**Radiocesium in migratory aquatic game birds using contaminated U.S. Department of Energy
reactor-cooling reservoirs: a long-term perspective**

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ABSTRACT

Low-level releases of radiocesium into former nuclear reactor cooling-reservoirs on the U.S. Department of Energy's Savannah River Site (SRS) in South Carolina, USA, dating primarily to the late 1950s and early 1960s, have allowed examination of long-term contaminant attenuation in biota occupying these habitats. Periodic collections of migratory game birds since the 1970s have documented ^{137}Cs (radiocesium) activity concentrations in birds of SRS reservoirs, including mainly Par Pond and Pond B. In this study, during 2014 and 2015 we released wild-caught American coots (*Fulica americana*) and ring-necked ducks (*Aythya collaris*) onto Pond B. We made lethal collections of these same birds with residence times ranging from 32 to 173 days to examine radiocesium uptake and estimate the rate of natural attenuation. The two species achieved asymptotic whole-body activity concentrations of radiocesium at different times, with ring-necked ducks requiring almost three times longer than the 30 – 35 days needed by coots. We estimated ecological half-life (T_e) for Pond B coots over a 28-yr period as 16.8 yr (95% CI = 12.9 – 24.2 yr). Pond B coot T_e was nearly four times longer than T_e for coots at nearby Par Pond where radiocesium bioavailability had been constrained for decades by pumping of potassium-enriched river water into that reservoir. T_e could not be estimated from long-term data for radiocesium in Pond B diving ducks, including ring-necked ducks, likely because of high variability in residence times of ducks on Pond B. Our results highlight the importance: (1) for risk managers to understand site-specific bio-geochemistry of radiocesium for successful implementation of countermeasures at contaminated sites and (2) of residence time as a critical determinant of observed radiocesium activity concentrations in highly mobile wildlife inhabiting contaminated habitats.

Keywords: ¹³⁷Cs, Ecological half-life, Lentic ecosystems, Nuclear industry, USDOE Savannah River Site, Wintering waterfowl

1. Introduction

Environmental releases of radiocesium can create wide-ranging negative consequences for ecosystem and human health, as well as devastating disruptions to food production systems and human presence (e.g., see Beresford et al. 2016). Although radiocesium contamination has been spread across vast regions of the globe due to nuclear weapons testing and catastrophic nuclear industry accidents, localized low-level releases from nuclear facilities also have occurred, often with inputs directly into aquatic ecosystems and resulting in chronic low-dose exposures. Numerous aquatic ecosystems on the U.S. Department of Energy's 78,000-ha Savannah River Site (SRS; White and Gaines 2000) in west-central South Carolina, USA have been contaminated by low-level releases of ¹³⁷Cs (radiocesium) and other radionuclides from nuclear material production activities for national defense dating back to the late 1950s (Carlton et al. 1992, 1994). Many of these releases occurred into several large, man-made, reactor cooling reservoirs (Figure 1). The Par Pond Reservoir System (PPRS; Figure 1 inset; Dukes 1984, White and Gaines 2000), was created to provide secondary cooling water for heat exchangers at two SRS reactors (P and R reactors). The closed-loop system is comprised of two smaller (≤ 87 ha) impoundments (Ponds B and C), their connecting effluent canals, and the 1,130-ha Par Pond reservoir. Radiocesium contaminating events for the PPRS have previously been described by Ashley and Zeigler (1980), Carlton et al. (1994) and Whicker et al. (1990). Briefly, peak introductions of ¹³⁷Cs to the PPRS occurred during 1963–64, amounting to 4.8 TBq (Carlton et al. 1994). Some portion of that discharge was retained within the Pond B impoundment (Whicker

et al. 1990) while much of the balance entered Par Pond North Arm (Figure 1 inset). The decommissioning of R reactor in 1964 effectively ended effluent circulation through Pond B and Par Pond's North Arm. However, P reactor continued to operate until 1988, when dispersal of its heated effluent through Pond C and the Par Pond Hot Arm ceased (Millings et al. 2003). Historically, biota from the smaller Pond B impoundment has been 17 – 41 times higher in radiocesium content than that of Par Pond (e.g., Potter 1987, Potter et al. 1989, Kennamer et al. 1993, 1995). Smaller quantities of other radionuclides including ¹³⁴Cs (physical half-life [T_p] = 2.06 year) were also discharged into the PPRS during these various release events, but ¹³⁷Cs would have been the only easily detected gamma-emitting isotope in biota over the last several decades due to the shorter T_p values and limited extent of releases for these additional gamma-emitting radionuclides. Cummins et al. (1991) reported SRS radiocesium releases to the environment (atmospheric and effluent) across a 35-year period with a ¹³⁷Cs to ¹³⁴Cs ratio of 1,000:1 (22 TBq ¹³⁷Cs, 0.022 TBq ¹³⁴Cs). Biota from Par Pond in the late 1960s exhibited ¹³⁷Cs to ¹³⁴Cs ratios of approximately 20:1 (Marter 1970). We therefore use ¹³⁷Cs and radiocesium interchangeably. Elsewhere on the SRS, the reactor cooling reservoir L-Lake (Figure 1) was created in 1985, occupying the floodplain of Steel Creek (White and Gaines 2000) which had been contaminated decades earlier by effluent releases originating primarily from P reactor (Marter 1970, Carlton et al. 1992, 1994). Following the construction of L-Lake, the reservoir received little if any input of radiocesium. Because of greater water depths in L-lake relative to other SRS reservoirs and confinement of the contamination in L-Lake primarily to the original streambed, radiocesium activity concentrations measured in L-Lake biota historically have been 2 – 3 orders of magnitude lower than in biota from the PPRS (R. Kennamer, unpublished data).

Concern arises for environmental releases of radiocesium because it behaves chemically like potassium (K), and therefore accumulates in biota found in contaminated habitats (Davis 1963). Though radiocesium can persist in abiotic components of natural systems for long periods of time due to its 30.17-yr T_p , numerous studies have shown much shorter periods of bioavailability attributed to ecosystem characteristics, such as high sedimentation rates or enhanced substrate binding capacity for the contaminant (e.g., Paller et al. 1999, Brisbin and Kennamer 2000, Peles et al. 2002). Ecological half-life (T_e), the term used to refer to the time required for a 50% decline of a radionuclide in a population in a natural ecosystem, is a particularly beneficial metric used in radioecology because it can be determined cost-effectively with relatively simple repeated measures of contaminant levels in biota over time. Models of ecological half-life can be valuable predictive tools for programs monitoring natural attenuation of radionuclides in the environment and for setting and evaluating limits on human consumption of food taken from areas affected by environmental releases of radioactivity (e.g., Hesson et al. 2000, Pröhl et al. 2006).

