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Mule deer antlers as biomonitors of strontium-90 on the Hanford Site

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Abstract

This study evaluated deer antlers as indicators of animal uptake of localized ^{90}Sr contamination on the Hanford Site in south-central Washington. Levels of ^{90}Sr were examined in 38 mule deer (*Odocoileus hemionus hemionus*) antler samples collected near and distant from previously active nuclear reactor facilities and from a reference site in central Oregon. Results showed that ^{90}Sr concentrations in antlers collected near reactor facilities were significantly higher ($P < 0.001$) than other Hanford samples. Reference samples contained nearly 5 times the levels of ^{90}Sr compared with Hanford. Strontium-90 concentrations in deer antlers collected at the reference locations were higher than Hanford site deer, presumably because the deer inhabited mountain regions during the summer months that received more atmospheric fallout from historic weapons testing. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Rocky Mountain mule deer (*Odocoileus hemionus hemionus*), an important herbivore of the shrub-steppe ecosystem, is valued for aesthetics and hunting. Mule deer are monitored on the Hanford Site — a former nuclear production facility — because they may be hunted and eaten when they migrate off site (Soldat, Price & Rickard, 1990), and thus may contribute to the radiation dose received by members

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of the public that consume game animals. Mule deer also are important as environmental indicators on the Site and provide useful information for contaminant clean-up efforts (Eberhardt & Cadwell, 1983).

Strontium-90 is a long-lived radionuclide (29.1-year half-life) produced by fission in irradiated fuel in nuclear reactors (NCRP, 1991). It also is a major component of world-wide atmospheric fallout from nuclear weapons testing activities. Strontium is retained less effectively than calcium in living organisms; however, it is generally accepted that ^{90}Sr is biologically analogous to calcium and is therefore concentrated in calcium-rich tissues (Coughtrey & Thorne, 1983; NCRP, 1991).

Normal male mule deer initiate antler growing in early spring and mature by autumn. These animals annually shed their antlers in late winter. Shed antlers can then be collected and used as biological material without sacrificing the animals and with minimal sampling effort. Strontium-90 in deer antlers comes primarily from two distinct sources (Schreckhise, 1974): (1) deposits already present in the skeleton that are remobilized and laid down in growing antler tissue, and (2) the uptake of ^{90}Sr found in forage, soil, and drinking water. A portion of the ingested ^{90}Sr is absorbed from the gastrointestinal tract, and the remainder is excreted in the feces and urine. The gastrointestinal-absorbed portion is deposited in the bone or distributed in an exchangeable pool of plasma, extracellular fluid, soft tissues, and bone surfaces (NCRP, 1991).

Schreckhise (1974) demonstrated the assimilation of ^{85}Sr into growing antler tissue of mule deer when they were fed an ^{85}Sr-spiked diet. However, ^{90}Sr found in antler tissue is not entirely representative of uptake occurring when the antlers are growing and may include translocated ^{90}Sr from other tissue compartments. Strandberg and Strandgaard (1995) noted a significant change in antler-to-bone ratio of ^{90}Sr in roe deer samples collected from 1989–1992. They concluded that this change indicates antlers are formed not as much from translocated bone material, but reflect ^{90}Sr uptake when the antlers were growing. The biological half-life of ^{85}Sr in mule deer was found to average 190 d with a range 127–300 d (Schreckhise, 1974). Dietary strontium and calcium deposition to bone has been found to be reduced in older animals (Farris, Whicker & Dahl, 1967; Schreckhise, 1974).

This study examined the use of a nondestructive approach for collecting a relatively large number of deer tissue samples for radiological analysis. Antlers are "true bone" (Wallmo, 1981), and therefore, may be a useful tissue for estimating ^{90}Sr burdens in animals. Zaleha and Kovach (1985) postulated that the concentration of ^{90}Sr in antlers reflects the degree of contamination within the animal's foraging areas. However, Schreckhise (1974) found it difficult to estimate levels of ^{85}Sr in specific ecological compartments (e.g., soil, vegetation) based on levels found in deer antlers. Information about animal movements would contribute greatly to the validity of using deer antlers for environmental monitoring, particularly if their home ranges included areas of known contamination. Consequently, the use of radio-telemetry to quantify an animals home range can contribute greatly to the validity of using deer antlers for environmental monitoring purposes.

The usefulness of monitoring antlers from a wild mule deer population to determine the potential exposure of ^{90}Sr in the deer's foraging environment previously has not been investigated on the Hanford Site. Earlier mule deer studies conducted on the Site indicated that concentrations of radionuclides in deer tissue were similar to concentrations expected from worldwide fallout (Woodruff & Hanf, 1992). However, traditionally, small sample sizes coupled with the low radionuclide concentrations have made it difficult to interpret the results and establish trends.

