1999, Gaines and others 2000a) using the following EPA criteria (USEPA 1997):

1. The species should exhibit sensitivity to the constituent(s).

Table 1. Categories, area, and percent composition of habitats for the 2000 version of the SRS HABMAP (Pinder and others 1998)[a]

Habitat category	Hectares	% Composition
Industrial	525.42	1%
Water	1822.32	2%
Bare soil/bare surface	236.97	<1%
Sparse herbaceous vegetation	1085.58	1%
Grasses and forbs	3076.11	4%
Shrubs, grasses, and forbs	2555.46	3%
Marsh/macrophyte	416.88	1%
Young, open-canopy loblolly	3631.23	5%
Open-canopy loblolly	12053.6	15%
Young, open-canopy longleaf	2615.85	3%
Open-canopy longleaf	2709.09	3%
Open-canopy slash	1587.5	2%
Young, open-canopy slash	6882.21	9%
Open-canopy pines	324.54	<1%
Young, dense-canopy loblolly	2546.46	3%
Dense-canopy loblolly	54	<1%
Dense-canopy longleaf	4153.77	5%
Young, dense-canopy longleaf	64.17	<1%
Young, dense-canopy slash	2874.69	4%
Dense-canopy slash	3702.24	5%
Dense-canopy pines	346.05	<1%
Evergreen hardwoods	845.37	1%
Upland hardwoods	6373.98	8%
Upland oak hardwoods	1469.07	2%
Mixed-composition floodplain hardwoods	1323.63	2%
Floodplain oak forests	1323	2%
Flodplain sweetgum forests	7010.73	9%
Mixed bottomland hardwoods	3486.96	4%
Bottomland Hardwoods and Cypress	308.43	<1%
Baldcypress/Water Tupelo	2595.87	3%
Upland Scrub Forests	2131.02	3%
Wetland Scrub Forests	84.78	<1%

[a]The map was compiled from supervised classifications of Landsat Thematic Mapper Data from February, April, and July 1997 with a resultant pixel size of 30 m. Additional detail was supplied by cross-referencing the classifications of spectral data with soil data (Looney and others 1990) and the U.S. Forest Service management plan for the SRS.

2. The species should have a likely potential for exposure based upon its residency status, home range size, sedentary nature of the organism, habitat compatibility, exposure to contaminated media, exposure route and exposure mechanism compatibility.
3. The species should exhibit life stage compatibility, considering that short-lived organisms react more rapidly to contaminants, have higher turnover rates and higher surface-to-volume ratios than long-lived organisms that respond more slowly, and have shorter turnover rates and lower surface-to-volume ratios.
4. The species should be easy to collect and monitor (high population density, and body burden analysis considerations such as large enough for adequate sample mass, etc.).
5. The species should be suitable for laboratory or field experiments (behavioral, body burden assimilation, toxicity toting, etc.).
6. The species, or surrogate, should have available toxicological effects and exposure information.
7. Ecosystem function considerations of the receptor (foodweb interactions, keystone species, performs vital ecosystem function, dominant species, or is exceptionally tolerant or intolerant to a parameter of interest, etc.) should be accommodated; and the species should be predictive of assessment endpoints.

Receptor species chosen from this list met at least one or more of these criteria. The goal was to use these criteria to develop a list that was appropriate for habitats and the contaminant concerns of the SRS. To accomplish this, the list had to be taxonomically diverse, sensitive to rare species, and include abundant species that could be used both as surrogates and focal receptors. Lastly, because hunting is allowed on and near the SRS, every attempt was made to include game species for human health assessment.

Step II: Develop Data Layers for the ERA Process

For the SRS, the DOE has detailed landscape data layers that can be used in a Geographic Information System (GIS) such as habitat, land use, hydrology, road networks, and other infrastructural information. In some cases, information on the spatial distribution of contaminants and waste units are also available. Historically however, most SRS habitat data layers have been constructed with a focus on timber management and harvest rather than being designed to describe the ecosystem structure of the SRS. As a part of the ERA effort, a comprehensive SRS habitat data layer that provides ecosystem stuctural information was created that resulted in 32 habitat classifications (Figure 1; Table 1). This data layer was constructed for the purpose of describing the abundance and distribution of habitats and land use covers within and around the SRS. Habitat information was classified in such a way as to allow an assessment of which animal species may be present at a location for use in the ERA process (Pinder and others 1998). The map was compiled from supervised classifications of Landsat Thematic Mapper Data collected in February, April, and July 1997 with a pixel size of 30 m. Additional detail was supplied by cross-referencing the classifications of spectral data with soil data (Looney and others 1990) and the USFS management plan for the SRS. In 2000, this habitat map was updated using timber harvest information provided by the USFS and was ground truthed by various field biologists.

Step III: Compile Existing Information

To assist risk assessors, a GIS database was developed to provide relevant information about each receptor species (Gaines and others 1999, Gaines and others 2000a). Information was primarily obtained from an extensive review of all scientific literature published by the University of Georgia's Savannah River Ecology Laboratory (SREL) and the USFS's Savannah River Institute (SRI). Both SREL and the USFS have been conducting research on the SRS since 1951, producing more than 3000 documents that have been published since 1954. Input files were developed for this Receptor Species-GIS database containing the following information for each individual record: species scientific name, reference citation, location name, habitat as described by the reference(s), contaminant of particular concern (COPC), and keywords from the citation(s). The most important features of this database for the risk assessor are the spatial links to the available abstracts, and the keywords providing information regarding life history, genetics, contaminant uptake, and the techniques used. This GIS has been extremely useful in identifying what data sources are available to help in a risk assessment and identifying potential data gaps. The data obtained from the literature survey can also be used to modify the input parameters for contaminant uptake modeling based on site-specific receptors (USEPA 1993).

Step IV: Develop Spatially Explicit Predictive Models for Wildlife Receptor Species

Although this GIS has proved to be a useful tool for risk assessors, it was limited in that it only provided information about a species if it was studied in the particular SRS area being queried. It also did not necessarily incorporate information concerning the life history of a receptor species and thus could not predict its distribution, which is crucial when developing a risk assessment. Therefore, using existing datasets that were identified from the Receptor Species-GIS, six receptor species (or groups) were chosen as a first effort to develop spatially explicit models that provided the probability (likelihood of being in an area) of finding each of those species in any of the habitats on the SRS. After identifying species that had sufficient data to support model development, the specific criteria used to select the most appropriate species for model building were (1) species that were currently being used to model contaminant uptake for the ecological risk assessments conducted on the SRS, (2) species that could act as surrogates for modeled species, or (3) species that would best define the ecological receptors at risk on the SRS. Each model was constructed as a standalone tool consisting of algorithms independent of the GIS data layers to which they were applied. These models are dynamic and therefore can respond to habitat disturbances such as timber harvest or changes in hydrology due to man-made water control devices, natural flooding/drought, and/or to natural succession.

