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ABSTRACT

In North America, wild hogs (*Sus scrofa*) are both sought after as prime game and despised due to their detrimental impacts to the environment from their digging and rooting behavior. They are also a potentially useful indicator species for environmental health for both ecological- and human-based risk assessments. An inductive approach was used to develop probabilistic resource selection models using logistic regression to quantify the likelihood of hogs being in any area of the Department of Energy's 805 km^2 Savannah River Site (SRS) in west-central South Carolina. These models were derived by using available SRS hog hunt data from 1993–2000 and a Geographic Information System database describing the habitat structure of the SRS. The model's significant parameters indicated that wild hogs preferred hardwoods and avoided pine and shrubby areas. Further, landscape metric analyses revealed that hogs preferred areas with large complex patch areas and low size variation. These resource selection models were then utilized to better estimate exposure of wild hogs to radionuclides and metals in a disturbed riparian ecosystem on the SRS using two different possible diets based on food availability. Contaminant exposure can be better estimated using these resource selection models than has been previously possible, because past practices did not consider home range and habitat utilization probability in heterogeneously contaminated habitats. Had these models not been used, risk calculations would assume that contaminated areas were utilized 100% of the time, thus overestimating exposure by a factor of up to 25.

Key Words: aluminum, ecological assessment, GIS, home range, landscape metrics, nickel, risk assessment, *Sus scrofa*, uranium, wild hog.

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INTRODUCTION

Wild hogs (*Sus scrofa*) have had an erratic history in North America, being sought after as prime game (Wooters 1973), while simultaneously being despised due to their enormous detrimental impact to fragile ecosystems (Mayer and Brisbin 1991). As a result they are an important species for management concern and can also serve as an indicator species for environmental health for both ecological- and human-based risk assessments (Stribling *et al.* 1986a,b). They have been used in this regard in their native regions in Europe for the study of ecosystem impacts (Groot Bruinderink and Hazebroek 1996) and contaminant transport of radionuclides (Švadlenková *et al.* 1996) and metals (Santiago *et al.* 1998). Further, spatial models have been developed specific to these regions to better predict where this species could occur (Aquilino *et al.* 2000). However, no studies have been found that integrated the risk assessment process with the spatial modeling of this species.

Understanding the fate and effects of environmental pollutants is an important concern, particularly when wildlife can act as vectors of contamination to the food chain of humans or other predators. On the U.S. Department of Energy's Savannah River Site (SRS), resident farmers who were moved off the site when it was closed to public access in 1952 left behind large numbers of domestic swine, which have flourished and expanded throughout the entire 805 km^2 facility. These animals subsequently bred with other free-ranging feral swine, which were already resident on the site. To control damage by wild hogs to pine plantations on the SRS, the U.S. Forest Service initiated an active live-trap and removal program in the 1950s. In 1965, controlled white-tailed deer (*Odocoileus virginianus*) and hog hunts were initiated and by the mid 1980s, hunters were taking hogs in significant numbers (Mayer and Brisbin 1991). Currently, wild hogs throughout the SRS are regularly harvested (average = 112/yr from 1982–2000) and consumed by hunters and thus can serve as a vector for direct contaminant exposure to the human food chain. Further, due to habits such as rooting for food items and digging in muddy areas to thermoregulate, this species has the potential to redistribute many contaminants found in soil and sediments. Because wildlife species such as the wild hog are often exposed to more environmental contaminants than human inhabitants, they can serve as sentinels for human hazards (NRC 1991; Suter *et al.* 2003) and thus be used as receptor species for focal contaminants.

Wild hogs are opportunistic omnivores, occupying different trophic levels of the food web. However, they will favor specific food items when available. For example, during the fall, hogs have been shown to prefer mast crop such as acorns and nuts (Henry and Conley 1972). These food items are high in carbohydrates and fats (Morrison 1956), which provide energy for high productivity and overall health (Matschke 1964). It has been documented that hogs will switch to a diet of roots and herbage when mast is not available through either mast failure, competition with other fauna, or seasonal depletions (Ackerman *et al.* 1978). It has been speculated that the physiological changes in roots and vegetation in the spring and summer may also increase the palatability of roots, tubers, and vegetation to hogs (Roark 1977). Studies have also shown that hog movements are highly correlated with seasonal availability of food items. For example, in the Great Smoky Mountains, the movement of wild hogs from low to high elevations in March and April, and back to lower elevations in August is based on food availability (Ackerman *et al.* 1978). Moreover, on the SRS, feral hogs occupying the Savannah River Swamp use this area almost exclusively, except in late winter when they move to the upland pine plantations bordering the swamp due to low mast availability (Sweeney 1970) and early summer corresponding to the ripening of fruits (Kurz and Marchinton 1972).

Wild hog hunts conducted on the SRS during the fall and winter assign hunters to a particular stand (hereafter referred to as stand hunters) location within a hunt compartment, thus creating a data source that can be used to better understand the spatial distribution of wild hogs and their contaminant burdens on the SRS. The SRS is divided into 37 hunt compartments that are hunted on a rotational basis from late October through January. Hunts are conducted by assigning hunters who use dogs (hereafter referred to as dog hunters) to a particular area within a compartment where their dogs are used to chase game. Each animal is assigned to the closest hunt stand to which it was shot within the respective compartment. For every hog harvested on the SRS, the hunt compartment and the location of the hunt stand are recorded, along with the animal's sex, weight, age, as well as reproductive condition (this final index was not used in the modeling process).

The purpose of this study is to develop probabilistic resource selection models from available hog hunt data to estimate the likelihood of hogs being in any particular area of the SRS, using information describing the habitat structure of the SRS. The second objective is to integrate these models in an established U.S. Environmental Protection Agency (USEPA)/DOE wildlife exposure model (Sample and Suter 1994) that is used to predict risk to wildlife receptors and to better estimate exposure of wild hogs to radionuclides and metals (Specifically Al, U, and Ni) on the SRS based on age structure. These estimates are then compared to the wildlife exposure model when the wild hog resource selection model is not integrated to show how taking wildlife habitat selection into account can help risk managers to more realistically estimate exposure.

STUDY SITE

The SRS is a 805 km^2 former nuclear production and current research facility located in west-central South Carolina (33.1° N, 81.3° W) that was closed to public access in 1952. The facility, which included five nuclear production reactors, has been intensely studied with regard to the bioaccumulation of radionuclides and metals in resident flora and fauna (Brisbin *et al.* 1974*a*,*b*, 1989; Gaines *et al.* 2000, 2002). The SRS produced plutonium and tritium and processed other nuclear materials for national defense and other industrial purposes. Throughout the period of nuclear materials production and waste storage, small quantities of radionuclides were released, causing contamination to the associated streams, their floodplains, and manmade reservoirs (Ashley and Zeigler 1980). Through these industrial processes, other contaminants such as metals have also been released throughout the SRS (Evans *et al.* 1992).

