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Toxicodynamic modeling of 137Cs to estimate white-tailed deer background levels for the Department of Energy's Savannah River Site

Karen F. Gaines, James M. Novak, Christopher W. Bobryk, & Susan A. Blas

Abstract The U.S. Department of Energy's (USDOE) Savannah River Site (SRS) is a former nuclear weapon material production and current research facility adjacent to the Savannah River in South Carolina, USA. The purpose of this study was to determine the background radiocesium (137Cs) body burden (e.g., from global fallout) for white-tailed deer (Odocoileus virginianus) inhabiting the SRS. To differentiate what the background burden is for the SRS versus 137Cs obtained from SRS nuclear activities, data were analyzed spatially, temporally and compared to other off-site hunting areas near the SRS. The specific objectives of this study were: to compare SRS and offsite deer herds based on time and space; to interpret comparisons based on how data were collected as well as the effect of environmental and anthropogenic influences; to determine what the ecological half-life/decay rate is for 137Cs in the SRS deer herd; and to give a recommendation to what should be considered the background 137Cs level in the SRS deer herd. Based on the available information and analyses, it is recommended that the determination of what is considered background for the SRS deer herd be derived from data collected from the SRS deer herd itself and not offsite collections for a variety of reasons. Offsite data show extreme variability most likely due to environmental factors such as soil type and land-use patterns (e.g., forest, agriculture, residential activities). This can be seen fromresultswhere samples from offsite military bases (Fort Jackson and Fort Stewart) without anthropogenic 137Cs sources were much higher than both the SRS and a nearby (Sandhills) study site. Moreover, deer from private hunting grounds have the potential to be baited with corn, thus artificially lowering their 137Cs body burdens compared to other freeranging deer. Additionally, sample size for offsite collections were not robust enough to calculate a temporal decay curve with an upper confidence level to determine if the herds are following predicted radioactive decay rates like the SRS or if the variability is due to those points described above. Using mean yearly values, the ecological half-life for 137Cs body burdens for SRS white-tailed deer was determined to be 28.79 years—very close to the 30.2 years physical half-life.

Keywords 137Cs . Body burden . Ecological half-life .Radiocesium. Toxicodynamics . White-tailed deer

Introduction

The purpose of this study was to determine the background radiocesium (137Cs) body burden (e.g., from global fallout) for white-tailed deer (Odocoileus virginianus) inhabiting the U.S. Department of Energy's (USDOE) Savannah River Site (SRS). The SRS, an 803-km2 facility located in west-central South Carolina, has had public access strictly controlled since its opening in 1951 (Fig. 1). The SRS was established by the Atomic Energy Commission (now the USDOE) for the purposes of making weapons-grade material for nuclear bombs and, as such, was comprised of five active nuclear reactors. By 1988, all five reactors ceased operations and are now in various stages of decommissioning. During processing, the reactors produced materials consisting of tritium (3H), uranium (U), plutonium (Pu) and ancillary fission products. The fission of 235U in fuel elements during normal operations, as well as leaks in storage containments, released 137Cs into the environment and, consequently, contaminated SRS terrestrial and aquatic ecosystems (Carlton et al. 1992; Gaines et al. 2000). Although technically a strong beta radionuclide, 137Cs is in a metastable state with 137Ba, a gamma-emitting radionuclide, with a physical half-life of 2.552 min. However, the 662 keV gamma ray appears with the half-life of 137Cs, which is 30.2 years, because the two isotopes are in secular equilibrium (Gilmore and Hemingway 1995). 137Cs is traditionally regarded and listed in tables as "the 137Cs gamma," although this energy is truly a daughter product and is therefore detected and quantified via gamma spectroscopy (Gilmore and Hemingway 1995). Since these releases, human activities and ecological processes in and around the SRS have influenced the bioavailability and transport of 137Cs, the most widely distributed radioactive contaminant on the site (Gaines et al. 2000).

Given that most of the SRS was/nor is currently industrialized, the vegetation structure is either relatively undisturbed or has been converted to pine for timber production. Concurrently, wildlife populations [primarily white-tailed deer and later feral hog (Sus scrofa)] grew during the early years of SRS operation due to the available habitat and the elimination of hunting pressure (Gaines et al. 2000). During the 1950s and early 1960s, because of the growing herd size, animal-vehicle accidents were increasing throughout the SRS. In 1965, based primarily on the concerns over the increasing number of accidents, as well as the health of the herd, the SRS began to sponsor an annual deer harvest, open to the public. Early SRS hunts were dog drive hunts and then from 1969 through 1980, a combination of dog drive and still hunts were used. In 1981, the hunts were changed back to a dog drive format exclusively. Hunts were conducted annually (the 2001 hunt was delayed due to security concerns and thus only a relatively small proportion of the site was hunted. From 1965 to 1969, all animals were monitored in the field with a G-M detector for gross beta/gamma activity levels (Fledderman 1992). This screening provided a means of releasing an animal to the hunter, although the activity was not quantified. Muscle plugs from approximately 20 % of the animals were sampled for laboratory analysis using the appropriate beta and gamma spectrometry to detect the radionuclides of concern, these results confirmed that the activity was indeed 137Cs (Rabon and Johnson 1973; Watts et al. 1983). In 1970, a portable scintillation detector was used in the field to screen all animals prior to release to the hunter; this system also provided a means of quantifying radionuclide concentrations in the animal (Rabon and Johnson 1973). The monitoring was performed to ensure animals are not released to the hunter if the hunter's dose (from consumption) would exceed the annual administrative dose limit. In the 1980s, a 100 pCi/g release limit was implemented for game animals. In 2006, an administrative release limit of 30 mrem was applied. In April 2012, the dose limit was further reduced to an even mor conservative dose of 22 mrem/year. In addition, cumulative estimated dose rates for hunters were calculated based upon the total number of deer harvested by each hunter each hunt year. The system for tracking cumulative hunter dose began in 2007.