The primary objective of this study was to determine the levels of ^{90}Sr in mule deer antlers collected near previously active nuclear reactor sites compared with those collected from more distant sites. In association with other studies of deer populations at Hanford, we also analyzed animal ages, movements, home-ranges and dietary composition of mule deer residing within these areas to determine to what extent these variables contribute to the observed ^{90}Sr concentrations. In addition, we examined and compared levels of ^{90}Sr in deer antlers to levels of ^{90}Sr in soil and vegetation samples collected under the Hanford Site environmental surveillance program.

2. Materials and methods

2.1. Study area

The study was conducted in south-central Washington on the US Department of Energy's Hanford Site (Fig. 1). The Site is located in the Columbia River Basin, a broad, low-elevation valley that has been occupied by settlers and used extensively for livestock grazing since the 1850s, and later, for agriculture and urbanization (Chatters, 1989). The Site was established in 1943 to produce plutonium for nuclear weapons and has been closed to public access since that date. The area is characterized by shrub-steppe vegetation such as big sagebrush (*Artemisia tridentata*) and Sandberg's bluegrass (*Poa sandbergii*) (Downs et al., 1993; Daubenmire, 1970) with approximately 16 cm of annual precipitation (Hoitink & Burk, 1994). The climate consists of hot dry summers and relatively cool winters when the bulk of annual precipitation occurs.

Hanford Site mule deer were studied throughout approximately 200 km^2 of land bordering the Columbia River. The study area was divided into north and south areas (Fig. 1). The southern area generally has been unaltered by Hanford-related activities and is characterized by sand dunes, abandoned farm fields, and shrub-steppe habitat that burned in 1984. Rabbitbrush (*Chrysothamnus spp.*) and bitterbrush (*Purshia tridentata*) occupy the dune habitat (Downs et al., 1993). The northern area contains six inactive production reactor sites (100-B/C, -K, -N, -D, -H and -F; Fig. 1), abandoned agricultural fields, and scattered patches of undeveloped shrub-steppe. In particular, the 100-N Springs area is known to have contaminated groundwater seepage along the Columbia River shoreline that has elevated concentrations of ^{90}Sr (Woodruff & Hanf, 1992).

The Columbia River shoreline supports a narrow corridor of riparian habitats and riverine islands commonly used by mule deer. Shoreline vegetation consists of broad-leafed deciduous trees, mostly mulberry (*Morus alba*), and shrubs, mostly willow