Important breeding and wintering habitats for resident and migratory waterfowl are found in aquatic ecosystems around the world, including at U.S. nuclear materials production sites (e.g., Willard 1960, Brisbin et al. 1973, Fitzner and Rickard 1975, Halford et al. 1981) and in regions of the world contaminated by nuclear accidents such as the Chernobyl site (Brisbin 1991*b*) and Fukushima, Japan (Tagami and Uchida 2013). On the SRS, which is closed to waterfowl hunting, thousands of migrant waterfowl representing as many as 28 different species visit the site annually (Kennamer 2005). Such migrant birds that forage in contaminated areas may subsequently travel hundreds to thousands of kilometers away from these contaminated sites

(Kennamer 2003, Cristol et al. 2012). For example, migratory ring-necked ducks (*Aythya collaris*) captured, banded, and released on SRS reservoirs in South Carolina have been harvested as far away as Manitoba and Nova Scotia in Canada (> 2,000 km), and southward to Cuba (> 1,100 km; Kennamer 2003). Concern naturally arises that these highly mobile birds may accumulate and transport contaminants to locations where they may enter the human food chain through sport or subsistence hunting.

Radiocesium activity concentrations in birds are often highly variable, being determined in part by contaminant bioavailability in the occupied habitats and by behavioral differences among species, particularly foraging habits and residence times in contaminated areas (Brisbin 1991a, Colwell et al. 1996, Kålås et al. 1994, Kennamer et al. 1998). In early research (Brisbin et al. 1973) on the waterfowl community found on the SRS, migratory American coots (*Fulica americana*; hereafter coots) were identified as a worst-case species for accumulating radiocesium, persistently attaining higher body burdens than other waterfowl species. Diet was the biological explanation given for this differentiation in accumulation (Brisbin et al. 1973), as coots primarily consume algae and aquatic vascular plants that are known to accumulate high levels of radiocesium (Potter 1987, Whicker et al. 1990, Brisbin et al. 2002), whereas diving ducks generally have a diet consisting more of benthic invertebrates (Hoppe et al. 1986). However, these early waterfowl collections on the SRS consisted entirely of opportunistically collected individuals, with unknown residence times, leaving the question of the relative importance of exposure time as a determinant of the observed activity concentrations. Long-term research quantifying radiocesium body burdens in coots at Par Pond on the SRS later demonstrated the natural attenuation of radiocesium in these birds during the 1970s and 1980s

($T_e = 4 - 5$ yr; Brisbin and Kennamer 2000). Similar T_e estimation for waterfowl using Pond B is lacking despite the fact that Pond B is the SRS reservoir that received greatest inputs of radiocesium. Further, Pond B, while smaller than Par Pond and L-Lake on the SRS, has a history of water management that contrasts from the other SRS reservoirs and has likely resulted in long-term radiocesium bioavailability differences among these reservoirs. Body burdens of radiocesium in coots and other waterfowl (primarily diving ducks, including ring-necked ducks, ruddy ducks [*Oxyura jamaicensis*] and buffleheads [*Bucephala albeola*]) have been examined on Pond B in the past, including primarily in 1975 (Brisbin, unpubl. data), 1986 (Brisbin, unpubl. data), 1987 (Potter 1987) and 1992 (Kennamer unpubl. data). For these earlier Pond B coot collections, >90% of the birds had radiocesium activity concentrations that would have exceeded the European Economic Community limit of 600 Bq/kg for ¹³⁷Cs in fresh meat established following the 1986 Chernobyl disaster (EEC 1986). However, it has been more than 20 years since any waterfowl have been collected from Pond B for analysis of radiocesium activity concentrations. Elucidation of current radiocesium levels in Pond B waterfowl along with historical data would offer the opportunity to estimate T_e for this component of the Pond B ecosystem, to compare and contrast T_e values between SRS reservoirs, and to make predictions of when radiocesium concentrating in the birds might be expected to decline to levels suitable for human consumption (e.g., EEC limit for ¹³⁷Cs in fresh meat [600 Bq/kg, EEC 1986]; U.S. Food and Drug Administration, Derived Intervention Level [¹³⁴Cs + ¹³⁷Cs: 1200 Bq/kg, USFDA 2005]). In doing so, we chose to continue to report our observed levels relative to the more conservative EEC (1986) limit.

In this study, we live-trapped coots and ring-necked ducks from L-Lake, rendered the birds flightless, and transported them to Pond B for release. We later collected the released birds to examine activity concentrations of radiocesium in whole-body, muscle tissue, liver tissue, and lower gastro-intestinal (GI) contents. We predicted that coots would achieve higher asymptotic radiocesium activity concentrations than ring-necked ducks based on earlier work pointing to dietary differences, but that both species would achieve their respective asymptotic levels by approximately 30 days. We also predicted that an estimated radiocesium ecological half-life for Pond B collected birds would be longer than that previously reported for Par Pond birds because of reservoir-specific long-term water management effects on radiocesium bioavailability, and that many of the Pond B collected birds would still have radiocesium concentrations in muscle tissue above the EEC (1986) radiocesium limit for fresh meat. Finally, we explored relationships among radiocesium levels in whole-body, muscle and liver tissues, and GI contents for predictive potential and insights into radiocesium uptake, tissue assimilation, and issues of residence time for these species.

2. Materials and methods

2.1 Bird captures and collections

From 7 December 2013 to 13 January 2014, we live-captured 34 coots from L-Lake on the SRS using welded-wire traps baited with corn (Haramis et al. 1982) and/or by dip-netting from a boat. The following year, from 8 December 2014 to 18 December 2014, we trapped/netted 50 additional coots and 56 ring-necked ducks from L-Lake. Live-captured birds in both years were transported to SREL where they were banded with U.S. Geological Survey (USGS) aluminum leg bands, body mass was recorded (nearest 1g), the primary flight feathers on one

wing were scissored to limit flying ability, and live whole-body radiocesium was determined (see description in section 2.2) for a random subsample of the birds ($N = 25$ coots, 7 ring-necked ducks). Colored nasal saddles (ring-necked ducks) or colored neck collars (coots) were attached to birds in the second year (only bands were used in the first year), with differing colors denoting differently timed releases of cohorts. All coots and ring-necked ducks were transported to and released onto Pond B within 24 hours of capture. Following a minimum of 30 days, which represented an elapsed time previously shown for coots to attain asymptotic radiocesium body burdens (Brisbin 1991a), we initiated lethal collections (using shotguns) of all coots and ring-necked ducks remaining on Pond B.