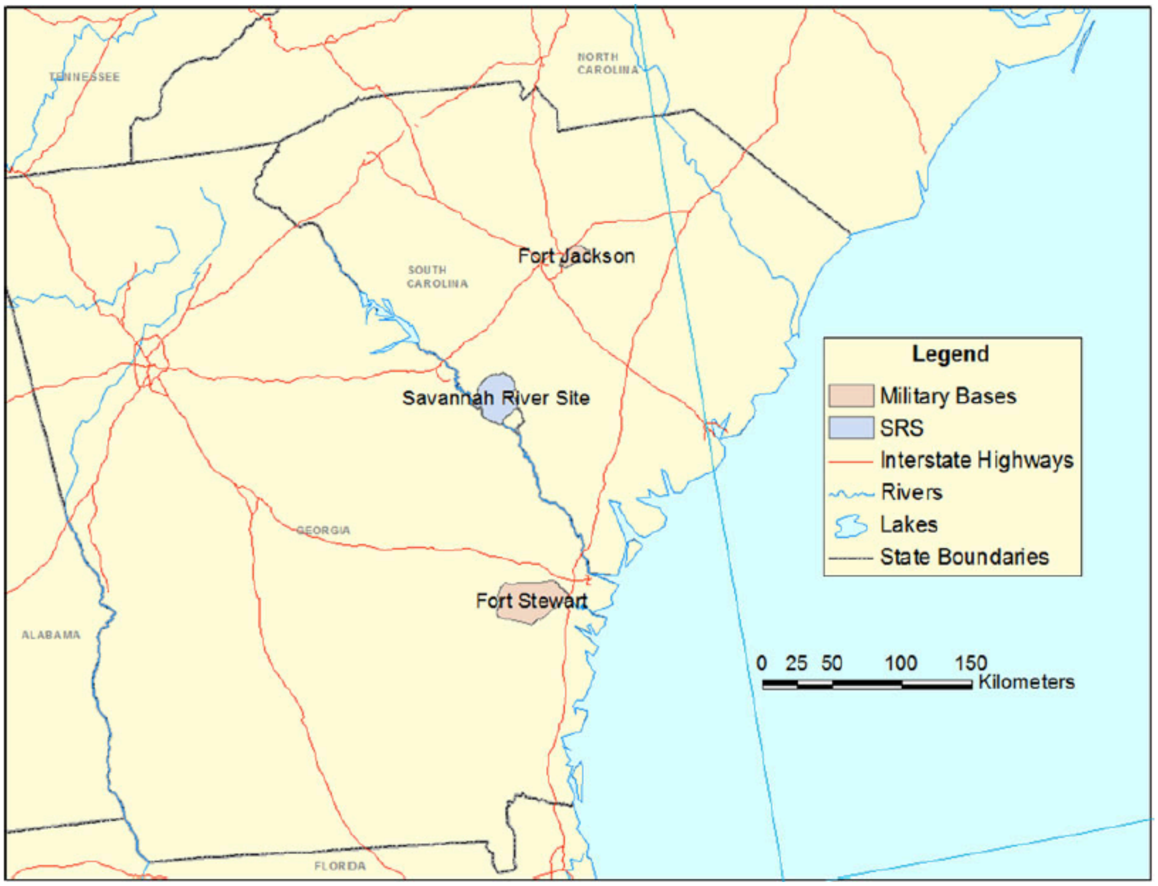

Fig. 1 Map of the Department of Energy's Savannah River Site (SRS) located in west-central South Carolina. Two military bases (Fort Jackson, Fort Stewart) where white-tailed deer were sampled for this study are also shown

137Cs acts as an elemental analogue to potassium (K) and, as such, if K is unavailable or limited in the environment, 137Cs will be taken up by biota [conversely, addition of K to soil has been shown to reduce uptake of 137Cs; (Bulgakov 2007)]. When there is a homogenous distribution (e.g., global fallout is the main source term), habitat variables, especially soil type, will dictate 137Cs bioavailability within a system (Jenkins 1975, Jenkins et al. 1971; Whicker and Pinder 2002). For example, clay soils tend to retain 137Cs, while sandy soils tend not to retain K due to leaching, thus increasing 137Cs bioavailability. For example, this is the most plausible reason why deer from the Lower Coastal Plain region in South Carolina (approximately 150 km from the SRS) consistently have higher levels of 137Cs compared to deer from the Upper Coastal Plain which is where the SRS is located (Jenkins 1975; Jenkins et al. 1971). Analyzing data based on such vegetation structure and soil type to explain some of the variation associatedwith deer body burden is ideal. However, such analysis must be performed within the scale of the harvest itself. With SRS hunt compartments ranging from 3,458 to 5, 273 ha, the compartment is a statistically sound scale to investigate deer 137Cs levels. That is, since deer are run with dogs throughout a hunt compartment (Fig. 2) and their home range (the area in which they naturally reside) exceeds the spatial scale of the hunt stand itself, analyzing variation in 137Cs in the SRS deer herd at the compartment level will not be affected by the aforementioned variables. Deer studies on the SRS support this choice of scale (Sweeney 1970; Wentworth 1998), with a more recent study (D'angelo et al. 2003) showing home ranges of up to 500 ha withmean deermovements during SRS hunts to be 0.8 km.

To provide a comparison of SRS deer herd 137Cs body burdens with offsite deer herds, South Carolina Department of Health and Environmental Control (SCDHEC) has collected deer muscle plugs from areas offsite, but near the SRS and other various control sites further from the SRS (Figs. 1–2). Concurrently, laboratories associated with DOE-SRS have sampled deer from the perimeter of the SRS proper (Fig. 2). Offsite samples are useful in providing baseline information regarding other deer herds, but present challenges for direct comparison. Specifically, samples taken from private lands are heavily baited with corn. Therefore, the uptake of 137Cs by these animals will be reduced based on increased K levels in the corn from fertilizers (Heckman and Kamprath 1992; Stewart et al. 1965). How the hunts are performed and how the data are collected dictate the approaches to properly discern what background 137Cs concentrations are in the SRS deer herd and the specific objectives that can be addressed. SRS hunts are managed by harvesting animals on a rotational basis using a compartmental approach (Fig. 3). Specifically, the SRS is broken down into 52 labeled hunt compartments. However, some compartments are never hunted due to site activities, while some have been merged over the decades leaving units that are not labeled sequentially. Compartmental borders are based on natural and man-made boundaries as well as consideration of size and juxtaposition to industrial activities. Within each compartment, hunt stands are established by placing hunters at known locations, safely distanced from each other to harvest animals during the dog drives. Each hunt compartment is not necessarily hunted at the same rate or intensity, and therefore, these aforementioned variations must be considered during data analysis.

