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A Spatially Explicit Model to Predict Radiocesium Body Burdens in White-Tailed Deer on the Department of Energy's Savannah River Site

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A Spatially Explicit Model to Predict Radiocesium Body Burdens in White-tailed Deer on the Department of Energy's Savannah River Site

By

Christopher W. Bobryk

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ABSTRACT:

A spatially explicit exposure model was developed to interpolate and predict radiocesium (^{137}Cs) body burdens found in white-tailed deer *(Odocoileus virginianus)* on the U.S. Department of Energy's Savannah River Site (SRS) in west-central South Carolina. Since 1965 hunting has been allowed from permanent stands as a mechanism to manage the herd and all animals have been monitored in the field for gross beta/gamma activity levels providing a long-term spatially explicit dataset. Until now no study has attempted to model deer ^{137}Cs at the hunt-stand level, but rather at the compartment level (1,000 – 5,200 ha). The models described here use the relative locations of the hunted stands to predict ^{137}Cs exposure distributions between the years of 1984 – 2005 and takes into consideration the number of deer harvested and their body burdens. Kriging was used as the first deterministic method that created an interpolation surface using a best linear unbiased estimator. This geostatistical approach was used based on its ability to use variance components of neighbors at multiple distances using mean ^{137}Cs body burdens as the weighted variable. Kriging enabled an increased confidence of the relationship between ^{137}Cs body-burdens, their spatial association with each stand, and enabled the differentiation between sources of ^{137}Cs to deer on the SRS. A series of regression models were then used to investigate if the bioavailability of ^{137}Cs and the number of deer harvested were a function of habitat composition, landscape structure, and clay content on the SRS. The interpolation surfaces, coupled with the regression analyses, provided a comprehensive assessment of deer ^{137}Cs body burdens and habitat structure on the SRS, which then may be used in human and ecological risk assessments.

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INTRODUCTION

Major sources of anthropogenic radionuclides primarily occur as global fallout due to above ground weapons testing and incidents such as, Chernobyl in 1986 and a major ^{137}Cs release in Goiânia, Brazil in 1987 (IAEA 1988, Carlton *et al.* 1992, Wentworth 1998, Kubica *et al.* 2004). Public interest in radiocesium (^{137}Cs) as a constituent of worldwide fallout has risen because of potential health hazards to humans through food chains (Garner and Comar 1971, Tahir 1975), primarily because it is a chemically reactive isotope that serves as a continuing source of radioactivity to animals including humans (Jenkins 1969, Garner and Comar 1971, Igarashi *et al.* 2005). Cesium-137 can pose environmental risk because: (1) it produces deleterious effects at low concentrations from both external and internal exposures, (2) it can freely substitute for potassium (K^+) in biogeochemical processes, and 3) it is environmentally persistent with a long radioactive half-life of 30.2 years (Nishita *et al.* 1960, Peters and Brisbin 1996).

The United States Department of Energy's (USDOE) Savannah River Site (SRS) (Figure 1) is a former nuclear material production and manufacturing facility located in west-central South Carolina, USA. It was established in 1951 by the Atomic Energy Commission (now the DOE) and by 1988, 5 nuclear reactors ceased production and are currently in various stages of decommissioning. During the years of operation, these reactors produced materials consisting of tritium, uranium, plutonium and their fission products. The fission processes released ^{137}Cs into the environment that consequently contaminated SRS terrestrial and aquatic ecosystems (Carlton *et al.* 1992, Gaines *et al.* 2004b). Human activities and ecological processes in and around the SRS have influenced the bioavailability of ^{137}Cs as well as its transport (Gaines *et al.* 2004a, Bulgakov 2007).

Exposure to gamma emitting ^{137}Cs may result in damage to the gastrointestinal or central nervous systems, bone marrow, and to DNA in any part of the body (Wentworth 1998). The bioavailability of radionuclides is often enhanced by several physical and chemical properties of both the soil and isotope (Jagoe *et al.* 1998, Gaines and Novak 2009). On the SRS, ^{137}Cs bioavailability is largely dictated by the concentrations of K^+ and ammonium (NH^{+4}) cations in the soil, which are subject to considerable interannual, seasonal, and daily fluctuations (Bulgakov 2007). The higher bioavailability of ^{137}Cs on the SRS is explained by its propensity to be absorbed by plants due to its similar size and hydration energy to K^+, which physiologically allows rapid uptake into living tissues (Wentworth 1998, Gaines and Novak 2009). Fine-fraction clays with high cation-exchange capacities bind ^{137}Cs and demobilize it. This restricts the distribution of ^{137}Cs to areas close to original deposition (Seaman *et al.* 2001). However, the majority of soils found on the SRS are low in clay content, highly weathered, and have a high kaolinite content, which poorly binds to ^{137}Cs. (Brisbin *et al.* 1974, Rogers 1990, Seaman *et al.* 2001, Gaines and Novak 2009). The lack of soil binding may allow the radioisotope to become mobile on the SRS (Bulgakov 2007). The vertical distribution of ^{137}Cs in SRS soils is shallow, with over 68% found in the upper 20 cm of soil (Brisbin *et al.* 1974). This spatial pattern also maintains ^{137}Cs in a biologically available position for white-tailed.

The SRS contains a heterogeneous set of environments that allows wildlife populations to thrive, especially white-tailed deer (*Odocoileus virginianus*). The increase in availability of habitat has occurred because of public access restrictions and elimination of hunting pressure. Consequently, the deer population residing on the SRS were able to grow from approximately 100 animals in 1951 to over 1,400 animals in 1963 (Carlton *et al.* 1992). Because of the growing herd size, there was an alarming increase of deer-vehicle collisions. In response, controlled hunts were established on the SRS in 1963 primarily to minimize these incidences (Comer *et al.* 2005). Since these deer are potentially residing in and near contaminated environments, understanding the dynamics of their exposure to best minimize risk to humans that consume these animals is an important focus for management. This includes deciphering between sources of ^{137}Cs, such as global fallout or site activities.

The effects of ^{137}Cs in the environment is an important concern, particularly when wildlife may act as vectors of contamination (Gaines *et al.* 2004a). The presence of radionuclides in game species as a result of atmospheric fallout has been well documented (Whicker *et al.* 1965, Jenkins 1969, Markham *et al.* 1982, Palo *et al.* 2003). Therefore, understanding the dynamics of ^{137}Cs on the SRS is critical and must be considered when managing these wildlife populations. To protect public health, all deer harvested at the SRS during controlled hunts are monitored for ^{137}Cs (Fledderman *et al.* 2008) allowing for continuous documentation that will keep record of a hunter's estimated exposure over time (Fledderman 1992, Fledderman *et al.* 2008). Monitoring the deer herd also provides information to better understand ^{137}Cs distributions enabling the development of models to predict exposure to human and other predators (Gaines *et al.* 2004a, Bulgakov 2007).

In South Carolina, many families are subsistence consumers of game and because deer in South Carolina tend to have high ^{137}Cs body burdens from global fall out, understanding the dynamics of their exposure could help minimize risk to these individuals that consume animals (Burger *et al.* 2001). Deer on the SRS are at an additional risk because of their ability to enter contaminated areas and forage, potentially obtaining body burdens above those from global fallout alone. This is most likely to occur for deer that spend the most time exposed to the contaminant and how it utilizes the habitat (Gaines *et al.* 2008). Due to a potential increase in uptake, as well as differing sources of ^{137}Cs to SRS wildlife, spatially explicit models to predict their body burdens and the risk to human consumers are necessary. Previous studies have linked ecosystem structure and radionuclide distributions to estimate exposure to both game and non-game species (Colwell *et al.* 1996, Gaines *et al.* 2004a, Gaines *et al.* 2004b). However, no study to date has developed a model for white-tailed deer to predict their ^{137}Cs body burdens.

Previous studies have predicted ^{137}Cs concentrations in white-tailed deer on the SRS at the compartment level, which are areas used to manage controlled hunts and range in size from 1,000 – 5,200 ha (Gaines and Novak 2009). The scale of this approach is spatially appropriate to ask questions regarding management at the compartment level; however, it may be too coarse to differentiate ^{137}Cs body burdens of deer that may be exposed to areas of contamination from those that obtain their burden from global fallout alone. Therefore, to differentiate ^{137}Cs exposure pathways to white-tailed on the SRS, a spatial approach must be used relative to the scale that an individual deer resides (Gaines and Novak 2009).

The purpose of this study was to explore the spatiotemporal dynamics of ^{137}Cs in white-tailed deer on the Department of Energy's Savannah River Site, specifically to gain insight into the main contributing sources and perhaps differentiate between them for harvest management. The objectives were to: (1) Develop a spatially explicit model that predicts ^{137}Cs body burdens using a biologically relevant scale, (2) Differentiate ^{137}Cs body burdens based on contamination sources, (3) Determine if ^{137}Cs body burdens are a function of habitat structure, and (4) To predict if white-tailed deer occurrences are a function of SRS habitat coverage, landscape structure, and soil type.

Using the first two objectives, we investigated the following hypothesis: (1) H_0: ^{137}Cs body burdens in deer across the SRS are spatially random. The next two objectives used habitat characteristics to explore the following hypotheses, respectively: (2) H_0: Bioavailability of ^{137}Cs to white-tailed deer on the SRS is independent of habitat type, landscape structure and soil type, and (3) H_0: The prediction of white-tailed deer occurrence on the SRS is independent of habitat coverage, landscape structure, and soil type.

STUDY SITE

The SRS is a 802-km^2 former nuclear production facility and current environmental research park operated by the United States Department of Energy (USDOE) (Figure 1) (Comer *et al.* 2005). It is located in west-central South Carolina, USA bordered on the west by the Savannah River and extending eastward covering portions of Aiken, Allendale and Barnwell counties. In 1965, the SRS was established as the first national environmental research park (NERP) dedicated to the ongoing investigations of human induced impacts and associated ecological interactions involving radionuclide bioaccumulation (Gaines *et al.* 2004b).

The habitat on the SRS ranges from lowland to upland forest and has remained relatively undisturbed from any development aside from SRS facilities (Workman and McLeod 1990). Pinder *et al.* (1998) was able to categorize 33 distinct habitat types from remotely sensed data as well as U.S. Forest Service timber management maps (Table 1). Much of the forested area of the SRS is managed primarily for commercial timber production directed by the United States Forest Service (USFS). Overall, approximately 54% of the habitat is composed of converted pine forests consisting of variable mixtures of loblolly (*Pinus taeda*), longleaf (*P. palustris*), and slash (*P. elliottii*) pines (Comer *et al.* 2005). These forest stands are interspersed with non-forested areas occupied by active facilities, roadways, disengaged reactors, and power line right-of-ways. The SRS is divided into 6 watersheds, including a portion of the Savannah River watershed, that primarily drain into the Savannah River via the Savannah River Floodplain Swamp (Figure 2). Primary aquatic features within each watershed exist as tributaries, isolated wetlands and man-made reservoirs. Two main tributaries, Steel Creek and Lower Three Runs, were dammed to make the L-Lake and Par Pond/Pond B reactor cooling reservoirs, respectively. Carolina bays, elliptical depressions seasonally inundated with water, also provide abundant wetland sources to wildlife (Gaines *et al.* 2004a).

Game management on the SRS includes annual deer and hog hunts conducted by the USDOE's primary contractor, Savannah River Nuclear Solutions (SRNS), in cooperation with the South Carolina Department of Natural Resources (SCDNR) (Davis and Janecek 1997). SRS Deer hunts encompass most of the site and are distributed among 52 hunt compartments of various sizes, ranging from 1,000 – 5,200 ha. Within the hunt compartments are designated stand locations where hunters are assigned during each hunt. The placement of hunters works on a rotational basis where the same stands are not necessarily hunted every year. The management goal is set to maintain a site wide population of approximately 4,000 animals (Comer *et al.* 2005). All current hunts on the SRS are dog driven, where hunters are placed at the permanent, georeferenced stands and dogs are released to disperse deer and provide hunters with the greatest probability of harvest. During these hunts, individual deer harvested are tagged with the hunter's name, social security number, stand location, and cinch number, which is a unique identifier for individual deer (Fledderman 1992). Using this cinch ID, all deer can be georeferenced to the hunt stand where it was harvested, thus providing a georeferenced dataset. Two independent studies conducted over 30 years apart have confirmed that white-tailed deer tend to remain in their home range during the hunting events and have a return rate of less than 48 hours (Jenkins and Fendley 1971, D'Angelo *et al.* 2003). Therefore, it would be appropriate to use white-tailed deer core area/home ranges as the biological scale to predict their ^{137}Cs body burdens.