Collected birds were returned to the laboratory where various body measurements were recorded (body mass [nearest 1g], tarsus, culmen, and keel lengths [nearest 0.01cm], and flattened wing-notch length [nearest 0.1cm]). Whole-body counting (see description in section 2.2) of intact carcasses was completed prior to initiating necropsy procedures. Muscle samples, liver samples, and lower gastro-intestinal (GI) contents (including the gizzard contents) were collected during necropsy of all collected birds. Wet mass of most muscle and liver tissue samples and GI contents was recorded before being freeze-dried, weighed again dry, and then homogenized. Wet and dry mass of samples was used to establish wet:dry ratios for individual samples, which allowed contaminant concentrations to be expressed on either a dry- or wet-mass basis. Some samples were missing either wet mass or dry mass values from this freeze-drying process; in those cases, an appropriate average wet:dry ratio was used to convert dry mass concentrations of contaminants in those tissue samples to wet mass concentrations. Our work with waterfowl on Pond B followed a protocol (#A2012 12-010-Y3-A5) approved by the

University of Georgia Institutional Animal Care and Use Committee (IACUC). Other permits relating to this research included South Carolina Department of Natural Resources Scientific Collecting Permit #05-2015, U.S. Geological Survey Bird Banding Permit #22002, and U.S. Fish and Wildlife Service Scientific Collecting Permit #MB65214A-4.

2.2 Radiocesium counting procedures

Whole-body radiocesium counting for collected waterfowl used a 10.2-cm x 15.2-cm NaI (Tl) gamma detector (Bicron Model 6H3Q/5) housed within a counting chamber (81 x 81 x 107-cm) constructed of lead bricks (~3,615 kg in total), lined on the inside with copper plating, and controlled by Canberra Genie 2000 gamma spectroscopy software (Version 1.3). A counting window (Region of Interest [ROI]) of 596 – 728 kiloelectron-Volts (keV) centered on 662 keV was used to record total detector absorptions from the ¹³⁷Cs emission of 662 keV photons. The system was calibrated daily, as counting took place, with a traceable ¹³⁷Cs source (New England Nuclear Gamma Reference Disc Source Set; Catalogue No. NES-101S; ¹³⁷Cs disc) by manually adjusting the system amplifier gain control to center the disc-generated peak on 662 keV. We used a device (Lucite cylinder) similar to one described by Morton et al. (1980) to confine birds to a specific geometry and positioning over the detector. Generally, 15-min count times were used for counting living birds; 30-min count times were used for counting collected/sacrificed birds and backgrounds; background-adjusted bird count rates (counts/sec) divided by a mass-specific counter yield were estimated as the ¹³⁷Cs activity content (Becquerels [Bq]; Bq/g, fresh whole-body mass). To produce mass-specific counter yields, we used background corrected count rates (counts/sec) from a series of eight aqueous standards with mass ranging from 76.5 g to 4,398 g and spiked with known quantities of ¹³⁷Cs (decay corrected for the date of counting);

for each of the eight standards, its background-corrected count rate (counts/sec) divided by its decay-corrected activity (Bq) produced an estimate of yield. Using data for the entire series, we then produced a power function equation of expected yield for a given mass (in grams; $\text{yield} = 0.4449 \times \text{mass}^{(-0.343)}$; $R^2 = 0.97$). This process for determining mass-specific counter yields has generally been repeated every one-to-two years to confirm continued detector stability. Because of low background count rates (measured 2–3 times daily) achievable with the substantial whole-body counting chamber (described above) and our desire to follow protocol that had been used in collecting the historical data, we did not construct blanks that approximated the matrix structure or geometry of the whole birds that we counted; we instead simply used an empty Lucite cylinder placed on the detector to generate background/blank count rates. It was thus possible for small negative activity concentrations to derive from our counting procedures. Minimum detectable concentrations (MDCs; Bq/g, fresh mass) were calculated for individual samples following Currie (1968).

Sub-samples of freeze-dried, homogenized muscle and liver tissues and GI contents were packed into scintillation tubes, net sample mass recorded, and then assayed for radiocesium. Dry-tissue/GI contents radiocesium counting used a Packard Cobra II auto-gamma counter (Model Cobra II 5003; Packard Instruments Co., Meriden, CT, USA) with a single 3-inch through-hole NaI detector. A ROI of 580 – 754 kiloelectron-Volts (keV) centered approximately on 662 keV was used for this system. The system was auto-calibrated daily, as counting took place, with a traceable ¹³⁷Cs source (SREL-0113). Generally, 60-min count times were used for counting samples and backgrounds (empty scintillation tube in every fifth position). Background-adjusted dry tissue count rates (counts/sec) divided by the counter yield were estimated as the ¹³⁷Cs

content of dry tissue samples (Bq/g, dry mass). To derive the counter yield, we first made a matrix-specific standard of commercially-available chicken breast muscle tissue which was dried to constant mass, pulverized into powder, spiked with a known quantity of Cs-137 (745 Bq; decay-corrected for the date of preparation), and then loaded/packed into a scintillation tube; its background-corrected count rate (counts/sec) divided by its decay-corrected activity (Bq) produced the estimate of counter yield that we used. Using wet:dry tissue mass ratios, individual dry activity concentrations were converted to wet activity concentrations (Bq/g, wet mass). Minimum detectable activity concentrations (MDCs; Bq/g, dry mass) were calculated for individual samples following Currie (1968).

2.3 Data analysis

Standard errors (SE) are presented with means in text and in tabular form. We made simple between-year (2014 vs. 2015 for coots) and between-species comparisons of radiocesium activity concentrations in whole-body, muscle and liver tissues, and lower GI contents using *t*-tests, in which variances were initially tested for equality (JMP Pro Version 10.0.1; SAS Institute Inc., Cary, NC). We examined muscle and liver tissue relationships to whole-body radiocesium activity concentrations using Spearman correlations (r_s) and simple linear regressions with intercepts constrained to zero, to produce slope estimates, β (JMP Pro Version 10.0.1; SAS Institute Inc., Cary, NC). We then used homogeneity of slopes models (Analysis of variance using least squares fits; JMP Pro Version 10.0.1; SAS Institute Inc., Cary, NC) to compare β estimates of the muscle and liver relationships to whole-body radiocesium activity concentrations between species.