In 1972, the entire SRS was designated as the nation's first National Environmental Research Park to provide a location where the effects of human impacts on the environment could be studied (White and Gaines 2000). Much of the suitable

Table 1. Categories, area, and percent composition of habitats for the 2000 version of the SRS HABMAP (Pinder *et al.* 1998). An identification number (HABID) was given to each habitat category and is often referenced as such (HABID) in the text. An "M" was given as an HABID if that habitat category was merged into the preceding numeric category before GIS analyses were performed.

HABID	Habitat category	Hectare (ha)	Percent composition
1	Industrial	525.42	1%
2	Water	1822.32	2%
3	Bare soil/Bare surface	236.97	0%
4	Sparse herbaceous vegetation	1085.58	1%
5	Grasses and forbs	3076.11	4%
6	Shrubs, grasses, and forbs	2555.46	3%
7	Disturbed and revegetated in 1997	124.29	0%
8	Marsh/Macrophyte	416.88	1%
9	Open-canopy pine	29804.04	37%
9M	*Young, open-canopy loblolly*	*3631.23*	*5%*
9M	*Open-canopy loblolly*	*12053.6*	*15%*
9M	*Young, open-canopy longleaf*	*2615.85*	*3%*
9M	*Open-canopy longleaf*	*2709.09*	*3%*
9M	*Open-canopy slash*	*1587.51*	*2%*
9M	*Young, open-canopy slash*	*6882.21*	*9%*
9M	*Open-canopy pines*	*324.54*	*0%*
11	Dense-canopy pines	13741.38	17%
11M	*Young, dense-canopy loblolly*	*2546.46*	*3%*
11M	*Dense-canopy loblolly*	*54*	*0%*
11M	*Dense-canopy longleaf*	*4153.77*	*5%*
11M	*Young, dense-canopy longleaf*	*64.17*	*0%*
11M	*Young, dense-canopy slash*	*2874.69*	*4%*
11M	*Dense-canopy slash*	*3702.24*	*5%*
11M	*Dense-canopy pines*	*346.05*	*0%*
23	Evergreen hardwoods	845.37	1%
24	Upland hardwoods	6373.98	8%
25	Upland oak hardwoods	1469.07	2%
26	Mixed-composition floodplain hardwoods	1323.63	2%
27	Floodplain oak forests	1323	2%
28	Floodplain sweetgum forests	7010.73	9%
29	Mixed bottomland hardwoods	3486.96	4%
30	Bottomland hardwoods and cypress	308.43	0%
31	Baldcypress/Water tupelo	2595.87	3%
32	Upland scrub forests	2131.02	3%
33	Wetland scrub forests	84.78	0%

forested area of the SRS is managed primarily for commercial timber production (54% pine; Table 1). Most of the SRS is drained by five tributaries of the Savannah River with small streams feeding each so that no SRS location is very far from flowing water (Dukes 1984). Twenty percent of the site is covered by wetlands, including

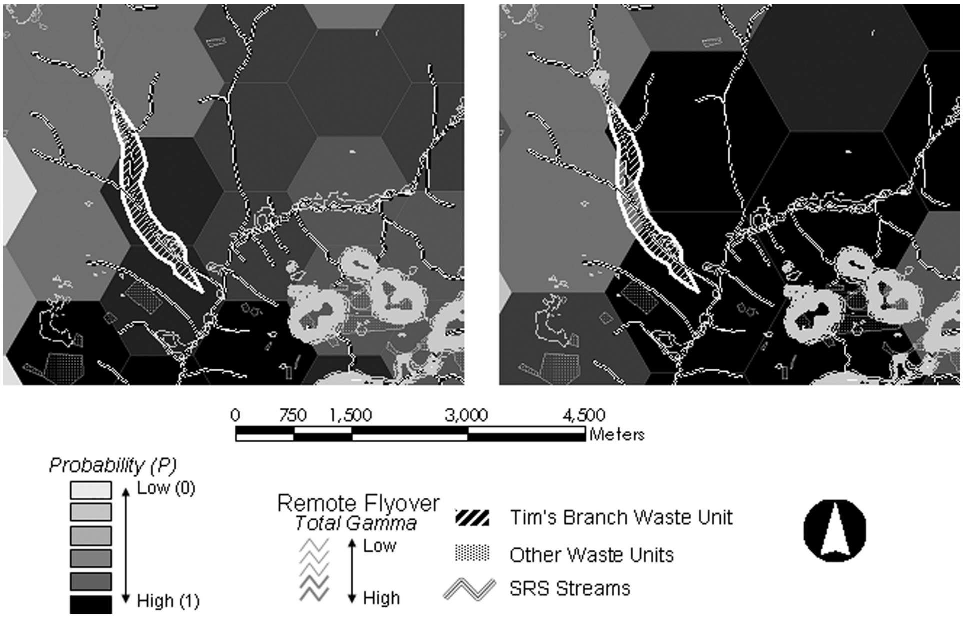

Figure 1. The Tim's Branch–Steeds Pond riparian corridor waste unit and associated gamma activity located on the U.S. Department of Energy's Savannah River Site overlaid on the wild hog resource selection models (350 ha and 770 ha model, respectively). Darker areas indicate a high probability of hog occurrence. This system is contaminated with uranium, nickel, aluminum, and other metals.

bottomland and swamp forests, two large nuclear reactor cooling reservoirs, creeks, streams, upland depressions, and small elliptical depressions, called Carolina bays (Lide and Davis 1993; White and Gaines 2000).

An important drainage tributary on the SRS that has received particularly large contaminant inputs is the Tim's Branch–Steed's Pond depositional system located in the northwest of the SRS (Figure 1). The resource selection model's prediction of wild hog occurrence presented here will be applied to this system to determine potential contaminant exposure. Steed's Pond is an abandoned farm pond that served as a *de facto* settling basin for contaminated sediments produced by upstream processing facilities from the mid-1950's until 1985 (Evans *et al.* 1992). This pond was reduced from 5.7 ha to 4.5 ha after partial failure and repair of its dam in the 1960's. Contaminants accumulated within the pond were predominantly U, Ni, and Al—which were subsequently left exposed in the wetland environment. Vegetation quickly colonized the area, stabilizing much of it from erosion, with the exception of several unvegetated areas within the stream proper.