Model Building

Developing predictive models to estimate the spatial distribution of wildlife species is not new. The U.S. Fish and Wildlife Service (USFWS) has been leading this effort within the framework of the Habitat Suitability Index (USFWS 1981) and methods have been statistically refined by techniques described by Manly and others (1993). This model building process has grown with the science of landscape ecology and has benefited from the development of remote sensing and other GIP technologies. Researchers have used these methods to model management scenarios for ecosystem restoration (DeAngelis and others 1998); however, relatively few studies have implemented these techniques to aid in the ERA process, especially in predicting probabilities of contaminant exposure. The field of ecotoxicology has acknowledged this need and has adjusted terrestrial wildlife exposure models to include animal and contaminant distributions in heterogeneous landscapes (Sample and Suter 1994).

Now, however, it remains necessary to establish accurate predictive models that will provide quantitative measures of wildlife distribution in disturbed systems. The modeling effort used in this study is robust and may be useful for both SRS–ERA activities for specific contaminants, and for quantifying the probability of a receptor species inhabiting any SRS area of interest. Specifically, these models provide the structure to (1) determine the probability that a potential receptor species might be present at a waste site, (2) provide a quantitative measure for exposure and uptake estimates, (3) model the effects of habitat disturbances on the species distribution, and (4) identify possible corridors for contaminant movement by wildlife vectors.

Spatial Model Development

The best approach in determining the likelihood of a species being in a specific area is through an understanding of its key life history components. The receptor species chosen were carefully selected on the basis of the quality and quantity of this available information. All models were constructed to err on the conservative side of "overprediction" because they were specifically designed to be incorporated into contaminant exposure and uptake risk assessment models.

Each model was developed using existing information from various sources specific to the SRS using a deductive–inductive approach (Corsi and others 2000). The deductive approach uses known species' ecological requirements to extrapolate suitable areas from the environmental data layers available in the GIS (Figure 2A). Within the GIS framework, the species–environmental relationship was deduced from literature (and in some cases through observational data) germane to the SRS. GIS data layers were then reclassified based on these habitat requirements using Boolean logic to derive new data layers. This resource selection function was then applied in the GIS to be visualized as the final wildlife habitat predictor for that receptor species. The scale at which each resource selection function was applied was specific to the organism being modeled (see model descriptions below). Model validation for deductive models were performed using recent empirical data sources (see model descriptions below). When the species–environmental relationships were not known *a priori*, the inductive approach was employed to derive the ecological requirements of the species from locations in which it occurs (Figure 2B). This approach uses empirical data, and therefore is more rigorous and is able to be validated both within the model framework and using independent data sources.

Within a GIS framework, the inductive approach uses different data layers in the form of habitat maps that are characterized to derive parameters that will be used in a statistical model to develop the appropriate weighted function that will be applied as the final wildlife habitat predictor within the GIS. Specifically, for the inductive approach, logistic regression was used to derive probabilistic resource selection functions (Manly and others 1993, Trexler and Travis 1993) across ap-

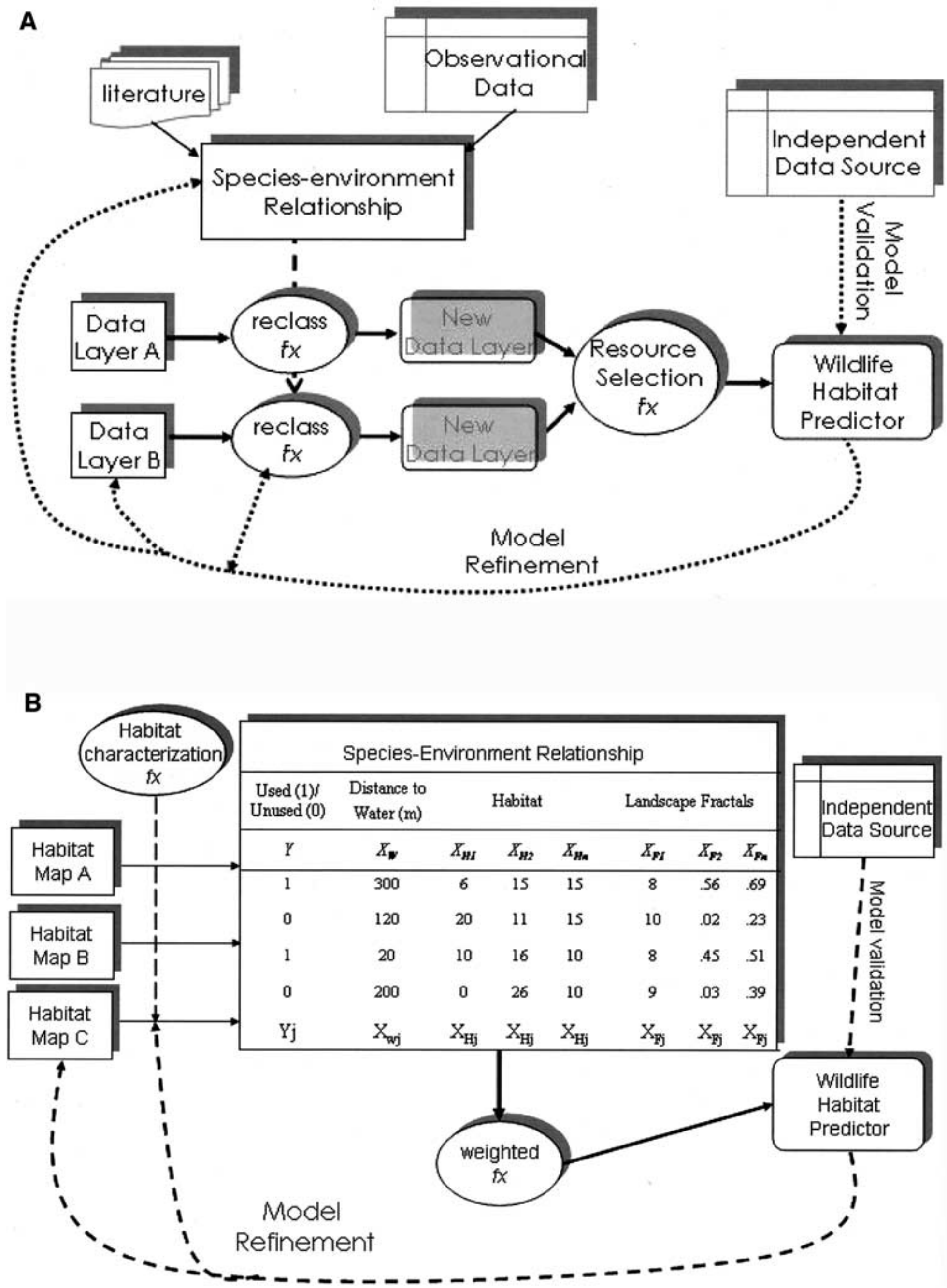

Figure 2. (**A**) Deductive approach used to develop resource selection functions to predict the occurrence of wildlife species on the Savannah River Site (SRS). *A priori* data from the literature and SRS observational field data are used to define the species-environment relationship. This information is used to reclass existing GIS data sources and combine them to derive the resource selection function that will define the wildlife habitat predictor. (**B**) Inductive approach used to develop resource selection functions to predict the occurrence of wildlife species on the SRS. SRS observational field data are employed to extrapolate the species-environment relationship derived from the characterization of the habitats used and unused by the animal. This information is used to derive the resource selection function that will define the wildlife habitat predictor.