For coots collected at Pond B from 1986 through 2015, we modeled the long-term natural attenuation of whole-body radiocesium activity burdens, as described by Brisbin and Kenamer (2000). We estimated model parameters and 95% confidence intervals (CI) from a simple linear regression ($\text{Ln}[y] = \alpha + \beta x$; JMP Pro Version 10.0.1; SAS Institute Inc., Cary, NC) describing the decline of whole-body radiocesium activity burdens ($\text{Bq } ^{137}\text{Cs/g}$, wet mass; y) for coots sampled from the Pond B reservoir during different collection years (x ; treated as a continuous variable). Estimated parameters included an intercept (e^α , where e is the base of the natural logarithm) and a slope (β). The resulting slope (with associated 95%CI) was inserted into the basic half-life equation, $T_{1/2} = \text{Ln}(2) / \beta$, to produce an estimate for T_e .

3. Results

3.1 Whole-body radiocesium uptake

For a random sampling of birds at the time of initial capture on L-Lake, whole-body radiocesium activity concentrations for 25 coots averaged $6.0 \times 10^{-4} \text{ Bq/g}$ ($\pm \text{SE} = 4.0 \times 10^{-4}$); for 7 ring-necked ducks, the average radiocesium activity concentration was $1.4 \times 10^{-3} \text{ Bq/g}$ ($\pm \text{SE} = 7.0 \times 10^{-4}$). Further, all 32 of these birds had whole-body radiocesium activity concentrations that were below their individual respective MDCs, which averaged 5.6×10^{-3} and $4.9 \times 10^{-3} \text{ Bq/g}$, fresh mass, for coots and ring-necked ducks, respectively.

We collected 35 coots in this study with known residence times on Pond B ranging from 32 to 173 days (14 January – 1 June; $\bar{x} = 67$ days); we collected 36 ring-necked ducks with known residence times on Pond B ranging from 33 to 173 days (14 January – 1 June; $\bar{x} = 71$ days). For all Pond B collected coots and ring-necked ducks, whole-body radiocesium activity concentrations were above their individual respective MDCs, which averaged 6.3×10^{-3} and 5.6

$\times 10^{-3}$ Bq/g, fresh mass, for coots and ring-necked ducks respectively. Whole-body radiocesium activity concentrations in the 35 coots collected from Pond B averaged 0.94 Bq/g, fresh mass (± 0.064 SE Bq/g; Table 1); in the 36 ring-necked ducks collected from Pond B, whole-body radiocesium activity concentrations averaged 1.18 Bq/g, fresh mass (± 0.097 SE Bq/g; Table 1). For coots, which were collected in both 2014 and 2015, a *t*-test indicated that whole-body radiocesium activity concentrations did not differ between years ($t = -0.52$, $P = 0.60$). A *t*-test indicated that whole-body radiocesium activity concentrations differed between species ($t = 2.04$, $P = 0.046$), with ring-necked ducks exhibiting higher radiocesium levels than coots.

As with previous work on the SRS investigating coot uptake of radiocesium (Brisbin 1991a), coots in this study on Pond B achieved and maintained equilibrium whole-body radiocesium activity concentrations from the onset of collections at 32 days post-release through 90 days post-release (Figure 2, top). Indications from a meager (< 5) sampling of coots > 90 days post-release suggested a possible decline in whole-body radiocesium (Figure 2, top). In contrast to coots, ring-necked ducks continued to increase in whole-body radiocesium between 33 and 90 days post-release (Figure 2, bottom), before they too apparently began a decline in the period > 90 days post-release (Figure 2, bottom).

3.2 Tissue/compartments distributions of radiocesium

Radiocesium activity concentrations in muscle and liver from all coots and ring-necked ducks collected on Pond B were above their respective MDCs. Muscle and liver radiocesium activity concentrations in the 35 coots collected from Pond B averaged 1.64 ± 0.118 SE Bq/g, wet mass, and 1.02 ± 0.062 SE Bq/g, wet mass, respectively (Table 1); in the 36 ring-necked ducks collected from Pond B, muscle and liver radiocesium activity concentrations averaged

2.24 ± 0.195 SE Bq/g, wet mass, and 1.25 ± 0.097 SE Bq/g, wet mass, respectively (Table 1). Lower GI content radiocesium activity concentrations averaged 1.72 ± 0.25 SE Bq/g, dry mass, and 1.90 ± 0.23 SE Bq/g, dry mass, for coots and ring-necked ducks respectively (Table 1). For coots, which were collected in both 2014 and 2015, *t*-tests indicated that radiocesium activity concentrations did not differ between years for wet muscle ($t = -0.80$, $P = 0.43$), wet liver ($t = -0.86$, $P = 0.34$), or dry lower GI contents ($t = -0.69$, $P = 0.50$). For wet muscle, a *t*-test indicated that radiocesium activity concentrations differed significantly between the species ($t = 2.64$, $P = 0.011$), but for wet liver ($t = 1.94$, $P = 0.057$) and dry lower GI contents ($t = 0.53$, $P = 0.60$), radiocesium activity concentrations did not differ by species. Ninety-seven percent (34 of 35) of coot muscle samples and 92% (33 of 36) of ring-necked duck muscle samples from Pond B were above the European Economic Community (EEC 1986) limit of 0.600 Bq/g in fresh meat established for human consumption (Figure 2).

Radiocesium activity concentrations in wet muscle and wet liver tissues were strongly (all $r_s \geq 0.88$) and positively related to whole-body radiocesium activity concentrations, for both coots (Figure 3, top) and ring-necked ducks (Figure 3, bottom). Radiocesium concentrated at a higher rate into coot muscle tissue ($\beta = 1.74 \pm 0.036$ SE) than into coot liver tissue ($\beta = 1.06 \pm 0.028$ SE); for ring-necked ducks, radiocesium also concentrated at a higher rate into muscle tissue ($\beta = 1.91 \pm 0.030$ SE) than into liver tissue ($\beta = 1.03 \pm 0.034$ SE). Comparisons of slopes for the relationships of tissue radiocesium activity concentrations to whole-body radiocesium between species was not significant for muscle (overall model: $F_{3,67} = 441.1$, $P < 0.0001$, $R^2 = 0.95$; slopes comparison: $F_{1,67} = 2.76$, $P = 0.10$) or liver (overall model: $F_{3,67} = 101.5$, $P < 0.0001$, $R^2 = 0.82$; slopes comparison: $F_{1,67} = 0.002$, $P = 0.97$). For muscle, the common slope

shared for both species was: $\beta = 1.85 \pm 0.025$ SE; for liver, the common slope shared for both species was: $\beta = 1.04 \pm 0.023$ SE.

