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FINAL REPORT on POSTATTACK ECOLOGY

December 1973

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DCPA Work Unit 3516C

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OAK RIDGE NATIONAL LABORATORY

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ORNL-TM-3837

Environmental Sciences Division

FINAL REPORT ON POSTATTACK ECOLOGY

by

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for

Defense Civil Preparedness Agency
Washington, D.C. 20301

through

Division of Biology and Medicine
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Washington, D.C. 20545

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Research was conducted according to the principles enunciated in the "Guide for Laboratory Animal Facilities and Care" prepared by the National Academy of Sciences—National Research Council.

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FINAL REPORT ON POSTATTACK ECOLOGY

S. I. Auerbach and P. B. Dunaway

SUMMARY

This final report summarizes progress on the cooperative studies of behavior of fallout simulants in natural systems; transfers of ^{137}Cs through soils, plants, and animals; retention of ^{54}Mn and ^{60}Co in pine voles; gamma and beta dosimetry; and effects of chronic and acute radiation on plants and animals in the laboratory and in the field.

Studies using fallout simulant showed that: (1) Initial fractions of fallout intercepted by vegetation varied as a function of foliage characteristics and particle size. (2) Loss rates were similar for a wide variety of plants. (3) Rapid loss of particles from plant surfaces occurred generally during the first week after deposition, but after about three weeks, particle loss rates were relatively constant and proceeded at a slow rate regardless of rain and wind conditions.

Cesium-137 was transferred directly from fallout simulant to fescue by foliar assimilation and to cotton rats by in-vivo absorption. Approximately 50% of radiocesium assimilated by the foliage moved rapidly to other parts of the fescue plant; of this amount, about 20% went to the root system, 20% to emerging floral structures, and 45% to mature inflorescence. Decrease in foliage concentration followed a negative exponential pattern, and accumulation in roots was a mirror image of foliar loss. Cotton-rat whole-body burdens of ^{137}Cs initially were influenced heavily by the amounts of fallout simulant and contaminated dead vegetation ingested, but as time progressed and the amount of radioactivity in living vegetation began to equilibrate, a relatively constant, lower body burden was reached. After 30-60 days chronic ingestion in the enclosures tagged with fallout simulant, cotton-rat body burdens were comprised of 4% in heart, liver, spleen, and kidney; 6% in stomach and intestines; 9% in pelt; 27% in gastrointestinal (GI) contents; and 55% in residual carcass (mostly in muscle). In the GI-tract contents, 79% of the ^{137}Cs was in organic matter and 21% in fallout simulant. Losses of injected ^{54}Mn and ^{60}Co from pine voles in natural populations were more rapid than from voles in the laboratory, with most of the difference occurring during the first two weeks postadministration. Surface water runoff from field plots never exceeded 2% of rainfall, and only about 0.015% of the fallout deposit will be redistributed in each precipitation event that produces runoff of $\geq$4 liters/m^2.

Dosimetry studies were done by using an area scanner and by use of microdosimeters at points of interest. Gamma dose rate 1 m above ground surface of the contaminated enclosures has not decreased significantly from the 2.46 rads/day measured early in the experiment,

but the beta dose rate rapidly decreased early as the fallout simulant descended toward the ground. Gamma dose to cotton rats decreased from 3.84 rads/day in February 1969 to 2.35 rads/day in July 1969, with no significant difference thereafter to April 1970. Early doses to plants in microsites (e.g., axils) were as much as 27.5 rads/day. Developing floral tissues in fescue during 1971 received about 4 rads/day, compared with about 17 rads/day in 1968. Crickets living near the ground received two to three times as much radiation as grasshoppers living higher on vegetation.

Various radiation-effects studies were done in both the laboratory and field. Production of normal and aborted pollen from irradiated fescue averaged 5 percentage units less and 6 units more, respectively, than that of controls, but no differences were observed in percentage of aberrant pollen. Seed production in irradiated fescue was only 50% that of controls, when dose rate was 11 to 17 rads/day, but when dose rate decreased by 40%, seed production was 20% less than controls. Cotton-rat grazing also reduced seed production, even one year after the rats were removed. Laboratory studies of acute beta or gamma irradiation effects in one species of Collembola showed that eggs and juveniles were more radiosensitive than adults. Chronic exposure of another species of Collembola to beta irradiation showed that radiation responses of the population was determined primarily by effects on fertility rates of adults. Population densities of 8 of 75 arthropod taxa were significantly smaller in the enclosures during summer 1970, and populations of six of the eight taxa again were smaller in summer 1971.

White-footed mice were irradiated each month for two years with an acute dose of 1050 rads and were caged in an outside environment. Mortality was lowest from May through September (42 to 55%), highest during November and December (90%), and ranged from 59 to 72% during the remaining months. Environmental conditions and/or endogenous factors acted synergistically with radiation during most of the year because mortality was usually greater and survival time shorter than for this species in the laboratory. Pine voles were irradiated with 700 rads and released with nonirradiated voles back into a natural environment. Significantly fewer recaptures of irradiated than nonirradiated females were observed, but this result may have reflected loss of territory during radiation sickness rather than death per se. Although irradiated voles exhibited pelage graying by day 105 postirradiation, they did not seem to be more vulnerable to predation.

INTRODUCTION

This is the final report of research on postattack ecology in the Environmental Sciences Division, Oak Ridge National Laboratory, sponsored by the Office of Civil Defense (OCD) in cooperation with the U.S. Atomic

Energy Commission. Studies began, in summer 1968, at specially constructed field facilities and in the laboratory on work related to OCD programmatic needs. Research emphasis was placed on the following categories: (1) behavior of fallout simulant in vegetation surfaces; (2) movement of ^{137}Cs through soils, plants, and animals; (3) environmental and organismal gamma and beta dosimetry; (4) effects of chronic and acute beta and gamma radiation on organisms; and (5) interactions of ecological factors in categories 1-4.

The field facilities constructed were: (1) Eight 100-m^2 enclosures on a fescue, Festuca arundinacea, community. Four of the enclosures were tagged uniformly with a fallout simulant containing ^{137}Cs. Particle diameter was 88-177 μ, mass loading was 72 g/m^2, and radioactivity was 2.2 Ci per enclosure. (2) Enclosed field plots for studies of fallout-simulant interception and retention by various grasses, crop plants, and trees. (3) A field aviary of 40 hives of honeybees irradiated with 0, 500, 1000, 2000, or 4000 R of gamma radiation. A related facility contained 33 hives in enclosures; these hives were irradiated with 0, 1500, or 3000 R. (4) A building open to the weather for tests of seasonal changes in radiosensitivity of rodents. In addition to these field facilities, supporting facilities were provided in the laboratory, in greenhouses, and in environmental chambers.

Unfortunately, an OCD budget decrease in 1969 forced us to terminate the promising study of honeybees, and termination of all OCD support in 1971 dictated that we stop all research under that funding. Cessation of OCD support was particularly unfortunate because we had begun to delineate unsuspected, long-term effects on natural populations of animals and plants from chronic, low-level, beta-gamma radiation. We also began to demonstrate that irradiation doses, irradiation effects, and radionuclide transfers in some cases were quite different from what would be expected from laboratory experience. We believe that the results provided under OCD support represent excellent value for the money received, but we suggest that long-term irradiation effects in plant and animal populations cannot be characterized fully in only two or three years.

Summarization of some of the work done in the past is presented in this report, but results of newer research and syntheses of past work have been emphasized here. For more detailed records of our past performance under OCD funding, a list of publications is included with this report. This list is not to be considered as a final summation, because a number of other publications emanating from this project will appear later.

FIELD STUDIES ON RETENTION OF SIMULATED FALLOUT BY PLANTS

J. P. Witherspoon and F. G. Taylor, Jr.

Summary

Several field studies on the retention by plants of local fallout particles (particles exceeding 44 μ in diameter) are summarized. Although initial fractions of intercepted fallout varied as a function of plant foliage characteristics and particle size, average retention values were similar for a wide variety of plants.

Rapid losses of particles from foliage and other plant parts due to weathering occurred generally during the first week following particle deposition. After about three weeks the loss of particles was relatively constant and proceeded at a slow rate regardless of subsequent rain and wind conditions. For general vegetation types, particle loss rates were in the order: trees > crop plants > grasses.

Introduction

Several experiments on the retention of different sizes of fallout particles by plants were performed on a range of plant types including mosses, lichens, grasses, crop plants, and trees. Results of these experiments have been published in the open literature (Peters and Witherspoon 1972, Taylor and Witherspoon 1972, Witherspoon 1970 and 1972, Witherspoon and Taylor 1969, 1970, and 1971).

Results

1. Lichen (Cladonia subtenuis) and moss (Dicranum scoparium) mats of uniform size were contaminated with a quartz fallout simulant (88-175 μ) containing ^{134}Cs (Taylor and Witherspoon 1972). Mass loading was 5.0 g of particles per ft^2 of soil surface area. Total rainfall during the experiment was 3.7 in. (eight events) with 0.25 in. occuring during the 0-1 day time period.

   Lichen mats intercepted 70% of the initial particles application and moss mats intercepted 100%. Weathering half-times were calculated for periods of 0-1 and 1-42 days. Half-times for particles during the 0-1 day component were 1.2 and 3.2 days for lichens and mosses, respectively. For the 1-42 day component, half-times were similar with values of 48.6 (lichens) and 49.4 days (mosses).

2. Five species of crop plants (squash, soybeans, sorghum, peanuts, and lespedeza) were tested in the field with two particle size ranges of quartz containing ^{86}Rb (Witherspoon and Taylor 1970, Witherspoon 1972). Mass loadings of 5.7 (44-88 μ particles) and 6.6 g of particles per ft^2 (88-175 μ particles) were applied to 6-week-old plants. Initial interception and retention up to 8 weeks were determined. The initial interception of smaller particles (44-88 μ diam) by foliage was 2.5 times that of larger particles (88-175 μ diam). Particle interception was correlated with leaf area and varied between species by a factor of 65 in terms of μCi ^{86}Rb per g of foliage.

   After rapid initial losses of fallout (67% in the first week after deposition), differences in retention between species became nonsignificant. Retention times of the two particle size ranges were also found to be similar. (Average weathering half-times for particles were 2.3, 9.0, and 16.0 days for time components of 0-1.5, 1.5-14, and 14-33 days, respectively.

3. Smaller particles (1-44, average 7.5 μ) containing ^{134}Cs were applied to 6-week-old soybean and sorghum plants (Witherspoon and Taylor 1971). Mass loading was 1.9 g of particles per ft^2 of soil surface area.

   Initial interception was similar, with 39.5 and 38.2% of the deposition quantity retained by soybeans and sorghum, respectively. Sites of interception, however, differed greatly between species.

   Particle weathering half-times were determined for whole plants and plant parts. Soybean foliage half-times were 4.4 and 24.4 days for 0-7 and 7-34 days, respectively. Sorghum foliage half-times were 3.9 and 17.9 days. Particles in the axil regions of sorghum, effective trapping sites, had a weathering half-time of 35.4 days — about twice that of particles on sorghum foliage.

4. A quartz fallout simulant containing ^{134}Cs was deposited (1.85 g of particles per ft^2) on four common species of grasses used for pasture or turf purposes (Zoysia, Bluegrass, Fescue, and Bermuda)(Peters and Witherspoon 1972). Initial interception of the fallout simulant varied from 68 to 82% between species. Weathering half-times (days ± 1 S.E.) of particles on foliage average 3.5 ± 0.6, 36.7 ± 8.6, and 80.5 ± 39.5, respectively, for time periods of 0-2.5, 2.5-34, and 35-48 days following deposition. Particles lost from foliage were mostly trapped by dense mats of stem and dead foliage, and transfer of particles to the soil surface amounted only to 31% of the original deposition at 48 days. As a result of greater retention during postcontamination fallout-contaminated grasses might be expected to receive greater radiation doses and supply more radioactivity for food-chain transfers than other agricultural plants with less effective structures for particle retention.

5. Small white pine (Pinus strobus) and red oak (Quercus rubra) trees were dusted in the field with a fallout simulant consisting of 88-175 μ-diam quartz particles containing ^{134}Cs (Witherspoon 1969). Whole plants were harvested at intervals up to 33 days after application of the simulant, and the ^{134}Cs retention by each species was determined.

   The initial fraction of the simulant retained by foliage was higher in the oaks (35%) than in the pines (24%). However after 1 hr, the broad-leaved oaks had lost 90.5% of the initial ^{134}Cs concentrations, while the pines had lost only about 10%. These early retention differences were related to the effects of wind on the two distinct foliage types.

   Effective half-lives were calculated for both species at intervals of 0-1, 1-7, and 7-33 days. For pine trees these values were 0.2, 4.5, and 20.7 days, respectively. For oaks, they were 0.1, 1.4, and 24.9 days.

   These studies demonstrated that early loss rates of particles from a wide variety of vegetation types are similar. Weathering half-times for various time components and vegetation types were within a factor of 2 difference.

   Tree species were shown to have a greater rate of early loss of fallout particles than agricultural plants. Matted plants such as some lichens, mosses, and grasses proved to be very effective in retaining fallout, thus demonstrating a high probability both of greater dose to these vegetation types and to animals that consume them.

Recommendations

1. Studies reported here have involved the use of fallout particles greater than 44 μ in diameter. Similar studies should be made on smaller particles which are likely to be dispersed over a wider area than close-in fallout following detonation of nuclear devices.

2. More information is needed on specific retention sites on plants. For example, grasses have a very effective retention site in the axil regions, and estimates of radiation dose should incorporate contributions of dose from these special regions.

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RETENTION OF FALLOUT SIMULANT PARTICLES ON FESCUE VEGETATION

R. C. Dahlman

Summary

Short-term (t_0 to 2 weeks) retention and weathering were determined for sand size (44-188 μ diam) particle deposits on fescue grass. Maximum retention ranged from 45% at t_0 to 11% at t + 1 hr, and particle weathering was described with a modified negative exponential function over a 2-week interval. Relatively short particle weathering half-times (3 to 5 days) would tend to reduce radiation exposure to foliage and would diminish the entry of radionuclide into food-chain pathways.

Experimental

Surface nuclear detonations produce close-in fallout particles, and this material represents a new dimension of environmental contamination. The behavior of simulant particles and the resulting effects of ^{137}Cs contaminant on plants, animals, and insects were investigated in a tall fescue (Festuca arundinacea Shreb) meadow.

Particle retention and weathering were determined for uniform stands of 10-week-old regenerated fescue grass. For a mass load (10 g/ft^2) applied to fescue (17 g/ft^2 34 stems/ft^2), initial retention (t_0) was 45% for small (44-88 μ diam) and 20% for large (88-177 μ diam) particles. Immediate particle loss from vegetation occurred because retention averaged 11% at t_0 + 1 hr; thereafter, particle weathering was described with a negative exponential model (Fig. 1a) of the form,

$$Y = (\alpha + 1)(1 - \alpha)e^{-\lambda t},$$

where α and λ parameters were 0.20 $\pm$ 0.02 and 0.26 $\pm$ 0.02, respectively. The model has also been tested with sorghum data (see Witherspoon, this report), and the continuous function weathering model described time-dependent retention on sorghum with a nearly similar λ parameter (0.26 versus 0.23), but with appreciably different α terms (0.20 versus 0.03).

