Conf-9205144--1

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CONF-9205144--1

DE92 011774

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Prepared for

"Seminar on The Dynamic Behaviour of Radionuclides in Forests"

Stockholm, Sweden

May 18-22, 1992

Dispersal of Radioactivity by Wildlife from Contaminated Sites in a Forested Landscape

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Abstract.-- Oak Ridge National Laboratory (ORNL) is located within the Valley and Ridge Physiographic Province of eastern Tennessee (USA). This area is characterized by deciduous forests dominated by hardwood and mixed mesophytic tree species. Wildlife populations have access to some radioactively contaminated sites at ORNL, and contaminated animals or animal nests within the Laboratory's boundaries have been found to contain on the order of 10^{-12} to 10^{-6} Ci/g of ^{90}Sr or ^{137}Cs, and trace amounts of other radionuclides (including transuranic elements). Animals that are capable of flight, like waterfowl, and animals with behavior patterns or developmental life stages involving contact with sediments in radioactive ponds, like benthic invertebrates, present the greatest potential for dispersal of radioactivity. Mud-dauber wasps (*Hymenoptera*) and swallows (*Hirundinidae*) may also transport radioactive mud for nest building, but over relative short distances (0.2 to 1 km). The emigration of frogs and turtles from waste ponds also presents a potential for dispersal of radioactivity over distances less than 5 km. Movement by small mammals is limited by several factors, and larger animals, like white-tailed deer (*Odocoileus virginianus*), are more likely vectors of radioactivity due to their greater body size, longer life expectancy, and larger home range. However, larger animals, like deer and waterfowl, tend to have lower ^{137}Cs concentrations than smaller

animals, like small mammals and insects. In deer hunts from 1985 to 1990, 0.8 to 5.7% of the animals killed were not released to hunters due to elevated levels of ^{90}Sr in bone; ^{137}Cs concentrations in deer were less than 5 pCi/g. Theoretical calculations indicate that nanocurie levels of ^{90}Sr in bone can arise from relatively small amounts (1%) of contaminated browse vegetation in a deer's diet. Measures that have been undertaken at ORNL to curtail the dispersal of radioactivity by animals are briefly reviewed.

INTRODUCTION

Oak Ridge National Laboratory (ORNL) is located within the Valley and Ridge Physiographic Province of east Tennessee, U. S. A. (latitude 35°58' north, longitude 84°17' west). Temperate deciduous forests, dominated by hardwood and mixed mesophytic tree species, surround the Laboratory. The forest community is mostly oak-hickory (*Quercus* spp. - *Carya* spp.) with scattered pines (*Pinus* spp.) and some pine stands. Species common to the mixed mesophytic association, which is typically found in bottomlands and on lower slopes, include yellow poplar (*Liriodendron tulipifera*), beech (*Fagus grandifolia*), and maple (*Acer rubrum and A. saccharum*). Hardwood stands, pine stands, and old fields comprise approximately 51, 30, and 8% of the habitats on the Oak Ridge Reservation (Boyle et al. 1982).

Since the mid-1950's, radioactively contaminated sites from past missions and the disposal of radioactive waste at ORNL have been described and characterized by numerous environmental studies (for example, Auerbach and Crossley 1958, Willard 1960, Crossley 1963, Dahlman and Van Voris 1976, Garten 1978, 1979). Human access to contaminated areas that are located away from the main site of the Laboratory, but still within its boundaries, is controlled by fences and perimeter warning signs. However, the activities of wildlife in contaminated areas and aspects of animal behavior may lead to the dispersal of radioactivity that is beyond reasonable and customary measures of control.

The purpose of this paper is to review radionuclide uptake by animals and potential and actual experiences with dispersal of radioactivity by animal movements on the Oak Ridge Reservation. Although there are long-term plans for the isolation, stabilization, and cleanup of radioactive waste disposal sites that remain as a legacy to the Laboratory from past missions, oversight of radioactive sites will continue to be part of the institutional responsibility for many years. While awaiting remediation, retired waste disposal areas and their environs provide the opportunity for animals to accumulate and disperse radioactivity as a result of movements associated with foraging and breeding. Although field studies indicate that fish and benthic invertebrate populations in contaminated drainages from the Laboratory contain measurable amounts of ^{137}Cs (Kolemenin 1972, Loar et al. 1987), the movement of aquatic organisms beyond the Laboratory's boundaries is currently impeded by White Oak Lake dam, and an additional rock barrier constructed at the confluence of White Oak Creek and the Clinch River (Figure 1). Therefore, the present report is limited to the dispersal of radioactivity by animals like insects, birds, and mammals that spend part or all of their life on the land.

SITE DESCRIPTION AND BACKGROUND

Radioactively contaminated areas include floodplains which received outfalls from past operations, sites of transfer line leaks, pits and trenches used 25 years ago for the disposal of liquid radioactive wastes, burial grounds for solid low-level radioactive wastes, and retired radioactive waste treatment ponds or retention basins (Figure 1). Some radioactive areas, like waste treatment ponds, are located in the immediate vicinity of buildings and roads of the main laboratory complex. Other sites (like radioactive waste disposal areas and contaminated floodplain or shoreline habitats) are located at a distance of 3 to 4 km from the Laboratory.

The areal extent and type of radioactive contamination varies greatly from site to site. In general, sites range in size from small waste ponds and sites of spills or leaks (≈0.01 ha) to areas the size of burial grounds and White Oak Lake (≈10 ha). Ground surface gamma exposure rates in the vicinity of these sites are on the order of 0.01 to 100 mR/hr (the gamma exposure rate at the ground surface from background radiation is ≈0.01 mR/hr). The principal radionuclides and radionuclide inventories at each site vary greatly, but ^{3}H, ^{60}Co, ^{90}Sr, ^{137}Cs, and ^{239}Pu (as well as other transuranic elements) are the radionuclides most frequently encountered.

In contaminated floodplains and seepage areas adjacent to burial grounds, concentrations of ^{90}Sr and ^{137}Cs in surface soils are typically on the order of 0.05 to 50 nCi/g (Dahlman and Van Voris 1976, Garten 1987). Concentrations of ^{239}Pu and other transuranics are less, typically on the order of 1 to 100 pCi/g (Adriano et al. 1980). Radionuclide levels are higher in the sediments of ponds and impoundments that were used for waste processing. Four of the ten waste impoundments at ORNL each contain more than 20 Ci of radioactivity and have radionuclide concentrations in sediments up to 5 μCi ^{137}Cs/g and 0.4 μCi ^{90}Sr/g (Francis and Sealand 1987). Two process waste settling basins, Pond 3513 (≈0.4 ha) and Pond 3524 (≈0.2 ha), each contain ≈5 Ci of transuranic elements ($^{238,239}Pu$, and ^{241}Am) with sediment concentrations as high as 10 nCi/g. The total activity in White Oak Lake bed sediments is estimated to be 644 Ci and includes 591 Ci ^{137}Cs, 33 Ci ^{60}Co, 20 Ci ^{90}Sr, and 0.87 Ci of transuranic elements ($^{238,239}Pu$, ^{241}Am, and ^{244}Cm) (Oakes et al. 1982).