propriate scales. This approach is employed using the underlying hypothesis that the species–environmental relationship can be predicted using habitat variables. Model output was the probability (p) that the variable

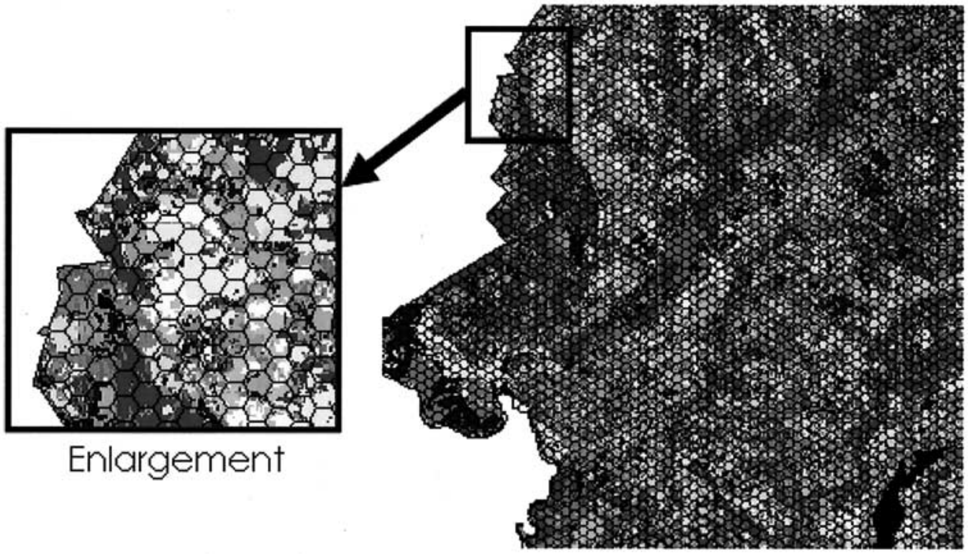

Figure 3. Example of the spatial sampling scheme used for inductively and deductively based terrestrial resource selection models. A hexagonal mesh was draped over the study areas for each model to derive parameters associated with habitat choice. For inductively based models, used versus unused hexagons were compared in the model-building process. For deductive models, habitat types were reclassified using a Boolean-based rule system. In this example 1 hexagon = 10 ha.

attribute combination at any given site defines the species habitat (Chou 1997, Apps and others 2001). From the GIS data sources, habitat composition (proportion of each habitat types, see Table 1) and indices were derived as independent variables to be considered for analysis of habitat selection under the assumption that the habitat associations of that species are largely influenced by habitat structure. Class-level landscape metrics (e.g., patch density, size metrics, edge metrics, shape metrics, fractal dimensions) using FRAGSTATS ver 2.0 (McGairal and Marks 1993) were also used as quantitative indices to describe landscape structure for some inductive terrestrial models (see receptor species descriptions below). In these models, the class represented the scale of the predictive parameters. Specifically, in the GIS environment, for these models a hexagonal mesh was draped over the SRS where each hexagon represented the class for which the metrics were derived (Figure 3). The size of the hexagon defined the scale at which the species resource use of the SRS was predicted and was determined during the model-building processes. That is, the hexagon represented a spatial scale that was appropriate to an animal's movement patterns (from the level of a core area to an entire home range). Class-level indices have been shown to correlate well with response variables of ecological processes and have been successfully used in landscape analyses for predicting wildlife habitat (O'Neill and others 1988, Turner and Gardner 1990, Mladenoff and others 1995, Tischendorf 2001). The hexagonal mesh has the intrinsic advantage that all neighboring cells of a given cell are equidistant from the cell's center point. This is useful in radial searches and retrievals around the cell's centroid. Furthermore, a hexagonal polygon is the least complex shape (lowest edge/area ratio) that most closely approximates a circle but can still be meshed without overlapping or producing gaps. This lower edge effect is desirable for habitat analyses and produces more transparent and explainable analyses of landscape patterns. It also facilitates multiple scale landscape pattern analyses such as those performed in this modeling effort (Elkie and others 1999).

Model Validation

Model validation is defined "as a comparison of a model's predictions to some user-chosen standard to assess whether the model is suitable for its intended purpose" (Heglund 2002). It is preferable to have an independent data source from the data used to derive the model for model validation. Of the six models derived for this modeling effort, only three had independent data available for validation (see receptor species description below). However, there are statistical procedures such as randomization functions that can be employed as the statistical validation procedure to evaluate a model's predictive strength (Manly 1998). For inductive-based terrestrial models, the leave-one-