Short-term (t_0 + 1 week) weathering half-times were approximately 3-5 days for both fescue and sorghum cases. These observations are important because, while initial (t_0) particle retention on coarse pasture grass may approach 50% of deposition, rapid weathering processes will decrease retention to only 10% within 1 hr. Rapid and exponential particle weathering will continue for several weeks, exhibiting particle retention half-times of 3 to 5 days. Prompt particle weathering

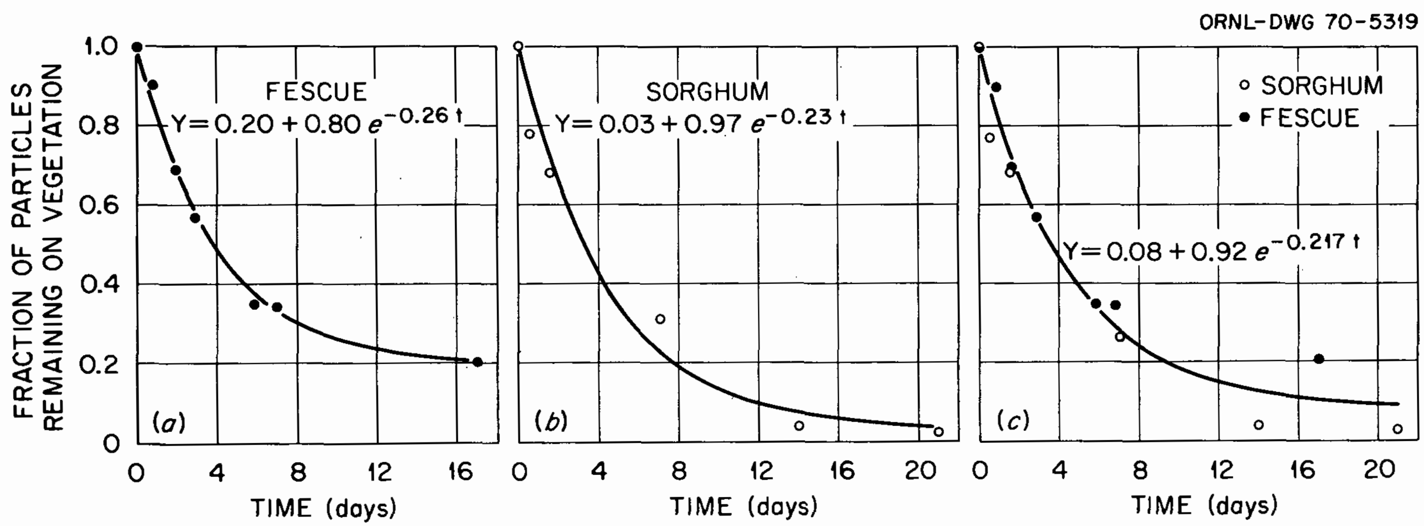

Fig. 1. Average effective particle retention by fescue and sorghum grasses. Data normalized to express t + 1 hr as initial retention. Sorghum and fescue data composited in (c). Sorghum data provided by Witherspoon and Taylor, this report.

affects several other radiological manifestations: (1) Radiation dose to grass foliage from contact exposure is reduced, direct radionuclide uptake by foliage from particle deposits is decreased, and resultant radionuclide entry into ecological food-chains is diminished. (2) In contrast, rapid redistribution of highly radioactive, short half-life fallout particles from foliage concentrates the deposit at soil surfaces which would increase the radiation dose to the meristems (growing points) of graminacous plants (grass, grain, corn), a mechanism which conceivably would increase radiation effects and damage to both native and agronomic plants. These manifestations would be influenced greatly by short-term particle and radionuclide behavior during the initial two weeks of contamination. Long-term considerations in radiological hazard assessment would scarcely be altered, however, by the new results on rapid weathering of particles as determined from these experiments.

Recommendations

1. Experimental work on particle retention and weathering on vegetation needs to be extended to include smaller size classes (0.5 to 5.0 μ diameter). Retention and deposition processes (plume dispersal, deposition velocity) need to be related to dust cloud characteristics.

2. Relationships between vegetation characteristics (leaf morphology, foliar crevices and other microsites) and particle retention need further elucidation.

3. Relationships between particle weathering rates and meteorological conditions (dew formation, precipitation, canopy air turbulence) need refinement.

4. Correlation of particle weathering rates with vegetative characteristics (phytotaxic growth, central axis elongation, wind-induced leaf-sheath flexation) needs further investigation for vegetable and forage crops.

DISTRIBUTION OF RADIOCESIUM ASSIMILATED BY FESCUE FOLIAGE

R. C. Dahlman

Summary

Foliar assimilation and intraplant redistribution of radiocesium by fescue grass were determined for a simulated contamination. As indicated by microautoradiographs, most of the ^{134}Cs was initially incorporated into internal tissues. Approximately 50% of the foliar radiocesium moved rapidly to other parts of the plant; of this amount, about 20% moved to the root system, 20% to emerging floral structures, 45% to mature inflorescence. Decrease in foliage concentration followed a negative exponential pattern and the accumulation in roots was a mirror image of foliar loss. This experiment illustrated the great mobility of radiocesium in plants, and similar patterns of uptake and distribution can be expected from foliar uptake of fallout deposits.

Experimental

Knowledge of radioisotope distribution patterns in plant parts of grass is important because foliage comprises the principal food base of the grass-cattle-human food chain. Ingested food stuffs will determine radioactivity body burden and internal dose to consumer organisms which feed on foliage, roots, and seeds.

Foliar assimilation of radiocesium and subsequent redistribution to other parts of fescue plants were determined in the laboratory during vegetative and flowering phases of the growth cycle. Grass plants were contaminated by submerging leaves in a ^{134}Cs solution. Most of the assimilated radiocesium was internal, because microautoradiographs of leaves disclosed activity distributed in veins rather than concentrations on the leaf surface. Uniformity in total uptake permitted subsequent analysis of intraplant distribution pattern (Fig. 2) with time and phenological developments. Significant quantities of foliar-assimilated radiocesium were promptly redistributed to different plant parts, about 20% to the root system in five days and then 20% to the flower structures as they emerged from the sheath 15 days after labeling. At floral maturity the content in inflorescence increased to 45% of the total present in the plant. Redistribution of radiocesium from root to inflorescence accounted for approximately half the initial burden in the flowering organs. Subsequent radiocesium increase in flowering parts was attributed to transport from foliage, and the rapidity with which transport occurs is illustrated by these results. Approximately 15% of total plant radiocesium moved to the emerging fescue inflorescence in a 2-day period.

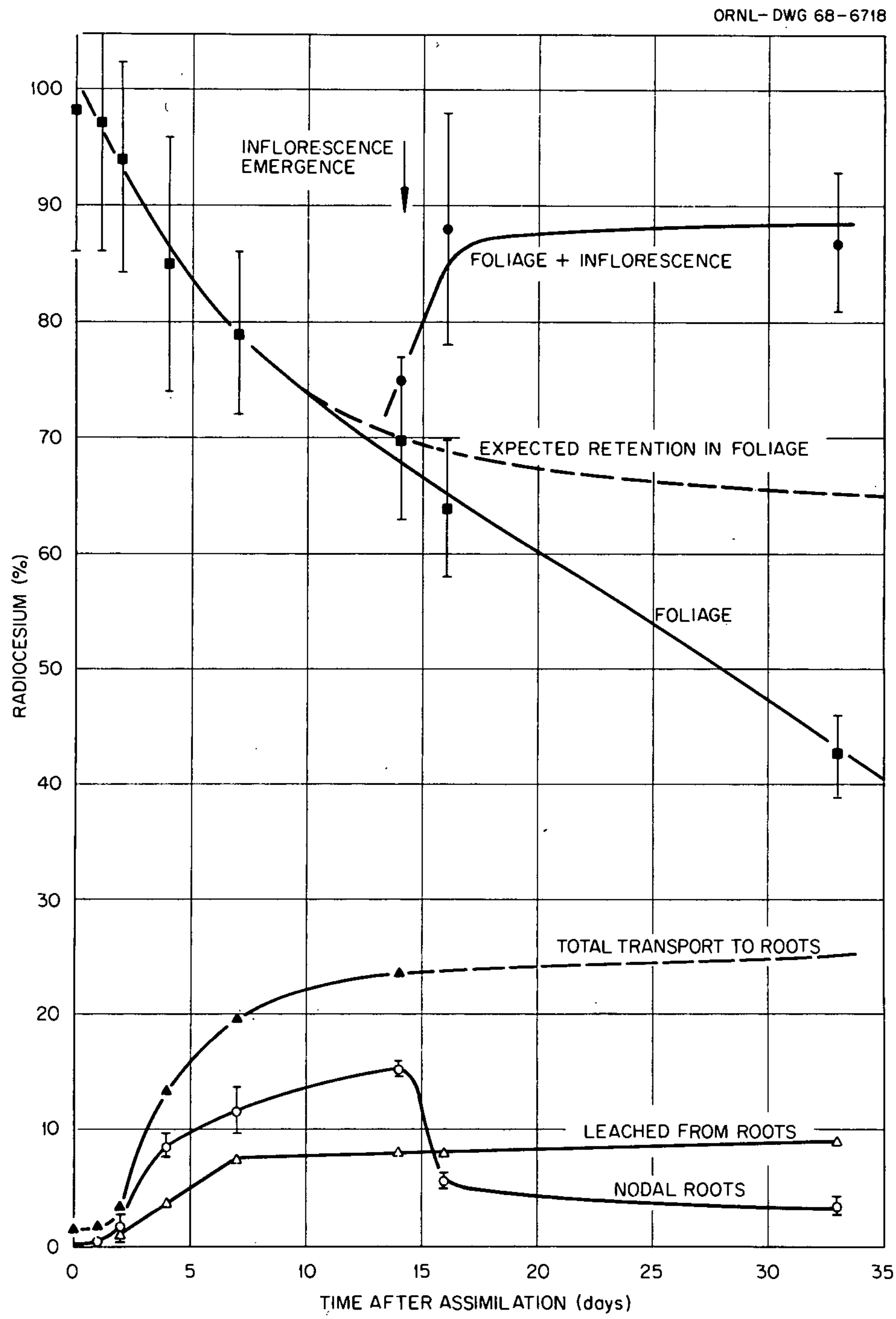

Fig. 2. Distribution of radiocesium in different organs of fescue following foliar assimilation. Large error terms for foliage and inflorescence attributed to variable retention on surface microsites and intercellular spaces.

Interesting radiocesium distribution patterns were observed between seminal and nodal roots of young fescue grass. The former originate from germinal tissue in the seed, and the latter develop from meristematic tissue of the stem nodes. Initially, radiocesium moved from shoots to seminal roots; then after four days nearly all the basipetal movement was to the nodal roots. Although less than 10% of the radiocesium present in the entire plant was leached from roots, this quantity reflects additional basipetal transport which would have gone undetected if the rooting media had not been examined for activity. Radiocesium leached from roots was roughly half of the total observed in the root system. The rate of radiocesium accumulation in the total root system followed an exponential pattern (Fig. 2) during the 2- to 14-day period following foliar assimilation. Coincident with inflorescence emergence, the direction of transport was reversed, and the nuclide moved back into the shoots. In the absence of flowering, accumulation in roots probably would have continued, but at a slower rate, such as that indicated by the extrapolated total transport to roots.

In the early phase of radiocesium transport from foliage, the reduction in activity appeared to follow a decreasing exponential pattern, somewhat a mirror image of accumulation in roots. But the emerging inflorescence provided an additional "sink" to which the mobile nuclide moved. This caused the rate of transfer from foliage to be maintained at a relatively high level, and eventually over 50% of the assimilated radiocesium moved out of the foliage. In the absence of inflorescence emergence, a slower rate of radiocesium transport from foliage would be expected during the late phase (plus 2 weeks) of redistribution, and expected retention in foliage (Fig. 2) was estimated at 65 to 70% of that assimilated. A two-phase rate of transport was suggested for radiocesium movement from foliage. Both free and bound cesium ions probably existed in plant tissues, and the early phase (1 to 2 weeks) consisted of transport of the readily available portion via the translocation stream. Then the rate diminished, because of decreased availability and pool size, and possibly due to physical-chemical and biological fixation of cesium in living protoplasm of the leaf tissue.

Similar patterns of distribution in fescue plants would be expected for the radiocesium assimilated from fallout, with the exception of accumulation in soil. If soil acted as a sink which continually absorbed cesium ions released from the roots, then transfer to the soil may be greater than that observed in this experiment. This mechanism would effectively remove the nuclide from biological circulation. On the contrary, if the soil presents an optimal physical-chemical and moisture environment, these factors would modify root stress, thereby reducing root loss. Root contribution to radiocesium accumulation in soils is not easily evaluated because precise measurement of transfers via this route is complicated by the difficulty of separating roots from clay-mineral residues.

Recommendations

1. Experimental studies should be done to determine rates and magnitudes of foliar incorporation of other fallout radionuclides (^{90}Sr, ^{144}Ce, ^{106}Ru). Internal uptake should be investigated in relation to modes of contamination, physiological and morphological features, and microclimatic conditions (dew formation, soil water status).

2. Physiological studies should be extended to determine the mechanism of radionuclide uptake in relation to stomatal openings, fissures in epidermal cutin, and gas-water vapor exchange processes.

3. Intraplant translocation and relative concentrations of assimilated radioactivity in plant organs should be investigated for vegetable and grain crops.

ESTIMATION OF RADIOCESIUM REDISTRIBUTION IN RUNOFF FROM A FESCUE MEADOW

R. C. Dahlman

Summary

Redistribution of ^{137}Cs in runoff from contaminated grass plots was calculated from fallout solubility and soil permeability characteristics, including estimates of soil erosion and surface water runoff. Observed runoff never exceeded 2% of rainfall input, and it was estimated that approximately 0.015% of the fallout deposit will be redistributed in each precipitation event that produces at least 4 liters runoff per m^2. Limited data on measured radiocesium transport were in reasonable agreement with predicted values of radioactivity loss for a grass-sod system.

Experimental

The precipitation regime of the Southeastern United States averages 50 in./year, and rainfall occasionally occurs as intense storms. Redistribution of fallout via erosion may influence radioactivity concentrations in foodstuffs and drinking water or affect the radiation dose to endemic organisms. Potential radioactivity redistribution was estimated for typical rainfall events prior to introducing the fallout simulant. Radioactivity in runoff was related to excess water runoff from precipitation events. Soil erosion was determined from an adaptation of a soil-loss equation (Wischmeier 1965) to fit grass-sod systems. Actual and predicted radiocesium losses were compared for a fescue meadow ecosystem. It was determined that radiocesium removal from the experimental area would be a function of (1) the quantity of water and eroded solids in runoff and (2) the quantity of ^{137}Cs dissolved in water and sorbed on solids. Runoff was related to soil moisture recharge and rainfall intensity, and generally the soil system had the capacity to absorb approximately 4 in. of rain, after which the soil became saturated and runoff occurred. This observed 4-in. recharge correlated well with the calculated water storage capacity based on available pore space [25% when soil water was 25% (field capacity is 28%)] assuming recharge of the top 15 to 20 in. of the profile. Indeed the soil system absorbed precipitation inputs, because runoff was inconsequential, and the maximum observed was 2% of the total input. Six of nine runoff events each yielded less than 1% of the rainfall input. An upper limit of radiocesium loss was estimated for an extreme case of 5% (2.5 times the observed) runoff, where 0.015% of the fallout deposit (I) would be removed in runoff (I x 0.15 [solubility] x 0.02 [K_d] x 0.05 [runoff] = I x 0.00015 or I x 0.015%; see Fig. 3).