DISPERSAL OF RADIOACTIVITY THROUGH NEST BUILDING

Mud Dauber Nests (*Hymenoptera*)

The dispersal of radioactive mud from waste pits and White Oak Lake bed by black and yellow mud-daubers (*Sceliphron cementarium*) and pipe-organ mud daubers (*Trypoxylon politum*) was first described in the early 1960's (Shinn 1964). Since that time, there have been continuing occasional discoveries of radioactive mud nests built by these two species of wasps. Mud dauber nests are sometimes built in inaccessible and hidden places, such as between building walls or behind instrument panels. Considerable variation has been observed in levels of radioactivity within and between mud-dauber nest sites at ORNL. Mud within a single nest may vary 4-fold in gamma activity, and concentrations of gamma emitters (^{137}Cs, ^{106}Ru, ^{60}Co, ^{65}Zn, and ^{144}Ce) have exceeded 350 μCi/g mud in some nests (Shinn et al. 1964). Of 23 nesting sites that were located within the main laboratory complex in 1964, only 4 gave readings > 0.5 mR/hr or had gamma radioactivity > 100 pCi/g. A higher percentage (50%) exceeded this limit in 30 nesting sites that were studied in the burial grounds south of ORNL the same year (Shinn and Shanks 1965). Studies indicate that these wasps carry mud to nest sites over distances less than 200 m from the source, however some data suggest that transport distances could be twice as far (up to 450 m).

Radioactive Bird Nests

Several species of birds use mud to partially construct their nests and two species, barn swallows (*Hirundo rustica*) and cliff swallows (*Petrochelidon pyrrhonota*), construct mainly mud nests, reinforced or lined with grass and other material (Kilgore and Knudsen 1977). Both types of swallows occur on the Oak Ridge Reservation, and there have been occasions when radioactive bird nests have been found in or on buildings in the vicinity of radioactive waste treatment ponds. Barn swallow nests are frequently found in association with nests of mud-dauber and pipe organ wasps (Jackson and Burchfield 1975). Mud nests of barn and cliff swallows average 25 to 35% silt and 11 to 16% clay. Cliff swallow nests, which are gourd shaped, are more fragile than barn swallow nests, perhaps because of their higher sand content (Kilgore and Knudsen 1977).

Cliff swallows may forage as far as 3.2 km from their nest site while barn swallows seldom forage more than 800 m from their nest site (Samuel 1971). Cliff swallows have been observed to carry mud up to distances of 1.2 km for nest building (Buss 1942). A single cliff swallow or barn swallow nest is estimated to weigh about 1 kg, and therefore, depending upon the source of the mud (ie. radioactive waste ponds or White Oak Lake), such nests may contain microcurie amounts of radioactivity. However, the relatively short distance over which these birds transport mud for nest building indicates that, like radioactive mud-dauber nests, this potential source of exposure is limited to areas within the laboratory.

Burrowing Animals

Animals can move radioactive wastes to the ground surface through their burrowing behavior. For example, woodchucks (*Marmota monax*), which are common rodents observed around the Laboratory, excavate burrows ≈1.5 m deep and 9 m long (Burt and Grossenheider 1964). Three ground hogs with body weights ranging from 3.4 to 3.9 kg were trapped from banks of Pond 3513 and 3524 in November, 1978, just prior to hibernation, and found to contain as much as 400 pCi ^{90}Sr/g bone (Garten, unpublished data). Burrow volume and the volume of soil removed during excavation of animal nests increases with body weight (Figure 2). Natural populations of small mammals and larger rodents, like *Marmota* spp., are reported to annually excavate on the order of 10 to 100

m^3 soil/ha (Golley et al. 1975). The construction of burrows and tunnels by animals may contribute to both the dispersal of radioactivity from contaminated sites and the entrance of water into buried radioactive wastes.

DISPERSAL OF RADIOACTIVITY THROUGH BIOACCUMULATION

Insects as Vectors in the Dispersal of Radioactivity

In the mid-1950's, taxonomic collections indicated more than 400 species of insects on the drained White Oak Lake bed. At that time, herbivorous insects from the site contained ≈150 pCi ^{137}Cs/g dry weight (DW) and 180 pCi ^{90}Sr/g DW (Auerbach 1959). More recent studies, involving the placement of honeybee hives near former radioactive waste disposal sites at ORNL, show small amounts of ^{3}H (≤110 pCi/g) and ^{137}Cs (≤15 pCi/g) in honey, and concentrations of up to 250 pCi ^{137}Cs/g in bees (Eldridge 1983). Past studies concluded that if all the insects on White Oak Lake bed left the site simultaneously, the loss of radionuclides would be about 3 μCi of ^{90}Sr and 3 μCi of ^{137}Cs. It appears that insect movements from contaminated areas in the White Oak Creek system are unimportant as a mechanism for the dispersal of radioactivity to surrounding areas (Crossley 1963). There have, however, been observations of more highly contaminated individual insects within the main complex of the Laboratory (exposure rates as high as 20 mrad/hr per individual). Most of these findings, which occurred a decade ago, appeared to be associated with the emergence of adult insects (chironomids) from radioactive waste treatment ponds.

Emergent aquatic insects from radioactive ponds are of special interest because insects like midges (*Diptera: Chironomidae*) and dragonflies (*Odonata*) have developmental stages that put them in intimate contact with aquatic sediments where the levels of radioactivity are higher than those found in the water (Voshell et al. 1985). Past studies show that dragonflies leaving a retired waste pond as winged adults contained on the order of 100 nCi ^{137}Cs /g DW. Concentrations of ^{137}Cs in the sediments of this pond are ≈16 µCi/g (Voshell et al. 1985). Considering the area of Ponds 3524 and 3513 (0.6 ha), estimates of emergent insect biomass (1 to 10 g/m^2 yr^{-1}), and assuming a concentration of 10^{-3} to 10^{-1} µCi/g, the theoretical calculated loss of activity from these ponds by insect emergence could be on the order of 0.006 to 6 mCi/year.

The extent of dispersal by contaminated insects is difficult to predict. Flies and mosquitos (*Diptera*) and dragonflies (*Odonata*) have been observed to travel up to 100 km (Figure 3). Generally, insect flight speed is directly correlated with body size (the product of wingspan and body length) and ranges from 1 to 35 km/hr, although the actual rates and duration of insect dispersal will be greatly influenced by meteorological conditions (Pedgley 1982). Contaminated insects may quickly lose a significant portion of their body burden following migration because the biological half-life of ^{137}Cs and ^{90}Sr in terrestrial invertebrates lacking calcified exoskeletons is on the order of 1 to 10 days (Reichle et al. 1970). Based on actual experience, the dispersal of highly contaminated emergent aquatic insects (those giving exposure rates > 10 mrad/hr) and their flight to areas within or beyond the Laboratory is a relatively rare event.

Dispersal of Radioactivity by Amphibians and Reptiles

In late May, 1991, four radioactive frogs were found dead on a road adjacent to Pond 3524 (an occurrence that was reported by both the national and international press). The frogs had been run over by vehicles and gave readings as high as 10,000 dpm with a Geiger-Mueller instrument. Since that occurrence, radioactive frogs were observed at other locations within the Laboratory (some with GM readings as high as 35,000 dpm).