To differentiate what the background burden is for the SRS versus 137Cs obtained from SRS nuclear activities, data were analyzed spatially, temporally and compared to other off-site hunting areas near the SRS. When radioactive isotopes are released into ecosystems such as those associated with the SRS, the isotopes will also have an ecological half-life. Theoretically, this is the time required for the activity of a radioactive substance (in this case, 137Cs), once established and at equilibrium within a given ecosystem compartment, to decrease by 50 %. This is a result of the isotope either becoming ecologically unavailable or being physically removed from a system (Brisbin 1991). The concept of ecological half-life I additionally constrained by the fact that ecosystem compartments are dynamic and rarely achieve equilibrium. As the time required to reach effective equilibrium increases, it becomes less likely that these conditions will remain constant (Peters and Brisbin 1996). Therefore, having a relative estimate of the ecological half-life of any contaminant as it relates to the species uptake and depuration rate is essential in modeling contaminant mobility. That is, once these parameters are known, the spatiotemporal patterns can be better predicted. Therefore, the specific objectives of this study were to:

(1) Compare SRS and offsite deer herds based on time and space.

(2) Interpret comparisons based on how data were collected as well as the effect of environmental and anthropogenic influences.
(3) Determine what the ecological half-life/decay rate is for 137Cs in the SRS deer herd.
(4) Give a recommendation to what should be considered the background 137Cs level in the SRS deer herd.

These objectives are based on the hypothesis that the majority of 137Cs acquired by deer, regardless of location, is from global fallout. The methods describe below address these objectives while simultaneously testing this hypothesis. The results from this study can be applied to other site-specific contaminated areas such as the Chernobyl and Fukushima sites as well as others located in the USA.

Methods

Collection sites

Data used for this monitoring and assessment study were for deer collected and analyzed on the SRS via hunts as described above. Samples were also collected and analyzed by SRS personnel from offsite locations (broken into quadrats; Fig. 2) near the SRS, as well as by SRS personnel from military bases in South Carolina (Fort Jackson, Fort Stewart; Fig. 1). Muscle plugs from deer were also collected and analyzed by SCDHEC from 11 offsite locations throughout South Carolina (Fig. 2).

Statistical analysis

Hip-monitored data for the SRS were analyzed at the compartment level, year, 5-year period, and sample decade (e.g., 10-year time block) from 1965 to 2006. The years 1991 and 2000 were not available for analysis as the USDOE did not release the data. Compartments were adjusted for merge effects to preserve the spatial consistency of the analysis. For example, if two compartment were merged into one compartment, then data from the two compartments were always analyzed as one compartment even prior to the merge. Offsite deer collected from SC-DHEC and SRS laboratories were analyzed by year and location. All statistical analyses were performed in SAS® 9.1.3 (2004). To determine the ecological half-life for deer residing in their native habitat, the decay rate was estimated using both the mean and median of the dataset as well as $38^{th}/62^{nd}$ percentile which is statistically comparable to the arithmetic mean's 95 % confidence limits (Zar 1999). Predicted 137Cs body burdens for the next 100 years (starting in 2007) in 5-year increments for the SRS deer population (pCi g-1) at the compartmental level (comp.) were estimated using an exponential decay model. Each specific model and statistical test performed is outlined in the "Results" section below for clarity. Data estimates are presented as the arithmetic mean with lower/upper 95% confidence limits (LCL/UCL). Therefore, these confidence limits should be used to ensure that the estimated mean falls within those limits. To determine best estimates for individual deer, the lower and upper 95 % confidence limits of the data (LCLD/UCLD, respectively) were calculated using the standard deviation. These confidence limits should be used to