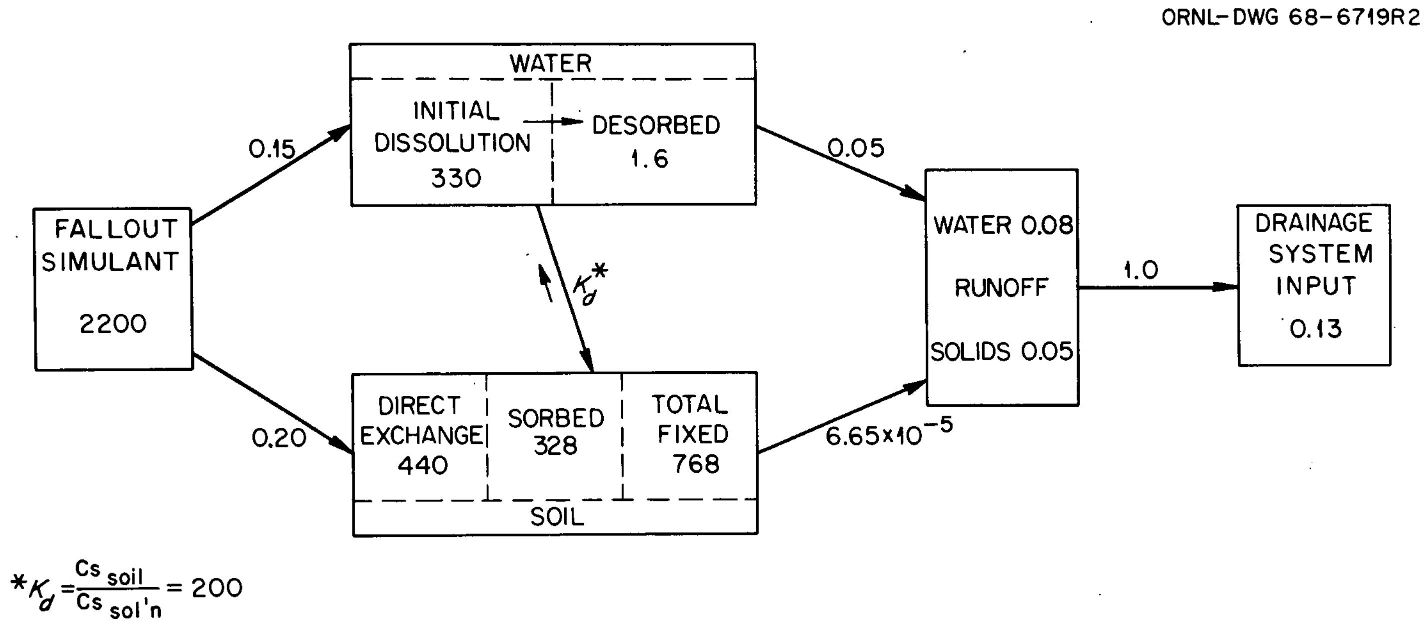

Fig. 3. Predicted movement of radiocesium from a >400-liters/100 m^2 (4 liters/m^2) runoff event shortly after application of 2 Ci (20 mCi/m^2) of ^{137}Cs fallout simulant. Numbers in compartments represent millicuries of ^{137}Cs, and other values indicate fractional transfer between compartments. Distribution coefficient ($^*K_d$ = Cs_{soil}/Cs_{water}) was 200 for illitic clay.

Within limits, linear extrapolation probably would hold for rainfall of greater magnitude. Dense cover of grass and litter filtered and removed most of the soil, and eroded solids were nearly absent from runoff water. Although the highest concentrations of radioactivity would be carried by solid materials, the total loss in this phase was negligible because the vegetative cover effectively prevented soil erosion.

Results from field experiments after contamination permitted a comparison of predicted and observed runoff and soil loss. For conditions of severe runoff, annual soil loss was predicted on the basis of 20 rainfall events, each producing 400 liters of runoff which would yield 16 g m^{-2} $year^{-1}$ of soil loss [(400 liters/event)(20 events)/(5 liters/g)(100 m^2)]. Agreement between observed and predicted (based on the soil-loss equation) erosion loss was reasonably good considering that the soil-loss model (Wischmeier 1965) was derived initially for cultivated systems, and the system in question was a grass meadow. Correlation was better when observed erosion was compared with the maximum predicted assuming extreme conditions of rainfall erosivity. For normal conditions, the Wischmeier and Smith model overestimated erosion from a vegetated sod by three to ten times that which was observed for simulant plots.

The important factors determining initial distribution of ^{137}Cs will be sorption on soil and movement of dissolved and solid materials in water. From laboratory tests it was determined that 10% of the ^{137}Cs simulant was soluble in water, and 24% of the radiocesium will transfer to clay in a 1:1:10 simulant:clay:water slurry. Equilibration occurred rapidly because only 26% transfer was observed after 7 days. For solubility (10%) and exchange (20%) parameters, a model (Fig. 3) was constructed to show the expected behavior of radiocesium under circumstances of a heavy rain (>4.0 in.) immediately following application of the contaminant to the plots. Because of the high K_d of cesium reaction with illitic clays (K_d = 200), the water was desorbed quickly by the clay; thus, most of the ^{137}Cs in solution was sorbed by soil.

In porous soil which possessed moderate recharge capacity (4 to 5 in. per storm event), rainfall intensity can be largely ignored when grass-sod constitutes the landscape surface. A rainfall event which produced 400 liters of runoff was predicted to contain 0.015% of ^{137}Cs contaminant (see above discussion and Fig. 3) or 0.33 mCi ($5.0 \times 10^{-6} \times 2.2$ Ci of that applied). During a test period involving winter rainfall, only one event produced appreciable runoff, viz. 400 liters (Table 1). Total measured activity removed from the plot was 0.118 mCi, less than one-third of the estimated removal (0.33 mCi per event).

Table 1. Observed Radiocesium in Runoff from Fescue Meadow

Runoff (l)	Erosion (g)	Total ^{137}Cs (mCi)
2	-	0.001
400[a]	0.5	0.118
2	0.3	0.001

[a]Runoff rate - 4 liters/m^2.

In conclusion, an approximate quantity of radioactivity carried in runoff from contaminated areas can be calculated from fallout solubility and soil sorption coefficients, from erosion estimates (negligible in grass systems) based on the soil-loss equation, and from estimates of surface water runoff. For radiocesium, a field test with a moderately soluble simulant and a sandy-loam soil containing illitic clay, approximately 0.015% of that deposited will be transferred in events where runoff exceeds 2% of the rainfall input. Total radiocesium removal via runoff can be estimated within acceptable limits based on a working knowledge of fallout and soil characteristics and an estimate of excess water runoff.

Recommendations

1. Redistribution of other fallout products (^{90}Sr, ^{106}Ru, ^{144}Ce) which exhibit variable solubility in runoff should be examined in relation to nuclide solubility, grass cover, and soil infiltration characteristics.

2. Localized fallout particle and nuclide redistribution patterns should be examined for fallow, vegetated, and cultivated soil to determine "hot spot" concentrations on the soil surface. Radioactivity reconcentrations should be related to small-scale models of erosion and sediment transport in efforts to predict radiation dose to cultivated or endemic organisms.

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RADIONUCLIDE CONCENTRATIONS IN COMPONENTS OF A GRASSLAND ECOSYSTEM FROM AN ACUTE CONTAMINATION EVENT

R. C. Dahlman

Summary

Radiocesium-tagged particles were applied to a fescue community in a simulated contamination event. Direct deposition on foliage resulted in ^{137}Cs uptake by the vegetation which was two orders of magnitude greater than chronic concentrations maintained by assimilation from the soil. Radiocesium was dynamically redistributed during the initial 2-week period by particle weathering, leaching, and intraplant movement. Thereafter new equilibria developed as biotic ^{137}Cs burdens were based on uptake from the soil pool. The litter component initially retained the greatest fraction of radioactivity and was characterized by the slowest turnover time ($T_{1/2}$ = 80 days). The important ecological implication is that long-term retention in litter will lead to substantial organism body burdens in detrital-based food chains. This integration and assimilation is valuable, because it would aid the design of ecological monitoring programs by identifying habitats and endemic organisms which would be exposed to maximum amounts of radioactivity.

There are convincing indications that the foliar interception mode of contamination will result in higher radioactivity concentrations in foliage and foodstuff compared with radionuclide uptake from soil (Krieger et al. 1966, Middleton 1959). When fallout simulant particles were deposited directly on fescue (Festuca arundinacea Shreb.), the ^{137}Cs content of living vegetation was two orders of magnitude greater than when the radionuclide was assimilated from an equivalent soil pool. The initially high radionuclide concentrations of foliage, due to direct deposition, decreased exponentially as a function of time after the contamination event.

Substantial radioactivity concentration in vegetation creates a relatively high hazard to other animals which may feed on the contaminated material during initial postcontamination periods (See Dunaway et al., this report). However, the high hazard potential is of relatively short duration, because weathering and growth processes decrease radionuclide concentrations to a level which is maintained by uptake from soil. Subsequently, a lower equilibrium between plants and soil becomes established, and chronic plant burdens are a function of routine plant nutrition processes and the quantity of radionuclide in the soil pool. Concentrations maintained by this equilibrium are several orders of magnitude less than the initial concentration caused by direct deposition on foliage. The chronic plant radionuclide burden will account for less radioactivity entry into food chains, where attendant radiological hazards are low level and of a long-term duration.

Results from field and laboratory experiments on the contamination of fescue grass have been integrated with the aid of systems modeling techniques to illustrate relative concentrations of radiocesium in different ecosystem components following a unit source deposition to a fescue meadow. Initial conditions and transfer functions used in the model are summarized in Table 2. Radiocesium transfers among plant-litter-soil components were defined as linear or exponential functions (τ's, Table 2), and the equations for change in state of six compartments were solved with a Runge-Kutta routine provided by Com-Share. Within limits, the results of this simulation (Fig. 4) fit observed concentrations and trends of radiocesium redistribution among different components of a grass-soil system as a function of time after contamination. The particle deposit from a single acute input initially was partitioned at 10 and 90% for foliage and litter, respectively (see R. C. Dahlman, this report). Results of the simulation illustrated the highly dynamic nature of radiocesium during the initial 2- to 3-week period following contamination. Particle weathering, leaching, and intraplant movement of radiocesium are processes which accounted for dynamic redistribution initially, and, thereafter, radiocesium fluxes became less dynamic as new equilibria depended on uptake from the soil pool.

Experiments which provided data for this simulation focused on particle dynamics in litter and foliage, plant-particle interactions, and radiocesium mobility in aboveground vegetation (Dahlman et al. 1969). Estimates of plant uptake from soil were based in part on other literature information. Data on radiocesium content of roots were incomplete, but the trend for root concentration was within an acceptable limit based on other reports of radiocesium root/shoot ratios (Dahlman 1972, Handley and Babcock 1970). Simulated radiocesium concentration trends in litter, soil, foliage, and fruit were accurate representations of observed redistribution in field and laboratory experiments. This was true for both trends of redistribution and relative magnitude of radiocesium in the different compartments as a function of time.

The significance of this simulation was the illustration of relative concentrations of a nuclide in different components of the ecosystem following an acute contamination event. These results, and apparently those of others (Rogowski and Tamura 1965), showed that the litter component initially retained the greatest fraction of radioactivity, and it also exhibited the slowest turnover time. After several months, this component still retained the largest fraction of the initial input. The radiocesium content of living foliage diminished rapidly, and one month later it approached a concentration level which was two orders of magnitude less than that at t_0. Soil acted as a sink for the contaminant, but equivalent amounts in litter and soil did not occur until 6 months after contamination according to this integration. An important ecological implication is that appreciable long-term retention in the litter component may lead to substantial concentrations in detrital-based food chains. Where dead organic material is an

Table 2. Initial Conditions and Transfer Functions Used in the Simulation of Radiocesium Dynamics in a Fescue Meadow

Compartment	Initial condition[a]	Functions of fractional transfer (τ) from specified compartment (day^{-1})		
		Definition	Form	Parameter
Foliage surface (E)	0.1	$\tau_1 = w_1 E$, particle weathering[b]	Negative exponential ($w_1 = e^{-\lambda t}$)	$X = 0.25$ t = day
		$\tau_2 = u q_1 E$, particle to leaf surface leaching[c]	Negative exponential ($u = e^{-\lambda t}$)	$\lambda = 1.38$ $q_1 = 0.15$ t = day
		$\tau_3 = c_1 E$, leaf turnover[d]	Constant linear	$c_1 = 0.005$
Litter (L)	0.9	$\tau_4 = c_2 L$, litter turnover[d]	Constant linear	$c_2 = 0.006$
Soil (S)	0.0008	$\tau_5 = c_3 S$, root uptake[e]	Constant linear	$c_3 = 0.0003$
Root (R)	0.0008	$\tau_6 = c_4 R$, translocation to foliage[f]	Constant linear	$c_4 = 0.004$
		$\tau_7 = c_5 R$, root excretion, turnover[g]	Constant linear	$c_5 = 0.0007$
Foliage burden (B)	0.0002	$\tau_8 = w_2 B$, leaf death and weathering[c]	Negative exponential ($w_2 = e^{-\lambda t}$)	$\lambda = 0.02$ t = day
		$\tau_9 = f_1 q_2 B$, translocation to inflorescence[c]	Exponential [$f_1 = (1 - e^{-\lambda t})$]	$\lambda = 0.35$ t = day
		$\tau_{10} = f_2 q_3 B$, translocation to root[c]	$f_2 = (1 - e^{-\lambda t})$	$\lambda = 0.12$ t = day $q_3 = 0.25$
Inflorescence (I)	0.0	Sink		

[a]Unit input was initially partitioned between foliage surface and litter. Initial soil content was specified as 8×10^{-4} of initial input; root content (8×10^{-4}) assumed to be equilibrated with soil; foliage burden specified as 0.2 of total plant content (0.1×10^{-3}, see footnote *d*). Inflorescence functions as a sink and receives input from foliage burden (B).

[b]R. C. Dahlman, 1972.

[c]R. C. Dahlman et al., 1969.

[d]J. M. Kelly et al., 1969.

[e]R. C. Pendleton et al., 1960.

[f]R. Handley et al., 1970.

[g]R. C. Dahlman et al., 1965.

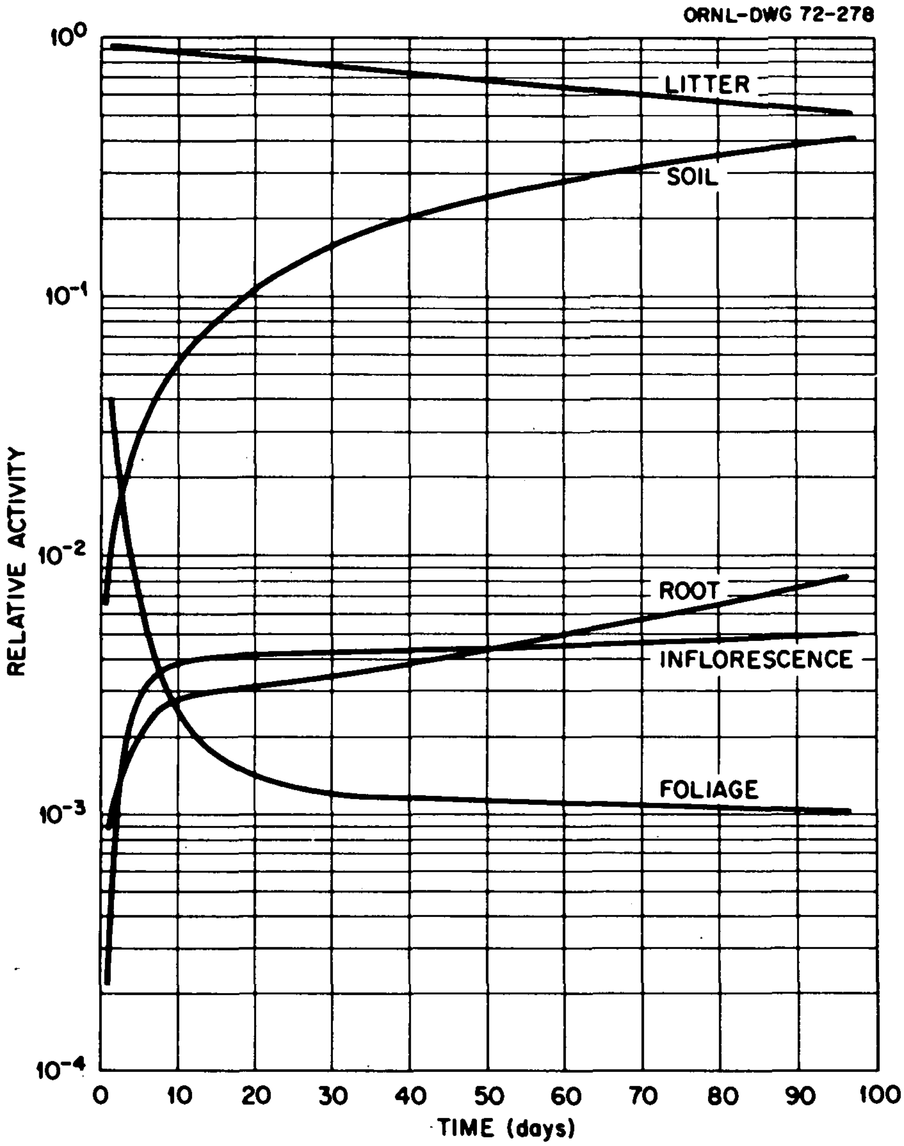

Fig. 4. Relative concentrations of ^{137}Cs in plant soil segments of fescue grassland contaminated with fallout simulant particles. Initial deposit was partitioned between foliage and litter in the ratio of 1:9.

important dietary constituent, radionuclide ingestion would be at least two orders of magnitude greater than if living plant material constituted the food base.