Rainfall and high humidity, particularly at night, are initiating factors in exploratory behavior by frogs. Adult leopard frogs (*Rana pipiens*) occasionally move extensively (>100 m) from their homes during nocturnal rains. Travel distances between 40 and 160 m, and rates of travel up to 47 m/hr have been recorded in a single night (Dole 1965). However, following such excursions, which usually end with the cessation of rainfall, adult frogs exhibit a strong tendency to return to their home range (Martof 1953, Dole 1965).

Movement behavior by recently metamorphosed frogs is distinctly different from the homing behavior exhibited by adults. For example, young frogs may disperse suddenly and completely from the pond where larval development occurs. In studies of young green frogs (*Rana clamitans*), where as many as 468 individuals were marked at a small pond (0.03 ha), 97% dispersed within one month (Schroeder 1976). Schroeder recaptured many young frogs at distances <500 m from the pond, however 10 frogs were found to disperse between 2.5 and 4.8 km. The dispersal of newly transformed individuals is characteristic in many ranids, particularly in response to high population densities and the lack of suitable habitat (Duellman and Trueb 1986).

Radionuclide levels have also been studied in turtles from White Oak Lake; 137 turtles of six species were captured from the lake in the mid-1980's (Meyers-Schone and Walton 1990). Although distances of more than 1 km can be traveled by dispersing turtles (Gibbons 1968), large scale dispersal by juveniles does not appear to be as important in turtles as in frogs. Average levels of radionuclides in turtles from White Oak Lake were ≈1 nCi ^{137}Cs/g muscle and 10 nCi ^{90}Sr/g bone, on a fresh weight (FW) basis. Concentrations of ^{90}Sr in turtle carapaces were similar to concentrations in bone. Maximum concentrations observed in yellow-bellied sliders (*Trachemys scripta*) were 14 nCi ^{137}Cs/g FW muscle and 120 nCi ^{90}Sr/g bone. Radiocesium has a biological half-life on the order of 100 days in yellow bellied turtles, while that for ^{90}Sr is approximately one year (Scott et al. 1986, Peters and Brisbin 1988).

Mark recapture studies indicated that most yellow-bellied sliders, which have live weights up to 2.8 kg, travel distances less than 300 m on White Oak Lake, although some data indicate a dispersal distance of up to 2.5 km (Meyers-Schone and Walton 1990). Home range size in the largest species of turtle found at the Laboratory (*Chelydra serpentia*), is reported to be on the order of 3 to 9 ha (Obbard and Brooks 1981). It is estimated that emigration of a single turtle (2 kg) from White Oak Lake could disperse on the order of 1 to 50 μCi of ^{90}Sr or ^{137}Cs.

Small Mammal Dispersal as a Vector of Radioactivity

Population densities in murid, microtine, and cricetine small mammals (rats and mice) typically range between 10 and 100 individuals/ha (French et al. 1975). Dispersal is a contributing factor or a key factor in the regulation of small mammal population densities (Lidicker 1975). The biomass of small mammals on White Oak Lake bed in July, 1959, was estimated to be between 1.9 and 3.1 kg/ha. At that time, the body burdens of ^{137}Cs in cotton rats were as high as 1.2 nCi ^{137}Cs and 16.2 nCi ^{90}Sr. Based on biomass and measured radionuclide levels in 1959, the estimated inventory of ^{137}Cs, ^{90}Sr, and ^{60}Co in cotton rats (*Sigmodon hispidus*) living on White Oak Lake bed was 120, 620, and 100 nCi/ha (Auerbach et al. 1960). The amount of radioactivity that could have been lost by complete emigration of these small mammals from an area the size of the dry lake bed ($\approx$10 ha) was $\leq$10 μCi.

Similar estimates can be made for small mammal populations inhabiting the site of a former radioactive waste retention pond on the White Oak Creek floodplain. A total of 84 small mammals (1.8 kg live weight or 0.63 kg DW), representing 5 species, were trapped from the floodplain research site in the mid-1970's. The highest small mammal body burden for ^{137}Cs was 675 pCi (Van Voris and Dahlman 1976), although higher body burdens (12 to 26 nCi) were measured in a few larger mammals (opossum and raccoon). Concentrations of ^{90}Sr up to 7.6 nCi/g bone have been recently measured in small mammals from the same area (Talmage and Walton 1990). It has been calculated that complete emigration of the small mammal population from the 2-ha site in 1975 would have resulted in a loss of <0.1 μCi of ^{137}Cs and <1 μCi of ^{90}Sr.

Small mammals have also been studied around the shoreline of Ponds 3513 and 3524 at ORNL. Body burdens of ^{137}Cs and ^{90}Sr in 4 muskrats removed from the ponds in 1960 were as high as 3.7 and 13.8 μCi, respectively. The gastrointestinal tracts (with contents) of these animals contained up to approx. 1 μCi ^{137}Cs and 12 μCi ^{90}Sr (Auerbach et al. 1961). In 1977, cotton rats (*Sigmodon hispidus*) trapped from the shoreline of Pond 3513 had average whole-body burdens of 44 nCi ^{137}Cs per individual (Garten 1979). The gastrointestinal tracts of these animals were found to contain on the order of 10 nCi ^{137}Cs and 10 pCi of ^{239}Pu (Garten 1981). It was estimated that the annual export of ^{137}Cs from Pond 3513 shoreline by cotton rat movements was on the order of 10 μCi.

Small mammals, like mice and rats, typically have home ranges between 0.5 and 1.5 ha, indicating that they may move distances on the order of 100 m during their daily activities. Dispersal of radioactivity from ORNL by small mammals is limited by physical barriers, like rivers and other water bodies, which lie to the south and west of the Laboratory. Home range size in mammals (R) increases as a power function of kilogram body weight (W) according to the relationship: $R = 6.76\ W^{0.63}$, where R is acres (1 acre = 0.40 ha) (McNab 1963). Therefore, larger animals (opossum, raccoon, rabbits, and deer) are more likely candidates as mammalian vectors of radioactivity from contaminated sites due to their greater body size, longer life-expectancy, and larger home range (Figure 4).

Strontium-90 in White-tailed Deer

White-tailed deer have been monitored for both ^{137}Cs and ^{90}Sr in all public hunts on the Oak Ridge Reservation since the first hunt in 1985. The total number of deer harvested between 1985 and 1990 was 3505 individuals (range 440 to 926 per hunt). A total of 106 deer were confiscated between 1985 and 1990 because of elevated levels of ^{90}Sr in bone. The percentage of deer not released to hunters has ranged from 0.8 to 5.7% each year. Concentrations of ^{90}Sr in bone from confiscated deer have been on the order of 1 to 800 pCi/g (Eldridge and Keele 1988a).