METHODS:

Deer Harvest Data

When deer are harvested, they pass through checkpoints prior to being relinquished to the hunter and removed from the site. Radiation emitted by ^{137}Cs is monitored at these checkpoints using a gamma radiation hip-monitor set for the photon energy 662 KeV. The meter is placed on the right hip of harvested deer and reports only ^{137}Cs in picocuries per kilogram (pCi kg^{-1}) (Fledderman 1992). The detection limit is

1pCi kg^{-1} or 37 becquerels per kilogram (Bq kg^{-1}). Additionally, a small muscle plug is taken from 10% (approximately every 10^{th} deer) for quality assurance/quality control, where ^{137}Cs is analyzed separately in the laboratory and thus, adding an extra measure of accuracy (Fledderman 1992).

This investigation began with using the physical and radiological data obtained from SRS deer hunts from years 1964 – 2005. The physical data provided information regarding the date harvested, weight, and sex of individual deer. The radiological data consists of ^{137}Cs measurements taken at checkpoints prior to deer being taken off site. Within the compartments are designated stand locations where hunters are randomly assigned during each event.

Using GPS coordinates, the hunt stand locations were digitized as points within a GIS and joined with radiological and physical data collected during all hunting periods. The initial 40-year data set was divided up into 3 time series, 1984 – 1990, 1992 – 1995 and 1996 – 2005. Data from 1965 – 1983 was not utilized due to variation in hunting technique and radiological assessment, where hunt stands were reconfigured due to safety issues during hunts. Therefore, these three time series were chosen because of the logistics of where hunt stands were located. There were complete data for all years except 1991 when radiological data were unavailable.

Scale

White-tailed deer home range/core area for the SRS was chosen as the most appropriate scale to investigate deer ^{137}Cs body burden distributions. White-tailed deer tend to stay in their home range of approximately 50 – 150 ha during hunting events and have a return rate after disturbance of 48 hours (Jenkins and Fendley 1971, D'Angelo *et* *al.* 2003). Also, many hunt stands are found within a single home range or core area, which would supply a robust sampling size at a biologically relevant scale. An area of 100 ha represents approximately 75% the maximum home range for SRS white-tailed deer and was chosen as the scaling unit.

A 100 ha hexagonal grid was created using Patch Analyst extension in ArcGIS (ESRI® ArcMap™ 9.3) and draped over the entire SRS to spatially examine ^{137}Cs distributions (Fig. 3). The following summary statistics were determined for each hexagon: average ^{137}Cs body burdens, percent clay content, percent habitat composition, and landscape metrics (McGairal and Marks 1993). Hexagons have low edge-to-area ratios and represent the closest feature to a circle without creating gaps. This geometry presents the advantage that all neighboring cells of a given hexagon are equidistant from the polygon's center point (Gaines *et al.* 2004a).

Modeling

Three spatially explicit models were developed to predict ^{137}Cs distributions using mean values of white-tailed deer body burdens for each hex from a 21-year time block. This block was further broken up into three time series that was used to run analyses: 1984 – 1990 (model 1), 1992 – 1995 (model 2), and 1996 – 2005 (model 3). Data from 1991 were not available for analysis.

ArcGIS (ESRI® ArcMap™ 9.3) was used as the primary system for storage, projection and analysis of all spatial information and interpolative analyses. Two geostatistical methods were implemented: (1) Ordinary Kriging and (2) Ordinary Cokriging. Ordinary kriging was used to explore the spatial dynamics of ^{137}Cs. Ordinary cokriging was used to examine the spatial dynamics of ^{137}Cs using a secondary variable, percent clay content.

The soil data used to determine percent clay content were acquired from a soil survey completed in 1987 by the Natural Resource Conservation Service (NRCS). A single map dataset identified as the Savannah River Plant Area was obtained through the web soil survey (WSS) provided by the United States Department of Agriculture (USDA) NRCS. The database consisted of 52 soil types with names, their respective areas, and characteristics such as slope, percent sand, silt and clay. This information was downloaded from the site and imported into GIS. The soil map was intersected with the 100 ha hexes and average percent clay was calculated for all hexagons.

A habitat layer (hereafter HAB map) was used to determine proportion of habitat types and their relative structure on the SRS. Pinder *et al.* (1998) initially categorized the SRS HAB map using Landsat Thermatic Mapper Data and provided ecosystem information (name, area), at a scale of 30m. Patch Analyst was used for the forest structure analysis for the entire SRS, as well as the 6 watersheds separately. A series of landscape class statistics were used to quantitatively describe the structure of SRS habitat and included metrics such as: 1) area, 2) patch size and density, 3) edge and shape, 4) diversity and interspersion, and 5) core area. It is well know that landscape metrics correlate (Gustafson 1998), therefore correlation matrices were used to eliminate redundant variables, with $r>0.6$.

Since ordinary kriging methods rely on the notion of autocorrelation and most importantly, aim to minimize the error variance (Isaaks and Srivastava 1989), a semivariogram was fit to determine the degree of spatial autocorrelation among pairs of sampled locations as a function of distance and/or direction for white-tailed deer on the SRS. The best-fit variogram model was determined as it is an optimal spatial predictor for unknown locations (Cressie 1991). Using this information, kriging models were developed to predict ^{137}Cs body burdens at unsampled locations and to provide insight into the distribution of ^{137}Cs over the SRS, especially particular areas of high average ^{137}Cs body burdens. The overall mean values of ^{137}Cs per hexagon were treated as the sample with a total of 910 hexagons that covered the SRS.

An exponential semivariogram model was used for all kriging datasets based on the following formula:

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\{Z(x_i) - Z(x_i + h)\}^2 \quad (1)$$

Where n equals the number of pairs of sample points separated by a distance of *h* (Fortin and Dale 2005). The lag size and number of lags used to control the semivariogram remained constant across all models as 1,333 and 12, respectively, where the lag size multiplied by the number of lags equated to half of the largest distance observed between two samples. A search neighborhood of 5 locations was used for all models with at least 2 neighbors always included. The auto-calculation option was used for determination of the major range, partial sill and nugget values; however, a visual cue was also used to establish a more conservative range since the exponential model never achieves a sill by definition. This range was used in concert with the search neighborhood to employ the best kriging model. A cross validation of the kriging function was used to determine the predictive rigor of the model. A predictive surface was then created depicting distributions of ^{137}Cs based on average body burdens within each hex.

Cokriging was used to determine if there was a cross-correlation between concentrations of ^{137}Cs and percent clay found on the SRS to try to improve the mean-squared prediction error of the overall model (Cressie 1991). That is, to make better predictions, ordinary cokriging was used to determine if clay content influenced the spatial distribution of deer ^{137}Cs body burdens more than the spatial proximity of deer with similar body burdens alone. Specifically, two semivariograms were simultaneously employed to estimate the covariation between clay content and ^{137}Cs body burden.

The percentage of clay content was used as the secondary variable for the prediction of ^{137}Cs levels at unsampled locations. The modeling process involved construction of the second semivariogram model using the same parameter options used for ordinary kriging as described above. Specifically, the estimation of the primary variable (mean ^{137}Cs concentrations) using the cross validations of the secondary variable (% clay) were used to create the model. The initial parameters (lag distance, number of lags, neighborhood search size, and search window) were kept the same for both models over all 3 time series.

Habitat Composition

A series of regression models were used to investigate the relationship between deer ^{137}Cs concentrations and habitat composition, landscape structure, and clay content. All regression models used a total of 20 variables where 11 consisted of habitat type categories (bottomlands, dense canopy, emergent, evergreen, floodplain, grasses, shrubs and forbs, open canopy, sparse herbaceous, upland and water). The remaining 9 variables were percent clay content (average clay) and the following landscape metrics: average weighted mean shape index (AWMSI), mean shape index (MSI), mean patch fractal dimension (MPFD), mean patch shape (MPS), mean perimeter-area ratio (MPAR), number of patches (NumP), median patch size (MedPS), patch size coefficient of variation (PSCoV), and class area (CA) (see Appendix A for detailed descriptions).

Seven models were run over the three time periods: 6 watersheds (Upper Three Runs, Lower Three Runs, Four mile, Steel Creek, Pen Branch and Savannah River/Swamp) and 1 overall model (SRS) to determine if ^{137}Cs concentrations were a function of habitat coverage, landscape structure, and clay content. The watershed approach was used since anthropogenic activities from forest practices and toxicological disturbance on the SRS have occurred at the watershed level. Maximum rescaled R^2 values, Akaike Information Criteria (AIC) and model p-values ($p<0.05$) were used as the discriminatory parameters to assess the strength of the models.

Ordinal logistic regressions were developed using a numerical bin range based on the geometric frequency of kills per hexagon as a function of hunting effort, habitat coverage, landscape structure and clay content. The bin range was determined by creating a frequency histogram to view where natural breaks in the data existed. Time series 1984 – 1990 used polychotomous divides determined by natural breaks, which translated to rankings that presented to be biologically relevant: (0) very low kills (<3, 12% of the data), (1) medium kills (3 – 13, 68% of the data), and (2) very high kills (>13, 21% of the data). Time series 1992 – 1995 used a dichotomous bin frequency where the dataset consisted of 0 and 1 (splitting the data based on natural breaks; where (0) low kills; and (1) high kills (>5 kills, 62% of the data), respectively. The third time series

1996 – 2005 used a polychotomous bin frequency where (0) very low kills (1 – 3 kills, 13% of the data); (1) medium kills (4 – 15, 58% of the data); (2) very high kills (>15, 28% of the data). Using the dichotomous and polychotomous bins, the best and most parsimonious models were chosen based on maximum rescaled R^2 values and Akaike Information Criteria (AIC) (Akaike 1974, Manly *et al.* 2002).

RESULTS

Kriging

Mean ^{137}Cs body burden concentrations were determined for each 100 ha hexagon that contained hunt stands where deer were harvested (Fig. 3). Three spatially explicit predictive surfaces were created using ordinary kriging geostatistical analysis (Figure 4A-C). The semivariance and covariance model descriptors differed among all three models using the same lag distance and number of lags. Time series 1984 – 1990 (Fig. 5A), maximum ^{137}Cs concentration (710 Bq), major range = 15,800.5, partial sill = 5,692.5 and nugget = 4,284.2. 564 samples were used to create the following kriging regression function (Fig. 5B):

$$y = 0.428 * x + 137.002 \quad (2)$$

For time series 1992 – 1995, the maximum ^{137}Cs concentration recorded was 555 Bq. The predictive model created used the following parameters: major range = 15,800.4, partial sill = 2,621 and nugget = 2,146.9 (Fig. 6A). There was a total sample size of n = 678 (Fig. 6B), with a kriging regression function of:

$$y = 0.470 * x + 105.733 \quad (3)$$

The semivariogram estimators for time series 1996 – 2005 consisted of the following: major range = 12,935.7, partial sill = 2,906.9 and nugget = 2,217.1. The maximum ^{137}Cs concentration found for this dataset was 810 Bq (Fig. 7A). The total kills for this data set was n=660 (Fig. 7B), and the cross validation reported a kriging regression function of:

$$y = 0.401 * x + 84.048 \tag{4}$$

Cokriging

The overall soil type was determined for the SRS (Fig. 8) and the mean clay content calculated for each hexagon. The cokriging models using mean clay content as the secondary predictive variable did not better estimate ^{137}Cs concentrations. For all models (1984 – 1990, 1992 – 1995, and 1996 – 2005) the overall cokriging regression functions consisted of the following, respectively:

$$y = 0.417 * x + 139.876 \tag{5}$$

$$y = 0.464 * x + 107.405 \tag{6}$$

$$y = 0.402 * x + 84.137 \tag{7}$$

Linear Regression

For time series 1984 – 1990, Pen Branch had the best fitting regression (maximum rescaled $R^2 = 0.4331$, $F_{(p\text{-value,df})} = 4.44_{(0.0047,\ 5)}$). Only 2 of 5 variables were significant ($\alpha < 0.05$) in explaining ^{137}Cs concentrations: floodplain and open canopy with p-values of 0.0102 and 0.0002, respectively (Table 2D).