It is estimated that approximately 44,000 kg of depleted U were released into Steed's Pond (Pickett 1990). Ninety-seven percent of the gross α activity released by the SRS was to the Tim's Branch—Steed's Pond stream system, with 61% of this activity being released between 1966 and 1968 (Evans *et al.* 1992). Until 1979, effluent discharge went to a drainage ditch that flowed into Tim's Branch and then into Steed's Pond. Following the breach of the wooden spillway in 1984, Steed's Pond released sediment-bound contaminants into the Tim's Branch depositional environment and continues to do so during episodic storm events (Batson *et al.* 1996). Previous investigations have shown that both U and Ni are bioavailable to wildlife residing in the Steed's Pond region (Punshon *et al.* 2003). Wild hogs continuously use this riparian zone as a food source and subsequently redistribute contaminants by their rooting activities.

METHODS

Wild Hog Model Development

Hunt compartment map rectification and hunt stand digitization

Each hunt compartment hardcopy map (53 mm = 1 mi) was scanned using a UMAX Mirage D-16L Scanner and saved as 300 dpi grayscale Tag Image File Format (TIFF) files in Adobe Photoshop ver. 7.0. Each TIFF file was rectified in ERDAS Imagine ver. 8.5 using existing SRS hunt compartment and road GIS data layers for georeferencing. For each rectification, at least 7 ground control points (GCP) were used. Because the hard copy hunt compartment maps were generated in 1993 from survey maps generated earlier (exact date unknown), the quality of the rectification had to be judged from the Root Mean Square (RMS) error log and visual inspection. RMS error ranged from 0.8 to 5.4 m. If the rectification was suboptimal, it was repeated until it was usable within the scale needed to digitize the hunt stands (*e.g.*, to be able to judge a stand's juxtaposition relative to a road, railroad track, stream).

Each hunt compartment has a series of locations (hunt stands) where hunters are positioned during a dog-drive hunt. Additionally, a series of locations (dog stands) are designated where dog-drivers that kill an animal can leave their game during the hunt. Both hunt stands and dog stands are fixed locations and are used on each hunt in that compartment during that year and in subsequent years. The data used for this modeling effort were for hunts conducted from 1993–2000. Each hunt stand and dog stand was digitized and converted into one GIS data layer. The database including information for each hog taken for each hunt was then merged with this data layer.

Data structure and model development

A habitat data layer of the SRS (HABMAP) with 32 habitat classifications (Table 1) was the primary data layer used for the modeling process. This detailed HABMAP was constructed with the purpose of describing the abundance and distributions of habitats and land uses surrounding the SRS. Habitat information was classified with the intension of assessing which animal species may be present at a location for use in ecological risk assessments (Pinder *et al.* 1998). The map was compiled from supervised classifications of 30 m Landsat Thematic Mapper imagery from February, April, and July 1997. Additional detail was supplied by cross-referencing the classifications of spectral data with soil data (Looney *et al.* 1990) and the U.S. Forest Service management plan for the SRS. In 2000, this habitat map was updated using timber harvest information provided by the U.S. Forest Service and was groundtruthed by various researchers from the Savannah River Ecology Laboratory (SREL). For the purposes of providing meaningful habitat categories germane to the life history of the wild hog, the 14 pine categories were merged into two PINE variables (open canopy and closed canopy) *a priori* to any habitat analyses; they were then later merged into one category after preliminary statistical analyses (Table 1). Further, herbaceous habitats were merged into the variable SHRUB (HABID 4–6); upland hardwood habitats were merged into the variable UPHRDWD (HABID 23–25); and floodplain forest habitats were merged into the variable FLDPLN (HABID 26–31). These merged habitat categories were used as candidate variables in the model only if the original habitat categories in the model were not significant. Therefore, an individual category was never used in the model if its merged category was a significant variable.

The wild hog model was developed using an inductive approach where the species–environmental relationship was treated as unknown (Corsi *et al.* 2000). Based on three telemetry studies (Kurz 1971; Crouch 1983; Hughs 1985) conducted in the Savannah River Swamp area on male and female wild hogs, two scales based on sexual seasonal movements were used to try to derive the proper resource selection models. These studies indicated that males tended to have larger core areas/seasonal home ranges (approximately 770 ha) than females (approximately 350 ha). However, the variances of mean male and female core areas overlapped. These two estimated scales were used to investigate habitat structure. Specifically, a hexagonal mesh GIS data layer for each scale was draped over the HABMAP data layer to analyze habitat composition for used (wild hogs harvested) and unused hexagons (no wild hogs harvested). 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. Further, a hexagonal polygon is the least complex shape (lowest edge/area ratio) that most closely approximates a circle that can still be meshed without overlapping or producing gaps. This lower edge effect is desirable for habitat analyses and allows transparent and highly explicable analyses of landscape pattern. It also facilitates multiple scale landscape pattern analyses such as the one performed here (Elkie *et al.* 1999).

Both scales, 770 ha and 350 ha, were used to determine whether male and female habitat utilization could be differentiated by using two separate models with the hypothesis being that if two separate models could be constructed based on sex, the best model describing male habitat utilization should be derived from the 770 ha scale and the best female model should be derived from the 350 ha scale. Habitat arrangement and landscape indices were determined for each hexagon and used as independent variables to be considered for analyses of habitat selection under the assumption that the habitat associations were largely influenced by habitat composition. The specific variables used were: habitat area and class-based landscape metrics (Patch Density and Size Metrics, Edge Metrics, Shape Metrics [Appendix 1] using FRAGSTATs ver 2.0; see McGarigal and Marks [1994] for further arithmetic narrative).

Logistic regression was used to derive probabilistic resource selection functions using the independent variables described earlier (Manly *et al.* 1993; Hosmer and

Lemeshow 2000). The number of wild hogs killed in a hexagon over the seven-year period was determined (*e.g.*, $0 \rightarrow n$) and used as a candidate weighting function within the regression. Hunt compartments were not hunted evenly over the seven-year period so a corrected kill per unit effort coefficient (# of kills/# of times hunted) was also used as a candidate weighting function. To minimize collinearity among explanatory variables, a correlation matrix was used to determine what variables provided redundant information. Variables with the best distributional characteristics and lowest correlations with other variables were used. All others were removed. Three models were constructed for each scale using: female kill data; male kill data; and all kill data. To derive the most parsimonious variable combinations that best discriminated used landscapes, the Akaike information criteria (AIC; Akaike 1974) was used.