It is believed that some deer accumulate radionuclides (particularly ^{90}Sr) from browse vegetation growing in seepage areas adjacent to the radioactive solid waste burial grounds and from vegetation growing along contaminated floodplains and shorelines in the White Oak Creek drainage (Garten and Lomax 1987). Concentrations in browse vegetation on the order of 1 to 100 nCi ^{90}Sr/g DW have been reported from various contaminated areas. Theoretical calculations indicate that relatively little contaminated vegetation in a deer's diet (1%) can lead to ^{90}Sr concentrations in bone between 1 and 2000 pCi/g (Garten and Lomax 1987).

Elevated levels of ^{90}Sr in some deer killed during the public hunts indicate that deer could forage in contaminated areas and then leave the Oak Ridge Reservation. Home ranges in white-tailed deer vary from ≈50 to 500 ha (Marchinton and Hirth 1984). White-tailed deer have elongated home ranges, and while daily travel on the order of 10 km is possible, average travel distances are probably <2 km. Distances traveled during dispersal can be much greater

(Figure 3). The average (± SD) home range for 15 radiocollared deer on the Oak Ridge Reservation was 345 (± 386) ha, and dispersal distances up to 33 km from the original point of capture have been recorded (Kitchings and Story 1979, Story and Kitchings 1982, 1985). Social pressures are a major stimulus to dispersal by deer, and yearling bucks, in particular, have a high dispersal rate (Marchinton and Hirth 1984).

Concentrations of ^{137}Cs in soft tissue samples (muscle or liver) from deer killed during the public hunts on the Oak Ridge Reservation have never exceeded 5 pCi/g. For comparison, ^{137}Cs concentrations in deer muscle samples obtained from over 1000 white-tailed deer throughout the southeastern United States from 1967 to 1971, a time when fallout from nuclear weapons testing contributed to body burdens of 137Cs in wildlife, averaged 4 to 45 pCi/g (Jenkins and Fendley 1971). The biological half-life of ^{137}Cs in deer is on the order of 10 to 20 days (Kitchings et al. 1976). Therefore, contaminated migratory deer that escape confiscation as a result of environmental monitoring can be expected to excrete most of their ^{137}Cs body burden within 2 months after leaving a contaminated site.

Export of Radionuclides from Contaminated Sites by Birds

Small birds (mostly wood warblers, sparrows, grosbeaks, buntings, finches, and chats) captured on White Oak Lake bed in the 1950's were found to contain up to 1.5 nCi ^{90}Sr/g bone and 18.6 nCi ^{137}Cs/g muscle (Willard 1960). Home range size in these small birds (10 to 40 g live weight) varies from 0.1 to 2.4 ha; the size of the feeding territory increases with bird body weight (Figure 4). Based on a population of 50 individuals/ha, the ^{90}Sr and ^{137}Cs inventory in birds was estimated to be 18 nCi/ha and 48 nCi/ha, respectively. It was concluded that a negligible amount of radioactivity (<1 μCi) would be removed from the lake bed by bird migration (Willard 1960).

In the early 1950's, 649 birds (mostly ducks) were banded and released on White Oak Lake. Some of the ducks migrated and were later killed by hunters as far away as Kentucky, Alabama, Louisiana, Texas, and Ontario, Canada (Oakes et al. 1982). More recently, studies of radionuclides in waterfowl have been conducted as part of the ORNL Biological Monitoring and Abatement Program (Loar et al. 1988, 1989, 1990). The average number of waterfowl present on White Oak Lake between October 1987 and February 1989 was 20 birds, but sometimes as many as 190 birds were counted. Canada geese (*Branta canadensis*), wood ducks (*Aix sponsa*), and mallards (*Anas* spp.) were observed most frequently and in highest density. Average ^{137}Cs concentrations in the breast muscle tissue of waterfowl from White Oak Lake has ranged from 4 nCi/kg in mallards to 19 nCi/kg in American coots (*Fulica americana*). Mallards kept on the lake for more than 2 months in 1989 accumulated 11 nCi ^{137}Cs/kg whole body and 10 nCi ^{137}Cs/kg breast tissue FW. Concentrations of ^{90}Sr in the mallard bones were 9 nCi/kg. Whole-body concentrations of 150 nCi ^{60}Co/kg have also been measured in a single adult wood duck.

An upper limit to the annual export of ^{137}Cs from White Oak Lake by migratory waterfowl can be calculated by assuming that 1000 birds with an average body weight of 1 kg each accumulate a whole body burden of 11 nCi ^{137}Cs/kg. The export of ^{137}Cs from the lake by migration of these birds could be on the order of 10 μCi. An upper limit to the export of ^{90}Sr is estimated to be about 10% less than that for ^{137}Cs. The biological half-life of ^{137}Cs in waterfowl is on the order of 10 days (Fendley et al. 1977), therefore migratory birds could loose most of their ^{137}Cs body burden within 3-weeks after leaving White Oak Lake.

The most highly contaminated birds found at ORNL have been Canada geese (2 to 4.5 kg live weight) captured in the vicinity of Pond 3513 and Pond 3524 during the late 1980's (Loar et al. 1989, 1990). The maximum concentrations measured in geese from these radioactive waste ponds were 4 µCi ^{137}Cs/kg muscle and 0.6 µCi ^{90}Sr/kg bone. Feces deposited by geese on streets near the ponds contained ^{137}Cs concentrations up to 460 pCi/g DW (Eldridge and Keele 1988b).

Banding studies show that most geese remain within 2 km of the site where banded, but some fly up to 16 km from the banding site (Loar et al. 1991). Therefore, geese with access to radioactive sites at ORNL can easily fly to nearby public reservoirs and farm ponds. Goose feces collected at a nearby reservoir contained trace amounts of both ^{60}Co and ^{137}Cs. The crop contents of waterfowl inhabiting White Oak Lake contain on the order of 3 to 270 pCi ^{137}Cs/g FW and 0.2 to 27 pCi ^{60}Co/g FW; feces from contaminated waterfowl that fly to locations beyond the boundaries of ORNL might be expected to contain similar concentrations of these radionuclides as well as pCi to nCi amounts of ^{90}Sr.

Radiological surveys of local flocks of geese indicate a low probability of encountering a contaminated bird. A total of 78 geese from ORNL and off-site locations were captured and live counted in 1988 and 1989. None of the geese had whole-body concentrations of ^{137}Cs exceeding 1.1 nCi/kg (Eldridge 1989). Experiences with the accumulation of radioactivity by waterfowl at ORNL indicate that under most circumstances the individual dose that would be received by eating a contaminated bird is <100 mrem. For example, the dose to a hunter who consumes a single bird from White Oak Lake has been estimated at approximately 0.25 mrem (Loar et al. 1989, Rogers et al. 1989).

