The Environmentalist **17**, 289–295 (1997)

Monitoring the dispersal of contaminants by wildlife at nuclear weapons production and waste storage facilities

MICHAEL L. MORRISON*, K. SHAWN SMALLWOOD AND JAN BEYEA

Department of Biological Sciences, California State University, Sacramento, CA 95819, USA

Summary

The US Government produced and acquired approximately 111 t of plutonium in support of its nuclear weapons programme. Verified reports of the loss of nuclear material into the environment, including loss by animals, has raised questions regarding the monitoring programmes in place on the nuclear facilities. Given these concerns regarding the fate of stored nuclear waste, the authors conducted a review of the wildlife monitoring programme used at nuclear weapons and storage facilities by (1) reviewing the key facets of the monitoring used at the facilities, (2) evaluating published and unpublished data from the facilities and (3) incorporating data from personal site visits. The study concentrated on the Department of Energy's Hanford Reservation in rural south–central Washington and the Rocky Flats Plant in central Colorado. Based on the review, it is concluded that an improved and rigorous environmental surveillance and monitoring programme is needed at both locations. The site surveys identified frequent instances of intrusion into burial sites by animals, most of which had gone unreported by Hanford and Rocky Flats personnel. It was apparent that a significant source of potential contamination was not being adequately monitored at the nuclear waste sites. It is recommended that the development of a systematic, well-planned programme of monitoring animal intrusion on burial sites be considered, coupled with improved training for responsible personnel.

Introduction

Numerous programmes to monitor the conditions and trends in abiotic and biotic resources are in place or under consideration. Some are relatively non-controversial, while some could ignite strong passions outside the scientific community. These programmes range from those applicable to regional and nationwide monitoring or broad-scale environmental conditions (e.g. the US Environmental Protection Agency–Environmental Monitoring and Assessment Program), to forest-stand productivity (e.g. timber stand assessment, the US Forest Service), to the determination of the demographics of endangered subspecies and populations (e.g. the spotted owl, *Strix occidentalis*).

Although critical attention to design and implementation is most often focused on politically sensitive programmes such as monitoring the numbers of rare species or monitoring the integrity of toxic waste sites, there are difficulties associated with the design and implementation of all monitoring efforts. Such difficulties include the gathering of an adequate sample size to achieve reliable statistical rigour (e.g. power analysis; Gerrodette, 1987), determining the effects of unplanned impacts (Green, 1979; Underwood, 1994; Wiens and Parker, 1995) and difficulties in maintaining large databases (White and Clark, 1994). For example, although much effort has been expended on monitoring forest conditions, including wildlife, most monitoring plans on national forests are inadequate (Office of Technology Assessment, 1992; Morrison and Marcot, 1995). Likewise, the recent efforts to document the declines in many bird species (e.g. declines of neotropical migrants; DeSante and George, 1994) have been criticized (e.g. James *et al.*, 1996).

* Dr Michael L. Morrison is adjunct professor of wildlife biology in the department of biological sciences, California State University. Dr K. Shawn Smallwood is a systems ecologist and may be contacted at 109 Luz Place, Davis, CA 95616, USA. Dr Jan Beyea is a physical scientist with Consulting in the Public Interest, 53 Clinton Street, Lambertville, NJ 08530, USA.

The concern over the development of reliable monitoring takes on special significance when applied to sites used for the production and storage of nuclear material that are managed by the US Department of Energy. This concern has been exacerbated by verified reports of the loss of nuclear material into the environment, including the contamination of air, soil, water and animals on and off the storage sites (Heeb, 1994; Department of Energy, 1995, 1996). Demonstration that the losses have not been significant requires rigorous statistical design of monitoring programmes.