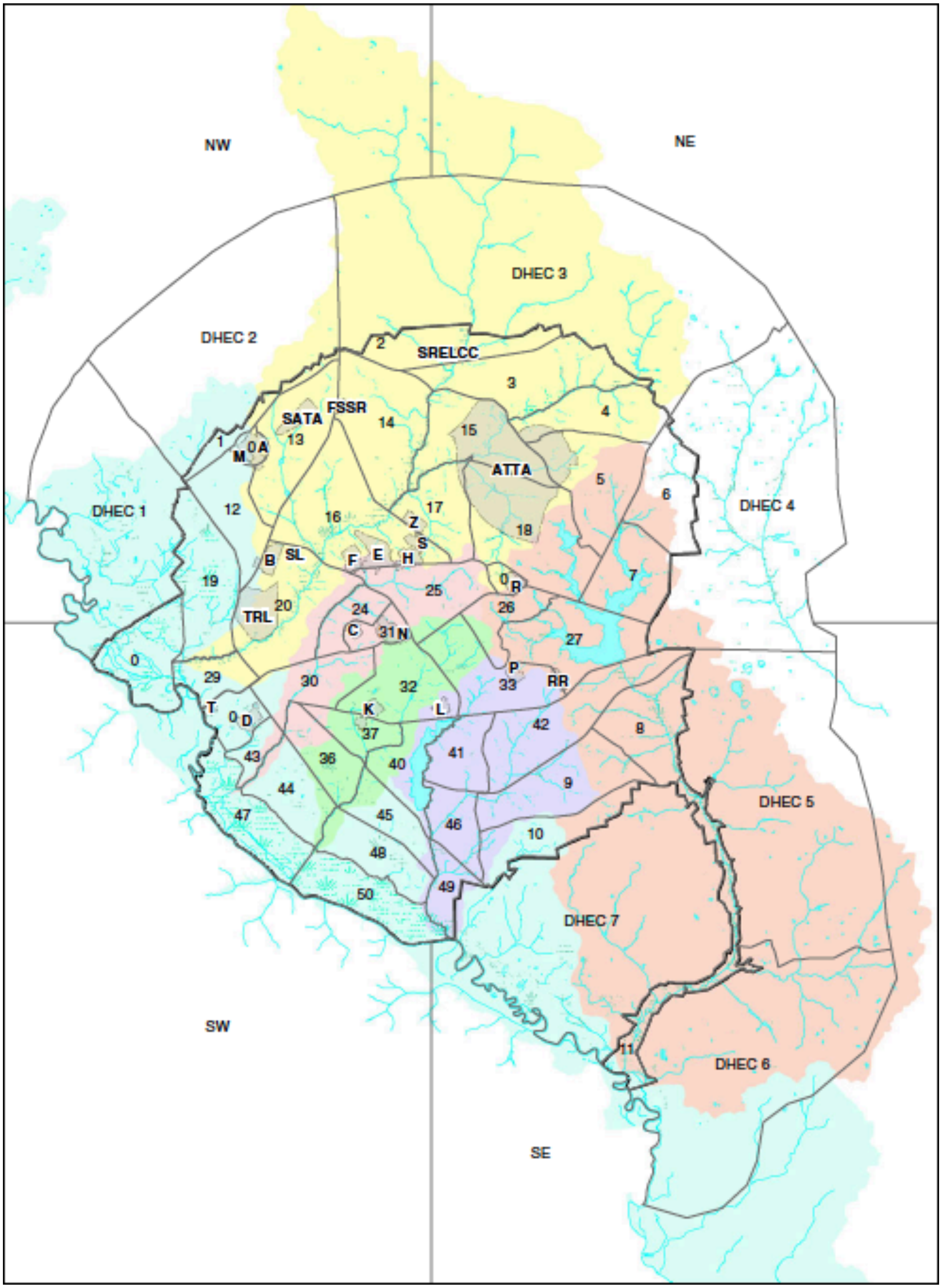

Fig. 2 Map of hunt compartments on the SRS (onsite) and nearby. sites off the SRS (quadrat: NW, NE, SE, SWand DHEC 1–7) that white-tailed deer were collected for this study. SRS facility areas that include industrial areas are also shown. Facility areas that are associated with radiological releases that present a potential exposure to game include F/H, L, P, and R areas

be 95 % confident that any individual deer's radiocesium body burden is in that range (Zar 1999). UCLDswere used for risk assessment purposes (e.g., to estimate the upper exposure threshold). These data are summarized by compartment, year, 5-year time blocks and 10-year time blocks. Analysis of covariance (ANCOVA) was used to test the effect of decade on the decline in 137Cs over time in white-tailed deer on the SRS. A nonsignificant slopeÅ~decade interaction would indicate a single trend following radioactive decay with no decade effect. This would imply that there is little or not enough remobilization/ new introductions of 137Cs in the environment to influence the uptake by the SRS deer herd. An analysis of variance (ANOVA) was used to determine if there were differences between body burdens in deer (pCi g-1) collected by SCDHEC from various areas off the SRS. An ANOVA was also used to determine if there were differences between body burdens in deer (pCi g-1) collected by SRS personnel from various areas off the SRS and directly adjacent to the SRS. 137Cs body burdens in deer (pCi g-1) collected near the SRS (Offsite SRS and Offsite SCDHEC) were summarized by year.

Results

SRS muscle plug data (yearly mean) were compared to the corresponding (yearly mean) hip monitor data using a Student's t test to determine if there is a difference in the two techniques. Muscle (x . 6:968 , SD=1.281) pCi g-1 was significantly higher than whole body (e.g., hip-monitored deer; x . 4:839 , SD=0.995) pCi g-1 (t=−4.338, n=9, P=0.0033). However, this analysis lacks statistical rigor because the samples themselves were not matched. Therefore, to ensure best estimates, only hip monitor data were used for all subsequent analyses because it provides much more strength in the statistical modeling. Moreover, only 20 % of SRS deer are sampled for muscle plugs, and the dataset archives do not always provide a matched ID with the hip monitor data, so estimating the true relationship between the hip-monitoring data and the muscle plug data over time is impossible. Since, other published reports have validated the muscle plug to hip monitor technique (see Fledderman 1992), there is no reason not to use these data to compare to other datasets.

137Cs body burdens in SRS deer (pCi g-1) at the compartmental level from1964 to 2006 showed large variation (Table 1). 137Cs body burdens in SRS deer (pCi g-1) analyzed at 5-year time blocks showed a slow decline with all half-decades significantly differing from each other except the 2nd and 4th time block (ANOVA: F=702.31, df=7, P<0.0001, R2=0.1128; Table 2). Moreover, the ANCOVA testing the effect of decade on the decline in 137Cs over time in white-tailed deer on the SRS showed a single trend following radioactive decay with no decade effect (Table 3). 137Cs body burdens in deer (pCi g-1) collected by SCDHEC ANOVA results showed that the "Sandhill" collection site was significantly higher than all other sites (F=27.27, df=10, P<0.0001) with no other sites being significantly different from each other (Table 4). 137Cs body burdens in offsite deer (pCi g-1) collected by SRS personnel ANOVA results (F=58.88, df=5, P<0.0001) showed that both the "Fort Jackson" and "Fort Stewart" collection sites were significantly higher than all other sites, but not significantly different from each other with no other sites being significantly different from each other