The Savannah River Floodplain/Swamp watershed produced the best models over the next 2 time series (1992 – 1995 and 1996 – 2005) with a maximum rescaled R^2 = 0.3982, $F_{(p\text{-value,df})} = 6.65_{(<0.0001,13)}$, and $R^2 = 0.2181$, $F_{(p\text{-value,df})} = 6.65_{(0.0015,13)}$, respectively. Time series 1992 – 1995 for the Savannah River Floodplain/Swamp watershed had 7 of 13 variables with significant results where $\alpha < 0.05$, (Table 2F).

Logistic Regression

The best-fit logistic regression of the number of white-tailed deer kills per hexagon for time series 1984 – 1990 used 4 variables consisting of the hunting frequency per compartment (HUNTED), 1 habitat type (dense canopy), and 2 quantitative landscape metrics, AWMSI and NumP (Table 3A). All variables exhibited positive values with a maximum rescaled R^2 value of 0.12. The best model was achieved using the following polychotomous (0, 1, and 2) dependent variable (number of kills): (0) very low kills, (1) medium kills, and (2) very high kills.

Time series 1992 – 1995 used a dichotomous bin frequency where 0 and 1 signified low kills and high kills, respectively (Table 3B). The best-fit model used 4 habitat categories, dense-canopy, floodplain, open-canopy, and upland, and 2 landscape metrics, MSI and NumP. All variables had positive parameter estimates and exhibited a maximum rescaled $R^2 = 0.09$.

Predicted white-tailed deer occurrences for time series 1996 – 2005 employed 7 explanatory variables (Table 3C) with 5 variables consisting of habitat types: bottomlands, dense canopy, floodplain, open canopy and uplands, and 2 landscape metrics: MSI and NumP. A polychotomous bin (0, 1, and 2) was also used for the dependent variable (number of kills) where (0) very low kills, (1) medium kills, and (2) very high kills. All parameter estimates were positive with a maximum rescaled R^2 = 0.12.

DISCUSSION

The mobility of ^{137}Cs on the SRS is based on several physical, chemical, and biological factors. Using over 2 decades of radiological and physical data collected during SRS deer hunts, it was determined that the overall mean of ^{137}Cs body burdens of white-tailed deer on the SRS are decreasing over time. This is most likely attributed to the physical decay of ^{137}Cs. Three kriging models predicted ^{137}Cs body burdens of white-tailed deer at un-sampled locations and indicated that ^{137}Cs distributions on the SRS are not spatially random and are decreasing over time. As the models increased with time (eg. 1992 – 1995 to 1996 – 2005) the distribution of raster cells that signified higher body burdens (Bq = 400 – 600) decreased in size and became more concentrated around areas such as Par Pond, L-Lake and Steel Creek (Fig. 4A – C). Kriging extrapolated ^{137}Cs concentrations by using a set of linear regressions that determined the best combination of ^{137}Cs values as weights to interpolate the data and thus, provided strong predictive surfaces. Further, kriging was used because it can minimize the variance based on the spatial covariance in the data (Fortin and Dale 2005).

Chronic ^{137}Cs releases to streams occurred during a period from 1959 – 1970 with a maximum annual release of 109 Ci ($4.033e^{10}$ Bq) in 1964 (Carlton *et al.* 1992). Over one half-life of ^{137}Cs (eg. 30.2 years) has passed since these releases and an overall site release total has not exceeded 1Ci ($3.7e^{10}$ Bq) in any year since 1974 (Carlton *et al.* 1992). These perturbations coupled with global fallout provide the source of contamination in the deer. The kriging models show that there is spatial autocorrelation in deer body burdens occurring from 0m to approximately 800m for all models (e.g. the visual range for all semivariograms (Figs. 5 – 7). Based on the cross validation results where most of the observed and expected values are congruent, it appears that the majority of deer ^{137}Cs body burden is being acquired from atmospheric fallout. The samples underpredicted by the model are most likely due to isolated spatially uncorrelated contaminated locations caused from SRS industrial activities or deposited ^{137}Cs within highly weather, low potassium soils. These contamination hot spots are elevating mean deer body burdens beyond what would be expected from global atmospheric fallout. Therefore, it is probable that deer whose ^{137}Cs burdens are underpredicted reside in specific isolated areas with known contamination or their home ranges overlaps a contaminated area and thus, have periodic access to it. Conversely, the cross validation will overpredict at low values due to the detection limit of 37 Bq. Thus, these low and high levels are pulling the cross-validation line in directions that will over and under predict at low and high concentrations, respectively.

The hexagonal grid approach where each hex represents the deer core area is the most biologically relevant scale to estimate the body burdens of deer on the SRS (D'Angelo *et al.* 2003; Jenkins and Fendley 1971). This scale allowed for the determination and inclusion of deer ^{137}Cs hot spots in the analyses, thus providing the necessary spatial scale to model the fate and transport of ^{137}Cs to this game species (Figs. 5 – 7).

The prediction models developed here used spatially explicit radiological and physical data of SRS deer hunts from 1984 – 2005, and linked them to the hexagonal level. This scale represents the area that deer are most likely to be found. We know that there are areas of contamination that contribute to the overall mean body burden of the deer population residing on the SRS. Therefore, modeling at the 100 ha hexagonal level helped to provide evidence that ^{137}Cs concentrations contributing to deer body burden is not spatially random. That is, there is enough spatial autocorrelation between samples that we are able to predict mean ^{137}Cs concentrations in deer. Further, the use of the 100 ha core area/home-ranges shows where the majority of deer could possibly have access to these isolated areas of contamination (Fig. 9).

The clay content used in the cokriging models did not explain any additional variation seen in ^{137}Cs body burdens for white-tailed deer on the SRS. Therefore, it did not improve kriging results and was dropped from the modeling process. This is most likely because the primary variable (mean ^{137}Cs concentrations) was adequately sampled at the proper spatial scale. The secondary variable (average % clay content) was not sampled at a spatial scale that was necessary to improve the kriging results. This indicates that the soil composition from which the percent clay was determined was most likely too coarse and thus, too simplified to connect any variation in correlations using the 100 ha hex scale.

The SRS consists of areas diverse in habitats, clay content and vegetative structure. The linear regression models determined that particular habitat types, as well as some landscape metrics, could contribute to understanding the dynamics of deer ^{137}Cs body burdens. For example, the time series 1984 – 1990 for Pen Branch watershed, approximately 43% of the variation was explained using 6 variables (5 habitat types and 1 landscape metric). The most influential habitat variables for predicting ^{137}Cs body burdens for this model were floodplain and open canopy (Table 2D), which suggests that

^{137}Cs is extremely bioavailable to deer in these areas. This could be due not only to an increase in plant uptake of ^{137}Cs from global fallout especially in the open canopy areas, but from contamination events linked to the 5 reactors on the site leaking radioactive material into the river systems and surrounding floodplains.

The swamp watershed had the greatest R^2 values for the next two time series (1992 – 1995 and 1996 – 2005; Table 2F). For time series 1992 – 1995, the best contributing variables to the model were 3 habitat types (dense canopy, open canopy and water), 4 landscape metrics (AWMSI, NumP, PSCoV, and CA) indicating that ^{137}Cs body burdens are most influenced by pine habitat in this watershed and that the structure of this landscape must be complex. These models would seem to be closely tied to deer habitat preference in general since deer acquire ^{137}Cs body burdens from foraging. However, the logistic regressions based on the number of deer harvested in a hexagon as a function of the same habitat variables used in the ^{137}Cs body burden regressions discussed above did not show the same relationships, and in fact tended to be very weak models at best. A notable exception is that both the dense canopy and NumP variables used in the logistic regression models were consistent over all time series (Table 3A – C). This suggests that the primary type of habitat that deer are most likely to be harvested in areas that have a dense canopy pine but also have a variety of habitat patches within the core area (e.g. 100 ha hex). The next 2 time series models (1992 – 1995 and 1996 – 2005) had a variation of habitat types, however, they both shared dense canopy, as well as MSI and NumP, indicating that through these 2 time series, habitat complexity within a deer's core area tends to influence the probability of harvest.

Although these patterns are interesting, it should be reiterated that the percentage of variation explained in all models generated from the logistic regressions was not high and yielded weak correlations among the independent variables and the dependent ordinal variable.

MANAGEMENT IMPLICATIONS

White-tailed deer are an abundant species on the SRS and must be managed due to deer-car accident risk as well as to maintain ecosystem integrity from over browsing. The 802 km^2 SRS provides a unique opportunity to hunters for both trophy and subsistence hunting. The risk of eating contaminated meat is very real and therefore, managing this risk properly to protect the hunter is of utmost importance. Differentiating between radiation from global fallout and specific contamination events is helpful to properly develop a spatially explicit management approach. Since ^{137}Cs is extremely bioavailable on the SRS, managers can use the 100 ha home-range/core area as an advantageous spatial approach because it provides a biologically relevant scale that may enable the isolation and management of individuals from the population, as well as concentrating in specific vegetative structures. Moreover, using a core area approach allows the opportunity to investigate how site-specific contamination may influence ^{137}Cs body burden, thus providing better estimates of the health risks associated with the consumption of white-tailed deer by hunters.

Since the general public, who participate in hunting events, are potentially at a higher risk for accumulating ^{137}Cs contamination from the consumption of game than those that hunt nearby, wildlife managers may use the information associated with the cross-validation models created by the kriging analyses coupled with the interpolated surfaces for risk assessment purposes to limit access to high-risk areas. Understanding the spatial, physical, and radiological parameters associated with areas that have a higher probability of ^{137}Cs bioavailability to deer will allow control over where the public may hunt and dramatically lower their risk for accumulating ^{137}Cs. Buffers may be created around locations predicted to have higher concentrations of ^{137}Cs and different management techniques can be used to minimize risks to hunters. For example, increasing harvest in such areas can lower overall body burdens by decreasing the number of older individuals in the population, which tend to have the highest burdens. Gaines and Novak (2008) showed through spatial simulations that this technique significantly reduces predicted ^{137}Cs body burden in raccoons (*Procyon lotor*). This could help manage hot spot locations and perhaps decrease the overall mean ^{137}Cs body burden of white-tailed deer on the SRS.