The US Government produced and acquired approximately 111 t of plutonium in support of its nuclear weapons programme (Department of Energy, 1995, 1996). The inventory difference (ID) is the difference between the quantity of nuclear material held according to accounting books and the quantity measured by physical inventory. The cumulative plutonium ID for the entire Department of Energy complex for the period 1944–1994 is at least 2750 kg. Contributions to the ID include measurement uncertainties associated with inventories, spills and accounting practices and undetected environmental releases (Department of Energy, 1995, 1996). This material, along with other toxic materials, is distributed between at least 23 facilities. Much of this waste is stored in burial pits covered only with earth. Concern has been raised by some workers that these burial sites are subject to the loss of plutonium and other contaminants as a result of intrusion by plants and animals. Such intrusions can bring contaminants to the surface where they are subject to dispersal by the wind, rain and animals (McKenzie *et al.*, 1986; Landeen *et al.*, 1990; Wing, 1992).

Given the concerns reviewed above regarding the fate of stored nuclear waste, the authors conducted a review of the wildlife monitoring programme used at nuclear weapons and storage facilities. This review was performed by (1) examining the key facets of the monitoring used at the facilities, (2) evaluating published and unpublished data from the facilities and (3) incorporating data from personal site visits. Although literature from many facilities was reviewed, the study concentrated on the US Department of Energy's Hanford Reservation in rural south–central Washington and the Rocky Flats Plant in central Colorado. Part of this work was conducted by one of the authors (K.S.S.) in connection with the preparation of expert testimony in two legal cases. Operating under court rules of discovery, the second author was able to obtain documents normally unavailable to investigators and gain access for the authors to contaminated areas on the sites.

Hanford Reservation is appropriate for such an emphasis because it was the primary producer of plutonium in the USA: 67 t of plutonium were produced by the nine production reactors at Hanford and the site stores approximately 11 t of waste material. The ID at Hanford was estimated to be 1265 kg (Department of Energy, 1995, 1996; see below) – 46% of the total ID is acknowledged to be lost. Rocky Flats is of special interest because it is located upwind only a few kilometres from rural housing and within 25 km of the Denver metropolitan area. Our recommendations are also generally applicable to other hazardous waste storage sites. For example, approximately 27 400 t of waste from nuclear power plants is stored in 'temporary' sites in 35 states. This material is planned for eventual transport to a permanent burial site.

Monitoring

The physical arrangement at Hanford Reservation and Rocky Flats is typical of the other sites, namely a concentrated industrial area or areas, waste storage sites scattered around the industrial sites and a largely non-developed area that surrounds the buildings and burial sites that serves as a protective buffer for the surrounding region. At the 1500 km^2 Hanford site, approximately 1700 ha are reportedly contaminated either on the surface or underground (Johnson *et al.*, 1994). Hanford Reservation was established in 1943 as a national security area to produce the plutonium used in nuclear weapons (Fig. 1). The Hanford site is one of the few large land areas in the region that has not been developed for agriculture. It is also unique because of the restricted access to the area since 1943 (Gray *et al.*, 1989; Johnson *et al.*, 1994).

The environment of Hanford Reservation is characterized as a shrub–steppe grassland and is composed of a variety of plant communities, including sagebrush (*Artemisia*), bitterbrush (*Purshia*), rabbitbrush (*Chrysothamus*) and various grasses. It is bounded on the north by the Columbia River, but the site itself is hot and dry

Fig. 1. Hanford Reservation site, Washington, USA, summer 1996, depicting (background) the original plutonium processing plant used in the production of nuclear weapons (around 1945). The observers are examining a nuclear waste burial site.

(Johnson *et al.*, 1994). Downs *et al.* (1993) reviewed the general occurrence of animals at Hanford Reservation.

The much smaller Rocky Flats Plant (2652 ha) was established in 1951 to produce atomic bombs made of fissionable plutonium that served as triggers for hydrogen bombs; numerous other military-related manufacturing activities were conducted there as well (Department of Energy, 1992). The environment is dominated by mesic mixed grassland and upland shrub communities. Interspersed across the site are riparian woodlands and meadows, with rivers that flow off-site towards rural and suburban housing (Department of Energy, 1992). The Department of Energy (1992) also described the terrestrial and aquatic animal communities at Rocky Flats.