Empirical and simulation information on relative concentrations, as shown here, also would aid the design of ecological monitoring programs, because it would identify segments of the system that have the highest hazard potential with regard to food-chain reconcentrations and exposure of endemic organisms.

Recommendations

1. Additional investigations of landscape contamination are needed in the ecosystem context to evaluate relative concentrations of other radionuclides in the functional components. Behavior of highly radioactive, short-lived contaminants should be used to assess short-term radiological hazards more realistically.

2. Grazing animals should be included as another ecosystem component in order to describe food-chain movements and resultant body burdens of radioactivity.

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EFFECTS OF SIMULATED FALLOUT RADIATION DEPOSITS ON POLLEN VIABILITY

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Summary

Qualitative attributes of fescue grass pollen were only slightly affected by exposure to a low-level, chronic radiation regime (3-4 rads/day). Normal pollen from irradiated fescue averaged 5% less than that of controls. Aborted pollen from irradiated plants averaged 6% greater than controls, but no differences were observed in percentage of aberrant pollen.

Experimental

Manifestation of a radiation effect on fescue grass (e.g., reduced seed production) under circumstances of low-level field irradiation (21 rads/day decreasing to 6 rads/day) prompted an investigation of possible effect on fescue pollen produced under similar exposure conditions. Fescue panicles were randomly collected from eight experimental areas (four control, four irradiated) as the first anthers were beginning to dehisce and release pollen in 1971. Pollen from mature but nondehisced anthers was mounted on slides, stained, and scored for aborted and aberrant development. Slide scoring has not been completed at this writing, and available data have not been evaluated statistically, but apparent differences in fescue pollen abortion—normality were observed from the field-source irradiation when the total 3-year dose was approximately 8400 rads—delivered at rates ranging from 17 rads/day initially and decreasing to 4 rads/day three years later. Developing floral tissues in 1971 received approximately 500 rads at dose rates of 3.5 to 4 rads/day.

Average percentage of normal fescue pollen was consistently lower for the irradiated collections; average normal pollen per anther from irradiated plants was 5% less than that of control areas (Table 3). Conversely, the average percentage of aborted pollen from irradiated areas was nearly 6 units greater than that of controls. While the results have not been subjected to statistical treatment, the 5-unit difference between irradiated and control probably is statistically significant because the data are characterized by large N and small variance values. No differences were observed in percentages of aberrant pollen. Another sign of radiation effect on pollen viability was the frequency of anthers in which all pollen grains were aborted. Of 600 slides, each representing an anther, which were examined for both treatments (irradiated and control), occurrence of completely aborted

Table 3. Percentage of Normal, Aborted, and Aberrant Fescue Pollen from Irradiated and Control ^{137}Cs Experimental Areas.

Irradiated[a]				Control[a]			
Plot	Normal	Aborted	Aberrant	Plot	Normal	Aborted	Aberrant
2	87.1	11.5	1.5	4	92.8	6.3	0.9
5	79.3	20.4	0.2	6	89.9	7.5	2.6
7	84.4	11.6	4.0	8	87.5	9.4	3.1
Average	83.6	14.5	1.9	Average	89.2	8.8	2.0

[a]Data for each experimental area were based on a subsample of 20 panicles from an original sample of 60, and 10 pollen preparations per panicle. Thus, each value is an average of 200 determinations.

pollen was 10 times greater for irradiated than for control. This suggests that radiation damage to the derivative mother cell of the anther had greatest influence on anomalous pollen production as opposed to subsequent cell-damage during later stages of spore formation when only individual or small groups of pollen spores would be affected. Dose rates were low (3-4 rads/day) during anther initiation and development, but reproductive tissues of grasses are initiated from meristems at the soil surface (which also was the zone of greatest radiation flux) and may have received as much as 500 rads total dose.

This experiment demonstrated that chronic exposure to low-level radiation from particle deposits indeed can cause a radiation effect. Under normal circumstances 5% reduction in pollen viability would be a negligible consequence in situations of large-scale contamination of grass, because these plants typically produce very large amounts of pollen. Yet, there are special cases where self-pollination is common in cleistogamous plants (self-pollinating in the bud as opposed to cross pollination), and tall fescue possesses this characteristic. In this case, reproductive capacity may be diminished to a greater extent when both genomes originate from the same irradiated parent. Repeated cleistogamous reproductive events in a native irradiated population could also result in genetic damage and possibly reduced biological vigor over many generations.

Recommendations

1. First generation effects of chronic low-level, ionizing irradiation on pollen development in grain plants (barley, oats, wheat) should be investigated because these species are also cleistogamous graminaceous plants.

2. Similarly, ovule development in grain plants should be investigated in regimes of chronic, low-level irradiation exposure.

EFFECTS OF SIMULATED FALLOUT RADIATION ON REPRODUCTIVE CAPACITY OF FESCUE

R. C. Dahlman, Y. Tanaka and J. J. Beauchamp***

Summary

The effect of chronic irradiation (<17 rads/day) on the reproductive potential of tall fescue (Festuca arundinacea Shreb.) grass was investigated for a fescue community contaminated with ^{137}Cs fallout simulant (Dahlman et al. 1973). Internal daily dose rate to apical meristems from radioactivity in tissue was less than 9 rads beta and 0.3 rad gamma per day at the beginning of vegetative phenophase, with an additional measured external exposure of 12 rads/day. By the end of first-year flowering, when the internal dose rate to meristematic tissues had decreased by a factor of 10 and total dose rate ranged from 11 to 17 rads/day, seed production was reduced approximately 50% relative to controls. At the conclusion of the second season, when dose rate had decreased by 40% and radioactivity concentration in tissue had decreased by a factor of 200 to 300, seed production was 20% less than controls. The number of germinable seeds per panicle, measured by seed germination, was not significantly reduced in either reproductive period. Diminished reproductive capacity indicates that floral organ initiation and development may be significantly affected by low-intensity simulated fallout radiation.

Experimental

Reproductive response of plants in a regime of chronic, low-level, in-situ beta-gamma radiation was determined for simulated fallout contamination in the ^{137}Cs grassland facility. Observations were made on the effect of combined internal-external irradiation on seed production and germination of Ky-31 tall fescue. Dose rates to the meristematic tissue-initiation zones were both measured with thermoluminescent dosimeters and calculated from tissue radioactivity concentration and are summarized in Table 4 for midsummer periods over two years (1969 and 1970) of observation. Total exposure for selected intervals was integrated for desired time periods by assuming a linear decrease in dose rate (a plot showed slight curvilinearity with a negative slope).

Average seed production was reduced by 50% in the first reproductive period, then the field radiation regime (Fig. 5) ranged from 21 to

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Table 4. Comparison of Dose Rate ($R_\beta + R_\gamma$) to Meristematic Tissue[a] Receiving Radiation Exposure from External Fallout Field and Internal Radioactivity.

Date	Gamma and Beta Dose Rate (rads/day)		
	External Source	Internal Source[b]	Total
August 1968	12[c]	4.6	16.6
June 1969	9[d]	0.5	9.5
July 1970	6[d]	0.0	6

[a]Meristem assumed to be 1 cm above soil surface and possessed 0.5-cm-diam by 1.0-cm-long average dimensions.

[b]Dose rate calculated from formulas given by Hine and Brownwell (1956), Parmely *et al*. (1962), and Marinelli *et al*. (1948).

[c]Measured dose rate.

[d]Interpolated dose rate.

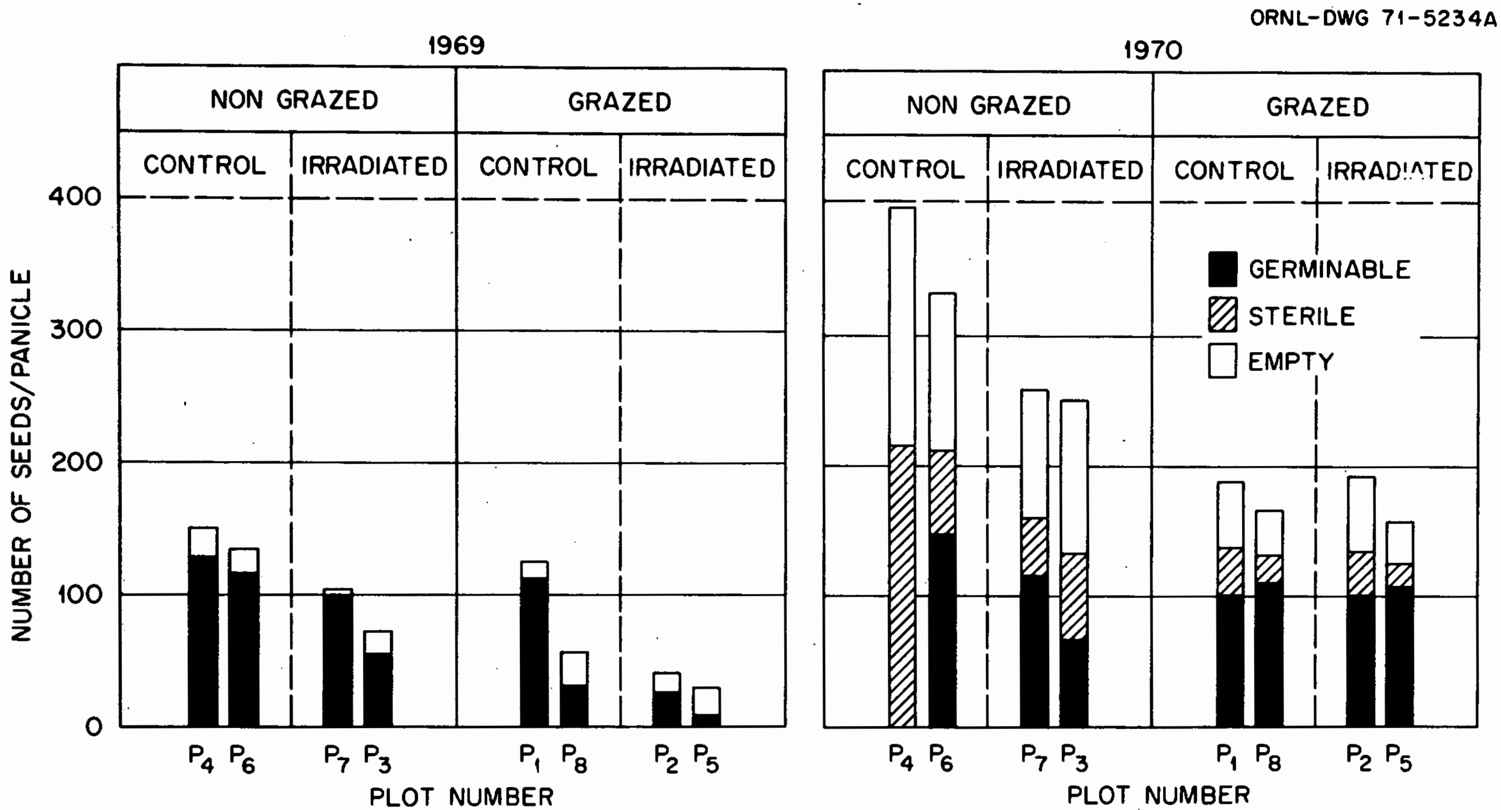

Fig. 5. Average number of germinable and nongerminable seeds per panicle in experimental plots, 1969 and 1970. Sterilized and empty seeds were lumped as one category in 1969. No seeds germinated in control P_4 in 1970.

10 rads/day. At the conclusion of the second season (1970) when dose rate had diminished by an additional 40%, seed production was 20% less than that of controls. Estimated cumulative exposure in the 3-month period prior to flowering (during the time of probable floral initiation) was 1100 and 550 rads for 1969 and 1970, respectively. Short-term cumulative dose to primordial reproductive tissue was considered more realistic and probably affected seed responses more than did total dose from long-term (1- and 2-year) exposures, because continuous turnover and replacement of plant structures (leaf, stem, tiller) characterize the growth pattern of grasses. In such a succession of tissues, each generation would receive a finite exposure and would be exposed to less than the cumulative dose. Derivative cells, however, may be affected by long-term exposures, because their genetic apparatus may persist for several cell generations. Results indicated that seed production was affected by dose rate rather than total long-term exposure to a chronic in-situ radiation source. Percentage reduction in the number of seeds per panicle was roughly twice as much in 1969 as in 1970 (50 versus 20%), and the decrease roughly corresponded to reduction in dose rate (<17 versus <9 rads/day) during periods of floral initiation.

Percentage germination of irradiated seeds was only eight units less than that of controls in 1969 (Fig. 5), but this difference was not significant according to ANOVA tests. Germination results for the 1970 collection were inconclusive because all 23,781 seeds from one control plot failed to germinate. The factor which caused this failure has not been determined, but it is not likely that complete germination inhibition is a natural phenomenon in tall fescue seed. Normal seed production was observed for collections from this plot in 1969, and the anomaly in 1970 was attributed to undefined germination conditions in the laboratory. The germination failure necessitated the use of an estimated value in the ANOVA tests, consequently there was no significant difference between irradiated and control treatments in 1970. Results for both production and germination disclosed that the latter was a less sensitive indicator of radiation effects than seed production. This can be explained by considering developmental sequences of sexual reproduction in angiosperms (including grass), where deleterious effects for each genome probably would not be transferred to subsequent reproductive events (i.e., anomalies at sporogenesis may vanish before the onset of fertilization). The anomaly would disappear from the genome and population, and it would not be detected when scoring for effects at later stages of germinule development.

Another independent experiment which involved cotton rats was in progress in the experimental plots during vernal vegetative growth, floral initiation, and panicle collection in 1969. Appreciable disturbance to vegetation by the cotton-rat grazing required special statistical treatment of the seed production and germination results. Cotton-rat grazing reduced seed production (Fig. 5) through direct but apparently subtle damage to the developing inflorescence. Relative to controls, the effect of grazing on seed production was significant in 1969 at the

5% level and in 1970 at the 1% level. The cotton rats were removed from the experimental areas in 1970, and suppression of production and germination in the second year was speculated as a carryover effect from prior grazing impacts.

Results from this study indicate that a dose rate of 9 to 17 rads/day caused detectable effects on fescue reproduction. However, the effects were demonstrable only when intensive sampling procedures and sensitive statistical analyses were employed. When compared with laboratory exposure data for approximately equivalent doses to meadow fescue (Sparrow 1971), the ORNL results indicate a factor of 10^3 reduction in the dose rates which will produce an effect on grass. This occurred when the radioactivity was intimately associated with the organism's reproductive tissue and while being affected by variable field climates. Decreased seed production of pasture or forage grass may not be a serious consequence of contamination in an actual fallout situation, because grasses are maximized for vegetative rather than seed yield. But if the same effect applies to cereal crop, and it probably would apply because wheat and corn are more radiosensitive than forage grass, then 50% reduction in grain yield could be expected if developing floral tissues were exposed to close-in nuclear fallout. Similar 50% decreases in seed production in native plant populations would greatly affect a species' reproductive capacity in terms of reduced ecesis and establishment. Resultant ecological manifestations would be lowered species success and changes in community composition, both of which would be indirect impacts attributable to sublethal deposits of fallout radiation.

Recommendations

1. Vegetative and reproductive responses of forage and edible plants should be examined for an _in-situ_ radiation source in which the decay rates and energy spectra of applied radioactivity resemble more closely the characteristics (chronic dose rates) of fallout from nuclear explosions.

2. Research should be designed to evaluate interaction effects, e.g., environmental stress or grazing versus _in-situ_ radiation.