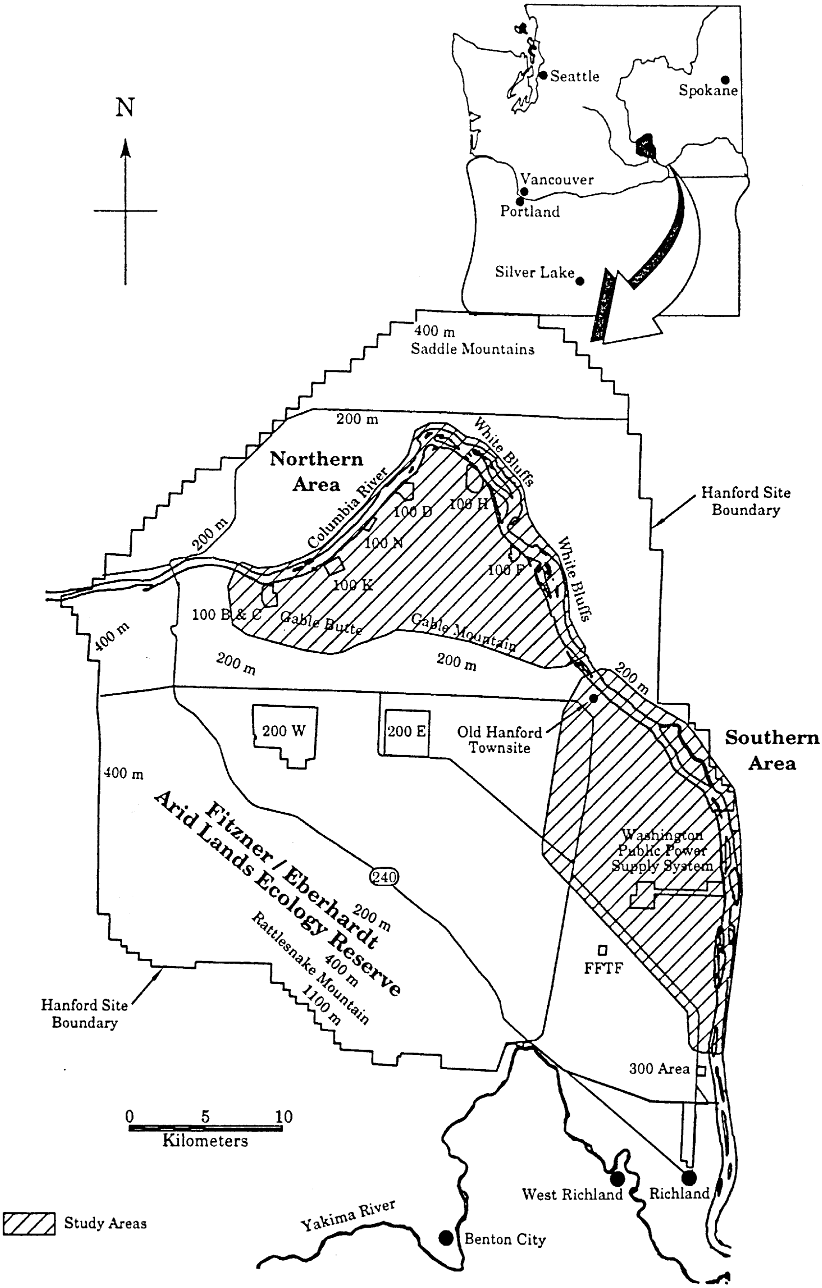

Fig. 1. The Hanford Site in Washington State, USA.

(*Salix spp.*) intermingled with a variety of perennial grasses and forbs (Downs et al., 1993; Sackschewsky, Landeen, Downs, Rickard & Baird, 1992). The riparian zone remains green throughout the summer months because its rooting zones are wetted by river water or shallow groundwater. Groundwater is known to contain elevated concentrations of ^{90}Sr that has accumulated in shoreline vegetation near the reactor facilities (Antonio, Poston & Rickard, 1993).

For comparison, antler and soil samples were collected near Silver Lake, Oregon (Fig. 1). This area was selected because of its remoteness from, but environmental similarity to, the Hanford Site (i.e., relatively arid shrub-steppe habitat). The ^{90}Sr found there is expected to come only from atmospheric fallout (Price, Cadwell, Schreckhise & Brauer, 1981). The mean annual precipitation around Silver Lake ranges from 25 cm in the valleys to approximately 60 cm in the mountains (WIC, 1974). Soil samples also were collected from the Cascade Mountains near Silver Lake. Annual precipitation on the Hanford Site averages 16 cm and rarely exceeds 40 cm (Hoitink & Burk, 1994).

2.2. Animal capture and handling

Deer were mass captured in drive nets (Beasom, Evans & Temple, 1980) at several locations along the Hanford Reach of the Columbia River during February and March 1991, 1992, and 1993. Mule deer were visually located from a helicopter, then driven into the nearby net line, which typically took the shape of an "L". In 1994, several deer were captured with a CODA® net gun fired from a hovering helicopter and slung in a cargo net for transport to a nearby staging area.

For all deer captured, ages were estimated, general health was noted, and an Advanced Telemetry Systems (ATS)® solar-powered radio transmitter was fastened to the ear of adult males. An ATS radio collar also was fastened around the neck of all adult females. An incisiform canine was removed from several males for age determination by cementum annuli analysis (Erickson & Seliger, 1969; Low & Cowan, 1963; Robinette, Jones, Rogers & Gashwiler, 1957).

2.3. Antler sampling

During each capture event, antler samples were collected from bucks by clipping a 3- to 5-cm portion from the tips of each antler point. This sampling design was used because Schultz (1964) and Zaleha and Kovach (1985) found the highest ^{90}Sr concentrations existed in the dense peripheral zone of the antlers. A stainless-steel cutting shear was used to snip the antlers.

2.4. Soil and vegetation sampling

The Hanford Environmental Surveillance Program retains records of radiological data collected as part of routine radiological monitoring efforts (Woodruff & Hanf, 1992). This data base was searched for measurements of ^{90}Sr in soil and vegetation samples collected from 1983–1993 within the areas used by deer in this study (i.e., sampling locations were already within the northern and southern study areas). Additionally, ^{90}Sr data collected during a riverine vegetation study conducted by Antonio et al. (1993) was examined to consider the significance of riparian vegetation as a source of ^{90}Sr uptake for mule deer.

Strontium-90 concentrations of soil and vegetation samples were obtained from Hanford Site environmental surveillance programs (Poston, Antonio & Cooper, 1995). Sampling locations were established to characterize background radionuclide concentrations and concentrations at locations closed to site facilities. Each sampling location covers about 200 m^2 and was sampled annually in the summer. Vegetation samples consist of a mixture of the current growing season's foliage of sagebrush (*Artemesia tridentada*) and rabbit brush (*Chrysothamnus* spp.) found growing in the sampling area. Soil samples consist of five sub-sampled cores collected at least 10 m apart. The cores were 2.5 cm deep and 10 cm in diameter. Only 1983–1993 data from site surveillance sampling locations found within the boundaries of the north and south study areas were used to characterize soil and vegetation concentrations of ^{90}Sr.