There is much debate concerning the actual amount of plutonium released into the environment at Hanford Reservation, as is demonstrated in the court papers of scientific experts, filed by various parties in connection with consolidated personal injury cases. For example, although Johnson *et al.* (1994) concluded that there was little evidence that plutonium had escaped from the Hanford boundaries, Goble (1996) countered that there was good evidence that there were releases in amounts hundreds of times greater than officially estimated. Goble (1996) concluded that, by itself, the release of buried plutonium by the wind resuspension of soils loosened by bioturbation exceeded official estimates by a factor of 20 or so. Also relevant to the debate is Cochran's (1996) finding that there were hundreds of unplanned atmospheric releases, spills, leaks and other contaminated surface areas in and around the production facilities at Hanford Reservation. Naturally, expert reports on the other side of the litigation challenge these views (Whicker, 1996). A consensus on releases cannot be expected, because the monitoring was not of academic quality. Had a statistically rigorous monitoring programme been in place, the debate over these releases would never have reached such proportions.

Similar controversies exist regarding accidental releases at Rocky Flats. For example, the idea of using solar evaporation ponds to dispose of liquid waste was rejected on the grounds that winds would carry spray and entrained contaminants for many miles (L.A. Matheson, unpublished, 1953). In addition, the idea of spraying diluted waste plutonium onto grasslands was initially rejected due to concerns that the low soil permeability would limit the contaminant to the top 0.3 cm of soil, where winds would resuspend and transport the contaminants. Despite these early warnings, the ponds and spraying programmes were initiated soon after plant production began because of the large volume of waste being handled (Owen and Steward, 1975; Setlock, 1987). Approximately 70–80 million gal (265–300 million l) of waste per year were sprayed onto the grasslands, much of which sheeted off the irrigated lands and into surrounding creeks (Setlock, 1987). Also notable was the leakage of waste stored in metal drums at an open-air location (known as the 903 Pad). The estimated leakage of 10–11 Ci of plutonium into the soil (Krey and Krajewski, 1972; Krey, 1976) could have been much larger (Budnitz, 1996; Goble, 1996).

Animals can be broadly categorized by their ability to interact with the waste facility. Some can carry contaminant off-site either internally or externally on fur or feathers, such as widely ranging ungulates, waterfowl, larger predators and small game. This contamination can be obtained directly from the air, soil or water or indirectly through the consumption of contaminated plants or animals. For example, waterfowl using wastewater ponds have been identified as having a high probability of contaminant transport to humans (review by Johnson *et al.*, 1994). Various species of small mammals, such as rodents and rabbits and large mammals, such as coyotes and deer, are known to serve as vectors of plutonium off-site (O'Farrell and Gilbert, 1975; Alldredge *et al.*, 1977; Arthur and Markham, 1983; Arthur *et al.*, 1986).

Other animals intrude into waste sites and move contaminants to the surface where they are subject to dispersal. Because most animals that burrow into waste sites move relatively short distances – such as pocket gophers (*Thomomys* spp.) and even the larger badger (*Taxidea taxus*) – there is usually little opportunity for these animals to move contaminants far off–site.

However, burrowing animals move substantial amounts of soil; such 'bioturbation' is one of the most influential forces in terrestrial ecosystems (Hole, 1981; Huntly and Inouye, 1988; Litaor *et al.*, 1996). In the USA pocket gophers have been recognized as the species showing the greatest ability to move soil (McKenzie *et al.*, 1986), although multiple other species are together more abundant than gophers and most confine their activities to the upper soil horizon where most plutonium is found.