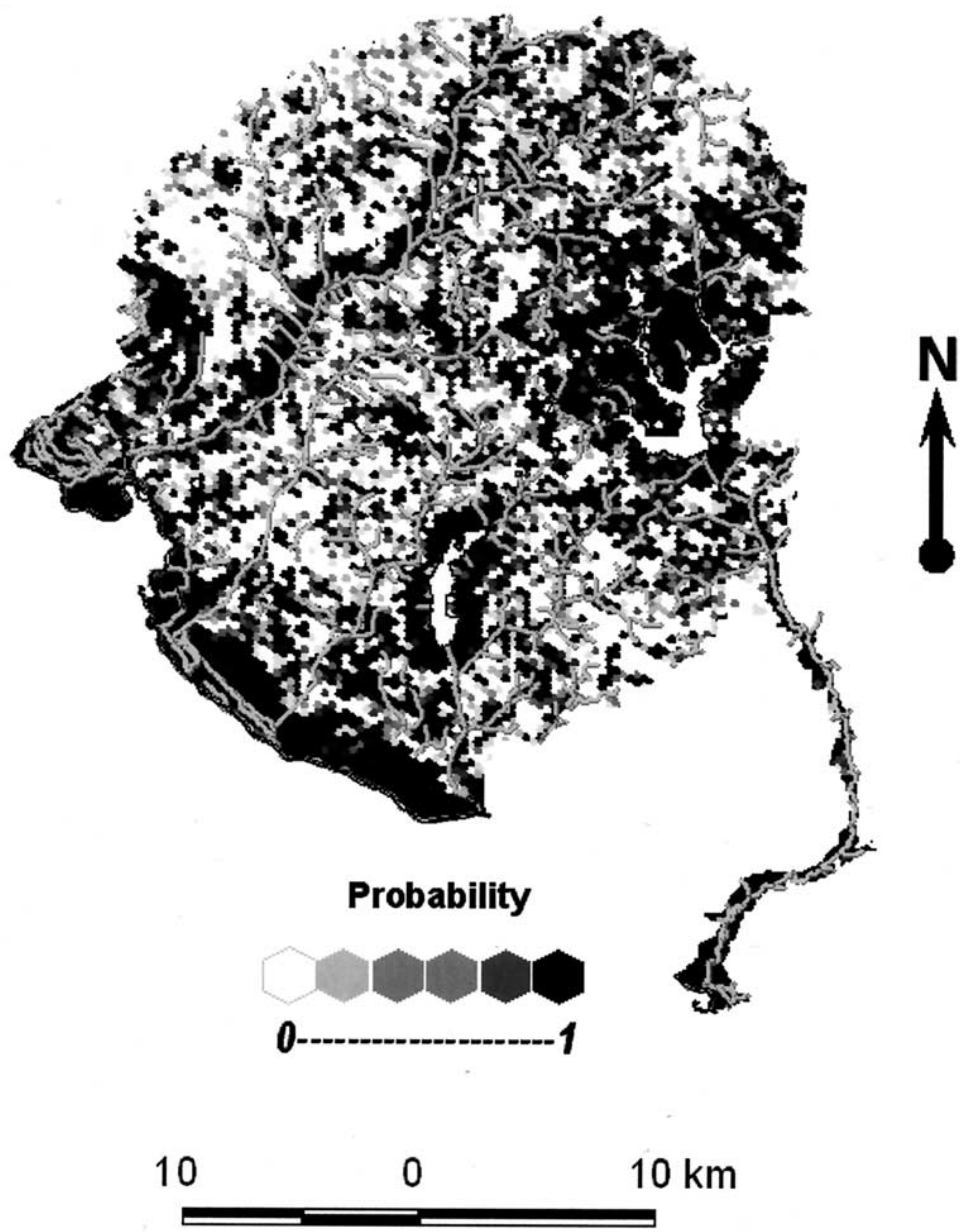

Figure 4. Example of the raccoon (*Procyon lotor*) resource selection model visualized in a Geographic Information System with the Savannah River Site wetlands overlaid in white. The user can query any of the modeled areas (shaded gray) to predict the probability (0–1) of that receptor species inhabiting that spatial location.

out cross validation procedure was used to produce the predicted observation by dropping the data of one observation from the dependent variable and reestimating the response from the tested model (Neter and others 1990). The observation is then put back into the data set and the procedure is repeated until all observations have been used. The model's validity can then be judged by dividing the number of correct estimates by the total number of observations in the dataset.

Receptor Species

Species on the current receptor list (Appendix 1) were chosen to be modeled based on their propensity to accumulate contaminants in the various ecosystems of the SRS. Furthermore, these species can also serve as vectors of contaminant transfer and redistribution. All have been well studied on the SRS, and there are sufficient data available to build meaningful predictive resource selection models, which can be used in site-specific risk assessments. Eight models have been completed and are being used by the DOE in the ERA process. These receptor species or groups were chosen based on the aforementioned criteria and the ability to obtain and verify data quality. Therefore, these initial eight models are biased towards mammalian and water-bird species (additional models are currently being constructed to expand the utility and biodiversital breadth). These models, as well as the descriptions of the methodologies used to derive it, can be obtained by contacting the author or SREL and referring to the appropriate model described below.

1. Raccoon (*Procyon lotor;* Gaines 2001; Figure 4): This species is found throughout the SRS and has been used as a receptor species in both human and ecological risk assessments on the SRS as well as other DOE sites. Information regarding home range, contaminant uptake, and food habits were available for populations both on and off the SRS. Several life history characteristics of raccoons make them potential agents of contaminant movement and dispersal including (1) high population levels with an extended range throughout North America in a variety of habitats, (2) their ability and proclivity to travel extended distances (Glueck and others 1988, Walker and Sunquist 1997, Gehrt and Fritzell 1998), (3) a propensity to utilize human-altered habitats in combination with an ability to move freely in and out of most toxic waste sites (Hoffmann and Gottschang 1977, Clark and others 1989, Khan and others 1995), and (4) a broadly omnivorous diet that includes components of both terrestrial and aquatic food chains (Lotze and Anderson 1979, Khan and others 1995).
   The raccoon is also a game species that is hunted in close proximity to areas of the SRS that are contaminated with the gamma-emitting radionuclide, ^{137}Cs. Previous investigations (Arbogast 1999, Boring 2001, Gaines and others 2000b) have shown elevated levels of this contaminant in these raccoon populations and have documented that individual raccoons move freely on and off the SRS. The raccoon is a useful species for both human and ecological risk assessment for these reasons. Because this species is extremely mobile, the likelihood of an animal's presence in specific microhabitats and the time spent in these areas must be estimated to calculate reasonable exposure estimates. Home range habitat utilization information for raccoons on the SRS supply the criteria needed to develop such a model. Specifically, habitat preference and movement data were derived from a 2-year radio telemetry study (see Boring 2001, Gaines 2003 for further description of radio telemetry procedures and results). Three years of harvest data and ^{137}Cs monitoring also provided the data to calculate spatially explicit exposure and uptake estimates as well as a spatially explicit human-based risk assessment (Boring 2001, Gaines 2003). The resource selection model was derived using an inductive approach where used areas were compared to unused areas (as determined from the radio telemetry study) in a logistic regression model. An independent data source was also available for quantitative model validation (Gaines 2003). Specifically, 5 years (1977–1982) of furbearer trap data from 10 trap-lines (habitats around trap-lines were verified to have corresponding habitat types during that time period from historical aerial photography) were available to validate the model using a Spearman rank correlation test ($r = 0.66$, $p = 0.03$, $df = 9$). Additionally, the take-one-out cross-validation procedure revealed that this model predicted use 100% and nonuse 62% of the time correctly near riverine areas; this portion of the model was applied to 80% of the SRS. The model predicted use 97% and nonuse 40% of the time correctly near reservoir areas; this portion of the model was applied to 10% of the SRS. Finally, the model predicted use 62% and nonuse 17% of the time correctly near isolated wetland areas; this portion of the model was applied to 9% of the SRS (see Gaines 2001, Gaines 2003 for specific mathematical derivations).
2. Wild Hog (*Sus scrofa;* Gaines 2002; Figure 5): Wild hogs throughout the SRS are regularly harvested and consumed by hunters and thus can serve as a vector for contaminant exposure to the human food-chain. Historically and currently, hogs are used as a receptor species for SRS exposure assessments (Stribling and others 1986, Gaines 2002) and have been used in this manner in Europe for accumulation of a variety of radionuclides and metals (Santiago and others 1998, Mietelski and others 2000). Wild hogs can acquire contaminants not only from upland vegetation but also from rooting in wetland habitats. This habit, along with its tendency to root-up and turn over soil litter profiles and its high mobility, make this species an important receptor for contaminant accumulation, as well as an agent for contaminant redistribution.
   Since 1965, controlled hog hunts have been conducted on the SRS during the fall by stationing hunters at particular stands within hunt compart-