2.5. ^{90}*Sr radiochemical analysis*

Analysis for ^{90}Sr in all samples was performed under contract by International Technology Company (Richland, Washington). Samples were ashed in a muffle furnace and dissolved in nitric acid. The dissolved ash was scavenged with barium nitrate, and the strontium was precipitated as a carbonate. The strontium carbonate precipitate was transferred to a stainless-steel planchet and counted on a gas flow proportional counter. At least 10 g of sample media was needed to attain a detection limit of 185 Bq/kg dry weight.

2.6. *Analyses of animal movements*

Animals tracked by radiotelemetry were systematically located by aircraft and/or by ground observers weekly (i.e., weather conditions permitting) during daylight hours. An ATS receiver and two H-element antennas were used to locate each animal. Location points were determined using a global positioning system (GPS). Mapping error associated with aerial relocations was between 0 and 100 m from equipment sources and estimated between 0 and 300 m from observer sources. The Geographical Resources Analysis Support System (GRASS) version 4.1, (Environmental Division of the U.S. Army Construction Engineering Research Laboratory; Champaign, Illinois) was used to plot deer location coordinates to examine the extent of intermixing among animals tagged with radio transmitters and to graphically illustrate animal home-range estimates. Home-range-size estimates of animals tracked by radio transmitter were determined using a computer program described by Ackerman, Leban, Samuel and Garton (1990). Animal location distributions were tested for bivariate normality, weighted bivariate normality, and bivariate uniformity using Cramer Von-Mises goodness of fit test (Smith, 1983; Samuel & Garton, 1985).

2.7. Dietary analysis

Seasonal diets were determined in 1994 by fecal analysis (Korfhage, 1974; Davitt, 1979) from radio-equipped males residing in the northern and southern study areas for 1 year. Radio-equipped bucks from each area were selected randomly each month and remotely observed until the animal defecated. Samples were then collected in a plastic whirl-pak^{tm} and stored in a freezer below 0°C until submission to the Washington State University (WSU) Diagnostic Laboratories for analysis. Two field technicians collected from 0 to 4 fecal samples/day, each from an individual animal with an average of 20 samples per month. Fecal samples from different animals were composited by area and season. Fall (Sept, Oct, Nov, Dec), spring (Jan, Feb, Mar, Apr), and summer (May, Jun, Jul, Aug) were chosen based on plant community changes typically seen in south-central Washington shrub-steppe. Three duplicate composite samples were submitted to the WSU Diagnostics Lab for each area and season (18 samples total).

2.8. Statistical treatment

Radioanalytical results were plotted on a relative frequency graph to examine ^{90}Sr contaminant concentration distributions. The Shapiro-Wilk (Shapiro & Wilk, 1965) test was used to test fit of normality. The non-parametric multi-response permutation procedure (MRPP) was chosen to test for significant differences in ^{90}Sr concentrations between sampling locations (Mielke, 1991). An analysis of variance (ANOVA) was conducted on Ln-transformed soil and vegetation data.

3. Results

3.1. Antler analysis

Thirty-eight deer antler samples were analyzed for ^{90}Sr levels. Fourteen (37%) samples came from animals captured in the northern study area, 14 (37%) were collected from animals captured in the southern area, and 10 (26%) were collected from the Silver Lake area.

Strontium-90 concentrations in antlers collected from the northern area were approximately twice ($p < 0.001$) as high as antler levels found in samples from the southern area. Mean ($\pm$ one standard error) dry-weight concentrations of ^{90}Sr in antlers collected from the northern and southern study areas were 15.2 ($\pm$ 2.2) and 7.0 ($\pm$ 0.74) Bq/kg, respectively. The mean concentration of ^{90}Sr found in antlers collected from the Silver Lake site was approximately five times (77.3 $\pm$ 5.9 Bq/kg) larger than those found in antlers from the northern study area.