To estimate the impacts of burrowing animals on the risk of environmental exposure from non-volatile chemicals and radioactive elements at a site, it is necessary to (1) catalogue the burrowing animal species, (2) estimate their spatial abundances, (3) determine the mean and maximum burrow depths, (4) determine the proportion of burrows within depth horizons, (5) determine the rate of soil excavation to the ground surface and (6) determine the characteristics of the excavated soil, such as texture, particle size distribution and structural fate. Other burrow attributes can aid in making these estimates, such as the mounds produced per animal per year, mound volume and mean burrow volume. Unfortunately, no single study has gathered all of the information necessary to estimate precisely the burrowing impacts of any species at any site. The present survey of the literature indicated that the sample sizes necessary to make accurate calculations of even some of these parameters are seldom quantified or justified and appear to be extremely low in most cases. Further, the methods and assumptions used by investigators are too varied to average their results without inserting a large degree of uncertainty into the results.

Harvester ants (*Pogonomyrmex occidentalis*) at Hanford Reservation transported plutonium to the surface from a broken pipe 3.7 m below ground (Johnson, 1984) and they continue to excavate plutonium to the surface to the present day (S. McKinney, personal communication). The backfill over waste at Rocky Flats was usually 0.6 m or less (Putzier, 1970; Owen and Steward, 1975), easily within range of burrowing by ants and other burrowing animals. The contaminants in these mounds are then exposed to erosional forces such as wind and precipitation and they can be ingested by animals or picked up in animal fur and feathers.

Researchers at the Pacific Northwest Laboratory identified biotic transport as a common phenomenon at shallow-land disposal sites (McKenzie *et al.*, 1986). They developed a simulation model (BIOPORT) to predict the magnitude of radionucleotide movement through the ecosystem. BIOPORT relied on data integrated from the literature, but used only a small portion of the studies available. Smallwood (1996) showed that the estimates in BIOPORT of the bioturbation were gross underestimates. Thus, researchers and managers were apparently being misled by an inadequate model with which to make decisions regarding the impact of bioturbation on contaminant dispersal.

Critique of nuclear waste monitoring

The uncertainty of risk analysis can be substantially reduced by the properly designed and conducted surveillance and monitoring of hazardous compounds released to the environment. To be effective, surveillance and monitoring programmes need to be developed from knowledge of the release history, including the quantities released, the dates and locations of release and the environmental conditions at the time of release. They also require knowledge of the potential pathways for the movement of contaminants. Once the magnitude of the contaminations is understood, the media of the pathways (e.g. particular animal species, wind, water and plant tissue) should be monitored for the hazardous materials that could possibly have escaped initial containment or location within the environment. It is clear that the operators at Hanford Reservation and Rocky Flats had ample reason to study and monitor the pathways of hazardous materials released to the environment.

However, based on the present review, a rigorous environmental surveillance and monitoring programme was not initiated at either location. At Rocky Flats, sampling of the plants, animals and soils was abandoned early in the site operation history because such monitoring was considered too expensive, time-consuming and unnecessary (J.B. Owen, personal communications). Intensive sampling was later briefly conducted in response to public concerns following the 1969 fire in building 776 that nearly resulted in a massive release of plutonium (Hammond, 1971). However, except for some water test wells and ambient air samplers, there appeared to be no evidence of the existence of regular monitoring of plants, soil and animals.

Buried waste sites at Rocky Flats are not being surveyed for intrusion by burrowing animals (Anne Siemen, personal communication, Rocky Flats) despite clear evidence of such intrusion occurring. For example, in the present authors' November 1996 survey of Trench T-9 extensive degradation of the trench cap, including a small collapse of the cap, due to animal burrowing was evident.

A 'baseline' biological survey of the Rocky Flats Plant done in 1991–1992 provided only cursory data on most animals. This study apparently represented the first attempt to establish a baseline data set for the plant. Small-mammal trapping was conducted for only 4 nights on each grid established; these records were supplemented by visual observation. They reported only one gopher sighting on the plant. This result is in contrast to the numerous sightings of gopher activity observed during the three surveys undertaken by the authors in 1996. Because rigorous baseline data were not collected before these visits, it cannot be determined whether these records indicate that a substantial increase in gopher numbers occurred between 1991–1992 and the 1996 surveys or whether they reflect non-rigorous baseline data collection. The workers responsible for environmental monitoring at the nuclear sites did not provide information that was useful for assessing the burrowing impacts of any species.