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RESPONSES OF ARTHROPODS TO IONIZING RADIATION

C. E. Styron and Gladys J. Dodson*

Summary

Responses of arthropod communities to ionizing radiation as it interacts with other environmental parameters have been investigated in (1) short-term laboratory studies on interactions of radiation with population dynamics of selected species, (2) studies of the biological and physical dosimetry of beta and gamma radiation in a fallout area, and (3) long-term field observations on interactions of simulated radioactive fallout with seasonal changes in arthropod community composition and structure. Population dynamics of adults, juveniles, and eggs of Sinella curviseta (Collembola) were studied in the laboratory following acute doses of (^{90}Sr-^{90}Y) beta radiation or (^{60}Co) gamma radiation. Fecundity rates (eggs/adult/day) of adults were increased 48% by the lowest dose (1880 rads) of beta radiation, but fertility rates were reduced by radiation at all other doses. Gamma radiation was more effective than beta in reducing fertility rates. Juveniles were more sensitive than adults to both types of radiation, and day-old eggs were the most sensitive stage studied. Data on chronic exposure of Folsomia (Collembola) to beta radiation from ^{90}Sr-^{90}Y fallout indicate that sensitivity of the population is determined primarily by sensitivity of fertility rates rather than by sensitivity of adults. Beta dose rates estimated to give an $LDR_{50-30\ days}$ (dose rate estimated to kill 50% of the population in 30 days) or $LDR_{50-60\ days}$ (dose rate estimated to kill 50% of the population in 60 days) for adults are more than twice as high as dose rates required to reduce fertility rates to zero. Lithium fluoride microdosimeters attached to the thorax and abdomen of insects in a fallout field indicated that closely related organisms may receive significantly different radiation doses ($P \leq 0.01$) due to differences in habitat.

There was no significant difference in variation between numbers of soil-, litter-, and grass-inhabiting arthropods collected in field enclosures before application of fallout in summer 1968. Significant differences ($P \leq 0.05$) in variation between control and contaminated communities appeared in summer 1970 ($P \leq 0.05$), disappeared in autumn 1970, and reappeared in summer 1971 ($P \leq 0.01$). Thus population densities for 15 of 75 arthropod taxa had been affected from 1969 to summer 1971 in the radioactive area, but only eight populations were significantly smaller ($P \leq 0.05$). Recovery was noted for two of these eight in summer 1971. No significant increase in taxa composition dissimilarity between the contaminated and control areas has been absorbed. Consequently, the threshold for effects of fallout radiation on taxa composition of the arthropod community must be above the 2.4 to 13.0 rads/day delivered over 3 years.

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Introduction

Early assessments of radiation effects at the ecosystem and biome levels consisted of extrapolations from laboratory studies on single organisms or populations. Acute doses of gamma radiation were used to establish relative sensitivities of different species. Little information was gained on effects of chronic irradiation on population parameters (e.g., fecundity and longevity) due to inherent difficulties in this type of experiment. Beta radiation effects received even less attention for lack of a satisfactory system for measuring dose.

This project was initiated to assess effects of beta and gamma radiation from simulated radioactive fallout on an old-field arthropod community. Three types of studies have been conducted: (1) short-term, intensive laboratory studies on interactions of beta and gamma radiation with population dynamics of selected species, (2) biological and physical dosimetry in a fallout area, and (3) long-term, extensive field observations on interactions of fallout simulant with seasonal changes in arthropod community composition and structure. This paper covers the first three years of observations on the arthropod community.

Effects of Acute Beta and Gamma Radiation on a Population of Springtails, *Sinella curviseta* (Collembola)*

Collembola play an important role in breakdown of organic material in the biological cycle of soil formation, and numerically they are usually second only to mites in the air-breathing fauna of soil. Information on interactions of beta and gamma radiation with population dynamics of such small, rapidly reproducing soil arthropods is of interest in predicting ecosystem responses to radiation from nuclear fallout. The objective of this study was to assess effects of acute doses of beta and gamma radiation on survival and reproductive ability of a Collembola population in culture.

Sensitivity of adult *Sinella curviseta* to gamma radiation is similar to that reported by Edwards (1969) for other species of Collembola when survival of irradiated individuals is the observed endpoint. Juveniles and eggs were more sensitive than adults to gamma as well as beta irradiation. The greatest fluctuations in population numbers during these experiments resulted not from death of irradiated individuals, but from changes in fecundity rates and egg mortality. Fecundity rates of irradiated adults increased by 48% during the first month following 1880 rads of beta radiation, and egg mortality increased by only 16%. In the field such an effect of increased fecundity could cause great increases in the population density of Collembola and shift

*Extracted from Styron 1971.

predator-prey balances. This is an area in which we have very little information. At other doses of radiation, fecundity rates were reduced and egg mortality was increased. Although adults receiving $\geq$4950 rads of gamma radiation laid eggs, 90-100% of the eggs died, and none of the juveniles reached maturity.

The eggs of Sinella are a critical stage in the response of a laboratory population to ionizing radiation. Their sensitivity is evident whether the parents or the eggs themselves are irradiated. It seems reasonable to assume that this is true for other populations of Collembola. The ecological significance of high egg sensitivity to a Collembola population may be masked, however, by seasonal cycles in reproduction. Population maxima are reached by different species in every season. If adults of a species are not in or are not just entering a reproductive phase when irradiated, sensitivity of eggs may not be an important factor in population survival. To another population, a dose insufficient to kill adults could collapse the population by reducing fecundity rates and increasing egg mortality. This selective elimination of Collembola species could, in the context of an entire ecosystem, upset interspecific interactions. Implications of this research are that sublethal doses of beta or gamma radiation can seriously affect the survival and reproductive abilities of Collembola populations, thereby curtailing their contributions to nutrient cycling.

Effects of Chronic Beta Radiation from Fallout on a Population of Springtails, Folsomia sp. (Collembola)*

In a natural situation, organisms are more likely to be exposed chronically to contaminating materials. The objective of this study was to assess effects of chronic doses of beta radiation from ^{90}Sr-^{90}Y simulated fallout on the survival and reproductive ability of a Collembola population in culture.

Survival and reproductive ability of these Collembola were reduced at all 19 beta radiation dose rates tested. The $LDR_{50-30\ days}$ (dose rate estimated to kill 50% of the population in 30 days) for chronically irradiated adults was estimated by least-squares regression analysis to be 174.5 rads/hr (total dose in 30 days of 125.5 krads) and the $LDR_{50-60\ days}$ was estimated to be 38.1 rads/hr (total dose in 60 days of 54.9 krads). The effects of chronic beta radiation on fecundity rates (Fig. 6) could not have been anticipated from studies (Styron 1971, O'Neill and Styron 1970) on the effects of acute irradiation alone. After each acute dose of ionizing radiation, fecundity rate of each population was sharply changed, but rates for Sinella curviseta frequently returned to control levels after one month. Under chronic irradiation conditions, however, all fecundity rates for Folsomia were initially

*Extracted from Styron and Dodson 1971, Styron in press.

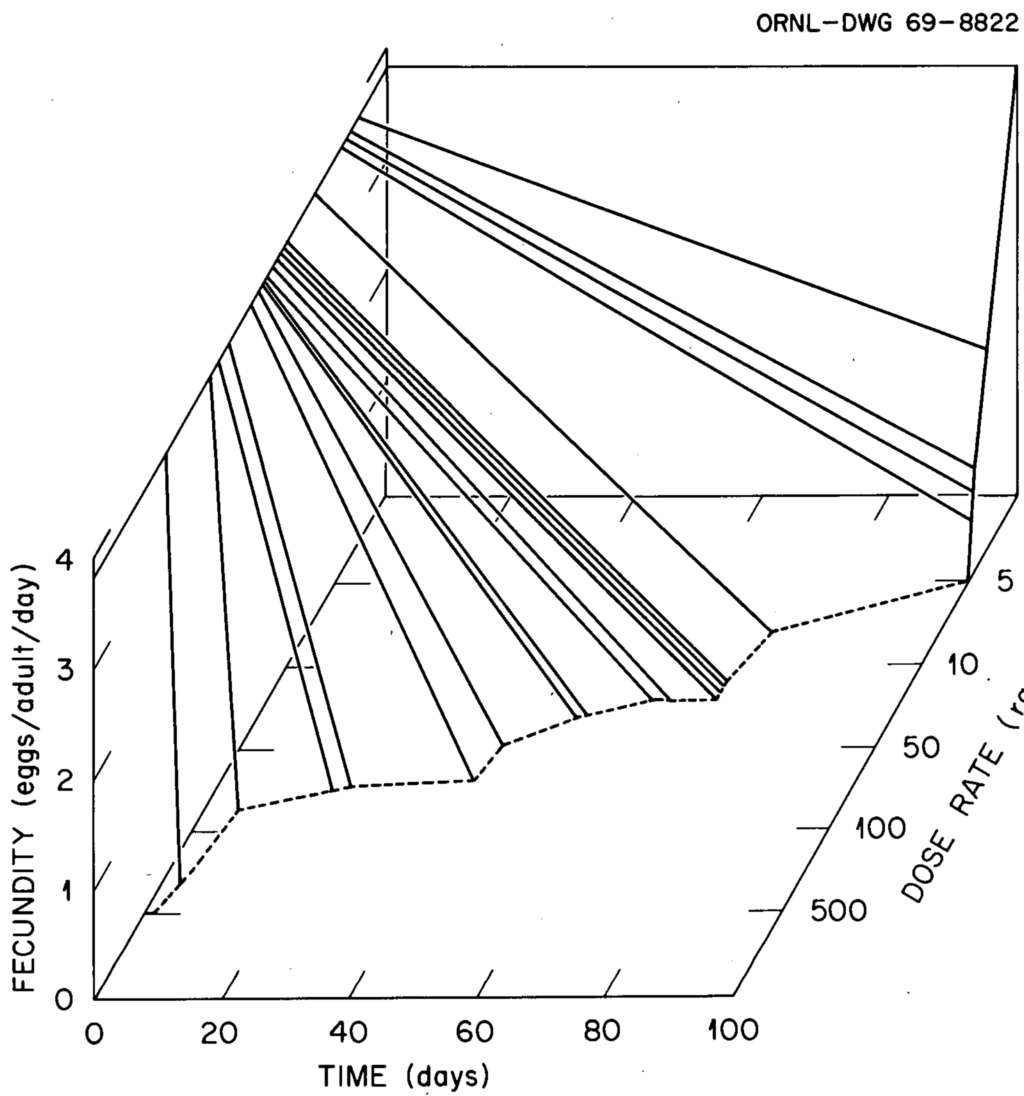

Fig. 6. Isometric projection of fecundity in eggs per adult per day on time in days and ^{90}Sr-^{90}Y beta-radiation dose rate for <u>Folsomia</u> sp. for continuous exposure at the indicated dose rates. The fecundity rates for each dose rate are presented as a regression on time since the fecundity of each population changed as the total doses of radiation were accumulated.

at control levels, but dose rates were reduced through time as doses were accumulated. Changes in fecundity rates under chronic irradiation conditions should therefore be represented as the slope of a regression line rather than as a point. At dose rates greater than 5 rads/hr, fecundity rates rapidly approached zero. Egg mortality (Fig. 7) was increased by chronic dose rates above 13.5 rads/hr, and no eggs hatched at dose rates above 17.4 rads/hr. At 14.5 rads/hr, 38% of the eggs matured to adults, but all were sterile.

These data again illustrate that radiosensitivity of a population of Collembola to beta radiation is manifest primarily in the effect on fertility rates (number of eggs surviving) rather than on mortality rates of adults. Dose rates estimated to give an $LDR_{50-30\ days}$ or $LDR_{50-60\ days}$ for adults are more than twice as high as dose rates required to reduce fertility to zero. As pointed out in the study on Sinella, if a natural population of Collembola were subjected to acute irradiation during a cycle of low reproductive activity, recovery could occur before the population entered its period of maximum reproductive activity. The ecological significance of the sensitivity of fertility rates to acute irradiation could thus be masked by seasonal cycles in reproduction. In contrast, research on Folsomia indicates that effects of chronic beta radiation would not be masked by seasonal cycles in reproductive activity, since recovery could not occur.

Effects of Simulated Radioactive Fallout on an Old Field Arthropod Community*

Studies reported above have illustrated the importance of beta and gamma radiation in population dynamics of small arthropods in culture. Impact of radiation on arthropods in the context of a natural system has been observed during the past 3 years at a unique experimental facility at Oak Ridge National Laboratory. A managed grassland ecosystem was selected for the initial experimental system, since grasslands cover large areas of this country and are extremely important as pastures for grazing animals.

The field site, experimental design, and application of fallout simulant have been extensively described by Auerbach (1969), Dahlman and Auerbach (1968), Dahlman et al. (1969), Lane (1967), Styron and Dodson (1971), and Styron and Dodson (in press).

Soil, litter, and grass components of the arthropod community received significantly different beta- and gamma-radiation doses due to changes in vertical distribution of fallout simulant and to the short range of ^{137}Cs beta particles. Results of a radiation profile in the middle of the contaminated enclosure 8 weeks after final application of fallout

*Extracted from Styron and Dodson 1971, Styron and Dodson in press.

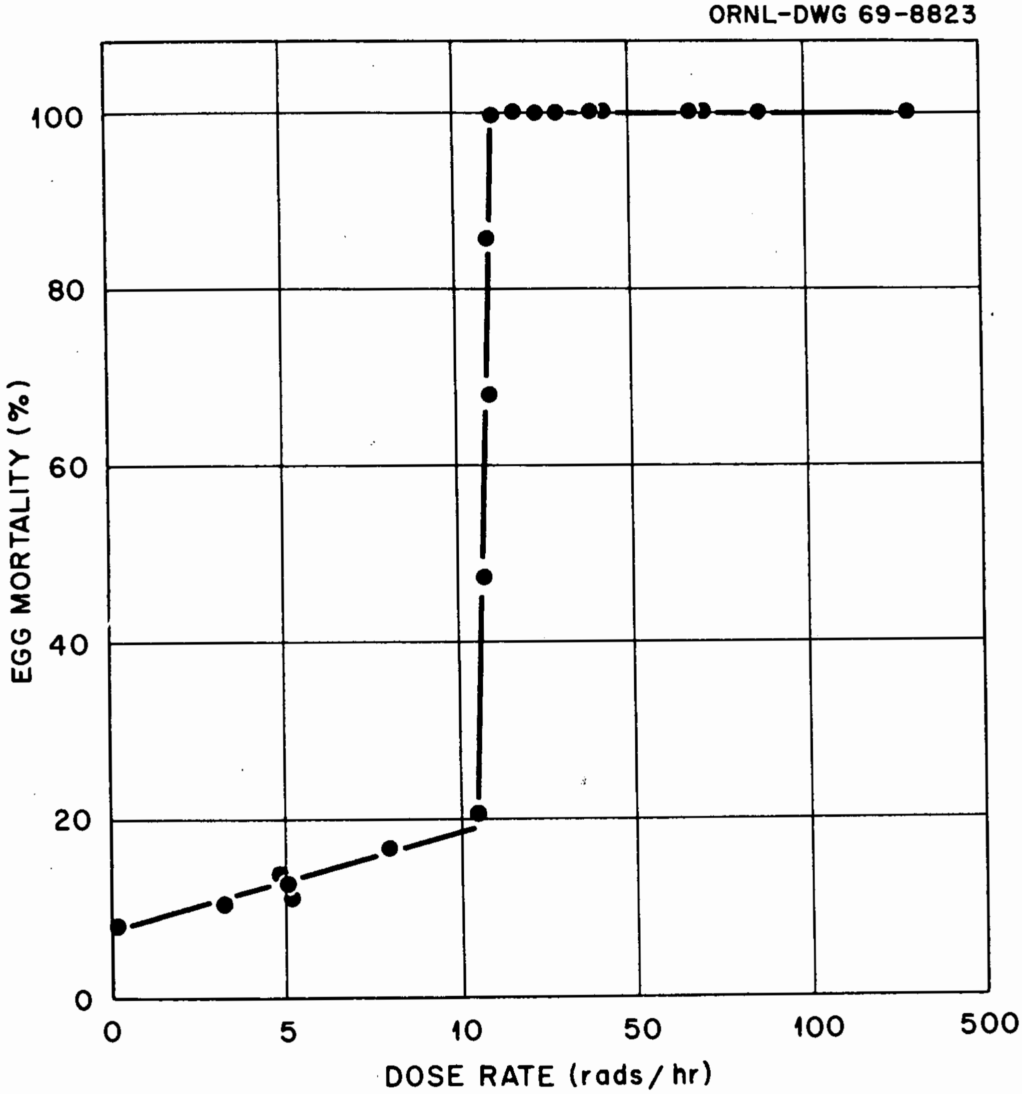

Fig. 7. Egg mortality plotted against ^{90}Sr-^{90}Y beta-radiation dose rate for Folsomia sp. for continuous exposure at the indicated dose rates. The point at 0 rads/hr represents the mean of 10 control populations.

simulant are shown in Fig. 8. These data have been used to estimate radiation doses to soil, litter, and grass components of the arthropod community (Table 5) to facilitate comparisons of radiation doses with biological responses.