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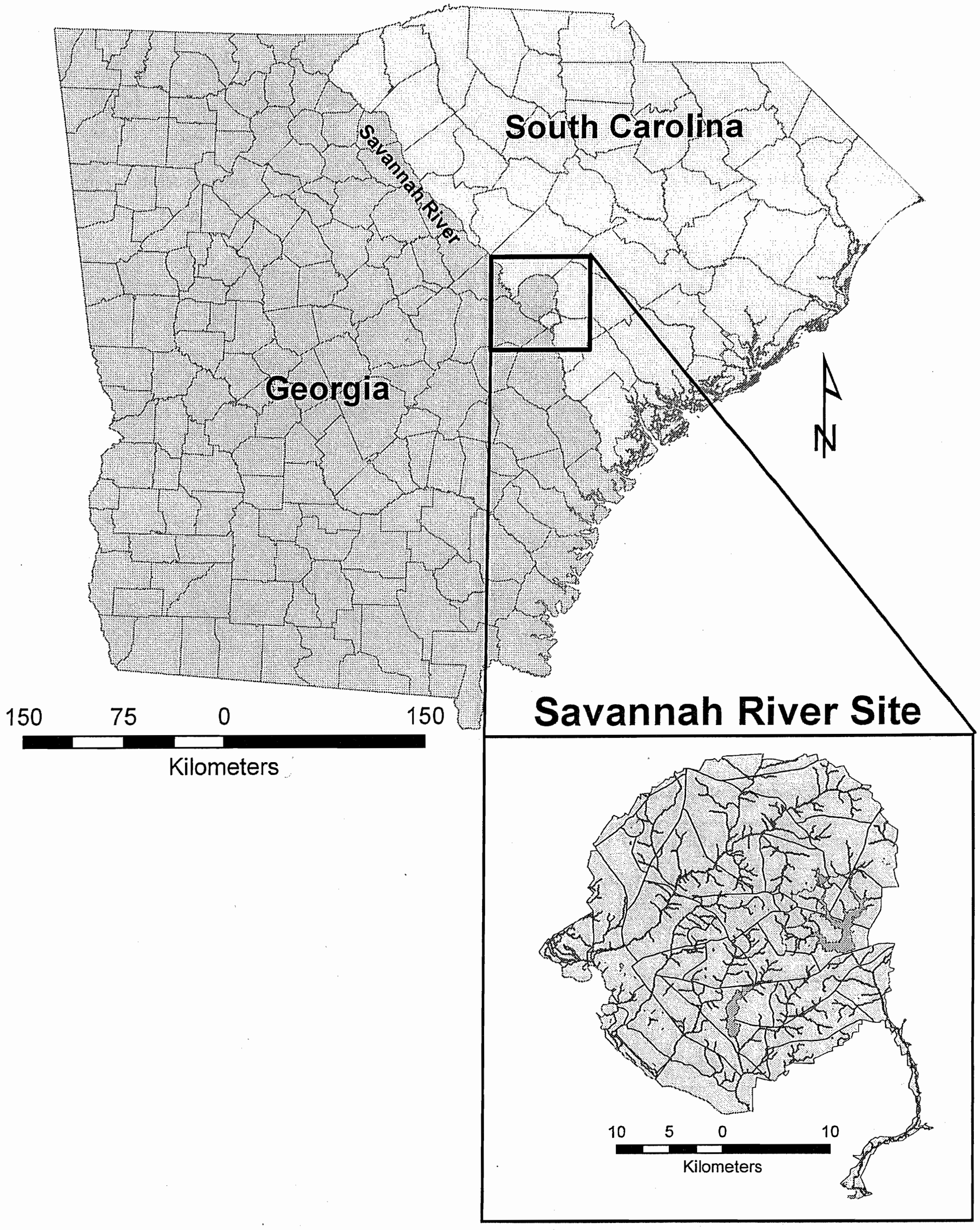


Fig 1. Map of the 802 km^2 Department of Energy's Savannah River Site (SRS), located in west-central South Carolina. The site encompasses three counties, Aiken, Allendale, and Barnwell, and is bordered by the Savannah River to the south west.

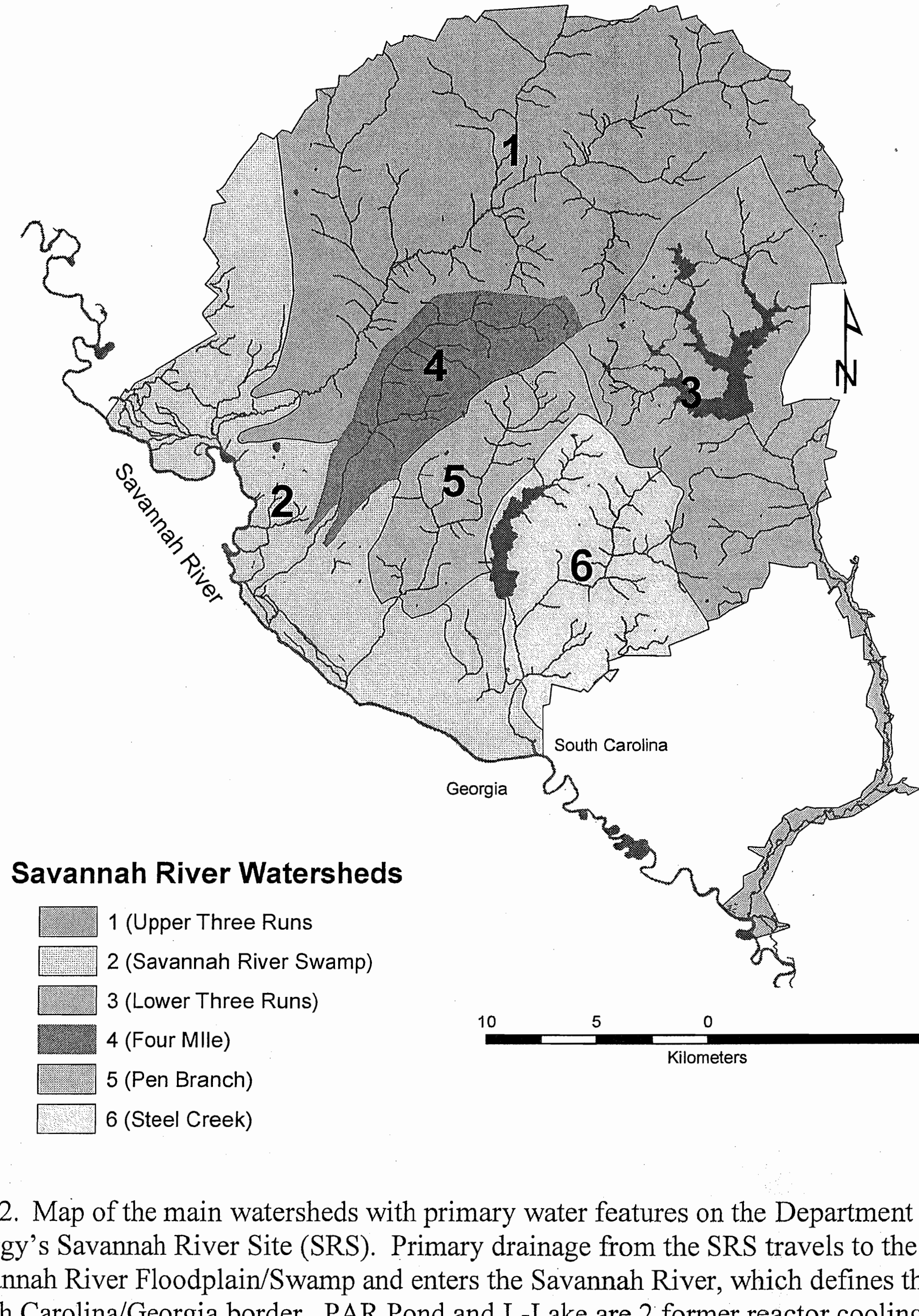


Fig. 2. Map of the main watersheds with primary water features on the Department of Energy's Savannah River Site (SRS). Primary drainage from the SRS travels to the Savannah River Floodplain/Swamp and enters the Savannah River, which defines the South Carolina/Georgia border. PAR Pond and L-Lake are 2 former reactor cooling reservoirs located in watersheds 3 and 6 respectively have received radiocesium (^{137}Cs) contamination from SRS activities.

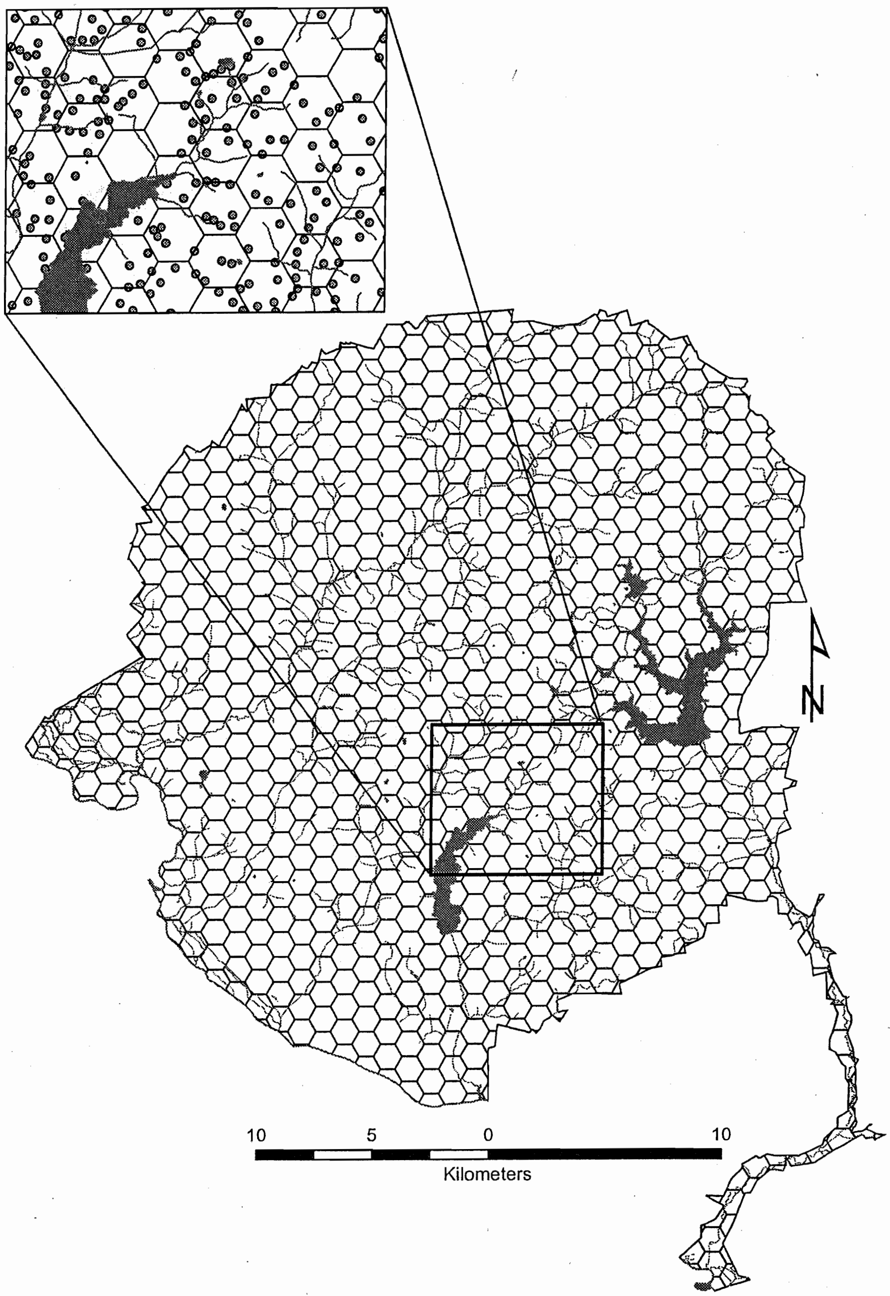


Fig. 3. The sampling scheme used to determine mean radiocesium (^{137}Cs) concentrations from white-tailed deer harvested on the Department of Energy's Savannah River Site (SRS). A 100 ha (SRS deer home-range/core area) hexagonal mesh was draped over the SRS and used to derive summary statistics (e.g. mean, range) obtained from harvested deer at multiple hunt stands located within each hex, indicated by points within hexagons in the map inset.