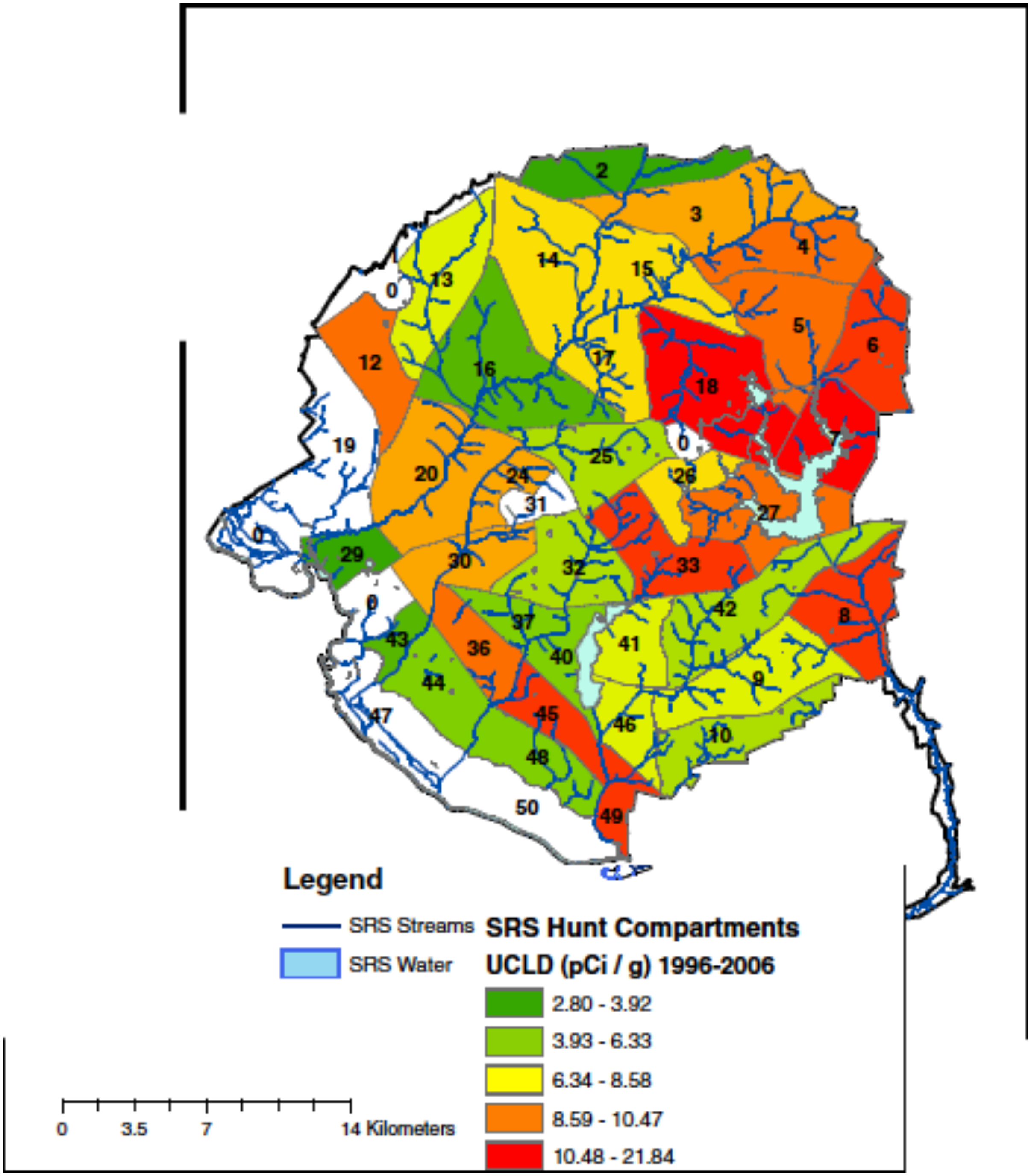

Fig. 3 Spatial distribution of the 95%upper confidence limit of the data (UCLD) for radiocesium (pCi g-1) in SRS deer at the compartment level from 1996 to 2006. Compartments (labeled) near and downstream from SRS nuclear activities tend to have higher radiocesium levels than the rest of the SRS. However, deer from unimpacted compartments far from industrial activities such as those in the north and western portion of the SRS also have elevated radiocesium levels compared to the rest of the SRS. Compartment numbers without color (e.g., 0, 1, 19, 31, 47, 50) are not hunted

Table 1 Radiocesium body burdens in SRS deer (pCi g^{-1}) at the compartmental level (Comp.) from 1964 to 2006

Comp.	N	LCL	$\overline{x}$	UCL
Missing	44	2.8642	4.2830	5.7018
2*	20	1.1802	1.4778	1.7753
3*	1,223	7.7176	8.0659	8.4143
4*	1,031	8.1683	8.6563	9.1444
5	1,990	8.3424	8.5990	8.8555
6	814	8.2382	8.6660	9.0937
7	961	8.7519	9.1518	9.5517
8	1,548	8.8010	9.2012	9.6014
9*	1,603	7.1325	7.3900	7.6476
10*	1,240	4.7290	4.9332	5.1373
12*	476	5.8492	6.2203	6.5915
13*	753	6.2712	6.6192	6.9673
14*	1,313	6.8470	7.1694	7.4919
15*	1,541	7.4855	7.7715	8.0575
16	1,680	4.6136	4.8267	5.0399
17	1,231	7.7482	8.0884	8.4286
18	1,904	7.6391	7.8814	8.1237
19	689	7.0814	7.4456	7.8098
20	1,605	5.0226	5.3027	5.5827
23	60	6.4856	7.6667	8.8478
24	285	7.9763	8.7657	9.5550
25	1,256	5.1703	5.4284	5.6865
26	447	7.7471	8.2826	8.8181
27	898	6.8063	7.1263	7.4463
29	1,286	2.4702	2.5922	2.7142
30	808	6.3566	6.7140	7.0715
32	934	5.0225	5.2665	5.5105
33	1,119	5.9746	6.2612	6.5477
36	758	6.9835	7.4121	7.8407
37	237	5.4802	6.3259	7.1717
40	492	5.6885	6.2144	6.7402
41	702	6.9324	7.3511	7.7699
42	1,650	5.6838	5.9392	6.1946
43	448	3.0677	3.3177	3.5677
44	2,121	5.0479	5.2813	5.5147
45	684	7.3293	7.8049	8.2805
46	918	4.8104	5.1213	5.4322
48	1,540	5.3679	5.6737	5.9796
49	346	6.5028	7.3487	8.1946
SRS	38,660	6.6658	6.7236	6.7814

Data are presented as the arithmetic mean with lower/upper 95 % confidence limit (LCL/UCL). Background compartments (2–4, 9–15) are indicated with an asterisk (*). Data that were not assigned a compartment were categorized as missing

Table 2 Radiocesium body burdens in SRS deer (pCi g^{-1}) an lyzed at 5-year time blocks

Years	N	LCL	$\overline{x}$	UCL
65–69	587	9.4464	10.1090	10.771
70–74	5170	7.7387	7.9321	8.125
75–79	6244	8.7623	8.9113	9.060
80–84	7102	7.9362	8.0995	8.262
85–89	4094	7.2020	7.3600	7.518
90–95	6387	5.4029	5.4829	5.562
96–01	5424	4.0237	4.1188	4.213
02–06	3652	3.2792	3.3777	3.476

Data are presented as the arithmetic mean with lower/upper 95 confidence limit (LCL/UCL). All half-decades significantly di fered from each other except the 2nd and 4th time block (ANOV $F=702.31$; $df=7, 38652$; $P=0.0000$; $R^2=0.1128$)

Mean 137Cs body burdens and 95 % confidence limits in SRS deer (pCi g-1) by year and the estimated decay rate based on both exponential and linear models with their coefficient of determination (R square) explained similar amounts of variation with similar slopes (Fig. 4). Specifically, the exponential model explains 50 % of the variation, while the linear model explains 46 % of the variation. The ecological half-life for 137Cs body burdens based on the linear model is 28.79 years, while the ecological half-life for 137Cs body burdens based on the exponential model is 28.17 years. Similarly, median 137Cs body burdens and 95 % confidence limits (nonparametric 38^{th} and 62^{nd} percentile) in SRS deer (pCi g-1) by year and the estimated decay rate based on both exponential and linear models with their coefficient of determination (R square) were similar to each other with similar ecological half-lives to those estimated for the mean. The exponential model explained 42 % of the variation while the linear model explained 37 % of the variation. The ecological half-life for 137Cs body burdens based on the linear model is 29.57 years,while the ecological half-life for 137Cs body burdens based on the exponential model is 22.36 years.