3.3 Ecological half-life (T_e)

In addition to data collected in the present study, historical data available for whole-body radiocesium in coots collected from Pond B included the winters of 1975–76, 1983–84, 1986–87, 1987–88, and 1991–92 (Figure 4, top). However, due to the lack of a clear long-term decline in Pond B coot whole-body radiocesium, specifically an apparent increase in activity concentrations from before to after the winter of 1984–85, we chose to model ecological half-life between 1986–87 and 2014–15 (Figure 4, bottom), using whole-body radiocesium data (natural log-transformed) from 96 coots. The linear regression analysis ($r^2 = 0.31$) produced an α estimate of 1.84 ± 0.25 SE, corresponding to an estimate of 6.30 Bq/g, fresh mass (95% CI = 3.86 – 10.28) for a hypothetical mean radiocesium activity concentration in Pond B coots in 1965. The β was estimated as -0.0412 ± 0.0064 SE, corresponding to a T_e estimation of 16.82 (95% CI = 12.91 – 24.19) years.

It was not possible to produce an estimate of T_e for ring-necked ducks (or diving ducks in general, including also ruddy ducks and buffleheads) using Pond B because whole-body radiocesium activity concentrations determined in this study using the birds that were restricted to Pond B, and fully-flight-capable ring-necked ducks in past collections, did not elucidate any pattern of long-term decline necessary for modeling of T_e (Figure 5).

4. Discussion

4.1 Whole-body radiocesium uptake

Randomly selected coots and ring-necked ducks for which whole-body radiocesium determinations were made at the time of initial capture on L-Lake had contaminant concentrations that were below the whole-body equivalent of the European Economic Community (EEC 1986) limit for fresh meat. Moreover, activity concentrations in none of these birds exceeded minimum detectable concentrations for our whole-body counting instrumentation and protocol. Both species, however, quickly accumulated measureable whole-body-burdens of radiocesium once released onto Pond B, with coots averaging 0.94 Bq/g, fresh mass, and ring-necked ducks averaging 1.18 Bq/g, fresh mass. By comparison, over a 15-yr sampling period in a nearby cooling reservoir (Par Pond) on the SRS, the highest average radiocesium activity concentration in any given year was 0.51 Bq/g, fresh mass (maximum: 0.71 Bq/g, fresh mass), from 1971–72 at the North Arm (Brisbin and Kennamer (2000; see Figure 1 for location relative to Pond B). Moreover, the current average radiocesium activity concentration in Pond B coots was more than an order of magnitude higher than the average for the most-recent sample of coots taken from the North Arm of Par Pond (1998–99), at 0.092 Bq/g, fresh mass (maximum: 0.22 Bq/g, fresh mass). Our findings were consistent with those of other researchers who observed higher radiocesium activity concentrations in Pond B biota than those found in samples collected at nearby Par Pond (e.g., Potter 1987, Potter et al. 1989, Kennamer et al. 1993, 1995, Paller et al. 2002).

Coots achieved equilibrium radiocesium levels after being restricted to Pond B for one month, which was consistent with earlier work with this species (Brisbin 1991a). However, for ring-necked ducks, an asymptotic level of whole-body radiocesium was not apparent until 2.5 months post-release, and activity concentrations attained by ring-necked ducks were higher than

those attained by coots. Mallards (*Anas platyrhynchos*) similarly restricted to Pond B in the late-1980s also exhibited a pattern of radiocesium uptake that extended well beyond that shown for coots (>175 days; George 1990, George et al. 1990). Whicker et al. (1990) found considerable variation in Pond B aquatic macrophyte and benthic macroinvertebrate radiocesium activity concentrations, ranging from 4 to 30 Bq/g dry mass and 0.9 to 14 Bq/g dry mass respectively, so differences in diets among bird species conceivably could explain observed patterns of whole-body and tissue activity concentrations of radiocesium. Diets of coots and ring-necked ducks contrast sharply, with coots favoring submerged aquatic vegetation such as *Hydrilla verticillata* and *Ceratophyllum* (Brisbin et al. 2002), while ring-necked ducks have a diverse diet of plant and animal foods, including seeds of white-water lily (*Nymphaea odorata*) and spikerush (*Eleocharis* spp.), snails (*Physella heterostropha*, *Helisoma* spp.), Asiatic clams (*Corbicula fluminea*), and dragonfly nymphs (Anisoptera; Hoppe et al. 1986). Perhaps more importantly, coots and ring-necked ducks contrast in their primary modes of foraging: coots generally feed at the surface or by making shallow dives to grasp submerged vegetation and hauling it to the surface; ring-necked ducks are tactile benthic feeders and so they come into frequent contact with bottom sediments while probing for and consuming food items, increasing the likelihood for ingestion of contaminated sediments. Whicker et al. (1990) found that 99% of the Pond B reservoir's total radiocesium inventory was contained in its sediments. Species differences in diets, foraging modes, digestibility of various foods taken, and varying radiocesium activity levels in food types (e.g., Davis 1963, Moss and Horrill 1996) likely explain our observed differences in the timing of attaining equilibrium levels of radiocesium between coots and ring-necked ducks.

The apparent decline in whole-body radiocesium we observed in the post-release period beyond three months for both coots and ring-necked ducks suggested a possible change in ¹³⁷Cs availability for biological uptake in Pond B. We noted the timing of these bird collections (late March through early June) was coincidental with a change in seasons, from winter to spring. Changes in levels of body fat, which incorporates radiocesium to a lesser degree than muscle tissue (e.g., Staton et al. 1974), and which are typical for waterfowl as spring migration approaches (see review by Arzel et al. 2006), could have explained our observed decreases in whole-body activity concentrations of radiocesium. Although we did not quantify body fat levels for birds in this study, body mass of our birds did not increase with residence time for either species, suggesting that the birds were not storing additional fat for an anticipated spring migration. Furthermore, muscle tissue concentrations of radiocesium exhibited a decline similar to whole-body values relative to the later residence times in our bird collections. We therefore do not believe that changes in body fat relative to whole-body mass occurred, and thus is an unlikely explanation for the observed declines in radiocesium activity concentrations. We cannot rule out the possibility that seasonal changes in coot and/or ring-necked duck diets (perhaps driven by changing availability of preferred food types), and variation in radiocesium content of various food types, may also play some role in explaining the apparent radiocesium decline, but importantly, both species of birds experienced the same decline, and so the foods being consumed by coots and ring-necked ducks likely were similarly affected by some ecosystem-wide change in radiocesium bioavailability. Our observations of this apparent decline in coot and ring-necked duck whole-body radiocesium might best be explained by some combination of bioavailability effects on all biota arising from a seasonal anoxic remobilization of ¹³⁷Cs from