The workers at Hanford Reservation concluded that burrowing animals were having no negative impact on the fate of buried waste. They stated specifically that gophers, although present on-site, were not penetrating the burial caps (Johnson *et al.*, 1996; Whicker, 1996). However, the authors' personal surveys during 1996 located both weathered and fresh gopher mounds and the burrows of pocket mice (*Perognathus* spp.), kangaroo rats (*Dipodomys* spp.), badgers, ants and other species on the caps. The radiological monitoring of small mammals at Hanford Reservation involves snap trapping (Law, 1982, p. 92), thereby excluding gophers as the subjects of this sampling. Specialized traps need to be placed carefully within gopher tunnels for their capture (Howard, 1952). By not using such traps, monitoring efforts will consistently exclude gophers and radiological monitoring will seldom detect radiation doses on or within gophers because the animals reside and perish below ground. To the present authors' knowledge, the first gopher collected on a burial site and sampled for radioisotope contamination was from a burrow that was discovered in June 1996 (site 218-W-4A). This gopher was found to have $^{89/90}Sr$ concentrations approximately three orders of magnitude greater than in the surface soils (Thomas D. McGinnis, validated results short report, 28 June 1996, sample no. S96E000756, unpublished). A reasonable sample of gophers from Hanford Reservation buried waste sites would reveal whether further contamination has occurred.

Raising further questions on the accuracy of animal monitoring at Hanford Reservation are the radiological surveillance reports conducted in April and May 1996. The personnel responsible recorded whether animals dug holes or burrows into waste sites and whether there were any signs of ant hills (Hayward, 1996). Such evidence was to indicate 'animal or insect intrusion'. Of the 69 records from this period, only five reported evidence of animal intrusion. The present authors conducted visual site inspections of burial sites at Hanford Reservation during June 1996; the methods were essentially the same as those conducted by the Hanford personnel. Of the 21 sites mutually visited by the Hanford surveillance personnel and the present authors, agreement as to animal intrusion occurred in only two instances. In the other 19 cases, the present authors observed evidence of intrusion (Fig. 2) where it had previously not been reported. Insufficient time had elapsed between the official radiological surveillances and the June 1996 visits to explain the disparity in findings. In addition, many of the gopher mounds observed by the present authors were at least several months old.

Out of 101 rankings of buried waste sites at Hanford Reservation made during 1990–1992, 88 sites (87%) were identified with waste mobility problems (attachment to WHC-EP-0489-2; see Mix and Winship, 1993). Of these sites, 21 were rated as having a history of spreading contamination, 18 showed evidence of bio-uptake or contamination beginning to move around and 28 were rated as having a 20–50% chance of migration or uptake by plants or animals. Gray *et al.* (1989) concluded that a satisfactory monitoring programme was in place at Hanford Reservation. However, they provided no details on wildlife monitoring, nor did they mention burrowing animals.

It is apparent from the present authors' on-site surveys, literature review and personal communications with site personnel that a significant source of potential contamination was not being adequately monitored at Hanford Reservation, Rocky Flats and apparently the other nuclear waste sites. This failure was based on (1) a lack of adequate research into the role of soil bioturbation in contaminant movement, (2) inadequate on-site monitoring and (3) inadequate training of monitoring personnel.