Discussion and management recommendations

Based on the available information and analyses, it is recommended that the determination of what is considered background for the SRS deer herd be derived from data collected from the SRS deer herd itself and not offsite collections for the following reasons:

Table 3 Analysis of covariance (ANCOVA) testing the effect of decade on the decline in radiocesium over time in white-tailed deer on the SRS

Source	nDF	Type III SS	Mean square	*F* value	*P* value
Decade	3	8.5181	2.8394	0.46	0.7118
Slope	1	19.2742	19.2742	3.13	0.0866
Slope×Decade	3	4.4620	1.4873	0.24	0.8669

Results (e.g., nonsignificant slope×decade interaction) indicate a single trend following radioactive decay with no decade effect. This would imply that there is little or not enough remobilization/new introductions of radiocesium in the environment to influence the uptake by the SRS deer herd. The denominator degrees of freedom is 32 for all tests

nDF is numerator degrees of freedom

(1) Offsite data show extreme variability most likely due to environmental factors such as soil type and land-use patterns (e.g., forest, agriculture, residential activities). This can be seen from results presented in Tables 4–6, where samples from Fort Jackson and Fort Stewart (x . 7:49; 8:87 pCi g-1, respectively) were much higher than both the SRS (previous two decades) and the Sandhills study site (x . 3:99; 3:90 pCi g-1, respectively).

(2) Deer from private hunting grounds have the potential to be baited with corn, thus artificially lowering their 137Cs body burdens compared to other freeranging deer. This is themost likely explanation for the extremely low values measured in deer near the perimeter of the SRS and the Bowman hunt club (Tables 4–5).

(3) Sample size for offsite collections are not robust enough to calculate a temporal decay curve with an upper confidence level to determine if the offsite herds are following predicted radioactive decay rates like the SRS or if the variability is due to those points described above.

Table 4 Radiocesium body burdens in deer (pCi g^{-1}) collected by South Carolina Department of Health and Environmental Control [SCDHEC, year(s) in parenthesis]

Site	N	LCL	$\bar{x}$	UCL
Bowman Hunt club (2000–03)	24	0.718	0.965	1.213
Sandhills (2006)	60	3.543	3.899	4.255
Hellhole1 (2004)	15	0.808	1.157	1.506
Hellhole2 (2005)	15	0.982	1.194	1.406
Zone1 (2000–2006)	40	0.907	1.270	1.633
Zone2 (2002–2006)	24	0.747	1.265	1.783
Zone3 (2000–2006)	37	0.689	0.951	1.212
Zone4 (2000–2006)	82	1.637	2.004	2.371
Zone5 (2000–2006)	76	1.213	1.485	1.758
Zone6 (2000–2006)	45	0.525	0.690	0.855
Zone7 (2000–2006)	51	0.968	1.348	1.728

ANOVA results showed that the "Sandhill" collection site was significantly higher than all other sites (F=27.75; df=10, 458; $P=1.94\times10^{-41}$; R^2=0.3773). No other sites were significantly different than each other. Data are presented as the arithmetic mean with lower/upper 95 % confidence limit (LCL/UCL)

Table 5 Radiocesium body burdens in offsite deer (pCi g^{-1}) collected by SRS personnel [year(s) in parenthesis]

Site	*N*	LCL	$\bar{x}$	UCL
Fort Jackson (1990, 1996)	54	6.176	7.498	8.821
Fort Stewart (1990)	20	6.517	8.874	11.232
QuadrantNE (1994)	31	0.015	0.160	0.305
QuadrantNW (1993–1994)	25	0.760	1.043	1.326
QuadrantSE (1993–1994)	53	0.512	0.724	0.937
QuadrantSW (1994–1995)	30	0.407	0.728	1.049

ANOVA results (F=58.88; df=5, 207; P=6.28× 10^{-38} ; R^2 =0.5872) showed that both the "Fort Jackson" and "Fort Stewart" collection sites were significantly higher than all other sites, but not significantly different from each other

The ANCOVA testing the effect of decade on the decline in 137Cs over time in white-tailed deer on the SRS indicate a single trend following radioactive decay with no decade effect. This would imply that there is little or not enough remobilization/new introductions of 137Cs in the environment to influence the uptake by the SRS deer herd. This is consistent with findings from time trend (1986–2003) analysis of 137Cs transfer to roe deer in Austrian forest regions that showed similar trends (Strebl and Tataruch 2007). Moreover, both decade and half-decade analyses showed that sequential time periods to significantly differ from one another. There are two main reasons for this. First, the robust sample size of the collection of the SRS deer herd allows for a very good estimate of the true populationmean and therefore the variance is minimized. Secondly, the physical decay of 137Cs and its ecological half-life on the SRS is a predictable downward trend.

Therefore, it is recommended that either the most recent decade or half-decade upper 95 % confidence limit of the mean for the entire SRS be used as an estimation of what the background 137Cs body burden for the SRS deer herd. All data analysis showed a statistically significant tendency toward normality and the coefficient of determination explained more model variation in the mean decay model than the median decay model. Since the half-decade values should provide the best estimate of the current background for the SRS deer herd, the upper 95 % confidence limit of the mean for this time period would be the best estimate to use. However, there are times when the SRS may not be hunted, or hunting is reduced. When that is the case, the decade analysis should be used to ensure adequate sample size. It is also recommended based on these analyses that this value be re-estimated using new data on a 5- to 10-year basis. Based on the exponential decay model presented in Fig. 5, the upper confidence limit for 137Cs body burdens for the SRS deer herd as a whole should be below detection limits (<1.0 pCi g-1) by the year 2071. Using the site-wide approach to best estimate what background 137Cs body burdens are for, the SRS deer population from global fall-out rather than site activities would be 3.4–3.5 pCi g-1, which represents the range from the mean to UCL for all SRS hip monitored for the last 5 years (Table 2). The extremely large sample size (n=3,652) minimizes the variance providing an extremely accurate estimate of the what the true background is for the site, by minimizing the effects of the occasional harvesting deer whose body burden was effected by site activities. To obtain a proper estimate of the UCLD to be used to determine if an individual deer belongs in that range, the upper confidence limit based of the standard deviation should be used. Using this approach based on site-wide estimates for the last decade, any deer collected fromthe SRS should fall within 1.0 (the detection limit) and 10.5 pCi g-1 (Table 9). This would represent the true variations of individual deer residing on the SRS. Although the entire site deer dataset could be used to establish background, stakeholder regulators wanted to determine the difference if the estimate was only based on deer data collected from hunt compartments on the SRS considered to be background. That is, data from deer collected from locations lacking 137Cs exposure related to SRS operations (Fig. 3). Using only what might be considered "unimpacted compartments", the UCLD from the background compartments vary from 2.8 to 9.7 pCi g-1 (Fig 3.) with a UCLD of 8.54 pCi g-1(Table 9).