sediments into the water column known to occur in SRS deep-water reservoirs (Evans et al. 1983, Alberts et al. 1987), including Pond B, and a seasonal cycle of accumulation and release of ¹³⁷Cs by the aquatic macrophyte communities in these same reservoirs as described by Pinder et al. (2010). Furthermore, Kelly and Pinder (1996) demonstrated that for some aquatic macrophytes occurring in Pond B, including species found in the diets of ducks and coots, foliar uptake of radiocesium was the principal mode of uptake, rather than root uptake, so cycles of radiocesium activity concentrations in at least some macrophyte species in Pond B have the potential to exist and coincide with the seasonal cycle of radiocesium remobilization from sediments into the water column.

4.2 Tissue distributions of radiocesium

In both coots and ring-necked ducks collected from Pond B in this study, radiocesium concentrated into muscle tissue at a higher rate than into liver tissue. Voluntary muscle has been well known as the dominant accumulator of cesium among tissues of animals, both in terms of a total-body basis and per-gram of tissue basis (Davis 1963), raising particular concern for human health risk assessors. Further, accumulations of radiocesium into muscle tissue are enhanced in potassium deficient environments (Davis 1963). In the mid-1960s to mid-1970s, water chemistry measurements were monitored in both Pond B and Par Pond, showing that potassium concentrations were only half as high in Pond B as in Par Pond (Tilly 1975), where the pumping of Savannah River water into Par Pond enriched potassium levels. This contrasting potassium availability for the reservoirs persisted until the drawdown and refill of Par Pond in 1991–1995, at which point the pumping of river water ceased. As further evidence of the potential for human intervention to decrease bioavailability of ¹³⁷Cs in an entire freshwater ecosystem, Smith et al.

(2003) made experimental additions of potassium chloride to lakes in Belarus, Ukraine, and Russia contaminated by the 1986 Chernobyl nuclear accident to increase potassium competition with ¹³⁷Cs for biological uptake, and thereby successfully lowered radiocesium activity concentrations in fish.

One of the potentially useful parameters in estimating risk to human consumers of game birds like the coot and ring-necked duck are slopes from relationships of whole-body to muscle tissue radiocesium activity concentrations. When robust relationships can be established, whole-body measurements of radiocesium can be made on living birds without the persistent need for lethal sampling, and muscle tissue activity concentrations can be reasonably estimated. Non-lethal techniques such as this also reduce costs associated with tissue sample collection, preparation, and analytical procedures. In this study, slopes describing the relationships of whole-body to muscle tissue radiocesium activity concentrations did not differ significantly for coots ($N = 35$) and ring-necked ducks ($N = 36$) and was estimated as $1.85 (\pm 0.025 \text{ SE})$ for the species combined. So for example, when this value was used to estimate a whole-body equivalent radiocesium activity concentration for the European Economic Community (EEC 1986) limit for radiocesium in fresh meat of 0.600 Bq/g, we found an associated value of 0.324 Bq/g, fresh mass, for whole-body radiocesium. Potter et al. (1989) had previously estimated a slope from this relationship for 19 coots as 1.27, which corresponded to a whole-body equivalent of 0.472 Bq/g, fresh mass. We suspect that the lower slope previously estimated by Potter et al. (1989) likely resulted from their collection of free-ranging coots that had not been residents on Pond B long enough to fully assimilate asymptotic levels of radiocesium into their muscle tissues.

4.3 Ecological half-life (T_e)

Our primary goal in this study was to estimate ecological half-lives (T_e) for coots and ring-necked ducks using Pond B. Recognizing that variability in residence times could influence perceived radiocesium distributions in a sampling of highly mobile birds, our approach of releasing wild-caught birds onto Pond B that were restricted in their ability to fly away, waiting for equilibrium radiocesium activity levels to become established, and then collecting the birds for gamma spectroscopy analysis was believed to be the best method to assure adequate data to assess current radiocesium activity levels and for association with historical data originating from collections of wild, free-ranging birds dating back to the early 1970s. This protocol worked well enough for coots that we were able to estimate the T_e for coots as 16.8 yr (95% CI = 12.9 – 24.2 yr) using data from 1986 through 2014. Potential reasons that pre-1986 Pond B coot data did not conform to a long-term decline include the likelihood that coots in those earlier years possessed residence times that were not long enough to allow for establishment of equilibrium radiocesium levels in whole-body or individual tissue compartments. This was more clearly the case in that historical Pond B duck radiocesium data was taken from birds undoubtedly collected well before any equilibrium levels became established. Despite the potentially confounding issue of residence time for migratory coots in our long-term samplings, a comparison of our T_e estimate for Pond B coots with T_e estimates for other animal populations at Pond B reservoir showed good agreement (Table 3). T_e estimates for Pond B largemouth bass (*Micropterus salmoides*) ranged from 13.6 yr (Peles et al. 2000) to 16.7 yr (Paller et al. 1999, 2002), and 13.4 yr for Pond B sunfishes (*Lepomis* spp.; Paller et al. 1999, 2002). In contrast, T_e estimates were lower for all Par Pond animal populations examined, including coots (ranging from 3.87 – 4.92

yr in different parts of that reservoir; Table 3), and fish (largemouth bass: 4.99 yr; sunfishes: 4.78 yr; Table 3).