Microdosimeters placed in and on fescue grass 8 weeks after the final application of simulant (Fig. 8) showed that most of the intercepted simulant had been removed from leaf surfaces but that some remained trapped in leaf axils. Beta plus gamma dose rates in axils ranged from 0.9 to 1.1 rads/hr. By combining biological and physical approaches to radiation dosimetry, differences between dose rates to crickets (thorax 0.22, abdomen 0.31 rads/hr) and grasshoppers (thorax 0.09, abdomen 0.10 rads/hr) have been observed that might not have been predicted from either models or from physical dosimetry alone. Grasshoppers and crickets are closely related taxonomically, but they occupy different microhabitats. Crickets dwell primarily on and in litter, where, in this instance, they were exposed to more beta radiation; grasshoppers dwell higher on blades of grass. Thus any attempt to predict ecological responses to radiation based on different radiation sensitivities of species should also deal with the problem of differential radiation exposure and niche occupation.

Biological data in the form of numbers of individuals of each of 75 arthropod taxa collected during 41 sampling periods were subjected to a sequential three-way analysis of variance to detect significant changes in structure of the community. Variation among sites, taxa, and sampling dates was first calculated using seven sampling dates (April 1 to June 25, 1968) before application of fallout simulant. An F test indicated significant differences among dates ($P \leq 0.01$) and taxa ($P \leq 0.01$) but not between control and contaminated pens of either pen and the roped area. Differences among sampling dates would be expected because of seasonal variations of the arthropod community, and differences among taxa would be expected because the taxa normally occur in varying population densities. Since the three field sites originally possessed comparable arthropod taxa compositions, subsequent differences in community structure cannot be attributed to pretreatment variabilities. Analysis of all 41 sampling dates (April 1, 1968, to August 17, 1971) confirmed the differences among dates ($P \leq 0.01$) and taxa ($P \leq 0.01$). When sampling dates were sequentially deleted from the beginning and towards the end of the study and the analysis of variance repeated after each deletion, a seasonally cyclic pattern of variance between all sites emerged. Comparisons of site variance by F test indicated greatest variance for summer samples, least for winter samples. During the winter fewer taxa are active, and the inactive taxa would not contribute to community variance. A larger number of active taxa during the summer leads to a greater possible variance between communities. Variance between the control and contaminated communities was greater--but not statistically significant--during the first summer (1969) than before fallout application. By August 8, 1969, the soil component of the arthropod community had received 1760

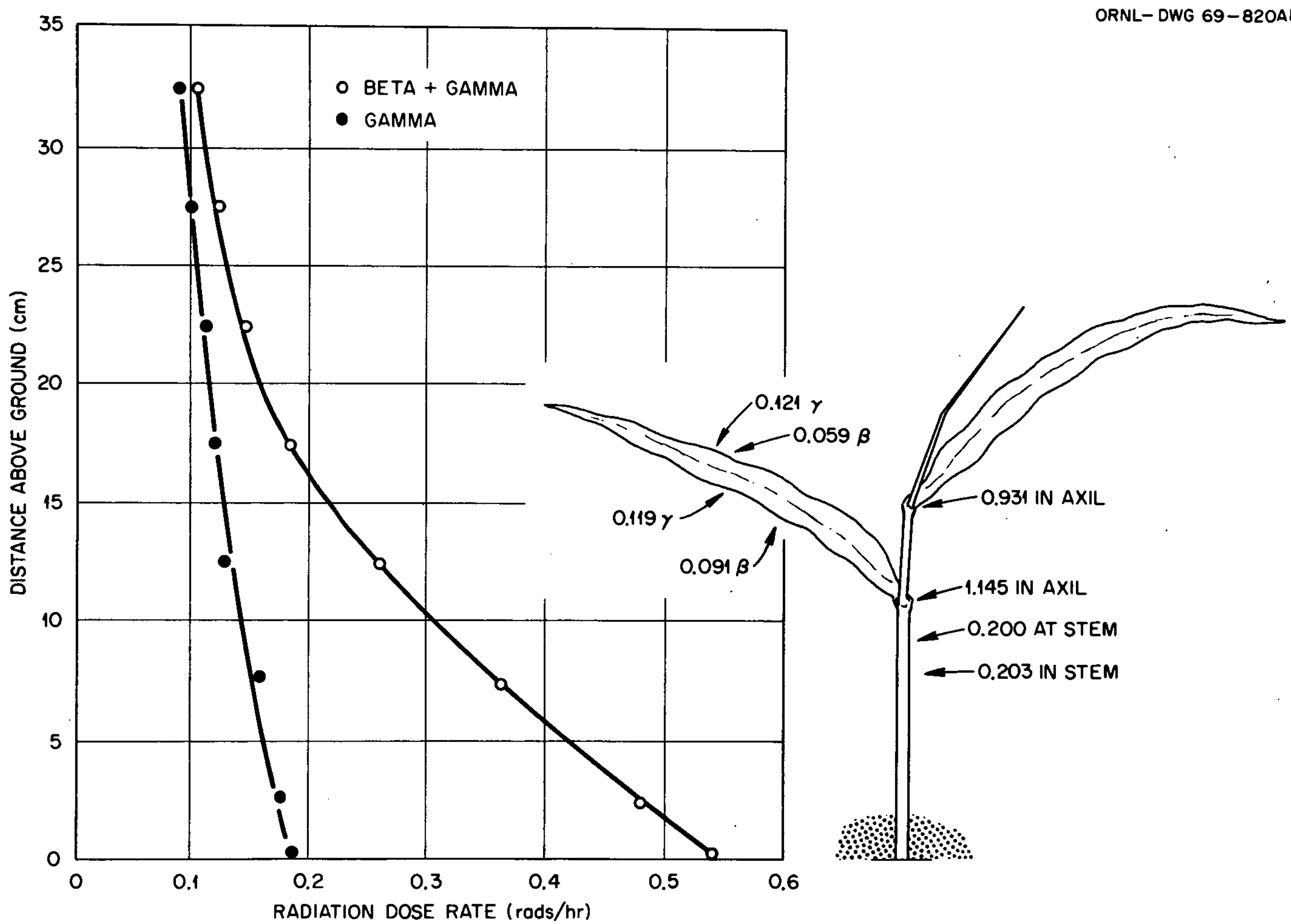

Fig. 8. Distance aboveground plotted against gamma and beta + gamma dose rates 11 weeks after the first application and 8 weeks after the second application. The profile was prepared for the middle of the contaminated enclosure at the 0800 Ecology Research Area. The distance between the two dose-rate lines represents the beta radiation dose. Beta, gamma, and the combined dose rates observed for a fescue plant are also presented.

Table 5. Radiation Doses from Simulated Radioactive Fallout to Three Components of the Managed Grassland Arthropod Community.[a]

Year	Sampling Date	Time after Simulant Application Weeks[b]	Dose[c] to Arthropod Compartments[d] (rads) Soil Surface	Litter	Grass
1968	Aug. 20	2.0	338 (137)	407 (129)	77 (60) to 300 (120)
	Sept. 10	4.9	601 (229)	645 (201)	131 (104) to 481 (195)
	Sept. 24	6.9	782 (229)	810 (257)	168 (134) to 605 (247)
	Oct. 30	12.0	1245 (456)	1230 (400)	262 (211) to 922 (370)
	Dec. 10	18.0	1776 (649)	1687 (572)	375 (303) to 1244 (527)
1969	Feb. 12	27.1	2566 (943)	2363 (834)	545 (444) to 1721 (765)
	Mar. 6	30.4	2862 (1049)	2620 (929)	607 (494) to 1902 (851)
	Mar. 27	33.4	3132 (1145)	2853 (1014)	664 (540) to 2067 (929)
	Apr. 30	38.1	3551 (1296)	3215 (1149)	752 (612) to 2323 (1052)
	May 6	39.0	3633 (1324)	3286 (1174)	769 (626) to 2373 (1075)
	July 1	46.9	4323 (1579)	3879 (1402)	917 (748) to 2791 (1282)
	July 15	48.9	4504 (1643)	4036 (1459)	954 (778) to 2902 (1334)
	Aug. 8	52.4	4743 (1757)	4223 (1562)	1018 (836) to 3035 (1424)
	Oct. 9	61.3	5329 (2036)	4678 (1814)	1172 (979) to 3364 (1647)
	Oct. 24	63.4	5474 (2105)	4791 (1877)	1210 (1014) to 3445 (1702)
	Nov. 26	68.1	5792 (2258)	5039 (2015)	1294 (1092) to 3622 (1823)
	Dec. 17	71.1	6998 (2356)	5199 (2104)	1349 (1141) to 3737 (1901)
1970	Feb. 11	79.1	6528 (2608)	5611 (2332)	1488 (1271) to 4034 (2102)
	Mar. 18	84.1	6866 (2770)	5875 (2478)	1577 (1353) to 4223 (2230)
	Apr. 7	87.0	7065 (2865)	6030 (2564)	1630 (1401) to 4334 (2306)
	June 10	95.5	7627 (3132)	6466 (2806)	1778 (1538) to 4649 (2519)
	July 1	98.0	7798 (3214)	6600 (2880)	1823 (1580) to 4745 (2584)
	July 17	100.0	7936 (3280)	6708 (2940)	1860 (1613) to 4821 (2636)
	Aug. 6	104.0	8124 (3365)	6850 (3017)	1912 (1668) to 4939 (2710)
	Sept. 16	108.0	8312 (3450)	6991 (3094)	1964 (1723) to 5057 (2783)
	Nov. 4	114.5	8612 (3588)	7218 (3219)	2051 (1814) to 5246 (2902)

Table 5 (Continued)

Year	Sampling Date	Time after Simulant Application Weeks[b]	Dose[c] to Arthropod Compartments[d] (rads) Soil Surface	Litter	Grass
1970	Nov. 25	117.5	8754 (3651)	7324 (3277)	2089 (1854) to 5335 (2956)
	Feb. 25	130.5	9331 (3926)	7759 (3528)	2275 (2048) to 5700 (3195)
	Mar. 17	133.5	9473 (3989)	7866 (3586)	2313 (2088) to 5789 (3250)
	Apr. 14	137.5	9661 (4074)	8007 (3663)	2365 (2143) to 5907 (3323)
	June 2	144.5	9983 (4222)	8250 (3798)	2459 (2242) to 6110 (3451)
	June 15	146.5	10079 (4265)	8322 (3836)	2485 (2269) to 6170 (3488)
	July 13	150.5	10267 (4350)	8464 (3913)	2537 (2323) to 6288 (3561)
	Aug. 17	154.5	10455 (4434)	8605 (3990)	2589 (2378) to 6406 (3634)

[a] No radiation dose was detected during seven sampling periods from April 1 to June 25, 1968, prior to fallout simulant application.

[b] Date of final application of fallout simulant was August 5, 1968.

[c] Doses are presented as beta + gamma (gamma).

[d] Soil component is at 0.0 cm above ground; litter component is at 0.1 to 2.5 cm; and grass component is at 2.6 to 32.5 cm.

rads gamma and 2990 rads beta radiation (Table 2); the litter component, 1560 rads gamma and 2660 rads beta; and the grass component, 836 to 1420 rads gamma and 182 to 1610 rads beta. Variance between control and contaminated communities did reach a level of statistically significant difference ($P \leq 0.05$) during the second summer (1970) when accumulated doses had nearly doubled. This variance declined in the ensuing autumn and winter, but reappeared during the third summer (1971) ($P \leq 0.01$).

Calculation of an index of taxa composition dissimilarity (Orloci 1963, Sokal and Sneath 1963, Sokal 1966, Grieg-Smith 1964) for each sampling date and site pair combination has verified the seasonal cycle in community composition (Fig. 6). The number of individuals in each arthropod taxon collected from a site on each sampling period was transformed and used to calculate in Euclidean hyperspace the taxa composition distance, d, between each pair of sites (control versus roped area, control versus contaminated, and roped area versus contaminated). The lower the value of d, the greater the similarity is between communities of the respective sites, and the higher the value of d, the lesser the similarity is between communities. This technique is relatively sensitive for detecting changes in community composition and is of great value for summarizing large amounts of data (Woodwell 1965). Results of the analysis (Fig. 9) showed no significant or consistent change in similarity between community of the contaminated enclosure either the control or roped area during the first summer (1969). When values of dissimilarity between these communities are plotted against time, seasonal cycles become evident.

Minima of dissimilarity for all combinations of communities were reached during winter months, and maxima occurred in the summer. During winter fewer taxa are active, and inactive taxa would not contribute to an index of dissimilarity. A large number of taxa during the summer leads to a greater possible dissimilarity between sites. The peaks of dissimilarity between control and contaminated communities in the summers of 1969 were followed closely by the control versus roped area. In the second (1970) and third (1971) summers, however, the control versus contaminated and the roped area versus contaminated were generally above the control versus roped area.

Because of differential radiation sensitivities and modes of exposure from mixed beta and gamma radiation, community responses were relatively small in comparison with what might have been predicted from laboratory studies (Styron 1969, O'Neill and Styron 1970, Styron 1971). By August 17 of the third summer the soil component of the arthropod community had received 10,400 rads (Table 2) of beta plus gamma radiation (4430 rads of gamma); the litter component, 8600 rads of beta plus gamma (3990 rads of gamma); and the grass component 2590 to 6400 rads of beta plus gamma (2380 to 3630 rads of gamma). If any of these doses were administered in an acute mode to the community, major ecological effects would be predicted (Styron 1971).

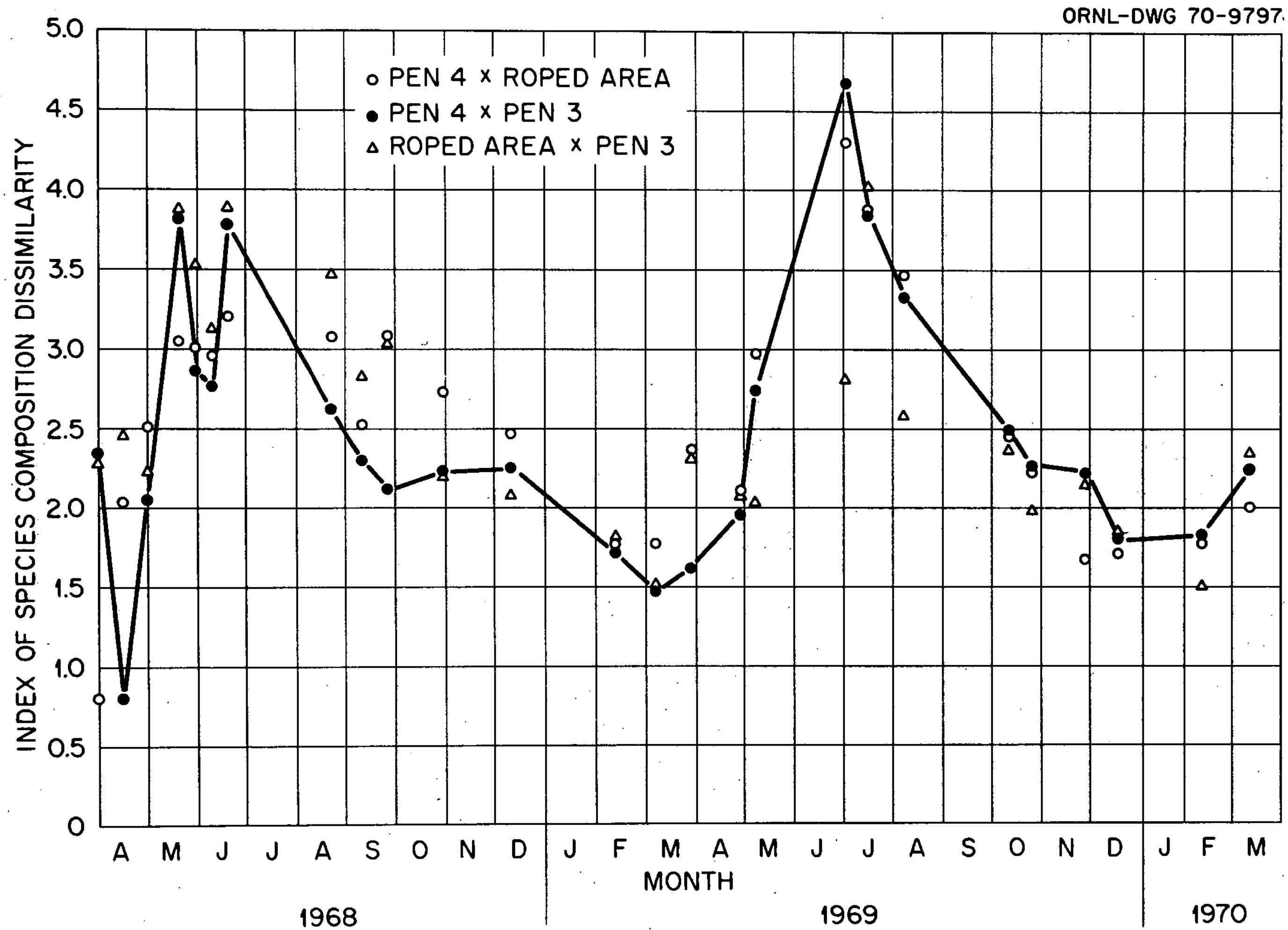

Fig. 9. Index of taxa composition dissimilarity for the control versus the roped area (O), for the control enclosure versus the contaminated enclosure (O), and for the roped area versus the contaminated enclosure (Δ) plotted against each sampling date. The effects of changes in taxa composition in the enclosures is superimposed on a seasonal cycle with minima of taxa composition dissimilarity in winter and maxima in summer. Natural variation in these systems obscures effects of fallout simulant. Dissimilarity was greatest for the control versus contaminated enclosure during summer 1969, 1970, and 1971. This possible trend will be checked in future observations.