(A)

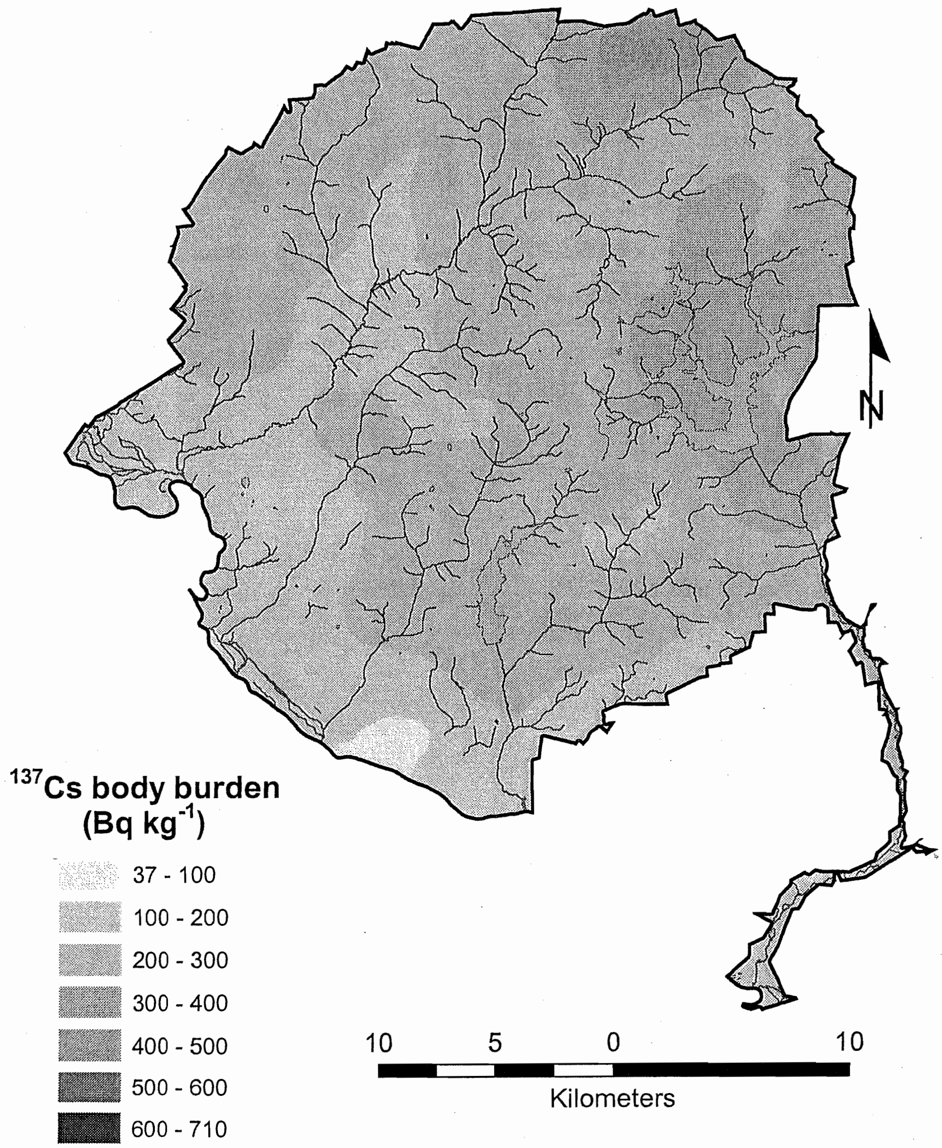
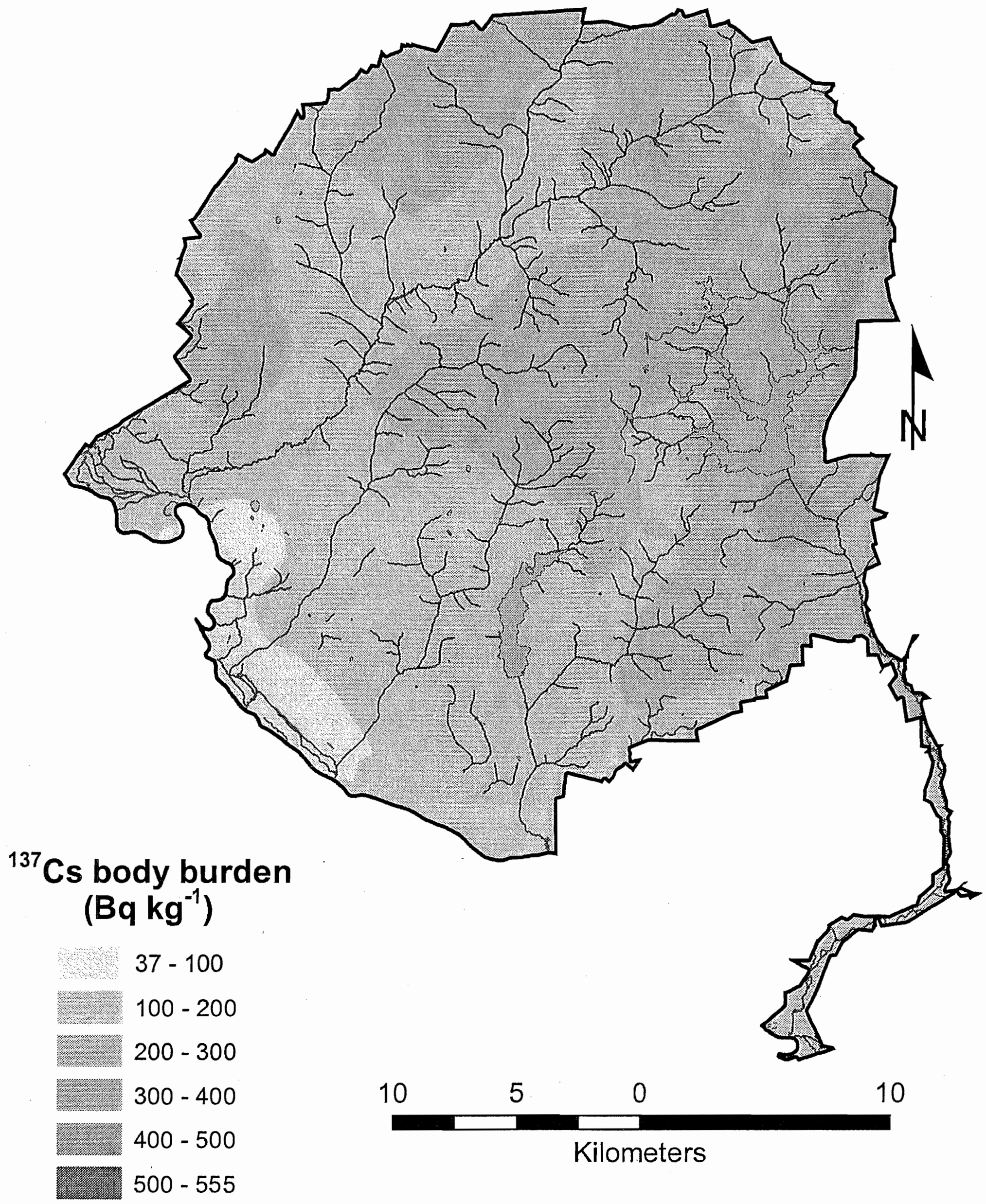


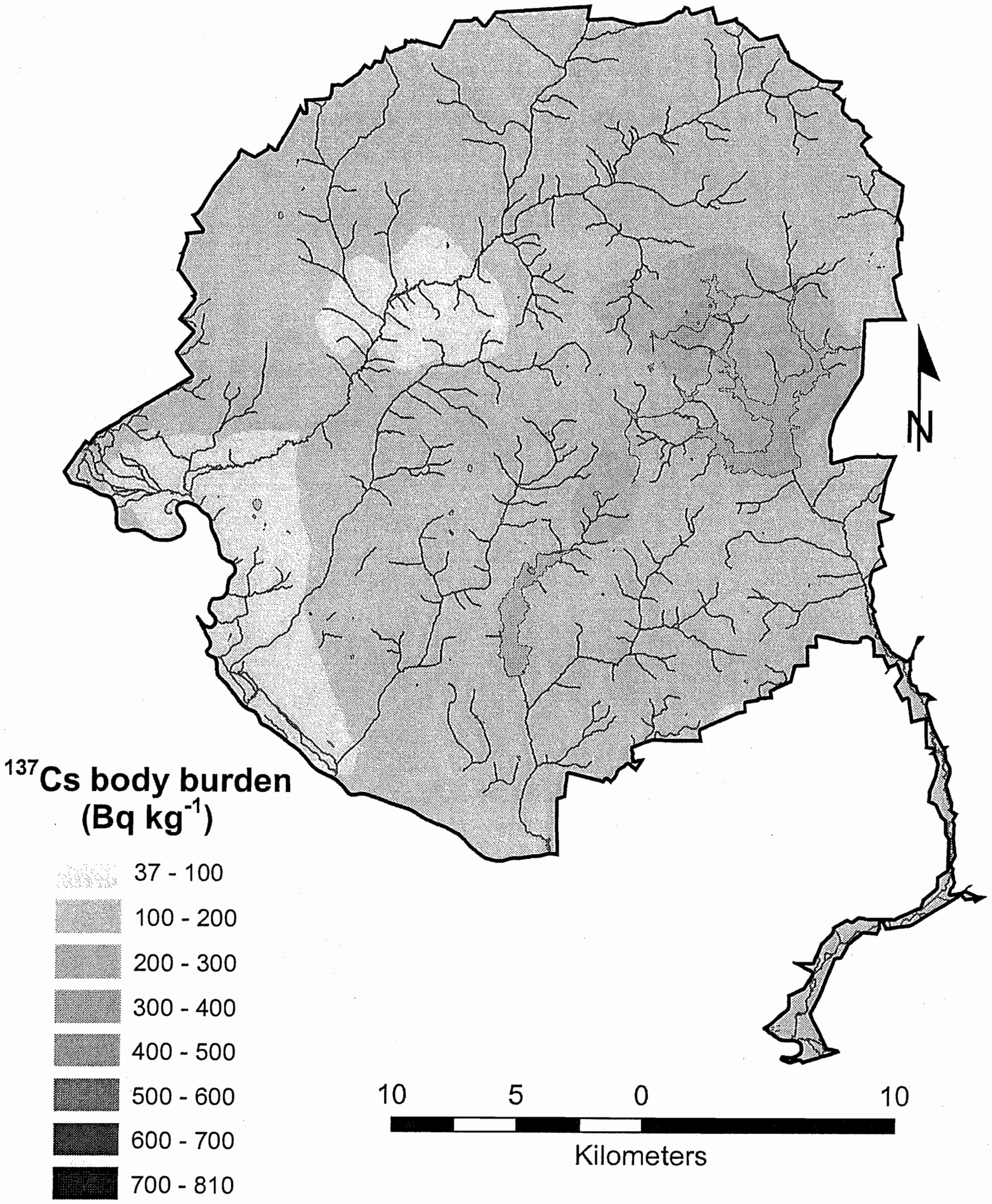
Fig. 4A – C. Three Ordinary kriging prediction surfaces of average radiocesium (^{137}Cs) body burdens (Bq kg $^{-1}$) for white-tailed deer on the Department of Energy's Savannah River Site (SRS), located in west-central South Carolina, USA. ^{137}Cs concentrations were gathered from SRS annual deer harvests for 1984-2005. The 21-year time frame was separated into three time series where kriging was used to predict ^{137}Cs distributions: (A) Model 1 (1984-1990), (B) Model 2 (1992-1995), and (C) Model 3 (1996-2005).