To determine which model(s) should be used, the six models were judged by their maximum rescaled R-square, and the number of similar variables between the three models within each scale (male, female, all). AIC could not be used to discriminate between the three models because each candidate model was composed of a different data set germane to sex. The final models were applied to each hexagon for the entire SRS which produced a probability (p) that the variable attribute combination at any given site within a hexagon defines wild hog habitat (Chou 1997; Apps *et al.* 2001).

Model validation

A randomization function was employed as the statistical validation procedure to evaluate each model's prediction strength (Manly 1998). The leave-one-out cross validation procedure was used to produce the predicted binomial observation (0 *vs.* 1) by dropping the data of one observation from the dependant variable and reestimating the response from the tested model (Neter *et al.* 1990). The observation was then put back into the data set and the procedure was repeated until all observations were used. The model's validity was then judged by dividing the number of accurate predictions by the total number of observations in the dataset.

Exposure Estimates

Exposure to contaminants

A series of exposure estimates for the wild hog were performed for the SRS's Tim's Branch riparian ecosystem, which is heavily contaminated with U, Al, and Ni. Exposure was estimated using formulae described in Sample and Suter (1994) that utilize an animal's home range in relation to the contaminated area and proportion of suitable habitat in the contaminated area. This parameter (proportion of suitable habitat) was substituted by the probability of the animal occuring in the area based on the resource selection model. These estimates were then compared to formulae described by Sample and Suter (1994) assuming these animal–habitat relationships were unknown. Thus, in that case habitat use was assumed to be used equally and only within the waste site.

Because SRS hunters shoot all size classes of wild hogs, exposure estimates were calculated by age structure based on toothwear and tooth eruption as described by

Table 2. Mean weights (kg) of wild hogs collected on the Department of Energy's Savannah River Site's (SRS) annual deer and hog hunts in the fall and winter from 1998–2001 by age class.

Age class	Age	Mean weight (kg)	N	SD
0	Neonates	1	5	0.2
1	Up to 7 mos	10	78	6.2
2	8 to 13 mos	34	66	9.3
3	14 to 20 mos	57	100	13.7
4	21 mos to 3 yrs	74	55	16.3
5	3 + yrs	88	61	20.7

Mayer and Brisbin (1991). Hogs were divided into five age classes (Table 2) and the mean weights for each age class from hunt data collected between 1998–2001 were used in exposure calculations. Exposure was estimated as:

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

where: E_j = total exposure to contaminant (j) (mg/kg/d), 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), A = area (ha) of waste site, HR = home range size or core area (area of hexagon from resource selection model; ha) of endpoint species, p = probability of a hog inhabiting an area associated with each hexagon from the resource selection model (modified from the proportion of suitable habitat in the contaminated area based on Sample and Suter (1994))

Although exposure from all pathways (E_{total}) is the sum of oral, dermal, and inhalation exposure, the estimates calculated here were only for oral exposure, which included food and incidentally ingested soils. These estimates assumed homogeneous contamination throughout the waste unit. Surface water was not included because this matrix was uncontaminated (Punshon and Gaines, unpublished). Inhalation and dermal exposure are considered minimal and also difficult to quantify. USEPA is currently still evaluating how to properly calculate dermal exposure for metals in general (USEPA 1992). Soil ingestion rates were determined as a component of the food ingestion rate using data from Beyer *et al.* (1994) for wild hogs on the SRS.

Wild hog food items and ingestion rates

The diets of wild hogs in the southeastern United States were reviewed to determine the percent composition of potential food items to use for exposure estimates (Henry and Conley 1972; Scott 1973; Roark 1977; Ackerman *et al.* 1978). Of these four studies, three showed that mast was the dominant food item followed by vegetation, invertebrates, and vertebrates. However, Henry and Conley (1972) in one year of a six-year study, found that root material comprised 14% of hog diets whereas Scott

Table 3. Percent composition of fall food items (by volume) for the wild hog as summarized by four southeastern studies.

Study	Henry and Conley (1972)	Scott (1973)	Roark (1977)	Ackerman *et al.* (1978)	
Location	Appalachian Mountains, TN	Great Smoky Mountains National Park, TN	Georgetown, SC	Great Smoky Mountains National Park, TN	
Season	Fall	Fall	Fall	Fall	Fall
Year (s)	1959–1966	1971–1973	1975	1975	1976
Vegetation					
Acorns/Nuts/Seeds	82.2	16.5	77.6	9	73.1
Fleshy Fruit	1.4	0	0	0	0
Leaves/Grasses	2.5	11.1	15.9	16.3	3
Litter	0	0	0	0	3.5
Roots	3.3	62.2	6	72.3	1
Animal					
Invertebrate	5.4	0.3	0.7	1	9
Vertebrate	1	0.2	0.7	1	11

(1973) showed that root material comprised 62% (Table 3). All studies discussed the importance of mast in wild hog diets and that these populations will switch to roots and litter vegetation during poor mast years. This scenario is realistic on the SRS during poor mast years and the winter when mast availability is lower. These studies did not estimate soil ingestion, so estimates of food and soil consumption were adjusted based on Beyer *et al.* (1994).

Two dietary scenarios were modeled based on Table 3. The first was for a good mast year where the estimated food consumptions would be: 77% mast, 7% leaves/grass, 3% litter, 5% roots, 3% soil, 2.5% invertebrate, 2.5% vertebrate. The second was for a poor mast year where the estimated food consumption would be: 13% mast, 7% leaves/grass, 3% litter, 7% soil, 64% roots, 3% invertebrate, 3% vertebrate. The soil ingestion rates were adjusted to account for increased rooting behavior during poor mast availability.

To calculate realistic exposure values for wild hogs, potential food items were collected opportunistically from two areas in the Tim's Branch–Steed's Pond system during the late fall. A transect around the entire forested perimeter of Steed's Pond was walked and vegetation, leaf litter, and mast items were collected under every dominant forest type. Traps were used to collect terrestrial invertebrates over a two-week period in the fall. This procedure was repeated along the Tim's Branch riparian zone by setting up 5–200 m-long transects perpendicular to the stream in an area known to have been impacted by downflow from Steed's pond (Gaines and Punshon, unpublished data).

Food ingestion rates (FIR_{dry}) for hogs were calculated from allometric regression models based on metabolic rate and body weight (BW) to estimate consumption in kg dry weight for placental mammals ($FIR_{dry} = 0.0687(BW)^{0.822}$; Sample and Suter

1994). These ingestion rates were then converted to fresh weight to be suitable for exposure estimates using the following formula:

$$FIR_{fresh} = \sum_{i=1}^{F} \left(P_i * \frac{FIR_{dry}}{1 - WC_i} \right) \quad (2)$$

where: FIR_{fresh} = total food ingestion rate (kg $food_{fresh\ weight}$/individual/day), FIR_{dry} = total food ingestion rate (kg $food_{dryweight}$/individual/day), F = total number of food types in the diet, P_i = proportion of the ith food type in the diet, WC_i = proportional water content (by weight) of the ith food type (as determined from drying the potential food items prior to metal analyses).