3.2. Age relationships

The relationship between age and ^{90}Sr concentrations in antlers was evaluated in both study populations, however, not all animals were aged. The southern population

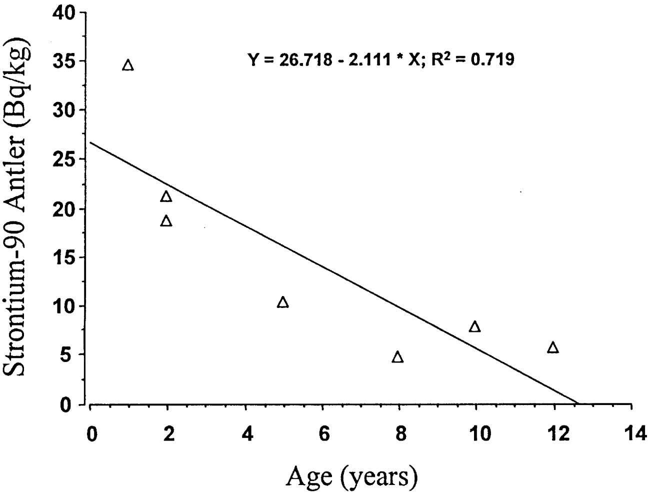

Fig. 2. Linear regression analysis of ^{90}Sr in antlers versus age in seven deer from the northern study area.

consisted of nine aged deer of which eight ranged from 2 to 3 years old. The remaining deer was 8 years old. A linear regression of age and ^{90}Sr concentrations had a correlation of $R = 0.154$ and was not significant ($P = 0.693$). However, the range of aged deer (6 years) was not suitable to draw a relationship between age and ^{90}Sr concentrations in antlers. The northern study population ($n = 7$ aged deer) contained a larger percentage of older deer and a range of 11 years (median age of 5, range from 1 to 12 years). There was a significant ($P = 0.0159$), negative correlation ($R = -0.848$) between age and ^{90}Sr concentrations in antlers (Fig. 2).

3.3. Soil analysis

Strontium-90 results from soil samples collected as part of the site-wide monitoring project from 1983 to 1993 were segregated into northern/southern areas. Histograms of surveillance soil data did not appear to be normally distributed. The soil data were Ln-transformed producing an apparent fit to a normal curve, and ANOVA was performed. No significant difference was found between the two Hanford study areas ($P = 0.551$). In Hanford soils where ^{90}Sr was historically deposited on the soil as fallout; 51–74% of the ^{90}Sr was retained in the top 5 cm of a 30-cm core (Price 1991). Poston et al. (1995) has also shown that decreases in ^{90}Sr in the top 2.5-cm layer of soil over a 10-year period was greater than the decrease associated with simple radioactive decay. Consequently, the soil samples may underestimate the total inventory of ^{90}Sr in soil, but should still be adequate for comparing the two study areas because precipitation was the same for both study areas. The median concentration of ^{90}Sr in the combined study areas was 7.6 Bq/kg dry soil.

Mean levels of ^{90}Sr from soil samples collected in the Silver Lake basin area, 6.8 Bq/kg (5.0–8.6 Bq/kg), did not correspond to the high values observed in antlers

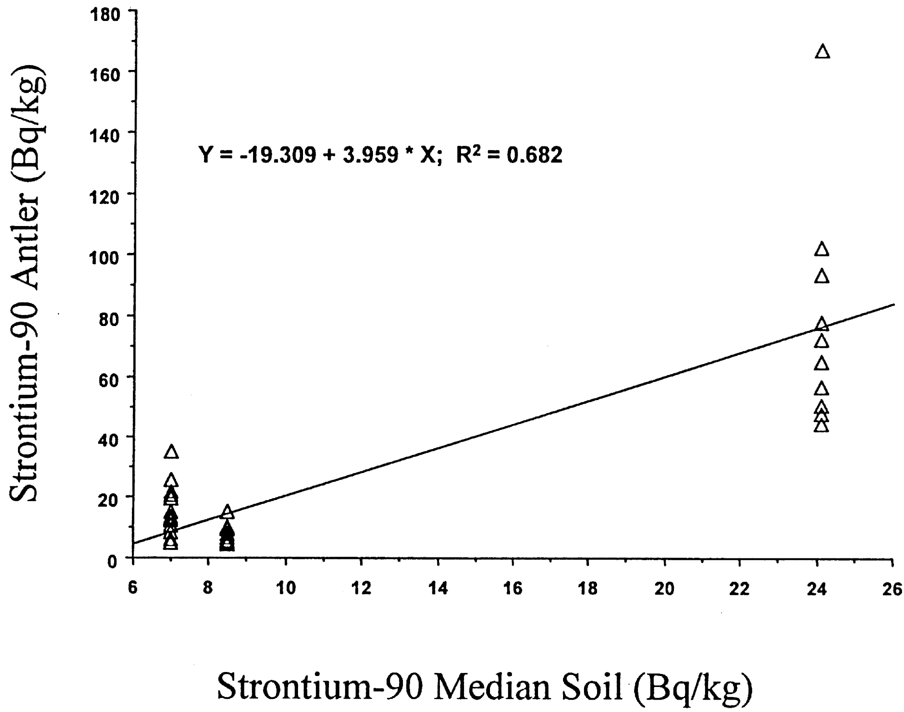

Fig. 3. Linear regression analysis of ^{90}Sr in antlers blocked on median soil concentrations from the southern, northern and Silver Lake study areas.