Analyses of community responses in this study revealed no permanent change in community structure. The multiple analysis of variance test and the analysis of taxa composition dissimilarity between communities pointed to differences only during the second and third summers of exposure. The transient diffence between control and contaminated communities occurred during summer periods of maximum reproduction and growth when the greatest number of factors must be coordinated for survival. Natural fluctuations in community dynamics obscured radiation effects. Thus the threshold for effects of mixed beta and gamma radiation from fallout at the community level must be above the 2.4 to 13.0 rads/day delivered over 3 years. A likely explanation for this degree of radiation effect in a field situation lies in homeostatic mechanisms that enable the community to respond to radiation stress in the same manner as to other environmental stresses (Platt 1965). One population might functionally replace another, and at the community level there would appear to be no effect. It is also conceivable that in the context of an entire ecosystem, any given population may exhibit threshold responses to radiation stress.

With the above supposition in mind, further analyses were directed toward describing responses of individual populations. In comparison with populations in the control enclosure, 15 arthropod taxa in the contaminated area had evidenced reductions in seasonal population density maxima by summer 1971. Only eight of these cases were statistically significant ($P \leq 0.05$). In 1969, population density declined for Thomisihomisidae ($P > 0.10$) and Lycosidae ($P > 0.10$)--neither significant. In 1970, population density decreased for *Entomobrya* sp. ($P > 0.05$), *Entomobrya griseolivata* ($P > 0.05$), *Kolla bifida* ($P \leq 0.05$), Carabidae ($P \leq 0.01$), Phalacridae ($P \leq 0.05$), Simuliidae ($P \leq 0.05$), Drosophilidae ($P > 0.10$), Agromyzidae ($P > 0.10$) Formicidae ($P > 0.10$), Thomisiade ($P > 0.10$), and Lycosidae ($P \leq 0.10$)--four significant. In 1971, population density declined for Poduridae ($P \leq 0.05$), *Entomobrya griseolivata* ($P \leq 0.05$), Sminthuridae ($P \leq 0.05$), *Kolla bifida* ($P \leq 0.05$), Aphididae ($P \leq 0.01$), Carabidae ($P \leq 0.05$), Drosophilidae ($P > 0.10$), Agromyzidae ($P > 0.10$), Trombiculidae ($P \leq 0.05$), and Lycosidae ($P \leq 0.10$)--six significant. Also in 1971 *Entomobrya* sp., Phalacridae, Simuliidae, Formicidae, and Thomisidae recovered to control levels. Of the five taxa showing recovery, only Phalacridae and Simuliidae had been significantly affected in the preceding years. The eight taxa that showed significant reductions in population density are all small insects (<10 mm in length). Five of these taxa are closely associated with soil and litter at some stage in their life cycle.

Recommendations for Future Research

1. Continued monitoring of the experimental site should produce a clearer understanding of relationships between affected populations and the community as a whole, and their interaction with beta and gamma radiation. Another advantage of the study would be the possibility of considering genetic as well as

somatic effects of radiation. The far-reaching, but more subtle, genetic responses of populations are among the most difficult parameters to extrapolate from short-term laboratory or field studies. Further, the experimental design incorporates a controlled environmental situation. Direct comparisons are possible between the contaminated and uncontaminated communities, for the enclosures have been treated in precisely the same manner except for application of fallout simulant. Long-term analysis of data will give a better understanding of redistribution of fallout in a contaminated grassland, responses of the arthropod community to the intrinsic beta and gamma radiation, as well as fundamental ecological responses of a grassland arthropod community.

2. Studies on the effects of fallout on arthropod communities of other types of ecosystems (croplands, forests, deserts, and marshes) should be undertaken to provide comparisons of responses to low dose rates in different ecosystems.

3. Results of these studies should be compared with effects predicted by postattack mathematical models, and the models should be refined. Sensitivity of these models to biological data needs to be improved. It cannot be stated too strongly that models which are insensitive to biological parameters cannot predict events accurately.

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RADIONUCLIDE ACCUMULATION AND RADIATION EFFECTS IN SMALL MAMMALS

P. B. Dunaway, J. T. Kitchings, J. D. Story, L. E. Tucker, and D. DiGregorio

SUMMARY

Mammal populations inhabiting an area contaminated by fallout from a nuclear explosion will receive both external and internal doses of radiation. The internal dose will result primarily from ingestion of fallout particles and contaminated food. Laboratory and field experiments were designed to measure: (1) irradiation dose, (2) radiation effects, and (3) radionuclide cycling in free-ranging mammals.

Whole-body retention and excretion of ^{134}Cs after a single ingestion of simulated fallout material were determined for cotton rats. The average biological half-life was 2.75 days. Concomitant studies using ^{134}Cs-tagged lettuce as a contaminated food source enabled us to: (1) determine uptake rates and equilibrium levels of ^{134}Cs in the cotton rat under chronic ingestion conditions and (2) determine retention curves for ^{134}Cs following termination of chronic feeding. Uptake curves were multicomponent and equilibrium was reached after 544 hr (22.7 days). Retention curves were characterized by two components. The biological half-life for the first component (liver, intestinal tract, etc.) averaged 5.70 days, while the second component (muscle, etc.) had a half-life of 8.20 days.

In 1968, field studies were initiated on the movement of ^{137}Cs in cotton rats that had been placed in areas contaminated with fallout simulant. Cotton rat whole-body burdens of ^{137}Cs initially were influenced by the amounts of fallout simulant and contaminated dead vegetation which were available for ingestion, but as time progressed and the amount of radioactivity in living vegetation approached that of the dead vegetation, a constant body burden was reached. Predator-prey transfer was also considered, based on the equilibrium body burden for cotton rats in the field. Factors influencing the trophic-level transfer of radionuclides are also examined.

Losses of injected ^{54}Mn from nonirradiated pine voles and ^{60}Co from irradiated voles in natural populations were more rapid than from comparable specimens of the species in the laboratory. Most of this difference occurred during the first two weeks postinjection. Consequently, irradiation doses were less in free-ranging than in captive animals.

Average gamma dose rates from both external and internal sources in cotton rats decreased from 3.84 rads/day in February 1969 to 2.35 rads/day in November 1969. Initial decrease in dose rate was due to

changing profile of the radiation fields in pens as the fallout simulant descended through the vegetation to the ground. Most of the fallout simulant has now reached ground level, forming an irregular plane source and resulting in a relatively stable dose rate of approximately 2.46 rads/day at height of 1 m. No effects of the ^{137}Cs radiation on either body weight or peripheral blood of cotton rats was apparent.

White-footed mice were trapped during the first of each month from June 1969 to May 1971, given 1050 rads, and caged in the outside environment. Mortality was relatively low from May through September (42.5 to 55.0%), high during November and December (90.0%), and ranged from 59 to 72.5% during the remaining months. Mean survival time declined from a high of 8.3 days in June to a low of 5.29 in November. Results demonstrated that some factor or factors interacting with radiation were more important than temperature alone as determinants of mortality and survival times.

A preliminary effort was undertaken to test (1) feasibility of analyzing radiation effects in a wild pine vole population by means of injecting trace amounts of radioisotopes into females and then whole-body counting the young from these females to ascertain the reproductive success in the two groups, and (2) irradiation effects in adults. After an acute dose of 700 rads, total number of recaptures for irradiated females (33) in the population was significantly less (<0.01) than total recaptures of nonirradiated females (65), but recaptures of irradiated males (35) were not significantly different from recaptures of nonirradiated males (40). The significantly fewer recaptures of irradiated female pine voles may not have been a reflection of irradiated death *per se*, but a loss of territory during radiation sickness. Pelage graying in irradiated voles caused no discernible increase in predation rate. Effects of irradiation on reproduction could not be ascertained because only two radioactive young appeared in the population.

Introduction

Consequences to biota from environmental contamination following a nuclear explosion should be considered from three aspects. First, absorption of radionuclides from ingestion of fallout particles *per se* and ingestion of contaminated foods should be measured. In our laboratory, ^{134}Cs-tagged particles were administered orally to measure absorption of cesium by the gastrointestinal (GI) tract. Concomitant chronic-feeding in the laboratory utilizing ^{134}Cs-tagged lettuce to simulate contaminated vegetation identified some of the events which could be expected during chronic exposure in the field. Field studies then described influences of environmental factors on radionuclide turnover. Second, irradiation doses actually delivered to organisms must be measured, because estimates of dose from radiation fields often are seriously erroneous. We utilized microdosimeters in cotton rats to measure gamma-irradiation doses and assayed tissues for estimations of internal beta dose. Third, effects that result from exposure to internal and external doses of radiation should be identified. Our field investigations have provided information on seasonal responses to acute irradiation and on the response of free-ranging populations to radiation insult.

Laboratory studies dealing with the effects of relatively high-level acute and chronic irradiation on both laboratory and wild animals are abundant. (Bond *et al*. 1965, Betz 1965, and Dunaway *et al*. 1969b) However, reviews of the literature (Auerbach *et al*. 1971a, Templeton *et al*. 1970, Auerbach *et al*. 1971b) relating to radiation effects on organisms have shown that very few studies have been conducted on the effects of chronic low-level radiation (from ingested radioactive material) on terrestrial populations. Accumulation and excretion of radiocesium also have been studied extensively under laboratory conditions (Hood and Comer 1953, LeRoy *et al*. 1963, Hakonsor and Whicker 1968, and Kitchings *et al*. 1969), and cycling studies have demonstrated that wild mammals readily accumulate radiocesium (Jenkins *et al*. 1969, Plummer *et al*. 1969, and Kaye and Dunaway 1963). Experiments demonstrating the movement of radiocesium in the food chain generally have shown an increasing ^{137}Cs concentration at the secondary consumer levels in the food chain (Jenkins *et al*. 1969, Hanson *et al*. 1964, and Pendleton *et al*. 1965). Although considerable information is available on irradiation effects at various doses for many organisms, virtually no information is available for measured irradiation doses to mobile organisms as they move through radioactive environments.

RADIONUCLIDE METABOLISM

The availability of radionuclides from ingested fallout particles to vertebrates is determined by (1) solubility rates of the nuclides from the particulate matter in the GI tracts, (2) transit time of the fallout particles through the GI tract, and (3) absorbability of the nuclides by the GI tracts.

Radiocesium Behavior in Cotton Rats in the Laboratory

Cesium-134 tagged simulants with varying *in-vitro* nuclide solubilities were analyzed with respect to ^{134}Cs solubilities in GI tracts and absorbabilities by GI tracts of cotton rats (*Sigmodon hispidus*) in laboratory studies. Determinations of whole-body retention and excretory patterns were used to discern variations in ^{134}Cs metabolism caused by solubility differences. Transit times of the particles through GI tracts were determined because the particles constitute internal point sources as long as they are present. Our data suggested that generally in-vivo leaching of ^{134}Cs from simulant was greater than the in-vitro leaching. LeRoy et al. (1963) also reported that more leaching occurred in the intestinal tract of man than in vitro. There also was a hint in our study of an increasing elimination of the absorbed ^{134}Cs with a decrease in solubility, but the evidence was inconclusive and a greater solubility gradient is needed to resolve this question. The average biological half-life of assimilated ^{134}Cs for the three groups of simulant tested was 2.75 days.

After fallout particles reach the soil or litter layer, the body burden of radioactive materials in small mammals normally is the result of chronic absorption of the nuclide from contaminated foods. Thus, chronic administration of an isotope in the laboratory was more likely to simulate uptake under field conditions a few weeks or longer after fallout cessation. A preliminary experiment was designed to: (1) determine uptake rates and equilibrium levels of ^{134}Cs in the cotton rat under chronic ingestion conditions, and (2) develop retention curves for ^{134}Cs following termination of chronic ingestion. Lettuce tagged with ^{134}Cs was used to simulate vegetative material contaminated by leachate containing the radioisotope. Lettuce tagged with ^{134}Cs was given daily in doses of 0.06 μCi to groups of laboratory-born and wild-trapped cotton rats for 4 weeks. Whole-body and excreta counts were made at various intervals over a 712-hr time span. After 712 hr, administration of the isotope was stopped and measurements of excretion of cesium were begun. Serial sacrifices were made during both the accumulation phase and excretion phase of the experiment and eight tissues were analyzed for ^{134}Cs.

The ^{134}Cs uptake curve for both the laboratory and wild animals groups appeared to be a multicomponent curve. The first component occurred from about hour 16 to hour 208. Uptake equations for each group were as follows (first component):

wild trapped: $Y = 0.7727 \cdot 10^{-2}\ X^{0.5614}$

lab born: $Y = 0.7746 \cdot 10^{-2}\ X^{0.5354}$

The second component began at about the 208th hr and ran to the 544th hr:

wild trapped: $Y = 0.4039 \cdot 10^{-2}\ X^{0.3448}$

lab born: $Y = 0.4327 \cdot 10^{-2}\ X^{0.3278}$

After the 544th hr (22.7 days) the rate increase approached was zero.

Subsequent field studies in the contaminated enclosures also indicated that equilibrium levels of radiocesium would be reached within a 30-day period. In March 1970, cotton rats were trapped 7 and 10 days after placing them in the contaminated pens; whole body burden was 0.3620 and 0.3579 μCi, respectively. These values were not significantly different from 0.3790 μCi determined on day 30. By 30 days, the cotton rats had essentially reached ^{137}Cs equilibrium, and any gain or loss would be negligible for an additional 30 days.

Retention curves, using the equilibrium level as 100% absorbed dose, were described with components. The first component (day 1 through 7), considered to be mainly representative of systems such as the liver and intestinal tract, gave retention equations and biological half-lives (T_b) of:

lab born: $Y = 92.8\ e^{-0.1332\ X}$, $T_b = 5.20$ days

wild trapped: $Y = 100.8\ e^{-0.1116\ X}$, $T_b = 6.21$ days

The second component (days 8 through 35) is, of course, reflective of the longer retention compartments, such as muscle, and is represented by:

lab born: $Y = 61.7\ e^{-0.0853\ X}$, $T_b = 8.12$ days

wild trapped: $Y = 79.0\ e^{-0.0827\ X}$, $T_b = 8.38$ days

The type of ingestion, acute (simulant) versus chronic (vegetation) may have influenced the metabolic kinetics of ^{134}Cs in cotton rats under laboratory conditions. However, since the short time interval (5.8 days) over which reliable measurements could be made for the simulant coincides with the time required for the fast component to clear in the chronic study, the λ_b and T_b reported for the simulant cesium may be appropriate for organs such as the liver and intestine in which retention time is short.