Metal analyses

Metal analyses were performed on wild hog potential food items from the Tim's Branch–Steed's Pond system. Tissues from potential animal food item (rodent muscle, liver, and kidney) tissues were digested in Ultrex ultrapure nitric acid in a microwave (MD 2000 CEM), using a digestion protocol of 3 stages of 10 min each under 50, 100, and 150 pounds per square inch (3.5, 7, and 10.6 kg/cm^2) at 70× power. Soil and plant material were homogenized and ground to a fine power in a sample grinder, and digested in 5 *M* HNO_3 + 30% H_2O_2 using a microwave dissolution technique in pure Teflon PFA vessels (CEM Corporation MDS-2000). Metals were analyzed by inductively coupled plasma mass spectroscopy (ICP-MS). The ICP-MS was calibrated using Custom Grade standards at the beginning of each batch, and after every fifteenth sample. Detection limits were expressed in parts per billion on a wet weight basis. Water was also collected from these sites and run on the ICP-MS. A USEPA standard was analysed at the beginning of each run for initial calibration verification. All specimens were run in batches that included blanks, a suite of calibration standards, and spiked sample specimens. The accepted recoveries for spikes were 80 to 120%.

RESULTS

Wild Hog Resource Selection Model

All six logistic regression procedures converged and derived significant models when the total number of kills in each hexagon over the seven-year study period was used as the weighting function. Model convergence did not occur when the corrected kill per unit effort coefficient (# of kills/# of times hunted) was used as alternative weighting function. Although 6 models were derived, the 770 ha scale consistently produced models with higher maximum rescaled R-square values (Tables 4–7). Moreover, models within scales produced similar significant variables, although parameters often differed between scales. Specifically, none of the 350 ha models used PINE as a model parameter, although all 770 ha models did. Further, FLDPLN was only used in the female 770 ha model, but it was used in all three 350 ha models. Also, marsh/macrophyte (HAB8) and water (HAB2) were used in most of the 350 ha models and never used in any of the 770 ha models. All six models tended to use similar landscape metrics.

Table 4. Parameter slope comparison and maximum rescaled R-square for the three logistic regression models (All kill; Female; Male) derived from the 770 ha scale. Positive slopes are indicated by plus (+) and negative slopes are indicated by a minus (−).

	Model		
Variable	All kill	Female	Male
SHRUB	−		−
PINE	−	−	−
HRDWD	+	+	
FLDPLN		−	
Upland scrub forest		−	
Wetland scrub forest	−	−	−
NumP	+		+
MEDPS	−		
PSCoV	−		
PSSD	−	−	
AWMSI	+	+	+
MPAR	−		
MPE	+		
MPS		+	−
Maximum rescaled R-square	0.7221	0.7226	0.6762

The two all kill models were used for validation and subsequent exposure estimates because maximum rescaled R-square values were similar between the male and female models within each scale, and the all kill models produced the highest maximum rescaled R-square values. The two all kill models were validated using the take-one-out cross validation procedure. The 350 ha model correctly classified the response variable 73% of time. Specifically, it classified “no kill” events correctly 32% of the time and predicted “kill” events correctly 100% of the time. The 770 ha model classified the response variable correctly 87% of the time with predicting “no kill” events correctly 43% of the time and “kill” events correctly 99% of the time.

The 350 ha model and the 770 ha model used similar habitat parameters (Tables 6–7). Specifically, the 350 ha model predicted that hogs used wetland areas, floodplain hardwoods, and upland hardwoods, but avoided shrubby areas. The 770 ha model also predicted that hogs would avoid shrubby areas, and favor hardwood areas. However, it predicted that hogs would avoid pine forests, whereas pine was not a significant parameter for the former. Similarly, both models used the same landscape metrics, except for MPAR, which was not used in the 350 ha model. These metrics indicated for both models that hogs tended to prefer larger patches with high area to shape complexity ratios and avoided smaller patches with high shape complexity.

Wild Hog Exposure Estimates

The metal concentrations in potential food items collected in the Tim’s Branch were highly variable as indicated by the high standard deviations (Table 8). Exposure

Table 5. Parameter slope comparison and maximum rescaled R-square for the three logistic regression models (All kill; Female; Male) derived from the 350 ha scale. Positive slopes are indicated by plus (+) and negative slopes are indicated by a minus (−).

	Model		
Variable	All kill	Female	Male
SHRUB		−	
PINE			
HRDWD	+	+	+
FLDPLN	+	+	+
Water	+		+
Marsh/Macrophyte	+	+	
Upland scrub forest		−	
Wetland scrub forest	−	−	
NumP	−	+	+
MEDPS	−		
PSCoV	−	−	−
PSSD	−	−	+
AWMSI	+		
MPAR	+		
MPE	+		+
MPS			−
TE			−
Maximum rescaled R-square	0.5106	0.4724	0.4522

Table 6. Logistic regression summary statistics for the recommended final model used to predict wild hog occurrence on the SRS (770 ha model). Analysis of maximum likelihood estimates.

Variable	DF	Parameter estimate	Standard error	Chi-square	*p*-value
Intercept	1	29.1239	19.5002	2.4782	0.1154
Nump	1	0.00822	0.00300	7.4877	0.0062
Medps	1	−16.2546	8.8000	3.4118	0.0647
Pscov	1	−0.00816	0.00205	15.8293	<0.0001
Pssd	1	−0.1170	0.0334	12.2330	0.0005
Awmsi	1	1.6214	0.3887	17.4023	<0.0001
Mpar	1	−0.0306	0.0170	3.2536	0.0713
SHRUB	1	−1.57E-6	9.401E-7	2.7877	0.0950
PINE	1	−7.49E-7	1.793E-7	17.4381	<0.0001
HRDWD	1	2.813E-6	1.287E-6	4.7755	0.0289
Wetland shrub	1	−0.00005	0.000015	10.779	0.0011

Maximum rescaled R-square = 0.7221.

Table 7. Logistic regression summary statistics for the alternative model used to predict wild hog occurrence on the SRS (350 ha model). Analysis of maximum likelihood estimates.