collected from that area. However, results from soil samples collected in the nearby mountainous area, 23.3 Bq/kg (19.9–25.5 Bq/kg), followed the relatively high values observed in antlers collected from the area. Levels of ^{90}Sr in Silver Lake soil samples generally were higher than the Hanford Site soil data summarized for this study. A linear regression analysis between median soil and antler data from the northern study area, southern study area and Silver Lake area (mountain soil samples) demonstrated a significant correlation ($P < 0.001$; Fig. 3).

3.4. Vegetation analysis

The sitewide monitoring database for vegetation (annual growth of rabbitbrush and sagebrush) was also evaluated for ^{90}Sr levels found in samples collected in the northern and southern areas. Data appeared to fit a log-normal distribution and, following Ln-transformation, were analyzed by ANOVA for differences between groups. The ANOVA was not significant ($P = 0.636$), corroborating conclusions that no difference existed in ambient levels of ^{90}Sr in the north and south study areas at Hanford. Unfortunately, vegetation samples were not collected from the Silver Lake location because it was assumed that the soil data would provide the necessary information about ^{90}Sr levels in the central Oregon environment.

Shoreline vegetation collected along the 100-N Area from 1990 to 1992 had an elevated concentration of ^{90}Sr compared with other Columbia River shoreline areas within Hanford Site boundaries (Antonio et al., 1993). Mulberry leaves were found to contain the highest ^{90}Sr concentrations, followed by dogbane (*Apocynum sibiricum*), yarrow (*Achillea millefolium*), chickory (*Cichorium intybus*), and willow (Table 1). Riparian plants collected from the northern study area clearly had higher ^{90}Sr concentrations than plants collected from the shoreline areas in the southern study area.

3.5. Animal movements

Home range areas and sub-population intermixing were examined to evaluate spatial patterns of the radio-equipped deer. Home ranges of 19 radio-equipped males were estimated using weighted bivariate ellipse because all animals fit ($P < 0.1$) Cramer Vone Mises weighted distribution tests (Samuel & Garton, 1985; Smith, 1983). Animals caught in the southern area ranged downriver extensively, but rarely were present at any distance upriver from this location (Fig. 4). Animals captured from the northern area (near old reactor sites) essentially were confined to these areas. From 1992 to 1994, 866 location points were collected for these deer with an average of 47 ± 9 (1 SD) locations per animal. The animals were tracked an average of 17 ± 6 (1 SD) months.

Weighted bivariate ellipse estimates for male deer on the Hanford Site suggested an average home range size of 52.3 ± 22.8 km^2 (1 SD). These results are consistent with findings by Eberhardt, Hanson and Cadwell (1982), who reported an average home-range size of 37 deer to be 39 ± 27 km^2 (1 SD) using the elliptical technique.

3.6. Dietary analysis

Fecal examinations from radio-equipped male deer indicated they frequently consumed shrubs growing along the shoreline. Summer composite dietary results from northern ($n = 11$) and southern ($n = 11$) study area deer showed that shrubs comprised nearly 70% of the animals' diets in both areas. Of the shrub species identified in fecal samples from the northern area, willow and mulberry — found only along the riparian zone of the Columbia River — were most common. Samples analyzed from the southern population also contained a large portion of shrubs; however, bitterbrush (*Purshia tridentata*), an upland species, was the dominant shrub.

Spring season diets suggest foraging preference for succulent grasses as opposed to shrubs, and results from the northern and southern study areas ($n = 19$) indicate less than 7% of the diet consisted of shrubs. The dominant grass species present in samples collected were cheatgrass (*Bromus tectorum*) and Sandberg's bluegrass (Tiller, 1996). Forbs-dominated by evening primrose (*Oenethara spp.*) and lupine (*Lupinus spp.*)– also were consumed more than shrubs during spring, indicating that these deer ate plants primarily away from the river in spring.