Contrasting bioavailability of radiocesium within Par Pond and Pond B, driven by differing limnological properties, likely explains the lower T_e values for biota in Par Pond than for biota in Pond B. Soils and sediments of the southeastern U.S. coastal plain are highly weathered, sandy, acidic, low in nutrient content, and contain primarily kaolinitic clay, and thus generally contribute to enhanced environmental mobility of ¹³⁷Cs (Alberts et al. 1987, Dahlman et al. 1975, Evans et al. 1983, Jenkins and Fendley 1971). For more than 30 years (from its 1958 creation until a 1991 drawdown), water was routinely supplied to Par Pond from the Savannah River (3 – 10 times the volume of annual direct rainfall input to Par Pond; Tilly 1975) to compensate for evaporative losses and thus maintain relatively constant water levels. These additions of river water had the effect on Par Pond of increasing concentrations of cations including K^+ (Newman et al. 1986, Tilly 1975), likely reducing the proportion of the lake's total ¹³⁷Cs inventory that was contained within its biota. In contrast, termination of Savannah River water pumping into Pond B in 1964 resulted in an ionic compositional shift in the limnological environment to one more typical of lakes of the U.S. Southeastern Coastal Plain (Tilly 1975), and this probably contributed to the exceptionally high Pond B water:biota ¹³⁷Cs concentration ratios reported by Whicker et al. (1990). As a result, it would be expected to take much longer for radiocesium to decline to near-background levels in biota from Pond B than in biota from Par Pond. Using our estimated T_e for Pond B coots of 16.82 years, we estimated that the mean whole-body radiocesium level for a collection of Pond B coots would not decline to the whole-body equivalent (0.324 Bq/g, fresh mass) of the European Economic Community (EEC 1986)

limit of radiocesium in fresh meat until 2037, and even longer (not until 2049) before approaching background ($1965 + 5 \cdot T_e$).

4.4 The issue of residence time

Birds and other animals constantly make decisions in attempting to improve chances for survival, including for example, when to move from one site to another to access higher resource densities or reduce exposure to predation risks (e.g., Hepp and Kenamer 1992, Nichols 1996). A potential indirect consequence of such movement decisions is the effect on contaminant exposure of individuals relating to the amount of time spent at contaminated sites before leaving. We were unable to estimate a T_e for ring-necked duck collections (or with the inclusion of data from other diving duck species) because no pattern of a long-term decline was evident in the data; when forced to remain on the reservoir for periods of a month or more, ring-necked ducks accumulated whole-body radiocesium activity concentrations that were four-to-five times higher than the historical data. Historical data were derived from collections of free-ranging migrant ducks and thus we believe our findings were clear evidence that these birds seldom spent more than a few days on Pond B (i.e., short natural residence times). Over the long-term, nearby larger reservoirs, Par Pond and L-Lake, likely have provided a far greater abundance of food resources than could be provided by the smaller, nutrient deficient, Pond B. Additionally, historical data for coot whole-body radiocesium activity concentrations may hold evidence of variability (annual) in residence time for that species on Pond B. We were unable to use coot data from the mid-1970s through the early-1980s to model T_e for coots using Pond B because coot radiocesium activity concentrations from latter half of the 1980s and early-1990s were higher. Although we cannot rule out other potential explanations for this pattern, annually varying residence times could

produce such results. Taken together, issues of residence time could have potentially important consequences. For example, if some condition(s) were to arise at Pond B that substantially lengthened the typical residence times for migrant visitors, particularly the ring-necked ducks, radiocesium activity concentrations could increase suddenly and dramatically. Management decisions for contaminated reservoirs will therefore need to be based in part on limiting conditions that may make such reservoirs more attractive to migrant waterfowl.

Quantifying residence time can be difficult to accomplish without the monitoring of movements by individuals (e.g., with the use of radio transmitters). For collections of randomly taken migratory birds in contaminant monitoring programs, finding a method of estimating residence time or the likelihood of having achieved an equilibrium level of a contaminant would provide valuable information to aid in interpreting contaminants data. Cadwell et al. (1979) suggested that use of a ratio of gastrointestinal to muscle radiocesium activity concentrations could index residence time, with high ratio values signifying recent arrivals and lower values indicating an approach to equilibrium levels. Given the reasoning offered by Cadwell et al. (1979), we hypothesized that the pattern of this ratio with increasing residence time would be approximated by a Ricker function (Figure 6), which has been characteristically used in modelling of fish populations (Ricker 1954). Using the data we collected for ring-necked ducks in this study, we evaluated whether this suggested ratio might have practical use. Ring-necked ducks collected with residence times from 33 to 41 days exhibited considerable variance in the ratio of radiocesium activity concentration in the GI contents to that found in the muscle, whereas those ducks collected with longer residence times, from 75 to 84 days, exhibited a narrowing of the range of values (Figure 7), suggesting a convergence on equilibrium levels of

radiocesium. Additional work will be required to more fully assess the utility of this approach to indexing residence time of birds using contaminated sites.

5. Conclusions

Risks associated with environmental releases of radionuclides are of potential ecological concern because of the long physical half-lives of certain isotopes, like radiocesium (¹³⁷Cs), which typically remain available for biological uptake over long periods (Hinton 1998). Our work demonstrates the value in long-term monitoring programs for establishing and validating estimates of natural attenuation rates of contaminants in the environment (in this case, Pond B coot T_e). Such site-specific and population-specific estimates are sensitive to changes in bioavailability of contaminants, and thus have an inherent capability to alert site managers to changing conditions in contaminated ecosystems, whether by deliberate action/remediation or natural shifts. Our findings also demonstrate the robust nature of ecological half-life estimates among wildlife species as diverse as migratory birds visiting these reservoirs only seasonally and fish confined to these reservoirs throughout their entire lives. We further showed that diets and foraging behaviors of aquatic birds, with concomitant variability in sediment ingestion, are important considerations in radiocesium uptake. Taken together, a complex suite of abiotic and biotic factors clearly interact to produce observed patterns of radiocesium activity concentration in wildlife species occupying contaminated aquatic ecosystems. Additional research is warranted to investigate the potential for seasonal differences in radiocesium accumulations in consumer biota as macrophyte communities that provide the underlying foraging base undergo annual cycles of contaminant sequestration and release. Likewise, we encourage future work to investigate ways to quantify residence time for wildlife collections based on tissue/compartiment

ratios such as the lower GI tract content:muscle tissue ratio that we explored. Accounting for this source of variation in radiocesium activity concentration distributions more fully would provide both valuable insights into human risks for acquisition of radiologically contaminated wildlife food sources and improved opportunities to manage such risks.