Table 6 Analysis of variance (ANOVA) results comparing SRS hip monitoring data to offsite data collected either by laboratories associated with the SRS or SCDHEC

Location	$\bar{x}$	SE	*df*	*F* value	*P* value
Offsite (SRS quadrat)	3.1627	0.2389			
SRS	5.1987	0.0359			
Offsite (quadrat) vs. SRS			1, 9646	71.03	4.02×10^{-17}
Offsite (SCDHEC)	1.6754	0.1281			
SRS	3.3089	0.0403			
Offsite (SCDHEC) vs. SRS			1, 5202	147.77	1.51×10^{-31}

In both cases, deer collected off the SRS were significantly lower than deer collected on the SRS. No other sites were significantly different then each other. Data are presented as the arithmetic mean with lower/upper 95 % confidence limit (LCL/UCL)

Since the SRS deer-herd background levels are spatially varied based on environmental variables, such as soil type and land use, another statistically and scientifically valid approach to determine what 137Cs background body burdens are for the SRS deer population would be to use the UCLD for the compartment with the highest mean value that does not have nuclear industrial activities associated with it (e.g., compartments 2–4, 9–10, 12–15) or lie in the lower watershed of a nuclear industrial impacted compartment such as Steel Creek compartments south of L-Lake (e.g., compartments 45 and 49) or Lower Three runs south of PAR Pond (e.g., compartment 8; Fig. 3). This approach assumes that the compartment level is spatially representative of the deer that are harvested in that compartment. Deer studies on the SRS support this assumption (Sweeney 1970; Wentworth 1998), with the most recent study (D'angelo et al. 2003) showing fall home ranges of up to 500 ha with mean deer movements during SRS hunts to be 0.8 km.With each hunt unit falling between 3,458 and 5,273 ha, the

Table 7 Radiocesium body burdens in deer (pCi g^{-1}) collected near the SRS [offsite (SRS quadrat)] by SRS personnel analyzed by year

Year	N	LCL	$\bar{x}$	UCL
1990	46	7.879	9.401	10.924
1993	30	0.171	0.318	0.464
1994	93	0.567	0.734	0.901
1995	16	0.394	0.843	1.291
1996	28	4.092	5.355	6.619

Table 8 Radiocesium body burdens in deer (pCi g^{-1}) collected near the SRS [offsite (SCDHEC)] analyzed by year

Year	N	LCL	$\bar{x}$	UCL
2000	40	0.5368	0.9399	1.3430
2001	40	0.9016	1.2584	1.6152
2002	58	1.5716	2.0457	2.5197
2003	57	1.0920	1.4266	1.7612
2004	65	1.2411	1.4946	1.7481
2005	81	0.8162	0.9957	1.1752
2006	128	2.1873	2.5007	2.8140

Data are presented as the arithmetic mean with lower/upper 95 % confidence limit (LCL/UCL)

compartmental unit is a reasonable scale to investigate deer 137Cs levels in deer that reside in the associated ecosystems wi thin those compartments, thus providing a better estimate of what background is based on the local biogeochemical properties. Further, the compartmental unit is hunted often enough and includes enough deer to provide a robust sample size to estimate what the 137Cs body burdens are for the subpopulations that reside in those regions if estimates are taken using the decade level approach. Using the exponential decay model presented I Fig. 4, the upper confidence limit for 137Cs body burdens for the SRS deer herd using a compartmental level approach should be belowdetection limits (<1.0 pCi g-

Table 9 Radiocesium body burdens in SRS deer (pCi g^{-1}) for pooled compartments based on contamination status from 1996 to 2006

	N	Max	LCL	$\bar{x}$	UCL	STD	UCLD
Total	9076	166.40	3.75	3.82	3.89	3.39	10.46
Unimpacted	2418	21.18	3.77	3.86	3.96	2.39	8.54
Impacted	6658	166.40	3.72	3.81	3.89	3.68	11.03
Min	20	3.81	1.18	1.48	1.78	0.64	2.80
Max	547	166.40	5.92	6.55	7.18	9.40	21.84

Data are presented as the arithmetic mean with lower/upper 95 % confidence limit (LCL/UCL). The standard deviation (STD) and upper 95 % confidence limit of the data (UCLD) based on the STD are listed. The lower 95 % confidence limit of the data based on the STD was always 1 pCi g^{-1} (the detection limit)

1) by the year 2087. The hunt compartments bordering nuclear industrial sites have higher deer 137Cs body burdens and therefore will take longer to fall below detection limits (<1.0 pCi g-1) which is why the compartmental estimates take approximately 26 years longer than the site-wide estimate described above. These higher body burdens are most likely due to the soils capacity to retain 137Cs from global fallout thus making it more bioavailable to the deer (Jenkins et al. 1971; Jenkins 1975). These trends were also seen in raccoons harvested on the SRS where some onsite reference areas were higher in 137Cs than offsite control areas (Gaines et al. 2000). Using the compartmental approach to best estimate what background 137Cs body burdens are for the SRS deer population associated with non-nuclear industrialized areas (e.g., global fall-out) would be 4.1–4.6 pCi g-1, which represents the range from the mean to UCL for those compartments with naturally high background levels (Fig. 3). To achieve adequate sample size to minimize variance, these estimates are based on decades rather than 5-year increments. However, site-wide estimates based on decade (mean= 3.8 pCi g-1) and UCL (3.9 pCi g-1) are very similar to half-decade estimates (Table 9 and Table 2 respectively). As previously mentioned, to obtain a proper estimate of the UCLD to be used to determine the range of individual deer, the upper confidence limit based of the standard deviation should be used. In that case, based on compartmental estimates for the last decade, any individual SRS deer collected from compartments not associated with nuclear industrial activities should fall within 1.0–8.5 pCi g-1. This would represent the true variations of individual deer residing in non-nuclear industrial areas on the SRS.