The most notable difference between diets of deer residing in the northern and southern areas was found during the fall. Shrubs, primarily mulberry and willow,

Table 1
Strontium-90 (Bq/kg dry weight) in riparian vegetation (leaves & stems) collected from the Columbia River shoreline in the Northern and Southern study areas[a]

Species	Study area	Mean	Median	Minimum	Maximum	Count
		Woody Shrubs/Trees				
Chokecherry *Prunus virginiana*	Northern	− 0.030				1
	Southern	9.25				1
Dogbane *Apocynum cannabinum*	Northern	19.1	3.5	0.029	96.6	7
	Southern[b]	.	.	.	.	0
Mulberry *Morus alba*	Northern	1410	12.4	0.081	16,200	14
	Southern	7.68	6.25	0.396	17.3	8
Willow *Salix* spp.	Northern	13.5	6.25	2.86	31.5	3
.	Southern	2.64	2.71	2.12	3.01	4
		Herbs/Forbes				
Chicory *Cichorium intybus*	Northern	13.9	7.25	0.611	48.1	5
	Southern	1.75	1.54	0.688	3.23	4
Milkweed *Asclepias speciosa*	Northern	5.55				1
	Southern	1.82	1.82	1.80	1.84	2
Yarrow *Achellea millefolium*	Northern	16.6	2.45	0.232	95.8	7
	Southern	1.29	0.766	0.536	2.58	3

[a] Antonio et al. (1993).
[b] No sample collected.

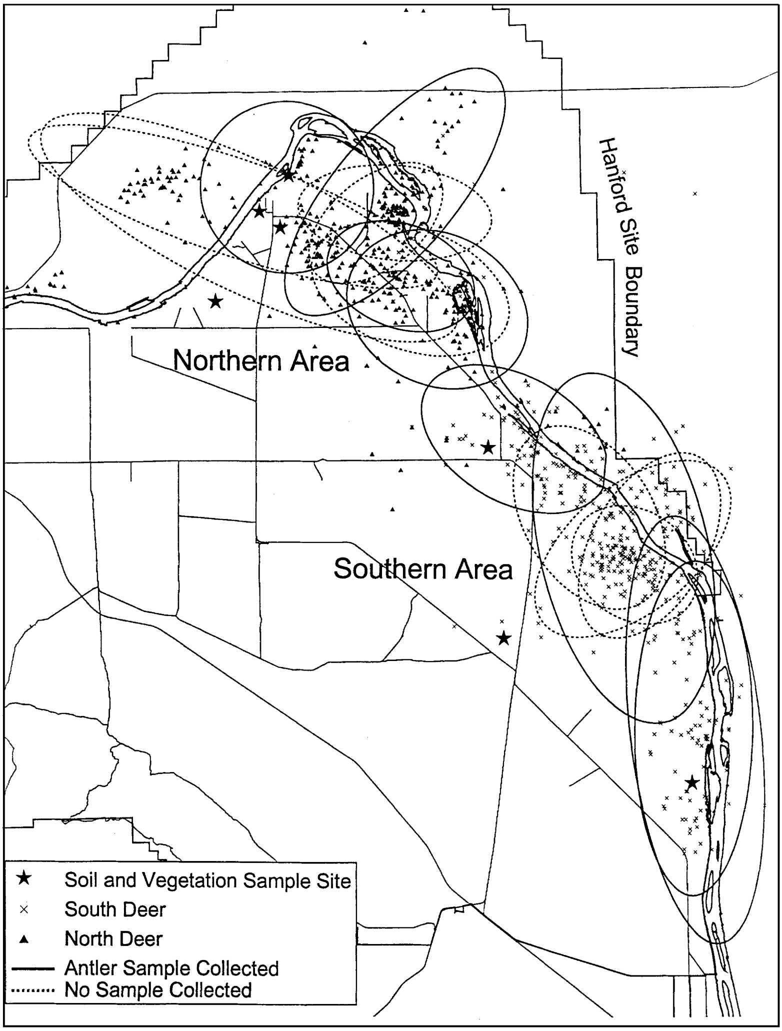

Fig. 4. Locations of radio-tracked mule deer on the Hanford Site.

comprised 63% of the deer diets in the northern area ($n = 13$) compared with 23% in the southern area ($n = 9$). Deer diets from the southern area contained over 30% Sandberg's bluegrass compared with only 4% in the northern area. These data reflect the availability of late-summer succulent grasses in the southern area (Downs et al., 1993), which comprises relatively undisturbed land where Sandberg's bluegrass is common. The northern area largely covers abandoned farm fields where cheatgrass predominates on the Hanford Site. Cheatgrass becomes desiccated in early summer while Sandberg's bluegrass persists as a succulent grass through September.

4. Discussion

Analyses of deer antlers detected differences in ^{90}Sr levels between the two Hanford study areas and the Silver Lake location. Observed differences were correlated to levels of ^{90}Sr found in soil samples in the deer's areas of use. In the Silver Lake area, deer migrate into the mountains in spring and reside there until winter, during which time antler growth is greatest (personal communication, Oregon Department of Fish and Wildlife). The relatively higher concentrations of ^{90}Sr were expected in the mountain Silver Lake soil samples because historic atmospheric fallout from nuclear weapons testing is associated with higher amounts of precipitation as found in central Oregon (WIC, 1974; Whicker, Farris, Remmenga & Dahl, 1965; Osburn, 1967; Whicker, 1983).