DISCUSSION AND CONCLUSIONS

Contaminated animals or animal nests at ORNL contain on the order of 10^{-12} to 10^{-6} Ci of ^{137}Cs or ^{90}Sr. The highest concentrations of ^{137}Cs have been found in emergent aquatic insects, and the muscle tissue of small birds and Canada geese, while the highest levels of ^{90}Sr have been measured in bones from turtles, and small mammals (Figure 5). Radiocesium concentrations, in animals studied at ORNL, decrease with body size; therefore the larger animals, like deer and waterfowl, that have correspondingly greater potential for dispersal than small mammals and terrestrial insects, tend to have lower ^{137}Cs concentrations. Studies indicate that animals from contaminated terrestrial environments that contain elevated levels of ^{137}Cs may also contain elevated amounts of other long-lived radionuclides, like ^{239}Pu (Figure 6; Garten and Dahlman 1978). However, concentration ratios (tissue concentration/soil concentration) for Pu in animals are small, similar in magnitude to those for natural Th (10^{-4}) and less than those for natural U (Garten et al. 1981; Trabalka and Garten 1983).

Dispersal of radioactivity by wildlife may come about as a result of the transport of contaminated materials to nest sites or the bioaccumulation and migration of animals from a contaminated site. Animals that are capable of flight and that have behavior patterns or developmental life stages involving intimate contact with contaminated sediments of radioactive ponds or White Oak Lake present the greatest potential for long-distance dispersal of radioactivity. Based on levels of radionuclides (Figure 5) and potential dispersal distance (Figure 3), emergent aquatic insects (*Diptera, Odonata*) and waterfowl (Canada geese) are the most likely vectors of radioactivity from contaminated aquatic habitats. The emigration of individual turtles from radioactive impoundments and White Oak Lake also presents a potential for dispersal of ^{90}Sr over short distances (< 5 km).

Migratory waterfowl as vectors of radioactivity have been the subject of study at several DOE managed facilities. At the Savannah River Plant in South Carolina, migratory waterfowl are estimated to remove up to 37 μCi of ^{137}Cs annually from a 7000 ha reactor cooling reservoir (Brisbin et al. 1973). Over 3000 waterfowl were censused on radioactive leaching ponds at the Idaho National Engineering Laboratory Site from 1974 to 1978 and the total amount of radioactivity exported from the ponds by birds over a four year period was ≈5 mCi (Halford et al. 1981). Consistent with the previous studies, the estimated amount of radioactivity that could be removed by wildlife from contaminated sites at ORNL is small (on the order of 0.001 to 10 mCi).

Although there are long-term plans for the isolation, stabilization, and cleanup of radioactive waste disposal sites that remain as a legacy to ORNL from past missions, oversight of radioactive sites will continue to be part of the institutional responsibility for many years. There have been and will probably be future occurrences where animals become contaminated because of their access to contaminated sites. Interim measures that have been and will be taken to curtail the accumulation and dispersal of radioactivity by animals fall into four categories: prevention, surveillance, restraint, and removal. When possible, access of animals to contaminated sites will be prevented by active management of the habitat. Surveillance and monitoring of wildlife will also continue to be an important part of preventing bioaccumulation and dispersal of radioactivity. Specialty fences may be installed to keep animals away from contaminated sites or to keep radioactive animals from dispersing. Prevention, surveillance, and restraint will help to minimize radioactive contamination of wildlife; however, when necessary contaminated animals are confiscated and disposed of in order to prevent their dispersal to off-site locations.

ACKNOWLEDGEMENTS

I wish to thank J. D. Story and T. L. Ashwood, ORNL, for their helpful reviews of the draft manuscript. This research was sponsored by the Office of Environmental Compliance and Documentation, ORNL, and by the Office of Health and Environmental Research, U. S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. Publication No. _______, Environmental Sciences Division, ORNL.

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Figure Legends

Figure 1. White Oak Creek drainage basin showing the location of radioactive waste disposal areas, tributaries, and research sites (ORNL-DWG 65-12157R9AR).

Figure 2. Burrow volume and amount of soil removed (m^3) by burrowing vertebrates. Data for mammals (mole, badger, fox, mice and voles) and a turtle (gopher tortoise) are from Golley et al. (1975) and McKenzie et al. (1986).

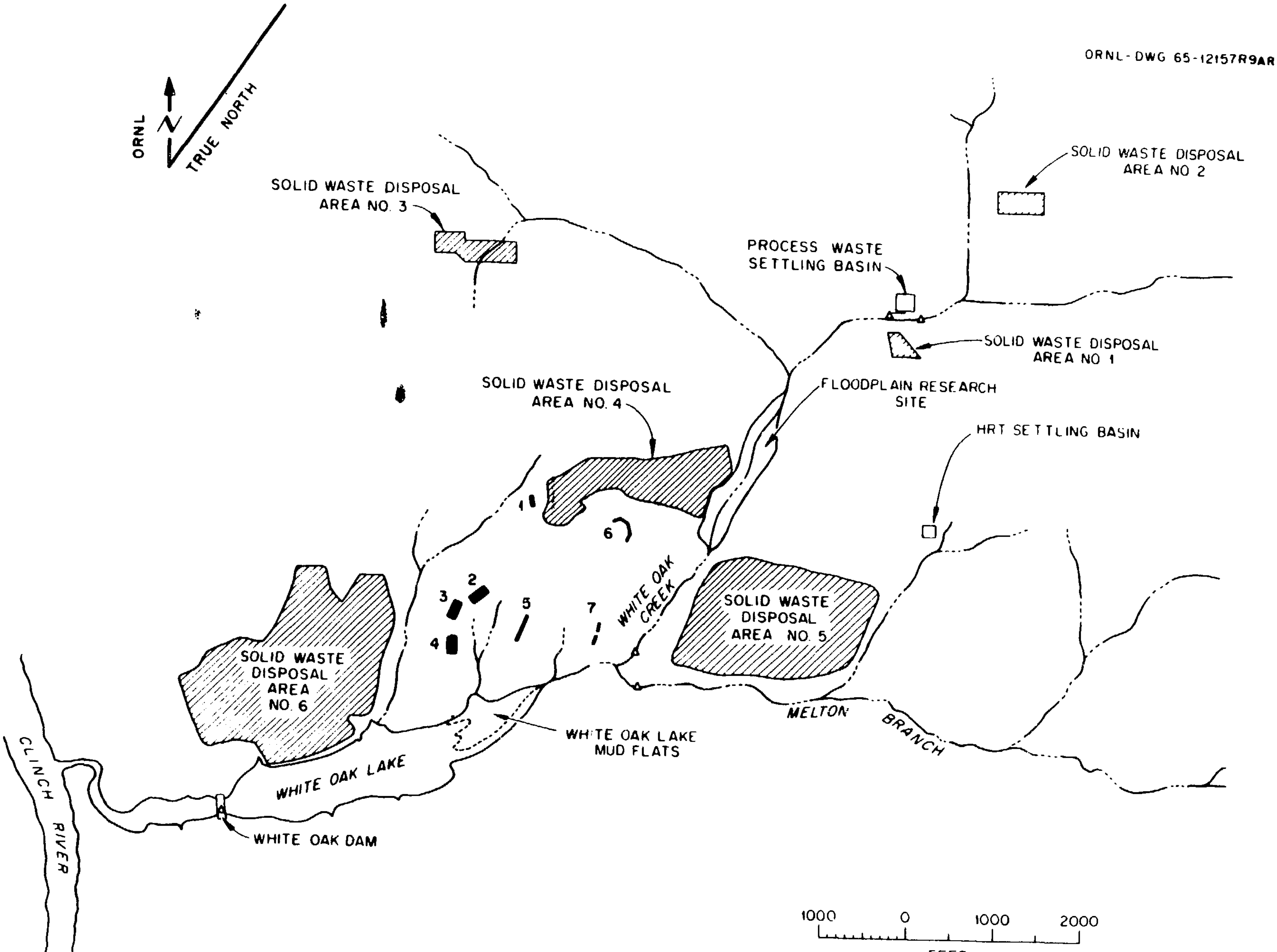
Figure 3. Estimated potential dispersal distances by animals. Data from various sources: white-tailed deer (Marchinton and Hirth 1984), waterfowl (Bellrose 1976), turtles (Meyers-Schone and Walton 1990), frogs (Schroeder 1976), small mammals (Furrer 1973), *Odonata* (Corbet 1962, Dingle 1985), *Hymenoptera* (Shinn 1964), *Coleoptera* and *Diptera* (Spector 1956, Dingle 1985).