Variable	DF	Parameter estimate	Standard error	Chi-square	*p*-value
Intercept	1	−0.7440	1.0417	0.5101	0.4751
Nump	1	.00837	0.00182	21.1183	<0.0001
Medps	1	−6.7008	3.4184	3.8425	0.0500
Pscov	1	−0.00335	0.000865	14.9743	0.0001
Pssd	1	−0.0214	0.00528	16.4480	<0.0001
Mpe	1	0.00028	0.000083	11.5200	0.0007
Awmsi	1	0.2070	0.0657	9.9180	0.0016
Water	1	2.74E-7	1.182E-7	5.3729	0.0205
Marsh	1	9.48E-6	5.177E-6	3.3562	0.0670
Wetland scrub	1	−0.000021	9.305E-6	4.9467	0.0261
SHRUB	1	−1.567E-6	6.093E-7	6.6154	0.0101
HRDWD	1	3.2E-6	8.02E-7	15.9066	<0.0001
FLDPLN	1	4.29E-7	7.458E-8	33.1150	<0.0001

Maximum rescaled R-square = 0.5106.

to these contaminants were assumed to be negligible outside the Tim's Branch corridor. Therefore, although the probability (p) of wild hogs using the Tim's Branch corridor was very high, from 0.87 to 1.0, the area of the Tim's Branch corridor relative to the home range (A/HR) of the hog was quite small, ranging from 0.003 to 0.064 (Tables 9a,b). Wild hog exposure to metals was higher on a diet based on a high percentage of roots compared to a diet based on a high percentage of mast (Tables 9a,b). Further, exposure decreased with age class due to the amount of contaminated food ingested relative to body weight (Equation 1). Predicted exposure to wild hogs using the 770 ha resource selection model, was less than one half of the predicted exposure using the 350 ha resource selection model (Tables 9a,b).

Table 8. Mean metal concentrations (fresh weight mg/kg) ± 1 standard deviation of potential wild hog food items (n = # of samples) collected from contaminated areas of the Tim's Branch corridor on the Department of Energy's Savannah River Site.

Food item	Al	U	Ni
Mast ($n = 63$)	0.139 ± .081	0.002 ± .004	0.009 ± 0.009
Soil ($n = 20$)	1076 ± 452	60 ± 38	23 ± 11
Vegetation ($n = 20$)	385 ± 375	19 ± 17	16 ± 11
Leaf litter ($n = 20$)	410 ± 209	4 ± 5	27 ± 20
Roots ($n = 16$)	172 ± 134	11 ± 11	13 ± 12
Invertebrates ($n = 50$)	0.941 ± 1.39	0.002 ± 0.004	0.002 ± 0.051
Vertebrates ($n = 30$)	3.62 ± 4.56	0.032 ± 0.083	0.132 ± 0.082

Table 9a. 770 ha resource selection model.

HEX	Tim's Branch area (A)	Prob (p)	A/HR	p*A/HR
1	490,500	0.875	0.064	0.056
2	408,600	0.879	0.053	0.047
3	376,200	0.999	0.049	0.049
4	25,200	1.000	0.003	0.003
Mean		0.938	0.042	0.039

			Al exposure		U exposure		Ni exposure	
Age class	Age	Weight (kg)	Mast	Roots	Mast	Roots	Mast	Roots
0	Neonates	1	31.92/ 1.23	68.69/ 2.65	1.69/ 0.07	3.84/ 0.15	1.20/ 0.05	2.93/ 0.11
1	Up to 7 mos	10	21.19/ 0.82	45.59/ 1.76	1.12/ 0.04	2.55/ 0.10	0.80/ 0.03	1.95/ 0.08
2	8 to 13 mos	34	17.04/ 0.66	36.67/ 1.42	0.90/ 0.03	2.05/ 0.08	0.64/ 0.02	1.57/ 0.06
3	14 to 20 mos	57	15.54/ 0.60	33.45/ 1.29	0.82/ 0.03	1.87/ 0.07	0.58/ 0.02	1.43/ 0.06
4	21 mos to 3 yrs	74	14.84/ 0.57	31.93/ 1.23	0.78/ 0.03	1.79/ 0.07	0.56/ 0.02	1.36/ 0.06
5	3+ yrs	88	14.39/ 0.56	30.96/ 1.20	0.76/ 0.03	1.73/ 0.07	0.54/ 0.02	1.32/ 0.06

Predictions of metal exposures (mg/kg/day; before model/after model) for wild hogs on inhabiting the Tim's Branch riparian zone of the Department of Energy's Savannah River Site (SRS). Predictions are presented separately by hog age classes and are based on a diet high in mast (77% mast, 5% roots) versus a diet high in roots (13% mast, 64% roots) using a 770 ha and 350 ha core home range (HR) in the focal contaminated area. The wild hog resource selection model was used to predict the probability (p) of hogs residing in the area based on the HR represented by each hexagon (HEX) of the resource selection model that intersected the focal contaminated area (A; in meters).

DISCUSSION

Model Prediction

The developed exposure model is a complex spatially explicit model that is an integration of both resource selection functions and contaminant exposure estimates. Like all models, the framework is an attempt to simulate reality with certain simplifications and underlying assumptions. It is, thus, useful to discuss the limitations of implementing such a spatially explicit ecological risk model. The effect of spatial aggregation has long been known as an important issue in any kind of ecological analysis and assessment (Clark and Avery 1976; Marinussen and Van der Zee 1996). In this research, the scale of a wild hog's home range and core area (*i.e.*, size of a hexagon) had been defined under careful consideration of life history components and model testing. Similar attempts in using home range/core area of another species for ecological risk assessment must carefully choose the appropriate scale for that particular ecosystem. As with any model, there are inherent biases associated with their execution. For example, both models tended to over-predict habitat use.

Table 9b. 350 ha resource selection model.