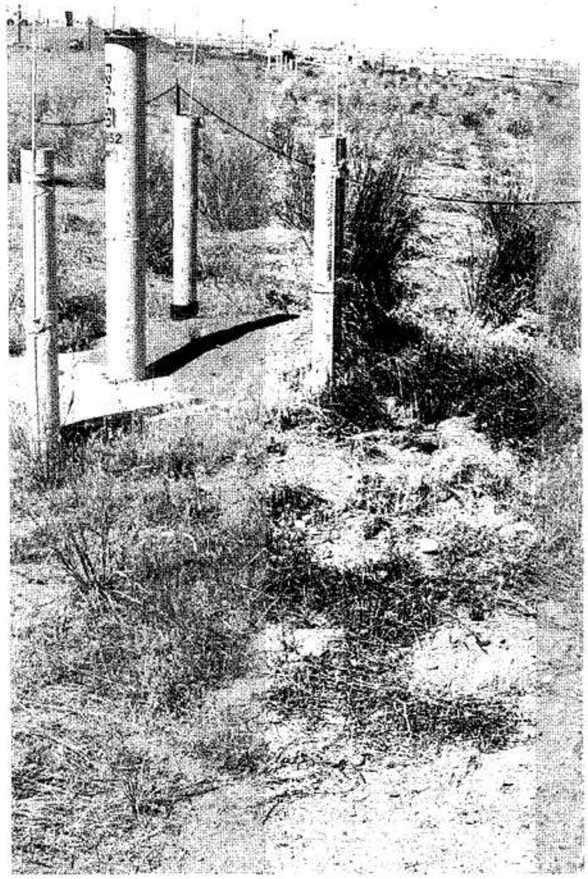

Fig. 2. An example of recent pocket gopher activity on a nuclear waste burial site, Hanford Reservation site, Washington, USA, summer 1996. Several gopher mounds occur adjacent to a test well.

Recommendations

Clearly, the development of a systematic, well-planned programme of monitoring animal intrusion on nuclear waste burial sites is warranted. The first step in such a programme would be the development of a set of specific goals, accompanied by success criteria and guidelines for initiating additional studies and remedial actions as indicated. A priority action should be (1) rigorous assessment (an inventory) of the current distribution and abundance of the animals on and near the burial sites, followed by (2) monitoring of burrowing animal populations so that trends in their abundance can be reliably determined. Such a monitoring programme would require a thorough analysis of the sampling intensity (e.g. the size and number of small mammal trapping grids) and the frequency (i.e. power analysis). Monitoring at nuclear waste sites should be conducted as a scientific investigation, rather than as an *ad hoc* series of control measures if and when problems are encountered.

It is also recommended that an independent peer review panel or panels be used to help ensure the initiation of an effective monitoring programme. Hanford Reservation initiated this process by establishing a contract with a private company to assemble a peer review panel to evaluate the Hanford Site Permanent Isolation Barrier Development Program (Wing, 1992). Although a detailed critique of the panel's report is beyond the present scope of this paper, little attention was given to the issue of animal intrusion. Nevertheless, peer review should only enhance the management of waste.

Rigorous monitoring requires an understanding of experimental design, including impact assessment and moderately-advanced statistics (such as factorial designs), advanced knowledge of field sampling methods and familiarity with the current scientific literature. Unfortunately, resource managers in general often do not possess the training necessary to design and implement a rigorous monitoring programme (Garcia, 1989; Morrison and Marcot, 1995). Thus, there is a need to initiate a comprehensive series of continuing education programmes that emphasize the specific requirements of monitoring intrusion into buried nuclear waste.

Acknowledgements

The authors thank Joe Wyman for assistance with the literature review and field work and the personnel of the Hanford Nuclear Reservation, Rocky Flats Plant and Los Alamos National Laboratory for assistance.

References

Alldredge, A.W., Arthur, W.J., III and Hiatt, G.S. (1977) Mule deer as a plutonium transport vector. In *Transactions of meeting on Rocky Flats buffer zone ecological and environmental research meeting* (D.C. Hunt, ed.). Golden: Rockwell International, Rocky Flats Plant.

Arthur, W.J., III and Markham, O.D. (1983) Small mammal soil burrowing as a radionuclide transport vector at a radioactive waste disposal area in southeastern Idaho. *J. Environ. Quality*, **12**, 117–22.

Arthur, W.J., Markham, O.D., Groves, C.R., Keller, B.L. and Halford, D.K. (1986) Radiation dose to small mammals inhabiting a solid radioactive waste disposal area. *J. App. Ecol.* **23**, 13–26.