Figure 4. Relationship between territory or home range size and body weight in birds (open symbols) and mammals (closed symbols). Data for mammals from Burt and Grossenheider (1964), McNab (1963), and Marchinton and Hirth (1984); data for birds from Schoener (1968).

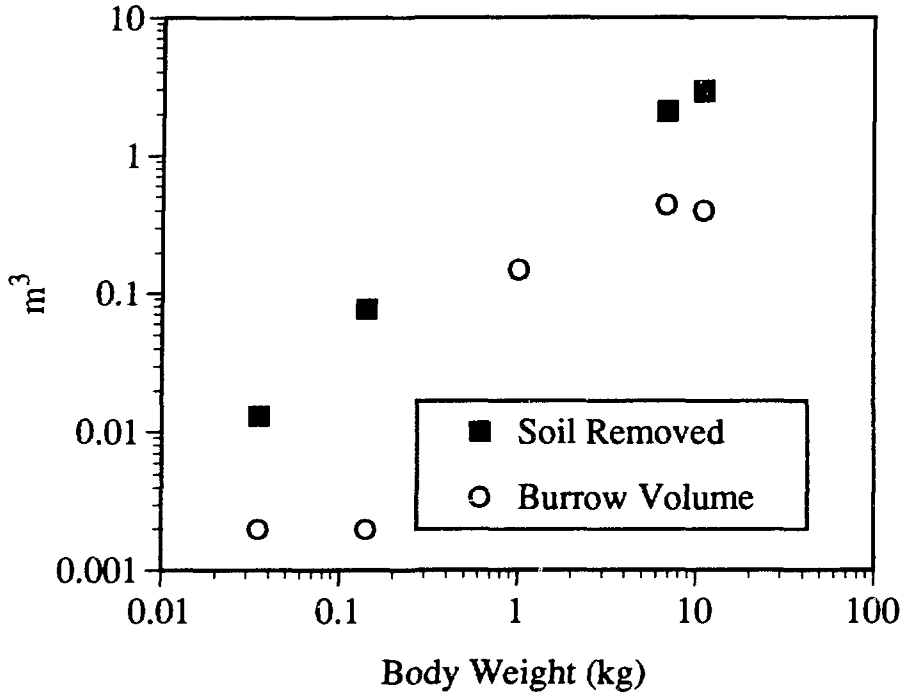
Figure 5. Representative concentrations of ^{137}Cs (above) and ^{90}Sr (below) in animals from contaminated habitats at ORNL. For vertebrates, ^{137}Cs concentrations are based on muscle and ^{90}Sr concentrations are for bone.

Figure 6. Relationship between ^{239}Pu and ^{137}Cs concentrations in biota from White Oak Creek floodplain forest in eastern Tennessee. Plants and

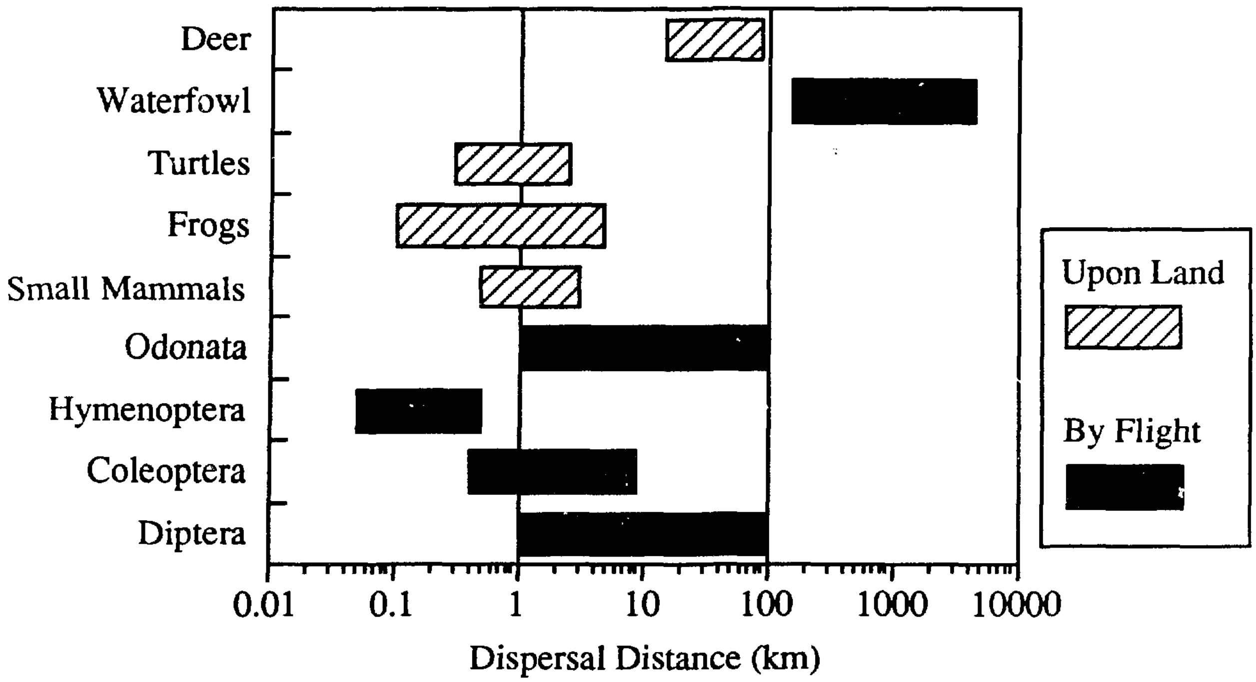
detritus (○): ground vegetation (1), leaf litter layers O_1 and O_2 (2), and lichen from standing trees (3). Invertebrates (●): snails (4), crickets (5), carabid beetles (6), isopods (7), millipedes (8), phalangids (9), miscellaneous beetles (10), mantids (11), grasshoppers (12). Vertebrates (■): *Cricetidae* pelts (13), *Soricidae* pelts (14), *Cricetidae* gastrointestinal tract and contents (15), *Soricidae* gastrointestinal tract and contents (16), entire body, minus gastrointestinal tract and contents, of *Peromyscus leucopus* (17), *Oryzomys palustris* (18), *Blarina brevicauda* (19), *Terrapene carolina* (20), *Natrix sipedon* (21). Miscellaneous small mammal carcasses (□): *Cricetidae* (22) and *Soricidae* (23.) Reprinted from Health Physics (1978) with permission of Pergamon Press, Ltd.