(B)



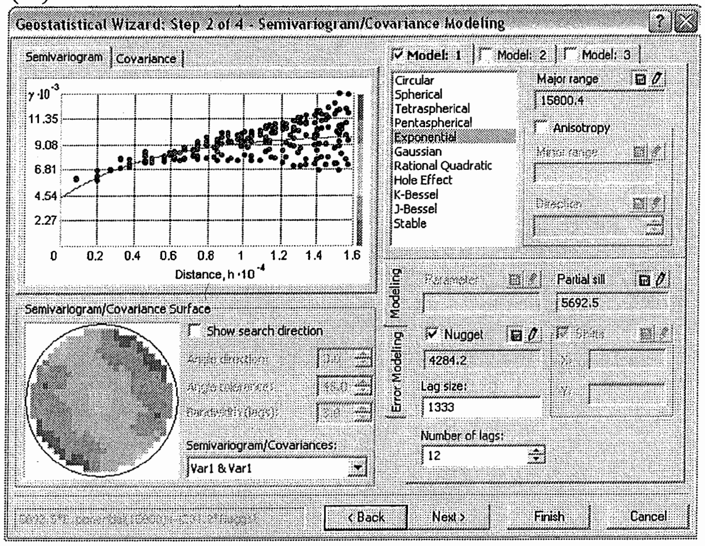
N
^{137}Cs body burden
(Bq kg^{-1})
37 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 555
10
5
0
10
Kilometers

(C)



^{137}Cs body burden
(Bq kg^{-1})
37 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
700 - 810
N
10 5 0 10
Kilometers

(A)



(B)

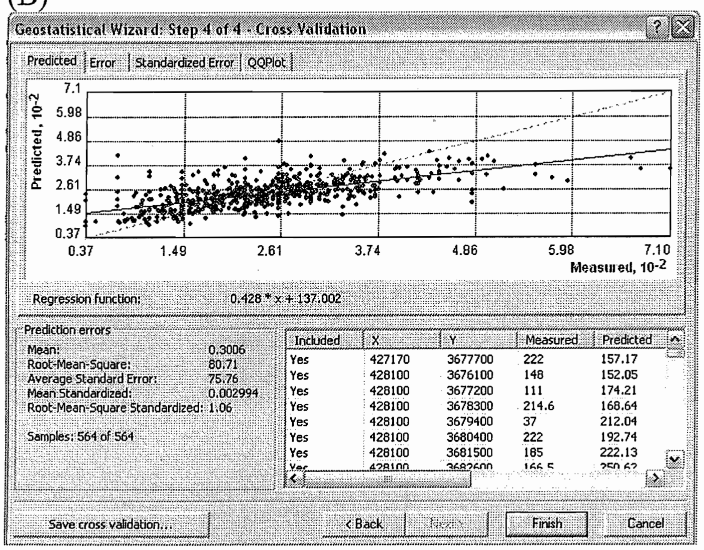
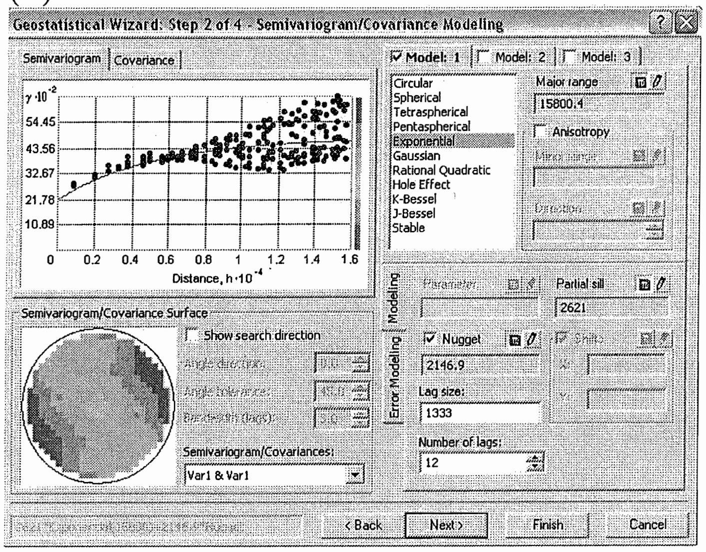


Fig. 5. Screen captures from the software module (ArcGIS ver. 9.3; ESRI Inc. ©) used for the ordinary kriging model using annual deer harvest data taken from 1984 – 1990 (data in screen capture are Bq kg^{-1}): (A) Exponential semivariogram showing the degree of autocorrelation between paired samples and (B) Cross validation that displays how the prediction values compare with actual values. This geostatistical interpolation function was used to determine the spatial autocorrelation between sampling locations, develop a surface to predict ^{137}Cs body-burdens for white-tailed deer on the Department of Energy's Savannah River Site, and to investigate outliers from the kriging prediction regression function.

(A)



(B)

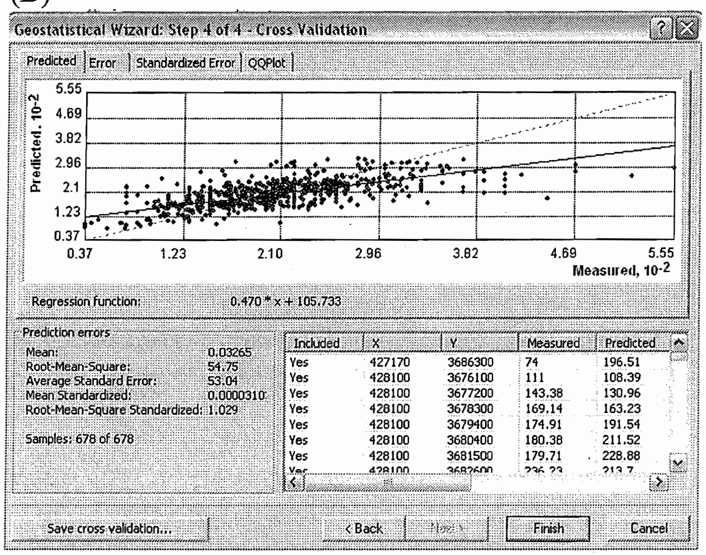
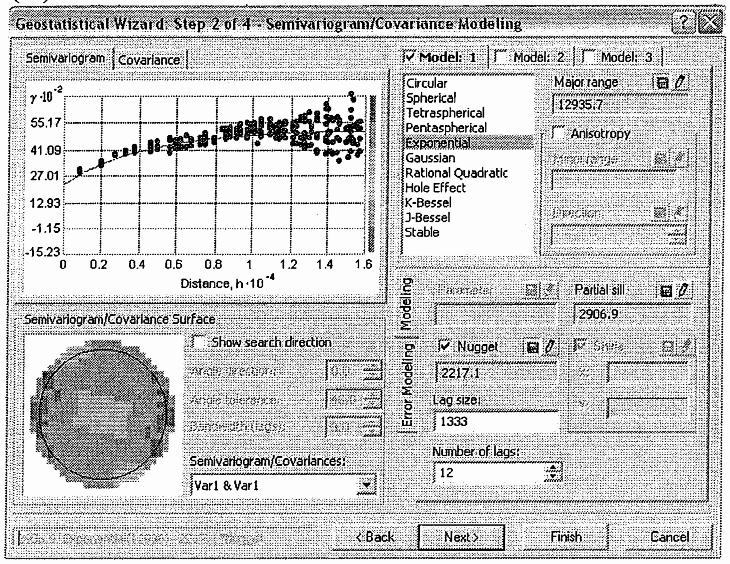


Fig 6. GIS screen captures of two processes used in ordinary kriging model using annual deer harvest data taken from 1992 – 1995 (data in screen capture are Bq kg^{-1}). This geostatistical process was used to develop a surface that predicted ^{137}Cs body-burdens for white-tailed deer on the Department of Energy's Savannah River Site. Data for 1991 was not available for analysis. (A) Exponential semivariogram showing the degree of autocorrelation between paired samples and (B) Cross validation that displays how the prediction values compare with actual values.

(A)



(B)

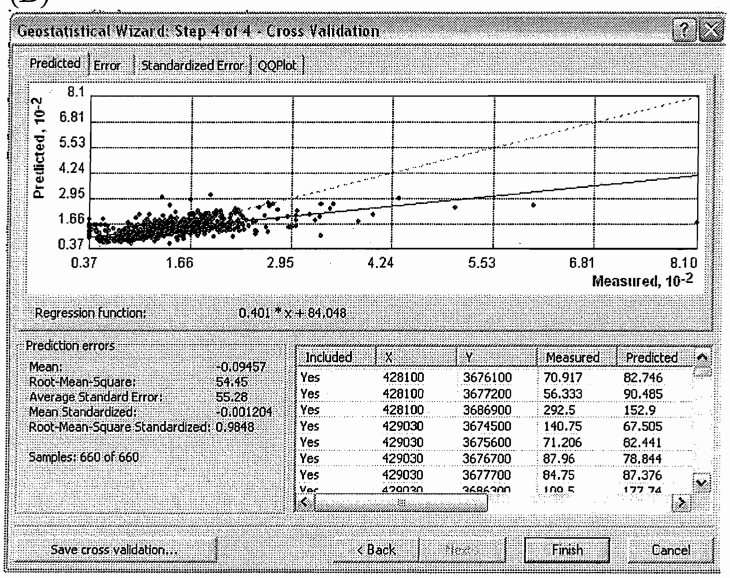


Fig 7. GIS screen captures of two processes used in ordinary kriging model using annual deer harvest data taken from 1996 – 2005 (data in screen capture are Bq kg^{-1}). This geostatistical process was used to develop a surface that predicted ^{137}Cs body-burdens for white-tailed deer on the Department of Energy's Savannah River Site. (A) Exponential semivariogram showing the degree of autocorrelation between paired samples and (B) Cross validation that displays how the prediction values compare with actual values.

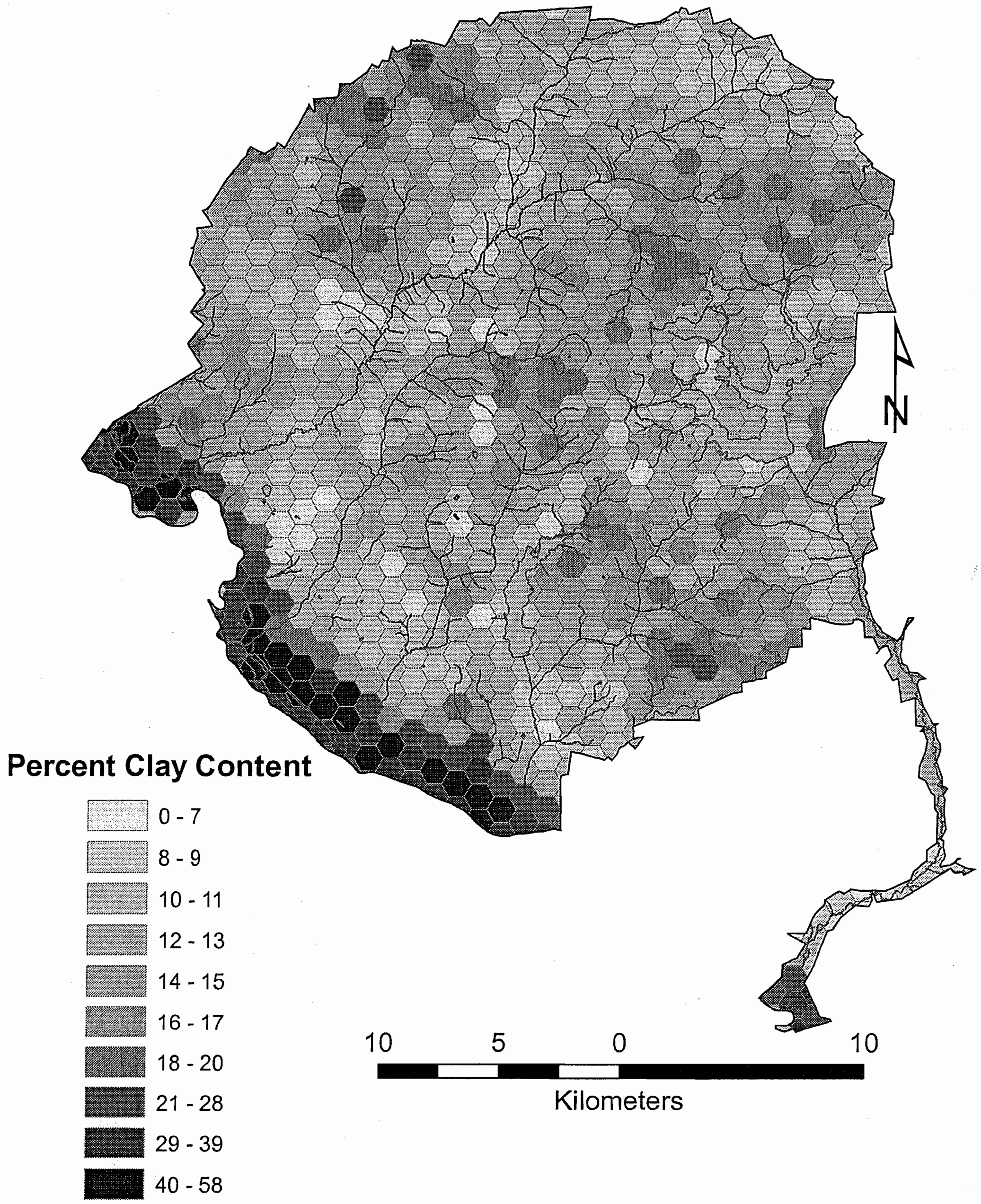


Fig. 8. Average percent clay content within each 100ha hexagon (e.g. white-tailed deer core/home-range size for the Savannah River Site (SRS)). Clay content is based on a 1987 soil survey conducted by the United States Department of Agriculture (USDA) National Resource Conservation Service (NRCS).