Budnitz, R.J. (1996) *Waste Management Practices Associated with the 903-Area Plutonium Releases*. Philadelphia: report to the Law Offices of Berger and Montague, PC.

Cochran, T.B. (1996) *Sources of Off-site Plutonium Releases at Hanford*. PC. Philadelphia: report to the Law Offices of Berger and Montague, PC.

Department of Energy (1992) *Baseline Biological Characterization of the Terrestrial and Aquatic Habitats at the Rocky Flats Plant*. Golden: US Department of Energy, Rocky Flats Plant.

Department of Energy (1995) *The Environmental Legacy of Nuclear Weapons Production in the United States (1942–1995)*. Washington, DC: US Department of Energy.

Department of Energy (1996) *Plutonium: The First 50 Years*. US Washington, DC: Department of Energy.

DeSante, D.F. and George, T.L. (1994) Population trends in the landbirds of western North America. *Studies Avian Biol.* **15**, 173–90.

Downs, J.L., Richard, W.H., Brandt, C.A., Cadwell, L.L., Cushing, C.E., Geist, D.R., Mazaika, R.M., Neitzel, D.A., Rogers, L.E., Sackschewsky, M.R. and Nugent, J.J. (1993) *Habitat Types on the Hanford Site: Wildlife and Plant Species of Concern*. Richland: Pacific Northwest Laboratory.

Garcia, M.W. (1989) Forest service experience with interdisciplinary teams developing integrated resource management plans. *Environ. Manage.* **13**, 583–92.

Gerrodette, T. (1987) A power analysis for detecting trends. *Ecology* **68**, 1364–72.

Goble, R. (1996) *Estimating Exposures from Releases of Radioactive Elements Other than Iodine at Hanford*. Philadelphia: report to the Law Offices of Berger and Montague, PC.

Gray, R.H., Jaquish, R.E., Mitchell, P.J. and Rickard, W.H. (1989) Environmental monitoring at Hanford, Washington, USA: a brief site history and summary of recent results. *Environ. Manage.* **13**, 563–72.

Green, R.H. (1979) Sampling *Design and Statistical Methods for Environmental Biologists*. New York: John Wiley.

Hammond, S.E. (1971) Industrial-type operations as a source of environmental plutonium. In *Proceedings of the Environmental Plutonium Symposium* (E.B. Fowler, R.W. Henderson and M.F. Milligan, eds) pp. 25–35. Los Alamos: Los Alamos National Laboratory.

Hayward, W.M. (1996) *Surveillance of 100/200/600 Area Inactive Outdoor Waste Sites* Richland: Bechtel Hanford Inc.

Heeb, C.M. (1994) *Radionuclide Releases to the Atmosphere from Hanford Operations, 1944–1972*. Richland: Battelle Pacific Northwest Laboratories.

Hole, F.D. (1981) Effects of animals on soils. *Geoderma* **25**, 75–212.

Howard, W.E. (1952) A live trap for pocket gophers. *J. Mammal.* **33**, 61–5.

Huntly, N. and Inouye, R. (1988) Pocket gophers in ecosystems: patterns and mechanisms. *BioScience* **38**, 786–93.

James, F.C., McCulloch, C.E. and Wiedenfeld, D.A. (1996) New approaches to the analysis of population trends in land birds. *Ecology* **77**, 13–27.

Johnson, A.R. (1984) *Findings of Biological Investigations into Contaminated Ant Mounds near the Inactive 270-E-1 Neutralization Tank*. Rockwell International (internal letter).

Johnson, A.R., Markes, B.M., Schmidt, J.W., Shah, A.N., Weiss, S.G. and Wilson, K.J. (1994) *Historical Records of Radioactive Contamination in Biota at the 200 Areas of the Hanford Site. Richland: Westinghouse Hanford Company*.