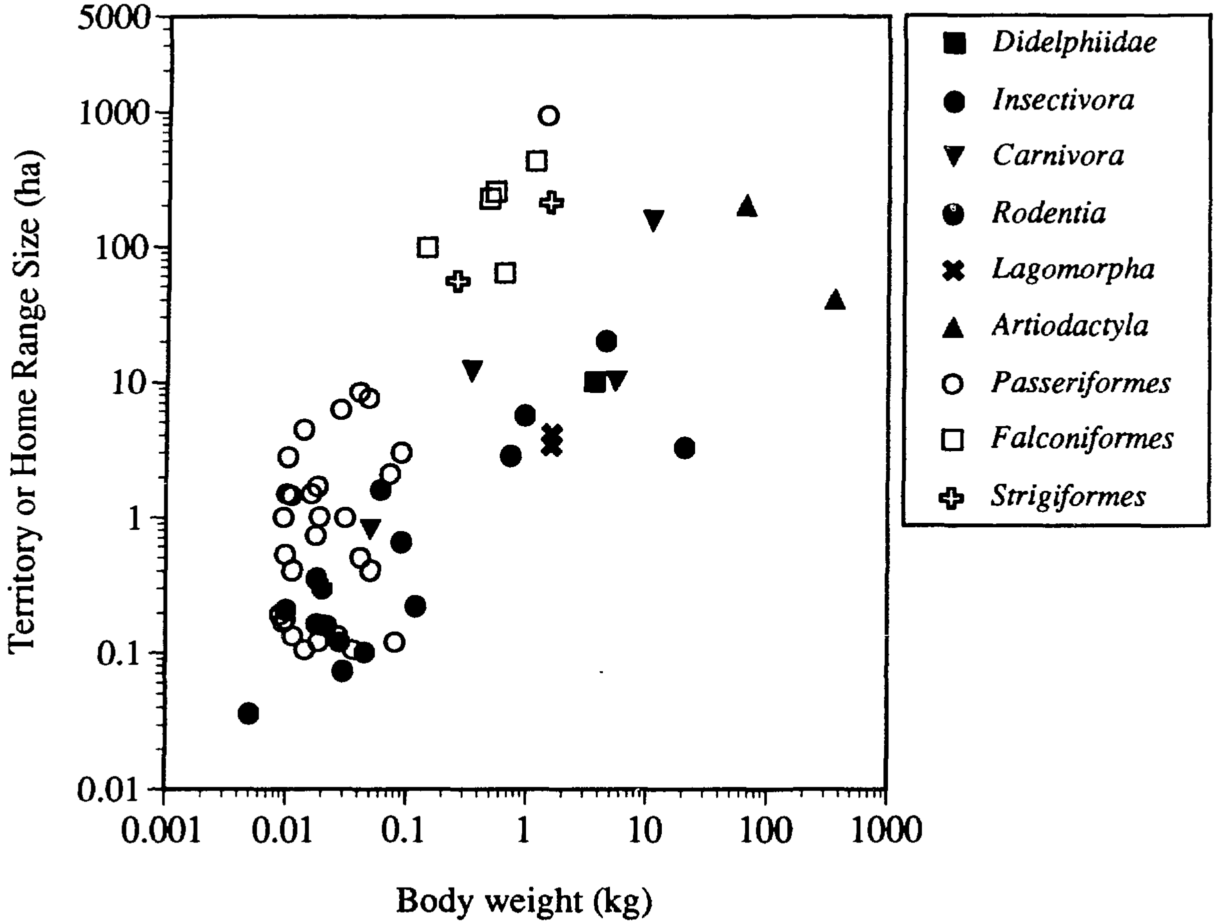


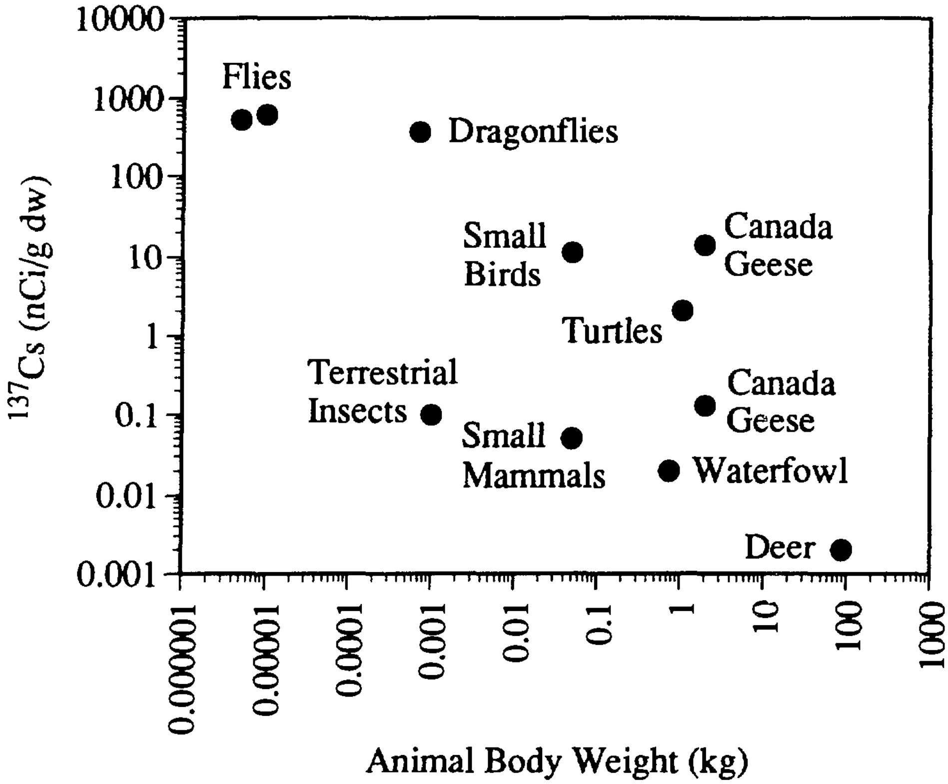
White Oak Creek Drainage Basin.