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Table 1. Descriptive statistics for radiocesium (¹³⁷Cs) activity concentrations measured in waterfowl collected from Pond B on the Savannah River Site (SRS) in 2014–2015.^a

Compartment	Variable	N	Mean	SE	Min	Max	Median	CV (%)
Coots								
Whole-body	Bq/g; fresh mass	35	0.941	0.064	0.190	1.850	0.885	39.9
Muscle	Bq/g; dry mass	35	6.258	0.448	1.248	11.805	5.950	42.4
	Bq/g; wet mass	35	1.636	0.118	0.279	3.006	1.559	42.7
	wet:dry ratio	35	3.814	0.043	3.423	4.530	3.756	6.7
Liver	Bq/g; dry mass	35	3.554	0.213	0.668	5.711	3.484	35.4
	Bq/g; wet mass	35	1.024	0.062	0.192	1.690	1.014	36.0
	wet:dry ratio	35	3.478	0.030	3.160	3.874	3.448	5.2
GI contents ^b	Bq/g; dry mass	34	1.718	0.254	0.319	8.086	1.194	86.2

	Bq/g; wet mass	34	0.760	0.086	0.157	2.588	0.597	66.1
Ring-necked ducks								
Whole-body	Bq/g; fresh mass	36	1.178	0.097	0.122	2.180	1.226	49.4
Muscle	Bq/g; dry mass	36	7.495	0.661	0.944	15.447	7.339	52.9
	Bq/g; wet mass	36	2.238	0.195	0.280	4.550	2.282	52.4
	wet:dry ratio	36	3.347	0.018	3.157	3.691	3.323	3.3
Liver	Bq/g; dry mass	36	4.311	0.331	0.707	7.583	4.159	46.0
	Bq/g; wet mass	36	1.247	0.097	0.184	2.235	1.211	46.5
	wet:dry ratio	36	3.455	0.031	3.137	3.987	3.439	5.5
GI contents ^b	Bq/g; dry mass	36	1.897	0.225	0.348	8.210	1.683	71.3
	Bq/g; wet mass	36	0.893	0.077	0.130	2.111	0.889	51.6

^aWild caught (L-Lake) American coots and ring-necked ducks were restricted to Pond B for a period of 32 – 172 days before collection.

^bGI contents are from the lower gastro-intestinal tract, including contents of the gizzard.

Table 2. ¹³⁷Cs ecological half-life estimates for species occurring at Pond B and Par Pond^a on the Savannah River Site (SRS).

Species	SRS Location	Ecological Half-Life (yr)	95% CI	Reference
American coot	Pond B	16.8	12.9–24.2	This Study
Largemouth bass	Pond B	16.7	14.3–20.3	Paller et al. 1999, 2002
Largemouth bass	Pond B	13.6	N/A	Peles et al. 2000
Sunfishes	Pond B	13.4	8.13–47.2	Paller et al. 1999, 2002

¹³⁷Cs Uptake and Ecological Half-Life in Waterfowl

American coot	Par Pond-North Arm	4.92	4.36–5.64	Brisbin and Kennamer 2000
American coot	Par Pond-Hot Arm	3.87	3.45–4.41	Brisbin and Kennamer 2000
American coot	Par Pond-West Arm	4.36	3.69–5.33	Brisbin and Kennamer 2000
Largemouth bass	Par Pond	4.99	3.65–7.88	Paller et al. 1999, 2002
Sunfishes	Par Pond	4.78	3.54–7.37	Paller et al. 1999, 2002

^aAll T_e estimates for Par Pond populations were from periods prior to the 1991 drawdown of that SRS reservoir.

Figure 1. Diagram of the Savannah River Site (SRS), showing the Par Pond Reservoir System (PPRS) and L-Lake. Inset shows details of the PPRS, including P and R-reactors, Ponds B and C, and Par Pond proper. Included are depictions of canals which carried cooling water periodically contaminated with radionuclides to the various reservoirs during periods of reactor operations.

Figure 2. Whole-body radiocesium (Bq/g, fresh mass) uptake by American coots (AMCO, top) and ring-necked ducks (RNDU, bottom) collected at Pond B on the Savannah River Site (SRS), following known residence times ranging from 32 – 173 days. Day 0 whole-body radiocesium activity concentrations represent measurements taken after live-capture on L-Lake and prior to being restricted to Pond B with flight feathers scissored (see Table 1). The horizontal heavy dashed lines represent the whole-body equivalent (0.324 Bq/g, fresh mass) to the European Economic Community (EEC 1986) limit for radiocesium in fresh meat (0.600 Bq/g, wet mass).

Figure 3. Muscle and liver tissue radiocesium activity concentration (Bq/g, wet mass) relationships (Spearman correlations, r_s) to whole-body radiocesium (Bq/g, fresh mass) for American coots (AMCO, top) and ring-necked ducks (RNDU, bottom), with lines showing linear fits constrained to intercepts of zero. The horizontal heavy dashed lines represent the European Economic Community (EEC 1986) limit for radiocesium in fresh meat (0.600 Bq/g, wet mass).

Figure 4. Top: Historical data and current data for whole-body radiocesium activity concentrations (Bq/g, fresh mass) available for use in modeling ecological half-life (T_e) for American coots (AMCO) on Pond B of the Savannah River Site (SRS). The horizontal heavy dashed line represents the whole-body equivalent (0.324Bq/g, fresh mass) to the European Economic Community (EEC 1986) limit for radiocesium in fresh meat (0.600 Bq/g, wet mass). Bottom: Linear regression fit of data (natural log-transformed whole-body radiocesium activity concentrations to winter of collection) used to estimate T_e (see text).

Figure 5. Historical data and current data for whole-body radiocesium activity concentrations (Bq/g, fresh mass) available for use in modeling ecological half-life (T_e) for diving ducks (ring-necked ducks [RNDU], ruddy ducks [RUDU], and buffleheads [BUFF]) on Pond B of the Savannah River Site (SRS). The horizontal heavy dashed line represents the whole-body equivalent (0.324 Bq/g, fresh mass) to the European Economic Community (EEC 1986) limit for radiocesium in fresh meat (0.600 Bq/g, wet mass).

Figure 6. Theorized relationship between a concentration ratio of migrant bird GI content to muscle tissue radiocesium activity concentrations and residence time on a radiocesium-contaminated site. Relationship is expected to be modeled as a Ricker function ($y = \alpha x * e^{-\beta x}$; Ricker, 1954).

Figure 7. Relationship between gastrointestinal (GI) content:muscle tissue radiocesium activity concentration ratios and residence time (two discrete periods: 33 – 41 days and 75 – 84 days) spent by ring-necked ducks restricted to Pond B on the Savannah River Site (SRS) before being lethally collected. Box plots represent the quartiles of the distributions.

Figure Legends

Figure 1. Diagram of the Savannah River Site (SRS), showing the Par Pond Reservoir System (PPRS) and L-Lake. Inset shows details of the PPRS, including P and R-reactors, Ponds B and C, and Par Pond proper. Included are depictions of canals which carried cooling water periodically contaminated with radionuclides to the various reservoirs during periods of reactor operations.

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