Johnson, A.R., Mitchell, R.M. and Schmidt, J.W. (1996). *Assessment of Documents Asserting Increased Plutonium-239 Exposure Resulting from Northern Pocket Gopher* (Thomomys talpoides) *Burrowing Activity at Solid Waste Burial Grounds on the Hanford Site*. Chicago: report for the Law Offices of Kirkland and Ellis.

Krey, P.W. (1976) Remote plutonium contamination and total inventories from Rocky Flats. *Health Phys.* **30**, 209–14.

Krey, P.W. and Krajewski, B.T. (1972) *Plutonium Isotopic Ratios at Rocky Flats*. New York: Energy Research and Development, Health and Safety Laboratory.

Landeen, D.S., Cadwell, L.L., Eberhardt, L.E., Fitzner, R.E. and Simmons, M.A. (1990) *Animal intrusion field test plan*. Westinghouse Hanford Company, Richland, Wash. WHC-EP-0253, April 1990.

Law, A.G. (1982) Annual Report for Fiscal Year 1981. Richland: Environmental Technologies Group, Rockwell Hanford Operations.

Litaor, M.I., Mancinelli, R., and Halfpenny, J.C. (1996) The influence of pocket gophers on the status of nutrients in alpine soils. *Geoderma* **70**, 37–48.

McKenzie, D.H., Cadwell, L.L., Kennedy, W.E., Jr., Prohammer, L.A. and Simmons, M.A. (1986) *Relevance of Biotic Pathways to the Long-term Regulation of Nuclear Waste Disposal*. Richland: Pacific Northwest Laboratory.

Mix, P.D. and Winship, R.A. (1993) *Hanford Site Surface Soil Radioactive Contamination Control Plan*. Richland: Westinghouse Hanford Company.

Morrison, M.L. and Marcot, B.G. (1995) An evaluation of resource inventory and monitoring program used in National Forest planning. *Environ. Manage.* **19**, 147–56.

O'Farrell, T.P. and Gilbert, R.O. (1975) Transport of radioactive materials by jackrabbits on the Hanford Reservation. *Health Phys.* **29**, 9–15.

Office of Technology Assessment (1992) *Forest Service Planning: Accommodating uses, Producing Outputs, and Sustaining Ecosystems*. Washington, DC: US Government Printing Office.

Owen, J.B. and Steward, L.M. (1975) *Environmental Inventory: A Historical Summation of Environmental Incidents Affecting Soils at or Near the U.S. AEC Rocky Flats Plant*. Golden: Rocky Flats Division, The Dow Chemical Company.

Putzier, E.A. (1970) *A Summary of On Site Radioactive Waste Disposal*. Golden: Rocky Flats Division, The Dow Chemical Company.

Setlock, G.H. (1987) *Spray Irrigation at Rocky Flats*. Colorado: Golden: Rockwell International, Rocky Flats Plants.

Smallwood, K.S. (1996) *Soil Bioturbation and Wind Affect Fate of Hazardous Materials that were Released at the Rocky Flats Plant, Colorado*. Philadelphia: report to the Law Offices of Berger and Montague, PC.

Underwood, A.J. (1994) On beyond BACI: sampling designs that might reliably detect environmental disturbances. *Ecol. Appl.* **4**, 3–15

Whicker, F.W. (1996) *Plutonium Releases from the Hanford Site: a Review*. Chicago: report for the Law Offices of Kirkland and Ellis.

White, G.C. and Clark, W.R. (1994) Microcomputer applications in wildlife management and research. In *Research and Management Techniques for Wildlife and Habitats* (T. A. Bookhout, ed.) pp. 75–95. Bethesda: The Wildlife Society.

Wiens, J.A. and Parker, K.R. (1995) Analyzing the effects of accidental environmental impacts: approaches and assumptions. *Ecol. Appl.* **5**, 1069–83.

Wing, N.R. (1992) *A peer review of the Hanford site permanent isolation Surface Barrier Development Program*. Richland: Westinghouse Hanford Company.