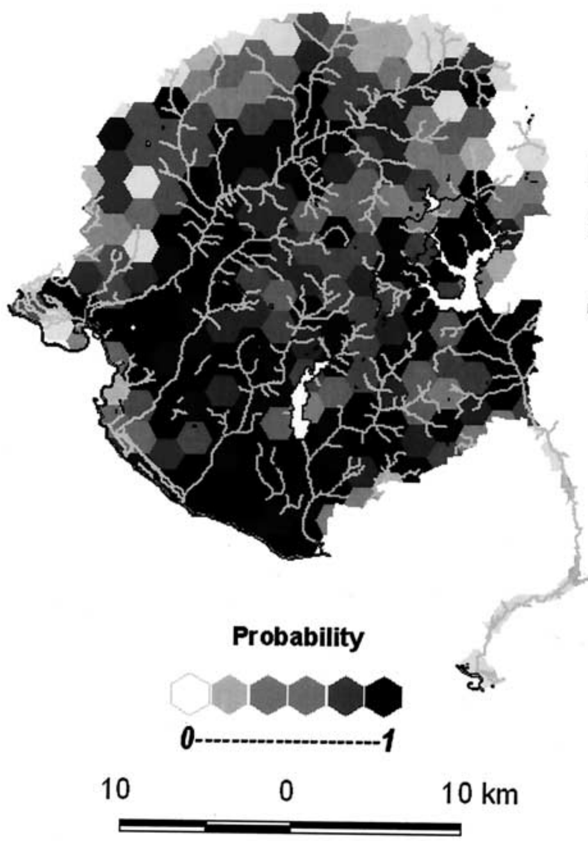

Figure 5. Example of the wild hog (*Sus scrofa*) resource selection model visualized in a Geographic Information System with the Savannah River Site wetlands overlaid in white. The user can query any of the modeled areas (shaded gray) to predict the probability (0–1) of that receptor species inhabiting that spatial location.

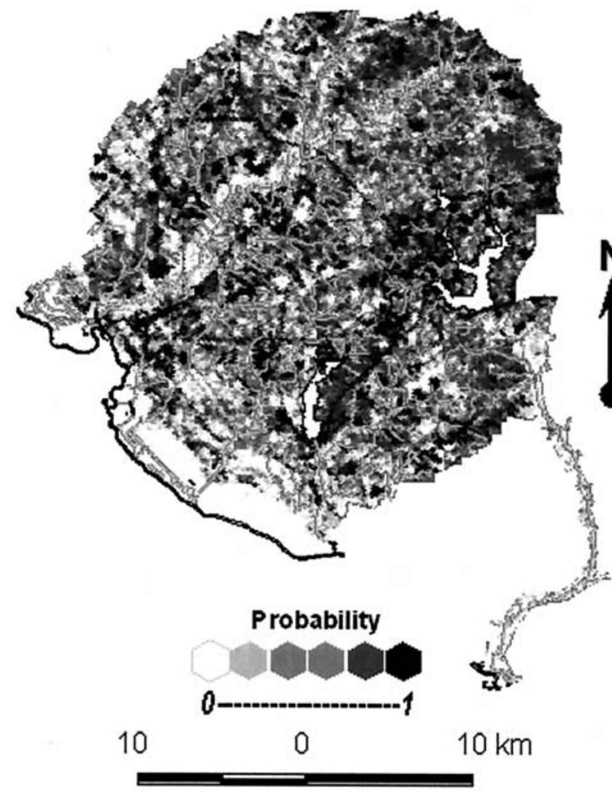

Figure 6. Example of the cotton rat (*Sigmodon hispidus*) resource selection model visualized in a Geographic Information System with the wetlands overlaid in white. The user can query any of the modeled areas (shaded gray) to predict the probability (0–1) of that receptor species inhabiting that spatial location.

ments. This extensive data set produced by monitoring the hogs taken in these hunts provided a means to investigate the spatial distribution of these animals in relation to the different habitat types of the SRS. With these data, a probabilistic model was developed to estimate the likelihood of a hog using any area of the SRS. This resource selection model was also derived using an inductive approach where used areas were compared to unused areas in a logistic regression model. Independent data sources from radio telemetry studies were available for qualitative model validation (Kurz and Marchinton 1972, Hughs 1985). These studies affirmed that the significant habitat parameters used in the model were also the dominant habitat types used by wild hogs during the radio telemetry studies. The take-one-out cross-validation procedures showed that the model correctly predicted use 100% of the time and nonuse 53% of the time.

3. Cotton Rat (*Sigmidon hispidus;* Novak and others 2002; Figure 6): The hispid cotton rat is the most common rodent in nonforested habitats of the southeastern United States (Webster and others 1985) and is ubiquitous in these habitats on the SRS (Golley and others 1965). Properties of this species' life history makes it very useful for site-specific ERAs. It is easy to monitor both in the field and in the laboratory, it has a small home-range (approximately 1 ha for males and 0.5 ha for females; Gardner 1975), and there are well-established monitoring techniques. Furthermore, for the SRS and other southeastern ecosystems, there is a wealth of literature describing population dynamics, habitat preferences, ecotoxicology, landscape use, and genetic responses to toxicant exposures (Cameron and Spencer 1981). Thus, it is an important receptor species for risk assessment on the SRS. More than 20 years of data focusing on cotton rat use in and around the SRS were used to derive

a deductively based, spatially explicit model of this species to provide the probability of it occurring in the different habitats of the SRS. An independent data source was also available for model quantitative validation. Specifically, empirical data from two small-mammal studies were used to validate presence of cotton rats in areas that predicted a high probability of occurrence (Punshon and others 2003) and low probability of occurrence (Reinhart 2003). This qualitative validation showed that cotton rats were the dominant species trapped in areas the model predicted to have a high probability of occurrence and were only caught on rare occasions (possibly transient movement) in areas the model predicted low occurrence.