HEX	Tim's Branch area (A)	Prob (p)	A/HR	p*A/HR
1	272,700	0.875	0.078	0.068
2	844,200	0.879	0.241	0.212
3	100,800	0.999	0.029	0.029
4	77,400	1.000	0.022	0.022
Mean		0.938	0.093	0.083

			Al exposure		U exposure		Ni exposure	
Age class	Age	Weight (kg)	Mast	Roots	Mast	Roots	Mast	Roots
0	Neonates	1	31.92/ 2.64	68.69/ 5.69	1.69/ 0.14	3.84/ 0.32	1.20/ 0.10	2.93/ 0.24
1	Up to7 mos	10	21.19/ 1.75	45.59/ 3.77	1.12/ 0.09	2.55/ 0.21	0.80/ 0.07	1.95/ 0.16
2	8 to 13 mos	34	17.04/ 1.41	36.67/ 3.04	0.90/ 0.07	2.05/ 0.17	0.64/ 0.05	1.57/ 0.13
3	14 to 20 mos	57	15.54/ 1.29	33.45/ 2.77	0.82/ 0.07	1.87/ 0.15	0.58/ 0.05	1.43/ 0.12
4	21 mos to 3 yrs	74	14.84/ 1.23	31.93/ 2.64	0.78/ 0.06	1.79/ 0.15	0.56/ 0.05	1.36/ 0.11
5	3+ yrs	88	14.39/ 1.19	30.96/ 2.56	0.76/ 0.06	1.73/ 0.14	0.54/ 0.04	1.32/ 0.11

Predictions of metal exposures (mg/kg/day; before model/after model) for wild hogs on inhabiting the Tim's Branch riparian zone of the Department of Energy's Savannah River Site (SRS). Predictions are presented separately by hog age classes and are based on a diet high in mast (77% mast, 5% roots) versus a diet high in roots (13% mast, 64% roots) using a 770 ha and 350 ha core home range (HR) in the focal contaminated area. The wild hog resource selection model was used to predict the probability (p) of hogs residing in the area based on the HR represented by each hexagon (HEX) of the resource selection model that intersected the focal contaminated area (A; in meters).

Because it is being used as a risk assessment tool, it was considered more conservative to over-predict than under-predict use of an area. Also, neither model can distinguish habitat use based on age structure, which could be important when trying to refine uptake and exposure models. These constraints are due to data availability, which are almost always a limiting factor in model-building processes.

Precision is yet another spatial issue to consider. In this research, each core area or home range is represented by a single value in a hexagon to indicate the likelihood of wild hogs occupying that particular spatial location. However, the accuracy of the final exposure estimation might be sensitive to rapid spatial changes in habitat use. Different habitat use estimations may result from different origins for the hexagonal mesh tesselation. This origin effect could be refined by performing a moving window analysis or Monte Carlo simulation to provide an estimate of probabilities for different origins. However, for the purposes of this risk assessment, because the waste site was smaller than the hexagonal unit itself, these potential errors should be limited.

There was no evidence that separate models appropriate to male or female hogs could be derived from the data. If separate models were suitable, then one would expect the maximum rescaled R-square to favor sex-specific models, which was not the case. The scale at which the hunt kill data are taken are probably too coarse to derive individual models based on sex because a kill is associated with a hunt stand. Further, the significant parameters between models within each scale generally had the same signed slopes indicating that both sexes were utilizing the resources similarly. That is, for the temporal and spatial scale to which the models were derived, both male and female hogs use the landscapes of the SRS in the same way. Further, it is likely that during the fall and winter hunts, hogs are traveling in groups consisting of both males and females in large core areas (Crouch 1983).

Although there was no independent dataset to validate the resource selection model, its predictions that wild hogs prefer hardwoods and avoid pine and shrubby areas are consistent with other findings on the SRS. Sweeney (1970) showed that hogs preferred swamps with their adjacent bottomlands and associations with wetlands changed with season. Specifically, in late winter and early spring, hogs were found in more upland habitats than other times of the year when they preferred river-swamps. Although no studies have been found that quantified wild hog utilization of different habitat patches using landscape metrics, other studies have confirmed the findings that hogs prefer areas that have homogenous land cover. Specifically, Kurz (1971) showed that hog home ranges were found in large homogenous landscapes that were up to twice the size of their home ranges on the SRS.

The 770 ha scale all kill model had a higher predictability based on the validation procedures as well as a higher maximum rescaled R-square value. Therefore, it is likely that this model is the most appropriate. However, because the larger scale model has fewer observations because each hexagon is treated as an observation, it is expected that it will have a higher maximum rescaled R-square value, because both models had approximately the same number of parameters. Although it may be biologically relevant to assume a smaller seasonal home range, there may be instances or studies that the 350 ha model should be used. However, both models' level of predictability should be considered along with scale in this decision-making process.

Future modeling efforts would benefit from the collection of wild hog habitat preference data during other seasons. Also, no independent data were available to quantitatively validate the estimates of resource selection and exposure estimates themselves serve more as an index and are difficult to validate without direct stomach content analysis from a large sample size. Future data acquisitions need to focus on testing these models' predictive strengths and the evaluation of what parameters may need to be further refined. Moreover, this model could be improved by collecting seasonal movement pattern data to determine if wild hogs are utilizing specific corridors that facilitate contaminant movement off the SRS. Besides being useful in the ecological risk assessment process, the information derived from this model has also contributed to knowledge of this species' natural history. Most studies in the past have not had such detailed land cover maps available to describe the habitats that these wild hogs are using. Moreover, the use of landscape metrics has allowed the description of what features of the landscape structure wild hogs are attracted to and which they avoid. This could be very useful in future ecological assessments because wild hogs are spreading through the United States and continue to be very destructive.

Exposure Prediction

Simply quantifying contaminants in consumed environmental media should not be the final determination of ecological risk. Using the wild hog resource selection model to estimate exposure of Al, Ni, and U to wild hogs inhabiting the Tim's Branch system provides a logical estimate of exposure to multiple contaminants that can cause acute and chronic effects. U is an alpha-emitting radionuclide with daughter gamma products, which can cause DNA damage (Gilmore and Hemmingway 1995). In combination with gamma/x-ray/ultraviolet radiation, and/or benzo[*a*]pyrene, Ni has been shown to contribute to the cytotoxicity and genotoxicity of mammalian cells (Hartwig 1995; Denkhaus and Salnikow 2002). Further, Al bioavailability and subsequent toxicity is dependent on its speciation in both the environment and in its metabolism, which is heavily influenced by the presence of co-contaminants (Berthon 2002). It is extremely important to derive and adequately refine risk models so that they are predictive of exposure to multiple contaminants at varying scales. Only then, through examination of ecological endpoints, will scientists and risk managers be able to gain a better understanding of how complex mixtures of contaminants behave when ingested. Tannenbaum (2003) points out that many studies suggest that detrimental impacts to wildlife receptors may be occurring from exposure to toxicants in the environment, yet few studies have demonstrated such effects and therefore ecological risk is not being characterized correctly. An essential component of the solution to this challenge is to understand the spatiotemporal aspects of the toxicant distribution as well as the receptors. Using the wild hog resource selection model in exposure estimates provides such a tool because having an improved estimate of exposure allows the next step of predicting contaminant uptake outside the laboratory more plausible. That is, more reasonable exposure models will aid in reducing some of the variability and uncertainty associated with predicting transfer factors to higher trophic levels.