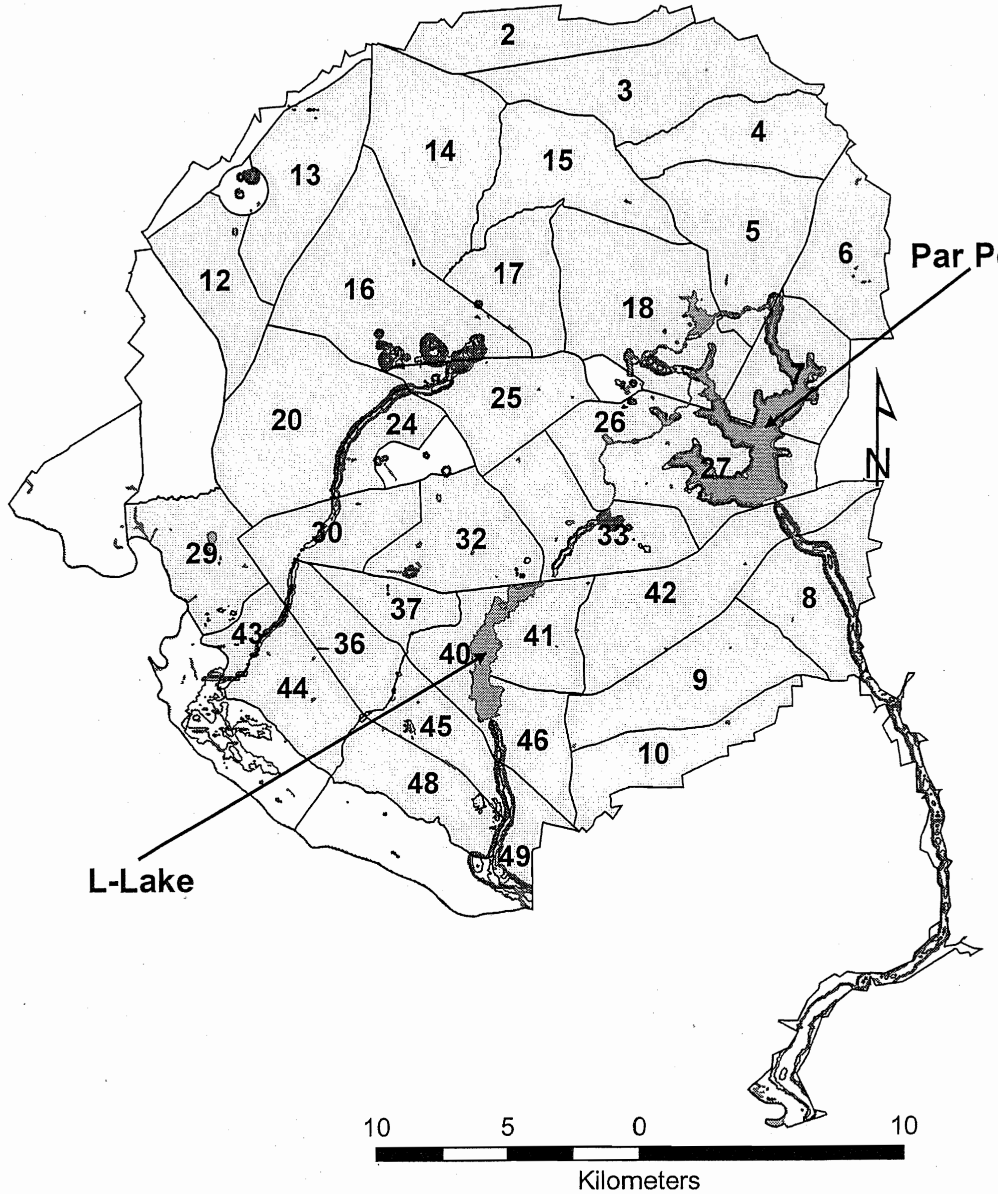


Fig 9. Map of the active hunting compartments on the Department of Energy's Savannah River Site (SRS) in relation to contaminated areas with radiocesium (^{137}Cs), as shown by red isopleths obtained by flyovers to detect gamma radiation. Areas in white are compartments not used during annual white-tailed deer hunts either due to inaccessibility, such as the Savannah River Floodplain/Swamp in the south west, or areas with industrial/commercial activity. Par Pond and L-Lake are two man-made reservoirs that have been contaminated from onsite activities.

Table 1. Habitat categories, identification numbers (HABID), area (ha), and percent composition of habitats found on the Department of Energy's Savannah River Site (SRS) located in west-central South Carolina, USA. Data was obtained from supervised classifications from 30m Landsat Thematic Mapper Data of the SRS (Pinder et al. 1998). HABID is the numeric identification given to each habitat type. HABIDs with "M" indicate habitats merged together (italicized habitat category names) with the above numeric value (capitalized habitat category name) before GIS analyses were performed.

HABID	Habitat Category	Hectare (ha)	Percent Composition (%)
1	BARE SOIL/BARE SURFACE	236.92	0
2	BOTTOMLANDS	6387.54	8
2M	*Bald Cypress / Water Tupelo*	2595.51	3
2M	*Bottom Hardwoods and Cypress*	308.40	0
2M	*Mixed Bottomland Hardwoods*	3483.64	4
3	DENSE - CANOPY	11478.86	14
3M	*Dense - Canopy Loblolly*	2708.83	3
3M	*Dense - Canopy Longleaf*	2545.98	3
3M	*Dense - Canopy Pine*	345.49	0
3M	*Dense - Canopy Slash*	2874.53	4
3M	*Young, Dense - Canopy Loblolly*	2615.33	3
3M	*Young, Dense - Canopy Longleaf*	324.54	0
3M	*Young, Dense - Canopy Slash*	64.17	0
4	DISTURBED & REVEGETATED IN 1997	123.76	0
5	EMERGENT	501.34	1
5M	*Marsh / Macrophytes*	416.59	1
5M	*Wetland Scrub Forests*	84.76	0
6	EVERGREEN HARDWOODS	842.75	1
7	FLOODPLAIN	9643.94	12
7M	*Floodplain Oak Forests*	1320.46	2
7M	*Floodplain Sweetgum Forests*	7001.63	9
7M	*Mixed - Composition Floodplain Hardwoods*	1321.85	2
8	GSF	5619.33	7
8M	*Grasses and Forbs*	3069.96	4
8M	*Shrubs, Grasses and Forbs*	2549.36	3
8M	INDUSTRIAL	525.39	1
9	OPEN - CANOPY	32052.48	40
9M	*Open - Canopy Loblolly*	12050.58	15
9M	*Open - Canopy Longleaf*	6879.21	9
9M	*Open - Canopy Pines*	3697.88	5
9M	*Open - Canopy Slash*	4153.54	5
9M	*Young, Open - Canopy Loblolly*	3630.13	5
9M	*Young, Open - Canopy Longleaf*	1587.15	2
9M	*Young, Open - Canopy Slash*	54.00	0
10	SPARSE HERBACEOUS VEGETATION	1084.17	1

11	UPLAND	9958.94	12
11M	*Upland Hardwoods*	6365.48	8
11M	*Upland Oak Hardwoods*	1465.37	2
11M	*Upland Scrub Forests*	2128.08	3
12	WATER	1811.13	2

Table 2A – G. Summary of 7 linear regression models and parameter estimates describing radiocesium (^{137}Cs) concentrations as a function of habitat types, average clay content, and habitat structure on the Department of Energy's Savannah River Site (SRS) located in west-central South Carolina, USA. Analyses were performed over three time series (1984-1990, 1992-1995, and 1996-2005) for 6 watersheds on the SRS (A) Upper Three Runs, (B) Lower Three Runs, (C) Four Mile, (D) Pen Branch, (E) Steel Creek, (F) Savannah River Swamp, as well as an overall model that incorporating the entire SRS, (G). The most parsimonious models were chosen based on Akaike information criteria (AIC) for all model variables. Variable output parameters denoted as "ns" were not used in selected models as determined via AIC.

(A)

Upper Three Runs			
	Time Series		
Model Parameters	1984 - 1990	1992 - 1995	1996 - 2005
F Value	16.58	8.67	7.13
Pr > F	<.0001	<.0001	<.0001
Adj R-square	0.2266	0.1868	0.1944
AIC	2402.46	2144.83	1981.35
	1984 - 1990	1992 - 1995	1996 - 2005
Habitat Variables	Pr>|t| (t-value)	Pr>|t| (t-value)	Pr>|t| (t-value)
Average Clay	ns	0.0063 (2.76)	0.0315 (2.16)
Bottomlands	ns	ns	0.1187 (1.57)
Dense Canopy	ns	0.0004 (3.61)	0.0095 (2.62)
Emergent	0.2521 (-1.15)	ns	ns
Evergreen	ns	0.0069 (-2.73)	ns
Floodplain	ns	0.0493 (1.98)	0.0099 (2.60)
Grasses, Shrubs and Forbs	0.0412 (-2.05)	ns	0.1267 (1.53)
Open Canopy	<0.0001 (5.77)	0.0005 (3.5)	0.0003 (3.66)
Sparse Herbaceous	ns	ns	0.0107 (2.57)
Upland	0.1091 (1.61)	ns	0.003 (3.0)
Water	ns	0.2711 (-1.1)	ns
MSI[a]	ns	ns	0.0121 (-2.53)
MPFD[a]	ns	0.2423 (1.17)	ns
MPS[a]	ns	ns	ns
NumP[a]	0.1205 (-1.56)	ns	ns
MedPS[a]	ns	0.0601 (1.89)	0.0127 (2.51)
PSCoV[a]	ns	ns	ns

[a]Patch Analyst habitat structure metrics: (see Appendix A for full metric descriptions).

(B)

Lower Three Runs			
	Time Series		
Model Parameters	1984 - 1990	1992 - 1995	1996 - 2005
F Value	3.44	2.68	5.86
Pr > F	0.0008	0.0173	<.0001
Adj R-square	0.1401	0.0692	0.1713
AIC	1254.87	1172.65	1232.75
	1984 - 1990	1992 - 1995	1996 - 2005
Habitat Variables	Pr>|t| (t-value)	Pr>|t| (t-value)	Pr>|t| (t-value)
Average Clay	0.0725 (-1.81)	0.2912 (-1.06)	0.0063 (-2.77)
Bottomlands	ns	ns	ns
Dense Canopy	ns	ns	ns
Emergent	ns	ns	0.0009 (3.38)
Evergreen	0.0894 (1.71)	ns	ns
Floodplain	0.188 (1.32)	0.0783 (1.77)	0.0082 (-2.68)
Grasses, Shrubs and Forbs	ns	ns	ns
Open Canopy	0.0201 (2.35)	ns	ns
Sparse Herbaceous	0.2461 (1.17)	0.0583 (-1.91)	ns
Upland	ns	0.1282 (-1.53)	ns
Water	ns	ns	ns
AWMSI[a]	0.0327 (-2.16)	0.0528 (1.95)	ns
MPAR[a]	0.2789 (1.09)	ns	0.2728 (1.1)
MPFD[a]	ns	0.1671 (1.39)	ns
MPS[a]	0.0007 (3.47)	ns	ns
NumP[a]	0.0224 (2.31)	ns	0.1446 (-1.47)
MedPS[a]	ns	ns	0.1611 (1.41)

[a]Habitat structure variables: (see Appendix A for full metric descriptions).