4. Beaver (*Castor canadensis;* Snodgrass and others 2002; Figure 7); Beaver activities such as foraging and dam building influence ecosystem structure and function in streams and adjacent terrestrial systems. Beaver impoundments change the character of stream channels by creating impoundments within the stream ecosystem, causing changes in the hydrology and dynamic interactions between terrestrial and aquatic habitats, as well as within aquatic habitats. Local beaver-impounded areas alter hydrologic conditions of reaches by increasing nutrient availability, while decreasing water velocities, leading to higher levels of biodiversity and assemblage structure in fish, invertebrate, and plant communities in aquatic habitats within a terrestrial matrix (Johnston and Naiman 1987). Beavers are found in every major watershed on the SRS, and habitat relationships have been described for populations occupying SRS streams. Impoundments of streams by beavers create aquatic environmental conditions that promote uptake of pollutants, such as metals, by aquatic organisms. Using aerial photography from 1992, Snodgrass (1996) constructed a GIS data layer of all beaver ponds on the SRS, ground-truthing each appropriate wetland to determine whether it was an active beaver pond. These data were used to construct an inductively based spatially explicit model of beaver activity on SRS streams using logistic regression.
5. Wood Duck (*Aix sponsa;* Kennamer and Gaines 2002): Waterfowl are appropriate as receptor species in the ERA processes because their mobility offers them unlimited access to most wetland habitats, and their feeding habits generally result in bioaccumulations of environmental contaminants when present (e.g., Vermeer and Thompson 1992). Moreover, waterfowl can be highly sensitive to habitat degradation (e.g., Williams and others 1993). In particular, female wood ducks are an ideal waterfowl receptor for the ERA process at the SRS for the following reasons: (1) they have a seasonally predictable diet (Drobney and Fredrickson 1979) and ability to bioaccumulate various types of contaminants (Blus and others 1993); (2) despite having the potential for being a highly mobile migratory species, locally they have limited dispersal distances (Hepp and Kennamer 1992) and home range sizes (Costanzo and others 1983); and (3) they are easily attracted to use nest boxes in lieu of natural cavities (Bellrose and others 1964), and thus access to the birds themselves and their young/eggs is facilitated. Because this species has been well studied both on and off the SRS, and because it is a year-round resident of the SRS, its likelihood of exposure should be easier to predict than that of many other migratory bird species. Population studies of wood ducks using nest boxes on the SRS have been conducted by SREL since the early 1970s (see Kennamer and Hepp 2000 for a review), thus providing the opportunity to utilize these data to develop predictive models that estimate the probabilities for these birds to nest in various SRS wetland habitats. Four inductive models were derived using ordinal logistic regression to predict wood duck nest box use in various wetland types across the SRS. These models estimated the probability of a nest box being used once, multiple times, or never, based on different hydrologic conditions, population densities, and habitat structure in and around the wetland. Because of the study design focused on nest box use, models could only be evaluated on their predictability of wood duck use. The riparian creek model used to predicted nest box use was correct 65% of the time; the beaver pond model used to predicted nest box use was correct 73% of the time; the small (< 2 ha) isolated wetland model was correct 79% of the time; and the large (>2 ha) isolated wetland model was also correct 79% of the time.
6. Large Wading Birds (Order: Ciconiformes; Gaines and Bryan 2003): Wading bird monitoring on the SRS began in the early 1980s to document the utilization of the site by the endangered Wood Stork (*Mycteria americana*). The present modeling effort was originally focused on constructing species-based models for the Wood Stork, Great Blue Heron (*Ardea herodias*), and Great Egret (*Casmerodius albus*). However, because of data limitations, three individual models could not be constructed that would each have a high level of predictability. Although these birds have different foraging strat-

egies, they tend to utilize the same habitats and consume similar food items (Kushlan 1978). Therefore, it was decided that one wading bird model with a higher predictability could be developed (combining all data from all three species) for ERAs for all Ciconiformes that have similar foraging patterns to these three species. Wading birds can be excellent bioindicators of ecological health of aquatic systems (Custer and others 1991, Kushlan 1993). They are predators, typically consuming small- to moderate-sized fish, and are near the top of the aquatic food web they utilize (Kushlan 1978). Thus, they are susceptible to bioaccumulation of contaminants. Furthermore, the Wood Stork is an endangered species, and there were SRS compliance requirements to monitor this species based on contaminant risk and habitat alteration. Weekly aerial surveys for wading birds using SRS wetlands from 1995 to 2000 were used to construct an inductively based model using logistic regression that predicts the probability of wading birds using SRS wetlands based on hydrology and season. Because of the study design focused on use of specific wetlands, this model could only be rigorously evaluated on its predictability of wetland use. The take-one-out cross-validation procedure revealed that the model predicted use of wetlands based on different hydrologic and season combinations correctly 79% of the time.

Exposure to Contaminants

Because the final resource selection models estimate the probability of a species occurring in an area, this information can be used to refine contaminant exposure and subsequent uptake estimates. Both the EPA and SRS use the same formulae to estimate contaminant exposure to terrestrial wildlife, and realize the need to estimate the area that the subject species may occupy in a given waste site (contaminated areas) (Sample and Suter 1994). Specifically, because many waste sites do not provide suitable habitats, exposure estimates are modified to be sensitive to the home range size (total area used by an animal) or core area (areas used most often within an animals home range) of the species as well as the probability of the species occurring in the area. Therefore, exposure through ingestion can incorporate these spatial parameters and be estimated as:

$$E_j = P\left(\frac{A}{HR}\left[\sum_{i=1}^{m}\left(\frac{IR_i * C_{ij}}{\mathrm{BW}}\right)\right]\right) \quad (1)$$

where

E_j = total exposure through ingestion to contaminant (j) (mg/kg/d)

P = average probability (from the resource selection model) of the receptor species inhabiting a waste site

A = area (ha) of waste site

HR = area (ha) that defines the receptor species home range or core area from a resource selection model

m = total number of ingested media (e.g., food, water, or soil)

IR_i = ingestion rate for media (i) (kg/d or L/d)

C_{ij} = concentration of contaminant (j) in medium (i) (mg/kg or mg/L)

BW = whole body weight of endpoint species (kg)

Model Implementation

Once resource selection models have been derived, they can be implemented and visualized within a GIS. This allows the user to query an area of interest to determine the probability of the receptor species occuring in that area (Figs. 4–7). In a risk assessment framework, data layers of contaminated ecosystems and waste sites can be overlaid onto these models to determine the probability of a receptor species occuring in that area. Using such information, site-specific exposure estimates can be quantified as described above. Calculations specific to the waste site's area to home range ratio (A/HR) as well as the average probability of a species inhabiting a waste site (P) are dependent upon each individual model's scale. For example, using the models that use hexagonal units to define the model's ecological scale as an example, if that unit is smaller than the species' home range (e.g., a core area was used for the scale), then an estimated home range polygon must be overlaid on that model (Figure 8). The average probability of all the hexagons within that home range polygon should then be used to estimate P and the sum of all of the hexagons multiplied by its scale (e.g., core area) should be used to calculate A. It is recommended that if the centroid of the hexagon does not fall within the home range polygon, then the hexagon should not be used in the exposure model. Monte Carlo randomization functions can be used to simulate resource use within and around the boundaries of the waste site to determine a distribution of exposures (Figure 8). If the resource selection model's scale is based on the receptor species home range (e.g., the hexagonal unit equals the home range size), then the size of the hexagonal unit itself is used to define HR and its subsequent probability P. In cases when the HR