Factors such as age, sex, season, and behavioral patterns could also influence exposure to wildlife endpoint species. For example, it is apparent from the data (Table 9) that if a wild hog shifts its diet from one high in mast to one high in roots due to low mast availability from yearly production variability or seasonal resource use, exposure will vary greatly. Because most of the contamination in the Tim's Branch area is in the soil and sediments, roots are much higher in contaminant load than other potential food items such as mast and vegetation. By considering this behavioral adaptation, a much more useful exposure assessment can be made. Further, because younger animals had higher exposure estimates because of lower body weights, there could be a higher risk to hunters who prefer to shoot younger animals because they are more palatable and easier to carry.

The predicted exposure of wild hogs to contaminants is extremely sensitive to the estimated area that the hogs may use relative to the contaminant distribution in the environment. For example, when using a 770 ha area to represent the home range of a wild hog, exposure is considerably less than if a 350 ha core area were used because the area to home range ratio (A/HR) is smaller (Tables 9a,b). Further, the likelihood of an animal inhabiting the area is also of great importance. Tim's Branch was chosen as a focal area to model wild hog exposure because both models predicted high hog use of that habitat and it was known from past investigations

(Gaines unpublished data) that hogs utilized this area. Although exposure estimates more than doubled when using the 350 ha core area, both models produced a much more realistic estimate than not taking home range and utilization probability into account. Assuming that the contaminated areas were being utilized 100% of the time, with the animals' home range or core area not taken into account (*e.g.*, assuming that the animal spends all its time in the contaminated area), exposure estimates would be approximately 12 and 25 times higher than the 350 ha and 770 ha model estimates, respectively. Moreover, taking EPA and the Agency for Toxic Substances and Disease Registry (ATSDR) oral exposure limits into consideration, conclusions about ecological and potential human health risks may be very different.

Based on the EPA's Integrated Risk Information System (IRIS), neither a reference dose (RfD) nor a reference concentration (RfC) have been derived for natural U or Al (IRIS 1997). For soluble salt U, the RfC is 3.0×10^{-3} mg/kg/day. Similarly, the U.S. Department of Health and Human Services, through the Agency for Toxic Substances and Disease Registry (ATSDR) has published a toxicological profile for U (ATSDR 1999) and a Minimal Risk Level (MRL) of 2.0×10^{-3} mg/kg/day has been derived for intermediate-duration oral exposure (protective for chronic-duration oral exposure) to soluble compounds of U based on a lowest-observed-adverse-effect-level (LOAEL) of 0.05 mg U/kg/day for renal effects in rabbits (Gilman *et al.* 1998). Bertsch *et al.* (1994) showed that the U in soil in Tims Branch was in a soluble form. The RfC for oral exposure for Ni compounds is 0.02 mg/kg/day (IRIS 1997). Although these are protective levels for humans and not wild hogs, what can be seen is that when the resource selection model is used to predict exposure these calculations in some cases exceed these limits by an order of magnitude. More importantly, if the spatial parameters from the resource selection model are not used in the exposure assessment, all calculations exceed the RfC or MRL for both U and Ni by several orders of magnitude (Table 9a,b).

RISK MANAGEMENT

The management of wildlife on large government facilities is done by the government organization often through the subcontracting of private companies or research institutions. In most cases, when issues such as contaminant exposure and transport by wildlife are of interest, an animal's distribution, foraging activity, and spatial use of an area are not taken into account. This is because those who are charged with the task of focusing on contaminant exposure and risk are often not trained in the wildlife field. This study showed that not taking these parameters into account may lead to very different conclusions of contaminant exposure and potential risk to wildlife and to those who may consume them. As habitat fragmentation continues from anthropogenic influences, large government facilities are now playing an important role in providing large tracks of land that wildlife utilize. Models such as these will help not only in the ecological risk assessment process, but will also benefit endangered and game species management. This model has been incorporated into existing DOE methodologies, which allows this approach to be used as a template for other large federal facilities. The wild hog model is one of six receptor species models [raccoon (*Procyon lotor*), beaver (*Castor Canadensis*), cotton rat

(*Sigmidon hispidus*), large wading birds (Order: Ciconiformes) and wood duck (*Aix sponsa*)] that are currently being used by the DOE. A graphical user interface (GUI) was also developed to allow the risk assessor to estimate exposure to potential contaminants based on different management scenarios. This modeling effort provides a stepping stone for risk characterization to estimate exposure in order to estimate endpoint effects to both ecosystem and human health by presenting uncertainties associated with the risks as well as summarizing results to risk managers.

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Appendix 1. Metric definitions of class landscape fractals calculated in FRAGSTATs ver. 2.0 (McGarigal and Marks 1994) that were used as potential explanatory variables in each logistic regression.

Acronym	Metric (units)	Definition
CA	Class Area (ha)	Sum of areas of all patches belonging to a given class.
TLA	Landscape Area (ha)	Sum of areas of all patches in the landscape.
NumP	Number of Patches (#)	Number of Patches for each individual class (*e.g.*, hexagon).
MPS	Mean Patch Size (ha)	Average patch size.
MedPS	Median Patch Size (ha)	The middle patch size, or 50th percentile.
PSSD	Patch Size Standard Deviation (ha)	Standard Deviation of patch areas.
PSCoV	Patch Size Coefficient of Variance (%)	Coefficient of variation of patches = PSSD/MPS*100.
TE	Total Edge (m)	Perimeter of patches.
ED	Edge Density (m/ha)	Amount of edge relative to the landscape area. ED = TE/TLA.
MPE	Mean Patch Edge (m)	Average amount of edge per patch. MPE = TE/NumP.
MPAR	Mean Perimeter-Area Ratio (unitless)	Shape Complexity = Sum of each patches perimeter/area ratio divided by number of patches.
MSI	Mean Shape Index (unitless)	Shape Complexity. MSI is greater than one, MSI = 1 when all patches are circular (polygons). MSI = sum of each patches perimeter divided by the square root of patch area (ha) for each class (hexagon), and adjusted for circular standard (polygons), divided by the number of patches.
MPFD	Mean Patch Fractal Dimension (unitless)	Mean patch fractal dimension is another measure of shape complexity. Mean fractal dimension approaches one for shapes with simple perimeters and approaches two when shapes are more complex.
AWMPFD	Area Weighted Mean Patch Fractal Dimension (unitless)	Shape Complexity adjusted for shape size. Area weighted mean patch fractal dimension is the same as mean patch fractal dimension with the addition of individual patch area weighting applied to each patch. Because larger patches tend to be more complex than smaller patches, this has the effect of determining patch complexity independent of its size. The unit of measure is the same as mean patch fractal dimension.