(C)

Four Mile			
	Time Series		
Model Parameters	1984 - 1990	1992 - 1995	1996 - 2005
F Value	3.62	3.92	2.67
Pr > F	0.0067	0.0026	0.0197
Adj R-square	0.3437	0.2289	0.1676
AIC	356.33	500.12	424.31
	1984 - 1990	1992 - 1995	1996 - 2005
Habitat Variables	Pr>|t| (t-value)	Pr>|t| (t-value)	Pr>|t| (t-value)
Average Clay	ns	0.0027 (3.15)	0.108 (-1.64)
Bottomlands	ns	ns	ns
Dense Canopy	0.0005 (3.93)	ns	ns
Emergent	ns	0.235 (1.2)	0.1652 (-1.41)
Evergreen	ns	ns	0.1249 (-1.56)
Floodplain	0.028 (2.32)	0.1112 (-1.62)	ns
Grass, Shrubs and Forbs	0.0058 (2.99)	0.0198 (-2.4)	ns
Open Canopy	0.0006 (3.87)	ns	ns
Sparse Herbaceous	ns	0.0991 (1.68)	0.0653 (-1.88)
Upland	ns	ns	ns
Water	0.1212 (1.6)	0.1069 (1.64)	0.1643 (-1.41)
MSI[a]	0.0465 (-2.08)	ns	0.0464 (2.04)
MPAR[a]	ns	ns	ns
MPFD[a]	ns	ns	ns
NumP[a]	ns	ns	0.0037 (3.04)
MedPS[a]	0.0284 (2.31)	ns	ns
PSCoV[a]	ns	ns	ns

[a]Habitat structure variables: (see Appendix A for full metric descriptions).

(D)

Pen Branch			
	Time Series		
Model Parameters	1984 - 1990	1992 - 1995	1996 - 2005
F Value	4.44	2.97	2.89
Pr > F	0.0047	0.014	0.012
Adj R-square	0.4331	0.1647	0.1761
AIC	247.79	518.71	492.1

	1984 - 1990	1992 - 1995	1996 - 2005
Habitat Variables	Pr>|t| (t-value)	Pr>|t| (t-value)	Pr>|t| (t-value)
Average Clay	ns	ns	0.1672 (-1.4)
Bottomlands	ns	ns	ns
Dense Canopy	0.0844 (1.81)	ns	0.3106 (-1.02)
Emergent	0.1159 (-1.64)	ns	0.129 (-1.54)
Evergreen	0.2609 (1.16)	0.0888 (-1.73)	ns
Floodplain	0.0102 (2.82)	0.1209 (-1.58)	ns
Grasses, Shrubs and Forbs	ns	ns	ns
Open Canopy	0.0002 (4.57)	0.0017 (-3.31)	0.1857 (-1.34)
Sparse Herbaceous	ns	0.1698 (-1.39)	0.0019 (-3.26)
Upland	ns	0.0261 (-2.29)	ns
Water	ns	ns	ns
MSI[a]	ns	0.2942 (1.06)	ns
MPAR[a]	ns	ns	ns
MPFD[a]	ns	ns	0.2034 (1.29)
NumP[a]	0.0845 (-1.81)	ns	0.0491 (2.01)
PSCoV[a]	ns	ns	ns

[a]Habitat structure variables: (see Appendix A for full metric descriptions).

(E)

Steel Creek			
	Time Series		
Model Parameters	1984 - 1990	1992 - 1995	1996 - 2005
F Value	3.15	4.36	4.25
Pr > F	0.0209	0.0002	0.0004
Adj R-square	0.1234	0.2072	0.1823
AIC	513.07	843.83	896.74
	1984 - 1990	1992 - 1995	1996 - 2005
Habitat Variables	Pr>|t| (t-value)	Pr>|t| (t-value)	Pr>|t| (t-value)
Bottomlands	ns	0.0087 (2.68)	ns
Dense Canopy	ns	ns	ns
Emergent	ns	ns	ns
Evergreen	ns	ns	0.25 (1.16)
Floodplain	ns	0.0043 (-2.93)	ns
Grasses, Shrubs and Forbs	ns	0.0034 (-3.01)	0.0028 (-3.07)
Open Canopy	ns	ns	ns
Sparse Herbaceous	ns	0.0001 (4.0)	<0.0001 (4.4)
Upland	0.0914 (-1.72)	0.1323 (1.52)	0.1981 (1.3)
Water	ns	0.0341 (-2.15)	0.1001 (-1.66)
AWMSI[a]	0.3072 (1.03)	ns	0.0282 (2.23)
MSI[a]	ns	0.0435 (2.05)	0.0726 (-1.82)
MPAR[a]	ns	ns	ns
MPFD[a]	ns	ns	ns
MPS[a]	ns	ns	ns
NumP[a]	ns	ns	ns
MedPS[a]	0.0251 (2.3)	0.1359 (-1.5)	ns
PSCoV[a]	ns	ns	ns

[a]Habitat structure variables: (see Appendix A for full metric descriptions).

(F)

	Swamp		
	Time Series		
Model Parameters	1984 - 1990	1992 - 1995	1996 - 2005
F Value	4.55	6.65	2.95
Pr > F	0.0003	<.0001	0.0015
Adj R-square	0.2202	0.3982	0.2181
AIC	754.01	909.15	733.54

	1984 - 1990	1992 - 1995	1996 - 2005
Habitat Variables	Pr>|t| (t-value)	Pr>|t| (t-value)	Pr>|t| (t-value)
Average Clay	0.0444 (-2.04)	0.0602 (-1.9)	0.1491 (-1.46)
Bottomlands	ns	ns	ns
Dense Canopy	0.3118 (1.02)	0.0008 (3.48)	ns
Emergent	0.2037 (1.28)	ns	ns
Evergreen	0.1414 (-1.49)	0.1252 (1.55)	0.1533 (-1.44)
Floodplain	ns	0.0693 (1.84)	ns
Grasses, Shrubs and Forbs	ns	0.303 (1.04)	0.0395 (2.09)
Open Canopy	0.0076 (2.74)	<0.0001 (5.95)	0.3077 (1.03)
Sparse Herbaceous	0.0892 (-1.72)	ns	0.0113 (-2.59)
Upland	ns	ns	0.2745 (-1.1)
Water	ns	0.0053 (2.85)	0.0418 (2.07)
AWMSI[a]	ns	0.0022 (-3.15)	0.0038 (-2.98)
MSI[a]	ns	ns	ns
MPAR[a]	ns	0.1938 (-1.31)	0.18 (-1.35)
MPFD[a]	0.0314 (-2.19)	0.1969 (-1.3)	ns
NumP[a]	ns	0.0034 (-3.0)	0.1905 (-1.32)
MedPS[a]	ns	ns	0.0005 (3.61)
PSCoV[a]	ns	0.038 (2.1)	0.0497 (1.99)
PSSD[a]	ns	ns	0.1839 (-1.34)
CA[a]	ns	0.0254 (2.27)	ns

[a]Habitat structure variables: (see Appendix A for full metric descriptions).

(G)

SRS			
	Time Series		
Model Parameters	1984 - 1990	1992 - 1995	1996 - 2005
F Value	12.63	16.01	6.48
Pr > F	<.0001	<.0001	<.0001
Adj R-square	0.2117	0.1506	0.1043
AIC	5105.93	5690.80	5477.78
	1984 - 1990	1992 - 1995	1996 - 2005
Habitat Variables	Pr>|t| (t-value)	Pr>|t| (t-value)	Pr>|t| (t-value)
Average Clay	0.002 (-3.1)	ns	ns
Bottomlands	0.0383 (2.08)	0.1293 (-1.52)	0.0028 (3.0)
Dense Canopy	0.0053 (2.8)	0.1659 (1.39)	0.0002 (3.72)
Emergent	0.0003 (3.64)	0.1624 (1.4)	<0.0001 (4.11)
Evergreen	ns	0.0965 (-1.66)	0.1335 (1.5)
Floodplain	0.0095 (2.6)	ns	0.0009 (3.35)
Grass, Shrubs and Forbs	0.0098 (2.59)	ns	0.0048 (2.83)
OPEN_CANOPY	<0.0001 (4.54)	<0.0001 (7.34)	<0.0001 (4.49)
SPARSE_HERB	0.1811 (1.34)	ns	0.0016 (3.17)
UPLAND	0.0015 (3.2)	ns	0.0002 (3.81)
WATER	0.0016 (3.18)	ns	<0.0001 (4.47)
AWMSI[a]	0.1451 (-1.46)	0.1315 (-1.51)	ns
MSI[a]	ns	ns	0.1445 (-1.46)
MPAR[a]	ns	ns	ns
MPFD[a]	ns	ns	0.1305 (1.51)
NumP[a]	0.0169 (-2.4)	0.0691 (-1.82)	0.2455 (-1.16)
MedPS[a]	ns	0.2121 (-1.25)	ns
PSCoV[a]	0.2555 (1.14)	ns	0.0418 (-2.04)
PSSD[a]	ns	ns	ns

[a]Habitat structure variables: (see Appendix A for full metric descriptions).

Table 3A – C. Logistic regression summary statistics for time series time series (1984 – 1990) to determine if the number of white-tailed deer harvested was a function of hunting occurrences per 100 ha hexagon (HUNTED), as well as habitat characteristics found on the Department of Energy's Savannah River Site (SRS) located in west-central South Carolina, USA. Polychotomous binning was applied to time series 1984 – 1992 (A) and 1996 – 2005 (C) where the number of white-tailed deer kills per hex were ranked as (0 = low, 1 = moderate, and 3 = high). Only time series 1992 – 1995 (B) used a dichotomous bin frequency for the number of kill as 0 = low, 1 = high.

(A) Logistic regression summary statistics for time series 1984 – 1990 using polychotomous bin frequency.

Analysis of maximum likelihood estimates					
R-Square	0.0974				
Max-rescaled R-Square	0.12	(n=564)			
Variables	*df*	Parameter Estimate	Standard Error	Chi-Square	Pr > Value
Intercept 2	1	-6.0753	0.8912	46.4678	<0.0001
Intercept 1	1	-2.3387	0.8418	7.7179	0.0055
HUNTED	1	0.2564	0.0452	32.1913	<0.0001
Dense Canopy	1	0.0245	0.00745	10.8263	0.001
AWMSI[a]	1	0.661	0.3024	4.7799	0.0288
NumP[a]	1	0.00759	0.00345	4.849	0.0277

[a]Landscape metrics describing habitat structure on the SRS (see Appendix A for full metric descriptions).

(B) Logistic regression summary statistics for time series 1992 – 1995 using dichotomous bin frequency.

Analysis of maximum likelihood estimates					
R-Square	0.068				
Max-rescaled R-Square	0.092	(n=678)			
Variables	*df*	Parameter Estimate	Standard Error	Chi-Square	P-Value
Intercept	1	-8.2314	2.2171	13.7838	0.0002
Dense Canopy	1	0.0401	0.00816	24.099	<0.0001
Floodplain	1	0.0502	0.00898	31.1963	<0.0001
Open Canopy	1	0.0304	0.00612	24.673	<0.0001
Upland	1	0.0266	0.0113	5.6073	0.0179
MSI[a]	1	3.57	1.437	6.172	0.013
NumP[a]	1	0.00816	0.00331	6.0839	0.0136

[a]Landscape metrics describing habitat structure on the SRS (see Appendix A for full metric descriptions).

(C) Logistic regression summary statistics for time series 1996 – 2005 using polychotomous bin frequency.

Analysis of maximum likelihood estimates					
R-Square	0.102				
Max-rescaled R-Square	0.115	(n = 660)			
Variables	*df*	Parameter Estimate	Standard Error	Chi-Square	P-Value
Intercept 2	1	-10.4684	1.9975	27.4644	<0.0001
Intercept 1	1	-8.5483	1.9833	18.5767	<0.0001
Bottomlands	1	0.0458	0.0107	18.4814	<0.0001
Dense Canopy	1	0.0423	0.00793	28.437	<0.0001
Floodplain	1	0.0474	0.00791	35.8141	<0.0001
Open Canopy	1	0.0329	0.00638	26.513	<0.0001
Upland	1	0.0594	0.0105	31.8011	<0.0001
MSI[a]	1	3.8696	1.2491	9.5965	0.0019
NumP[a]	1	0.00765	0.00305	6.2741	0.0123

[a]Landscape metrics describing habitat structure on the SRS (see Appendix A for full metric descriptions).

APPENDIX A. LANDSCAPE METRIC DEFINITIONS

Class level metrics used to describe the structure of habitats on the Savannah River Site (SRS) and used in linear and logistic regression analyses as potential explanatory variables for white-tailed deer mean ^{137}Cs concentrations and white-tailed deer occurrences.

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 patches 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)	Amount of edge relative to the landscape area. ED=TE/NumP.
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 1 for shapes with simple perimeters and approaches 2 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.