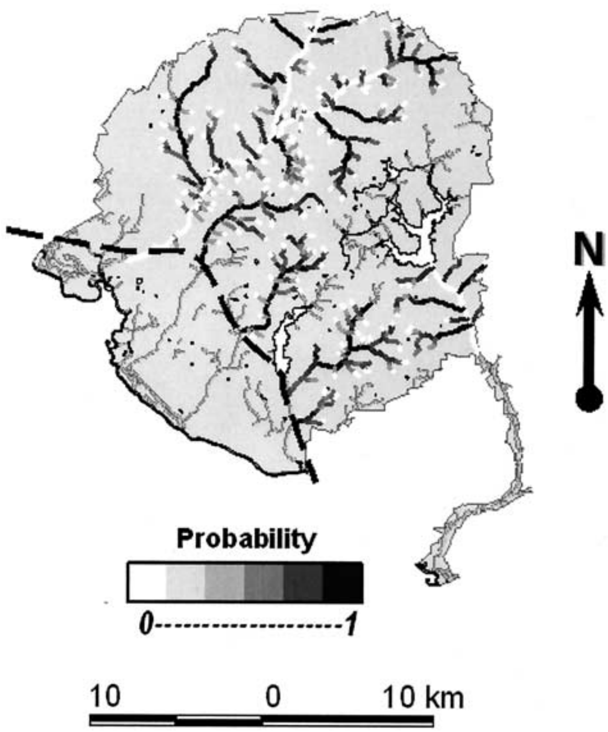

Figure 7. Example of the beaver (*Castor canadensis*) resource selection model visualized in a Geographic Information System with the wetlands overlaid in white. Stream reaches that have been impacted from thermal effluents were not modeled in this effort (areas south of the black dotted line). The user can query any of the modeled areas (shaded gray) to predict the probability (0–1) of that receptor species inhabiting that spatial location.

size is larger than the waste site, a randomization function may again be appropriate to avoid biases based on the placement of the hexagon in relation to the actual waste site.

For wetland-based models such as the wading bird or beaver model, the aforementioned approach may be modified. Most often, the wetland itself should be used as the waste site and therefore the *A/HR* ratio may not be needed. For example, because wading birds only will use wetlands to forage, it is appropriate to drop the *A/HR* term from the exposure model and only use the probability of species occurrence at that wetland, assuming that the concentration of the contaminant in the prey base is consistent throughout the wetland. If it is not, then the wetland may need to be disagregated into different compartments (which would be considered separate wetlands in the model below). Therefore, the number of wetlands used in their foraging area should be determined and the exposure model should be refined as follows:

$$E_j = \frac{\sum_{i=1}^{w} P_w\left(\left[\sum_{i=1}^{m}\left(\frac{IR_i{*}C_{ij}}{BW}\right)\right]\right)}{w} \qquad (2)$$

where

w = the number of wetlands within a species foraging area

Management Implications

The modeling approach used in this project utilized the expertise both of scientists associated with academia and basic research as well as DOE policy-focused risk assessors to develop an approach that is economically feasible and biologically relevant. The goal of the entire modeling effort, including the initial habitat map and literature-based wildlife survey, is to provide the necessary tools to conduct ecological risk assessments, at various scales and hierarchical levels, from the desk-top using a GIS platform utilizing the wealth of data and information available for the SRS. The use of SRS-specific data supports informed DOE management decisions on the SRS based on site-specific data rather than typical default values imposed by regulatory agencies such as the EPA, if such default values even exist, as many do not. A fundamental understanding of how each model was derived and its level of predictability must be considered prior to its application. Because a model is an attempt to best represent reality, all have limitations and inaccuracies; some are just better than others. The resource selection models presented here were derived specifically for the purposes of being incorporated into spatially explicit risk assessments for the SRS. Their levels of predictability varied, and all were constructed to err on the conservative side of overpredicting use, so further steps in predicting contaminant uptake and exposure would tend to overestimate rather than underestimate contaminant movement.

The risk assessment process for the SRS focuses on the receptors at risk and not necessarily the contaminat that often drives the management decisions regarding cleanup. The risk to the wildlife receptors inhabiting the SRS cannot be established unless information is available on the distribution and use of these species within contamination areas. It is based on this premise that the receptor-specific distribution models were developed. Each model has been implemented and incorporated into the DOE's GIS in the form of a graphical user interface (GUI) to facilitate use. Also, randomization techniques used to estimate exposure are also

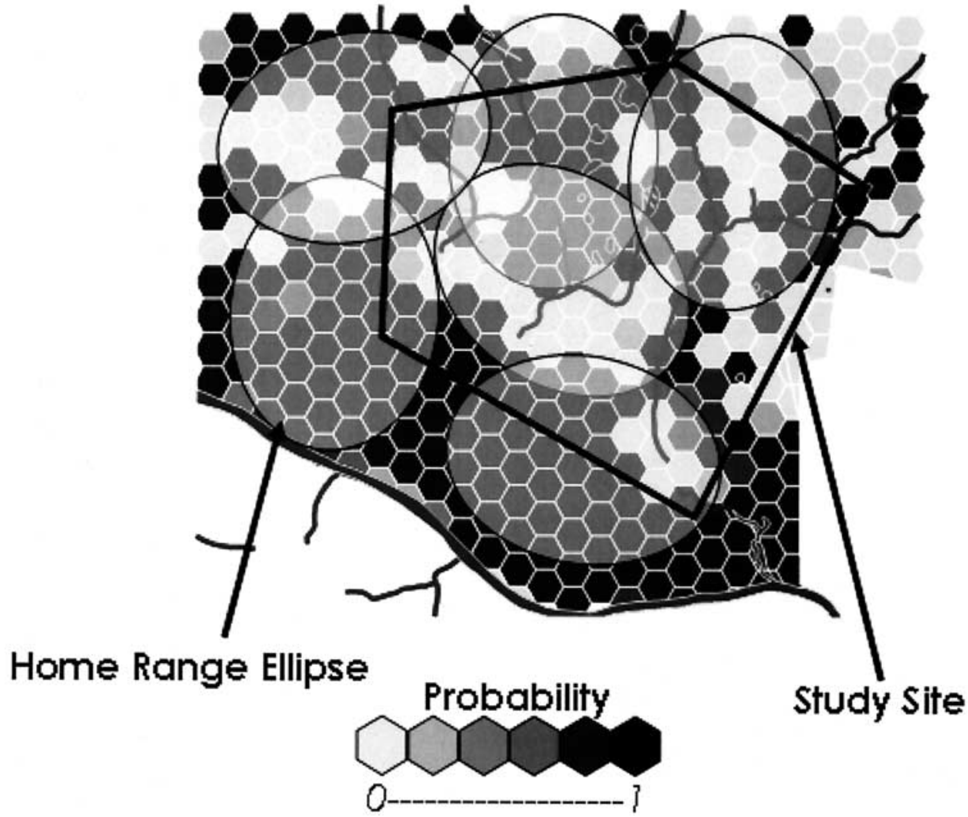

Figure 8. Procedures used to quantify the probability of a species occurring in an area if the scale (hexagonal unit) is smaller than the animal's home range. If the home range is smaller than the study site (as shown), then randomization techniques can be employed to create a probability distribution. This randomization should include areas within and around the focal study site (as shown).

being integrated into these GUI's. The radomization effort will allow risk assessors to quantify the exposure based on site-specific wildlife receptor data on home range and habitat usage providing a more realistic exposure rather than currently used worse-case default values.