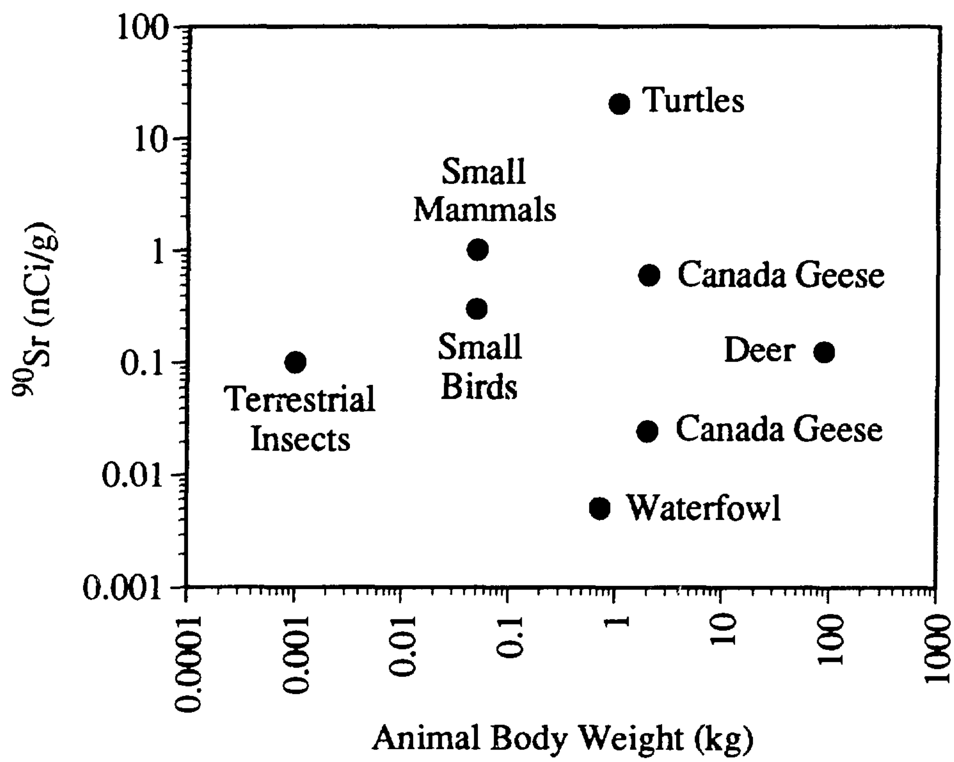
10
1
0.1
0.01
0.001
m³
0.01
0.1
1
10
100
Body Weight (kg)
Soil Removed
Burrow Volume


Deer
Waterfowl
Turtles
Frogs
Small Mammals
Odonata
Hymenoptera
Coleoptera
Diptera
0.01
0.1
1
10
100
1000
10000
Dispersal Distance (km)
Upon Land
By Flight

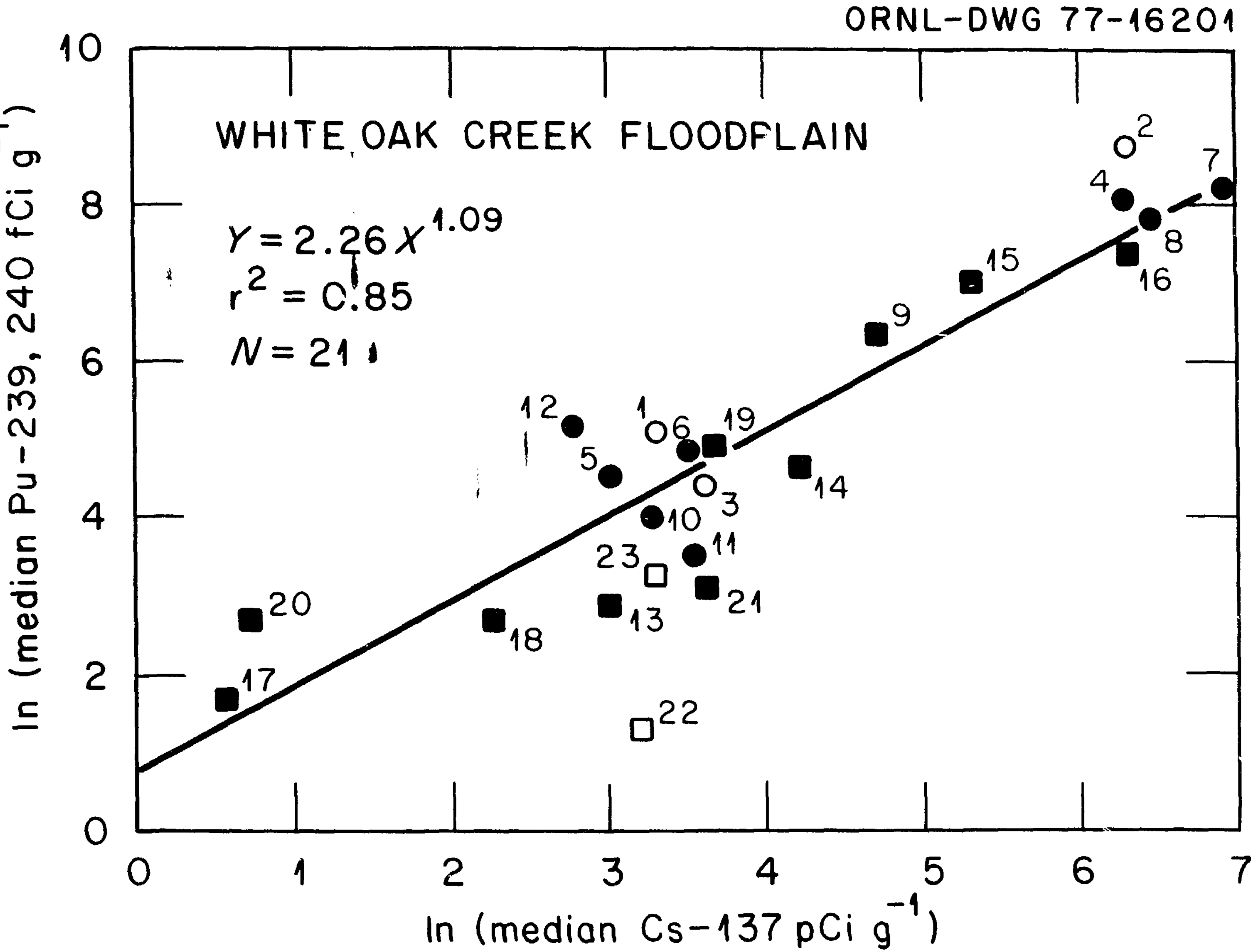

5000
1000
100
10
1
0.1
0.01
Territory or Home Range Size (ha)
0.001
0.01
0.1
1
10
100
1000
Body weight (kg)
Didelphiidae
Insectivora
Carnivora
Rodentia
Lagomorpha
Artiodactyla
Passeriformes
Falconiformes
Strigiformes



10000
1000
100
10
1
0.1
0.01
0.001
Flies
Dragonflies
Small Birds
Canada Geese
Turtles
Terrestrial Insects
Canada Geese
Small Mammals
Waterfowl
Deer
0.0000001
0.000001
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
137Cs (nCi/g dw)
Animal Body Weight (kg)



100
10
1
0.1
0.01
0.001
Turtles
Small Mammals
Canada Geese
Deer
Small Birds
Terrestrial Insects
Canada Geese
Waterfowl
0.0001
0.001
0.01
0.1
1
10
100
1000
90Sr (nCi/g)
Animal Body Weight (kg)



ORNL-DWG 77-16201
WHITE OAK CREEK FLOODPLAIN
Y = 2.26 X^1.09
r^2 = 0.85
N = 21
ln (median Pu-239, 240 fCi g^-1)
ln (median Cs-137 pCi g^-1)