To understand the 137Cs dynamics of white-tailed deer on the SRS, the best approach is to analyze the data using a spatiotemporal approach because of the distributions of different biogeochemical properties of the site coupled with the temporal decay of the radioisotope. However, a component that cannot be ignored that will affect the soils ability to retain 137Cs especially in sandy soils is rainfall. During drought years, 137Cs is much more bioavailable in many soil types (Golmakani et al. 2008; Goor et al. 2003; Heckman and Kamprath 1992; Hinton et al. 2006; Leigh and Johnston 1983; Nimis 1996). This is most likely demonstrated in the variability of the data for nonindustrial impacted compartments throughout the SRS. In early investigations of this dataset, precipitation data were used as covariables, but the available data lacked the spatial resolution to be included in the modeling effort. Based on these stochastic variations, it is extremely likely that deer will achieve (background) 137Cs levels in drought or otherwise water stressed years in excess of 8.5 pCi g-1 and fall within the upper 5 % of the data range. For some background compartments (e.g., compartments 3–4) this number could approach 20 pCi g-1 and still be attributed to global fallout.

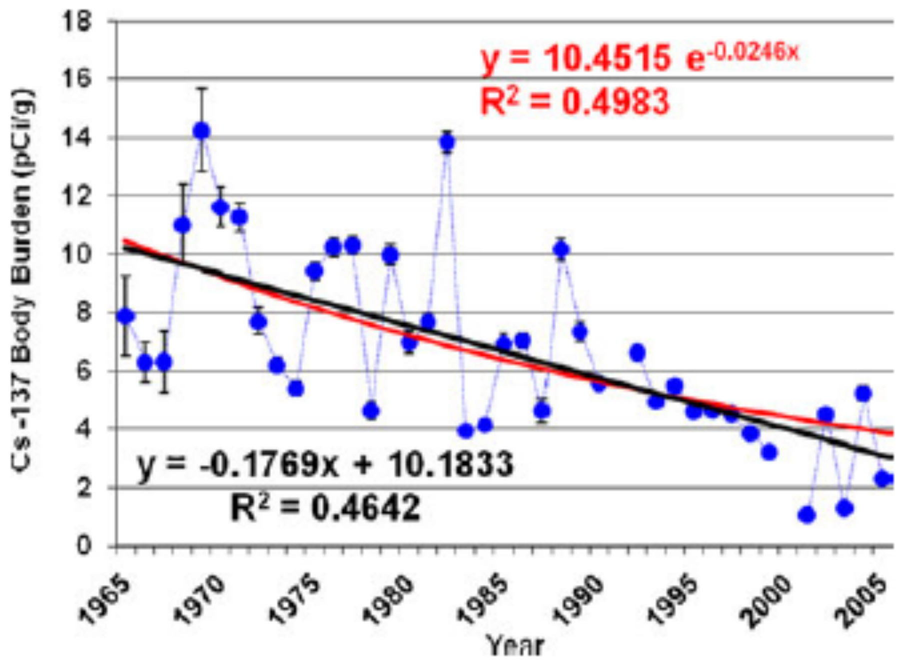

Fig. 4 Mean radiocesium body burdens and 95 % confidence limits in SRS deer (pCi g^{-1}) by year and the estimated decay rate based on both exponential (*red line* and text) and linear (*black line* and text) models with their coefficient of determination (*R* square). The exponential model explains 50 % of the variation while the linear model only explains 46 % of the variation. The ecological half-life for radiocesium body burdens based on the linear model is 28.79 years, while the ecological half-life for radiocesium body burdens based on the exponential model is 28.17 years

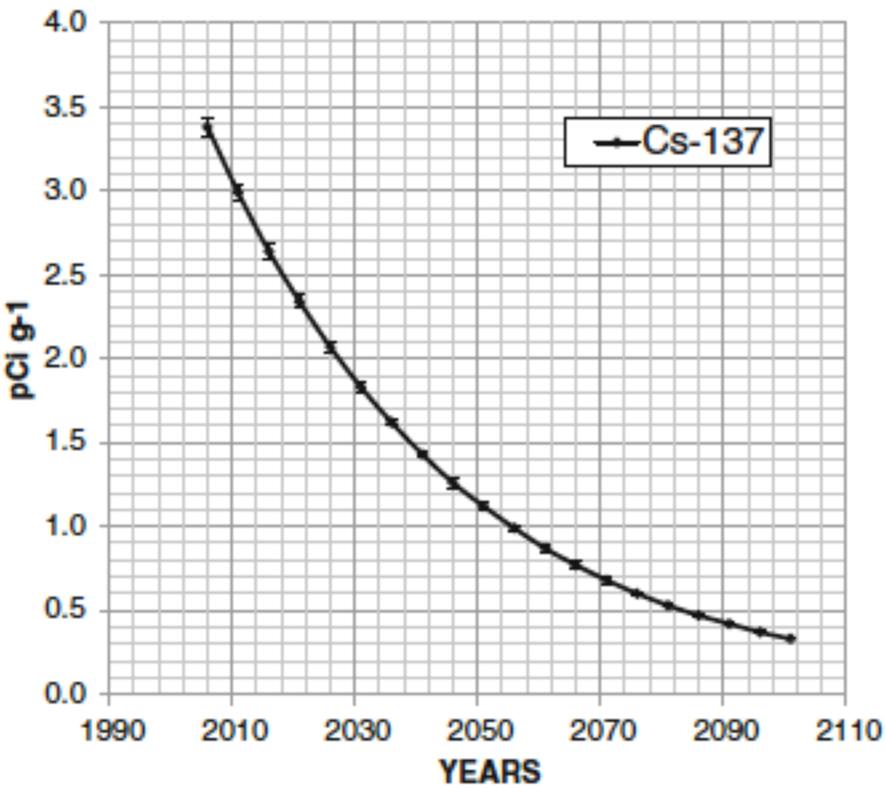

Fig. 5 Predicted radiocesium body burdens for the next 100 years (starting in 2007) in 5-year increments for the SRS deer population (pCi g^{-1}) using the exponential decay model presented in Fig. 4. Data are presented as the arithmetic mean with 95 % confidence limits

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