A side benefit of using a GIS platform is the accessibility of data to SRS stakeholders (regulatory agencies, natural resource trustees, and the public). By providing a copy of the GIS project on CD, the stakeholders have access to all the data and evaluation tools used by the scientists proposing the recommendations for cleanup decisions for the SRS. The accessibility of the information provides a level of comfort that the approach is technically defensible, and questions that arise can be facilitated so that all parties can exercise their own evaluation based on the most recent information available. As these GIS tools continue to be developed, it is acknowledged that only through a better understanding of animal habitat associations at the landscape level can the relationship between contaminants in the environment and the transfer of toxicants through the foodweb be better understood. With this understanding comes the next level of models and GIS automation supporting the ERA process for the SRS. The approach that is presented here is currently being used by DOE risk assessors at the SRS for large-scale watershed investigations. The framework has been built on a solid foundation of more than 50 years of research on ecosystem processes as well as contaminant movement in the environment. It was developed to be robust in order to be refined as new information and technologies become available.

Appendix:

Receptor species list compiled for use in ecological risk assessment activities on the Department of Energy's Savannah River Site (SRS) that use wildlife as endpoints using EPA criteria (USEPA 1997)[a]

I. Birds (21 species)	
Common Name	**ScientificName**
American Coot	*Fulica americana*
American Crow	*Corvus brachyrhynchos*
Anhinga	*Anhinga anhinga*
Bachman's Sparrow	*Aimophila aestivalis*
Bald Eagle	*Haliaeetus leucocephalus*
Barn Swallow	*Hirundo rustica*
Black Vulture	*Coragyps atratus*
Eastern Bluebird	*Sialia sialis*
Eastern Screech Owl	*Otus asio*
Great Blue Heron	*Ardea herodias*
Kingfisher	*Megaceryle alcyon*
Mallard Duck	*Anas platyrynchos*
Mourning Dove	*Zenaida macroura*
Northern Mockingbird	*Mimus polyglottos*
Pied-billed Grebe	*Podilymbus podiceps*
Red-cockaded Woodpecker	*Picoides borealis*
Red-tailed Hawk	*Buteo jamaicensis*
Ring-necked Duck	*Aythya collaris*
Wild Turkey	*Meleagris gallopavo*
Wood Duck	*Aix sponsa*
Wood Stork	*Mycteria americana*
II. Mammals (17 species)	
Common Name	**Scientific Name**
Beaver	*Castor canadensis*
Bobcat	*Felis rufus*
Cotton Mouse	*Peromyscus gossypinus*
Cotton Rat	*Sigmodon hispidus*
Eastern Cottontail	*Sylvilagus floridanus*
Eastern Coyote	*Canis latrans*
Eastern Mole	*Scalopus aquaticus*
Feral Hog	*Sus scrofa*
Gray Fox	*Urocyon cinereoargenteus*
Gray Squirrel	*Sciurus carolinensis*
Mink	*Mustela vison*
Raccoon	*Procyon lotor*
Seminole Bat	*Lasiurus seminolis*
Southern Flying Squirrel	*Glaucomys volans*
Southern Short-tailed Shrew	*Blarina carolinensis*
Virginia Opossum	*Didelphis virginiana*
White-tailed Deer	*Odocoileus virginianus*
III. Reptiles and amphibians (16 species)	
Common Name	**Scientific Name**
American Alligator	*Alligator mississippiensis*
Brown Water Snake	*Nerodia taxispilota*
Bullfrog	*Rana catesbeiana*
Common Snapping Turtle	*Chelydra serpentina*
Eastern Box Turtle	*Terrapene carolina*
Eastern Mud Turtle	*Kinosternon subrubrum*
Gray Rat Snake	*Elaphe obsoleta*
Green Anole	*Anolis carolinensis*
Green Treefrog	*Hyla cinerea*
Brown Water Snake	*Nerodia taxispilota*
Bullfrog	*Rana catesbeiana*
Common Snapping Turtle	*Chelydra serpentina*
Eastern Box Turtle	*Terrapene carolina*
Eastern Mud Turtle	*Kinosternon subrubrum*
Gray Rat Snake	*Elaphe obsoleta*
Green Anole	*Anolis carolinensis*
Green Treefrog	*Hyla cinerea*
Common Name	**Scientific Name**
Ground Skink	*Scincella laterale*
Leopard Frog	*Rana utricularia*
Marbled Salamander	*Ambystoma opacum*
Mole Salamander	*Ambystoma talpoideum*
Mudpuppy	*Necturus maculosus*
Southern Toad	*Bufo terrestris*
Yellow-bellied Slider	*Trachemys scripta*
IV. Fish (16 species)	
Common Name	**Scientific Name**
Bluegill	*Lepomis macrochirus*
Bluehead Chub	*Nocomis leptocephalus*
Channel Catfish	*Ictalurus punctatus*
Dusky Shiner	*Notropis cummingsae*
Eastern Mosquitofish	*Gambusia holbrooki*
Gizzard Shad	*Dorosoma cepedianum*
Lake Chubsucker	*Erimyzon sucetta*
Largemouth Bass	*Micropterus salmoides*
Redbreast Sunfish	*Lepomis auritus*
Sailfin Shiner	*Pteronotropis hypselopterus*
Shortnose Sturgeon	*Acipenser brevirostrum*
Spotted Sucker	*Minytrema melanops*
Tadpole Madtom	*Noturus gyrinus*
Tessellated Darter	*Etheostoma olmstedi*
Yellow Bullhead	*Ameiurus natalis*
Yellowfin Shiner	*Notropis lutipinnis*

[a]Receptor species chosen from this list met at least one or more of these criteria. The goal was to use these criteria to develop a list that was appropriate for habitats and the contaminant concerns of the SRS. The list is taxonomically diverse, sensitive to rare species, and includes abundant species that could be used both as surrogates and focal receptors. Because hunting is allowed on and near the SRS, every attempt was made to include game species for human health assessment.

Acknowledgments

This project was funded through the Financial Assistance Award DE-FC09-96SR18546 from the U.S. Department of Energy to the University of Georgia Research Foundation. We thank T. G. Chandler, H. N. McKellar, dand M. E. Hodgson for reviewing earlier versions of the manuscript for this paper. We also thank J. M. Novak, J. Snodgrass, A. L. Bryan, Jr., R. A. Kennamer, and D. J. Karapatakis, for their contributions to the receptor species model development.

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