In determining differences in ^{90}Sr levels between the northern and southern Hanford populations, the age of animals had to be considered because age has been inversely correlated with radio-strontium concentrations (Farris et al., 1967; Schreckhise, 1974). In this way, a bias could exist if animals sampled in the northern area were much older than those sampled in the southern area. However, for this study, the opposite was found to be true for deer from the northern area where age and antler ^{90}Sr concentrations were determined (Tiller 1996). It is possible that ^{90}Sr data collected from the northern deer herd might be biased low because more older animals were sampled compared with the southern deer herd. However, additional age-related data would be required to substantiate this finding.

A deer's body burdens of ^{90}Sr are influenced by dietary uptake throughout the year (Schreckhise, 1974). Analyses of soil samples from the mountainous home-range area of Silver Lake deer indicated higher concentrations of ^{90}Sr than those found in the shrub-steppe areas at Hanford. Soil and terrestrial vegetation monitoring data indicated no difference in ^{90}Sr concentrations between the northern and southern areas. However, studies of riparian vegetation (1990–1992) indicated that vegetation, particularly mulberry and willow, growing near the 100-N area had elevated concentrations of ^{90}Sr. These plants were found to be common in deer diets.

Elevated concentrations of ^{90}Sr found in deer antlers collected from the northern study area may reflect higher consumption of shrubs occurring along the river where ^{90}Sr contamination was known to be elevated. Shoreline vegetation from the 100-N Area represents one potential source of contamination that may explain the apparent elevated levels of ^{90}Sr found in antlers collected from this area. If the 100-N Area were the major ^{90}Sr source for deer uptake, continued monitoring of deer antlers should show a decrease in antler ^{90}Sr concentrations now that contaminated vegetation from the 100-N shoreline has been removed (Poston et al., 1995). Other unknown sources of ^{90}Sr could exist.

Previous research has demonstrated the use of monitoring animal movements in relation to levels of contaminants found in the animals (Eberhardt & Cadwell, 1983; Nelin, 1995). Monitoring year-round movements of deer along the Columbia River at Hanford corroborated the grouping into a northern and southern sub-populations. In this study, variability in the ^{90}Sr levels was reduced when deer were grouped by study area. Monitoring subsequent movements of several sampled animals residing within the northern/southern areas strongly supported observed differences in levels of ^{90}Sr

found in antlers. Considering the non-migratory patterns of resident Hanford mule deer supported by movement data, it can be concluded that the concentration of ^{90}Sr found in antlers is indicative of elevated environmental levels of radionuclides in areas defined by the home ranges of these study animals. Thus, we conclude that antlers can be used to examine localized levels of ^{90}Sr in the Hanford Site environment.

Concentrations of ^{90}Sr measured in the antlers were low and do not indicate relatively high radiation exposure to the deer. Antlers collected from the northern deer population had significantly higher levels of ^{90}Sr than antlers collected from the southern population. However, levels of ^{90}Sr in Hanford deer antlers were much lower than deer antlers collected from central Oregon.

The monitoring of antlers for ^{90}Sr is a useful indicator of the effectiveness of waste management practices on site. Because ^{90}Sr does not accumulate in edible muscle, there is no implied human hazard associated with observed elevated levels in antlers. Shoreline vegetation sampled from 1990 to 1992 clearly demonstrated that at certain locations along the Columbia River, concentrations of ^{90}Sr were elevated, but in no instances were corresponding concentrations of ^{137}Cs in vegetation also elevated (Antonio et al., 1993). In the past, access by deer to low-level waste areas in central Hanford has resulted in increased concentrations of ^{137}Cs in muscle and ^{90}Sr in bone (Eberhardt et al., 1982). Low-level waste ponds located in central Hanford (Emery & McShane, 1978) were sources of potential exposure to deer that would drink the water and eat other shoreline vegetation around the ponds. In this case, antler sampling for ^{90}Sr was a valid non-destructive method for biomonitoring potential exposure to contaminants and would also indicate that deer may also have elevated ^{137}Cs concentration in muscle. In the present scenario where ^{137}Cs is not found in the 100-N springs, elevated concentrations of ^{90}Sr in antlers do not suggest elevated concentrations of ^{137}Cs in muscle. Surveillance results of deer muscle from the 100-N Area for the study period do not show elevated ^{137}Cs concentrations in muscle (Poston & Cooper, 1994; Poston, 1997). Consequently, in this instance, the observations of elevated ^{90}Sr in antlers in deer inhabiting the northern study area do not portend a hazard associated with other radionuclides routinely associated with waste management areas at Hanford.

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