Radiocesium Behavior in Cotton Rats in the Field

Field studies in enclosures were designed to follow the movement of ^{137}Cs as it related to the position of the simulated fallout and to determine the primary source of ^{137}Cs in cotton rats, whether from ingested particulate matter or vegetation. Cesium content in four components (whole body, total tissue, organic matter, and fallout simulant) increased from December 1968 to February 1969. After the February analysis the amount of ^{137}Cs in the samples began to decrease

(Fig. 10). The initial rise in cotton rat whole-body ^{137}Cs was influenced by the relative proportions of living and dead vegetation in their diet. As living vegetation decreased during winter, rats foraged closer to the ground; thus, their diet consisted of increasing amounts of dead vegetation. Radioactivity was considerably greater in dead vegetation than in living vegetation (Dahlman et al. 1969), and therefore as the fallout simulant descended to ground level, its availability for ingestion coupled with the cotton rat's increased intake of dead vegetation helps explain the midwinter increase in whole-body ^{137}Cs. As time progressed, however, radioactivity of living and dead vegetation approached each other, resulting in a relatively constant body burden in cotton rats. Curves of these measurements parallel that of the dosimetry and again reflect movement of fallout simulant toward the ground (Fig. 11).

Figure 12 shows relative amounts of ^{137}Cs in each of five compartments: internal organs, GI tissue, GI contents (organic matter and fallout simulant), pelt (skin and hair), and residual carcass. The percentages include both 30- and 60-day samples over the entire experimental period because no significant increase or decrease from 30 to 60 days was noted. Cesium-137 in the cotton rats was contained mostly in the residual carcass (Fig. 12). Pelt, which includes skin and hair, accounted for 8.9% of the whole-body radioactivity. Most of the pelt, in terms of weight, is muscle. Because of muscle specificity for ^{137}Cs (Hamilton 1947, and Kereiakes et al. 1961) and amount of muscle in the mammalian body, it is apparent that most of the total body ^{137}Cs was contained in muscle. The average ^{137}Cs in the GI tract contents was 27% of the whole-body burden. Of the total amount of radioactivity in the GI contents, 79% was in organic matter and 20.9% was in fallout simulant. In the early part of the experiment, the radioactivity contributed by fallout simulant was approximately 10 times that of the last sample period. Weathering caused leaching of ^{137}Cs from the fallout simulant into the soil and subsequently onto the plants. With increasing time, vegetation radioactivity will reflect radioactivity levels in the soil; therefore, future body burdens of herbivores and saprovores living in contaminated areas will reflect ^{137}Cs levels in living and dead vegetation, respectively.

Turnover of ^{54}Mn and ^{60}Co in a Population of Pine Voles

The role of environmental factors in influencing the rate of radionuclide elimination in a population of pine voles (*Microtus pinetorum*) was investigated using ^{54}Mn and ^{60}Co. Pine voles were selected for study because populations of this species were at relatively high, stable densities in comparisons with populations of most species of small mammals at the time. Manganese-54 and ^{60}Co were selected because these elements are important radioecologically and physiologically (Wangersky 1963 and Lowman 1963), yet little is known of their behavior in free-ranging mammal populations. Laboratory studies were conducted to serve as a "control" so that the influence of environmental

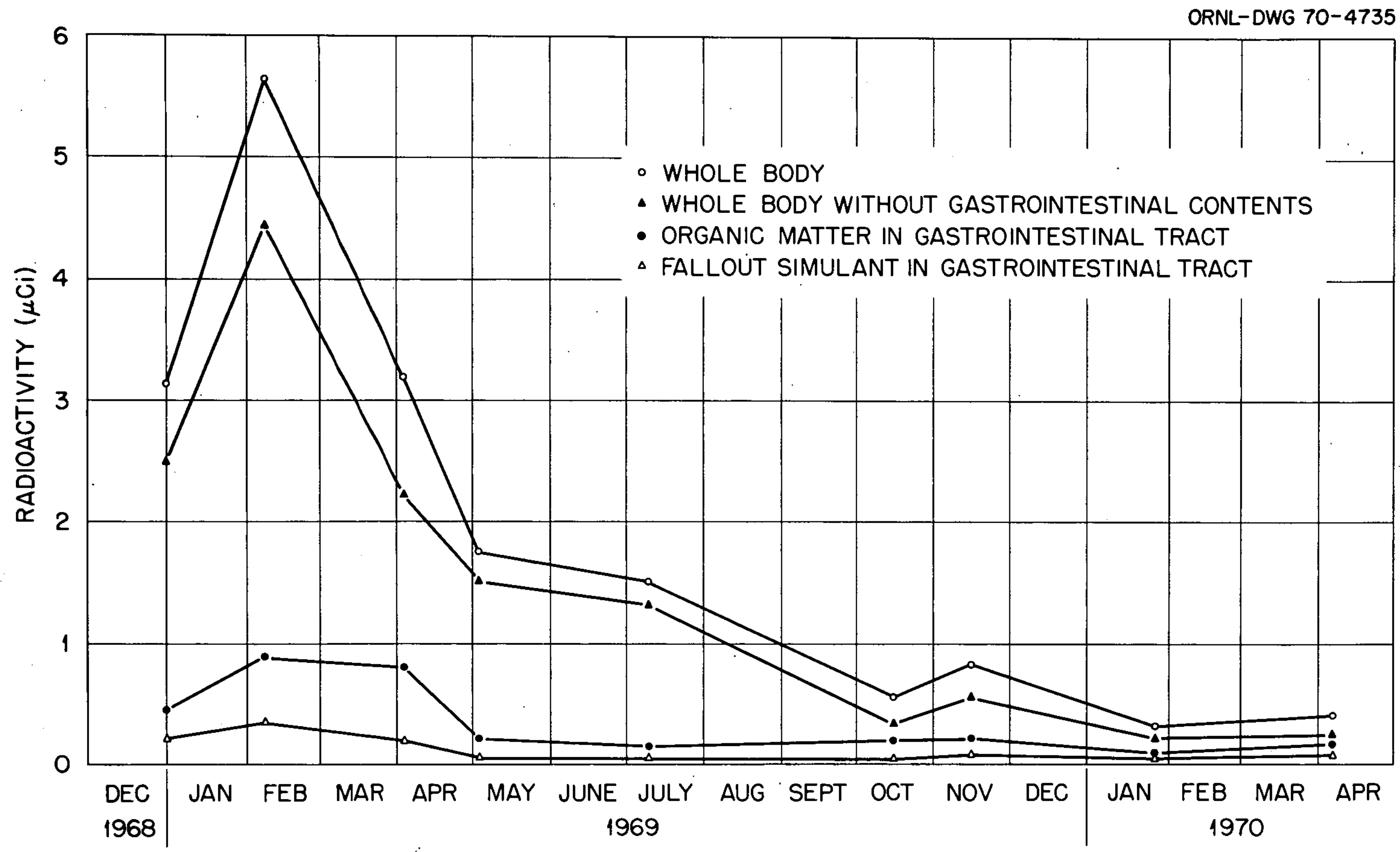

Fig. 10. Total radioactivity (μCi) in cotton rats after chronic ingestion of ^{137}Cs-contaminated fallout simulant and vegetation for 30 or 60 days.

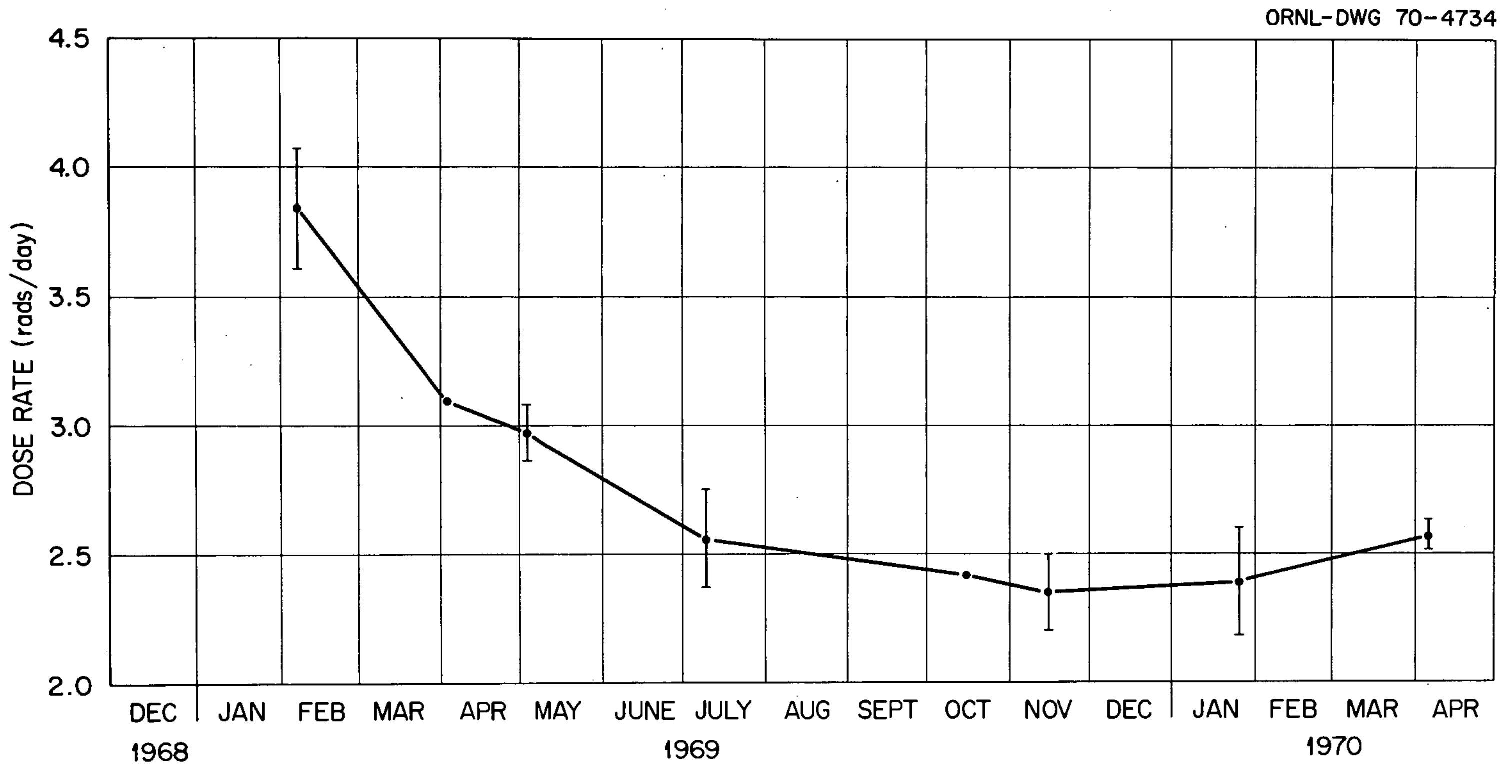

Fig. 11. Gamma dose rate to cotton rats living in ^{137}Cs-contaminated enclosures from February 1969 to April 1970. Means of dorsal and ventral dosimeters are represented by O. Vertical lines represent standard error of the mean, and absence of vertical lines denotes standard error too small to plot.

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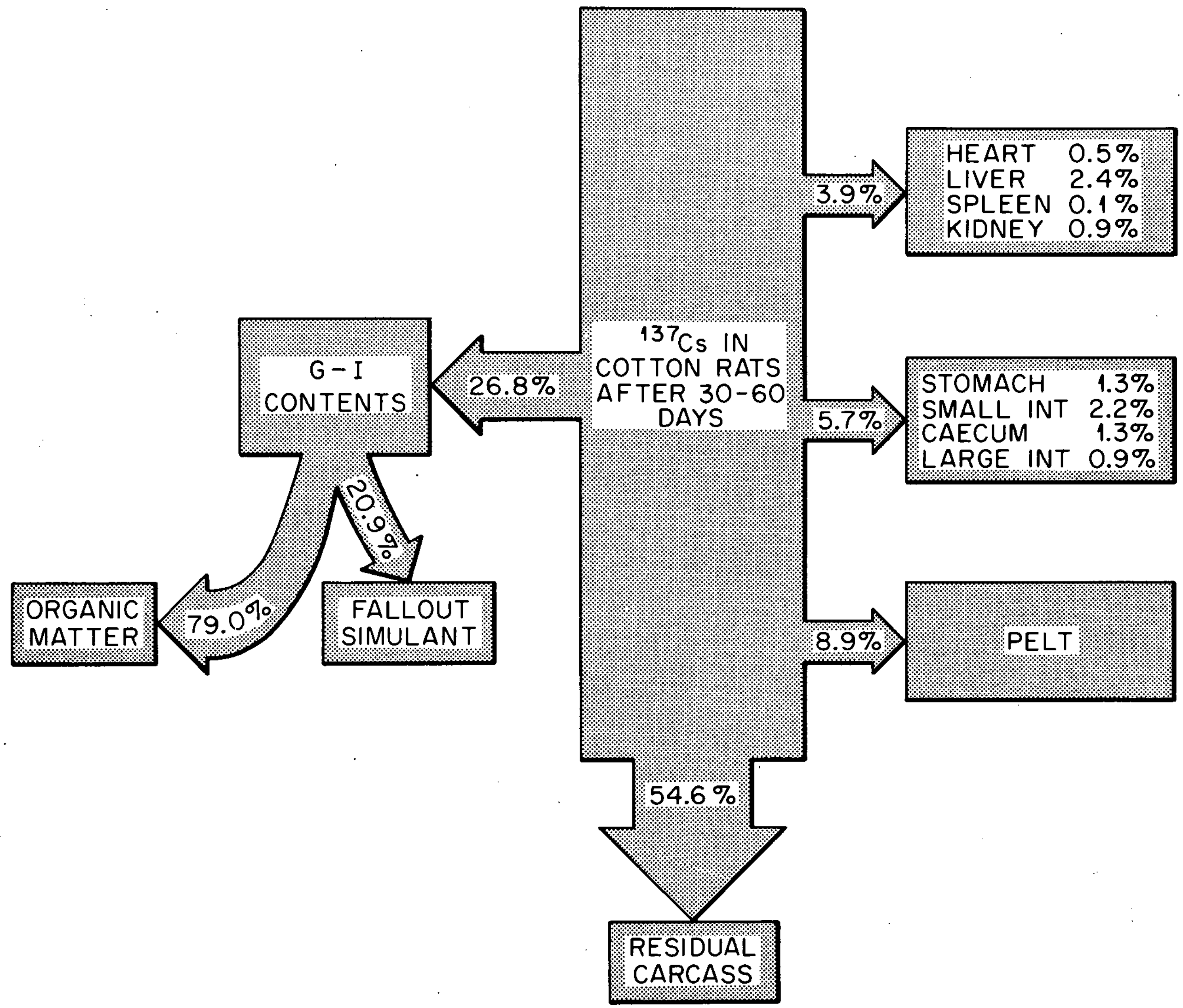

Fig. 12. Percent of radioactivity in various components of cotton rats after 30-60 days chronic ingestion of ^{137}Cs-contaminated fallout simulant and vegetation.

factors might be assessed. Only females received radioisotopes (to ascertain maternal parentage); those receiving ^{54}Mn were not irradiated and those receiving ^{60}Co were given 700 rads.

The most striking result of the radioisotope measurements was the more rapid loss of ^{54}Mn and ^{60}Co from the pine voles in the field population than from the voles held in the laboratory (Figs. 13 and 14). Most of this difference occurred by day 14 for ^{54}Mn and day 21 for ^{60}Co, and thereafter the loss rates are not significantly different. It is possible that greater activity by the voles in the field was responsible for the more rapid loss of ^{54}Mn and ^{60}Co. Chew (1971) showed that exercised Peromyscus polionotus excreted ^{65}Zn faster than nonexercised old-field mice. Mathies (1972) showed that losses of ^{60}Co and ^{137}Cs from white-footed mice were slower from body burdens acquired chronically than acutely, and we found a similar phenomenon for the cotton rats in the previously discussed experiment. Differing diets of the laboratory and field voles also may have affected radionuclide excretion. French (1967) discussed possible effects of type or form of vegetation on element uptake, but his discussion was oriented toward ingested elements. One explicit assumption has been that radionuclide excretion depends in large part on metabolic rate. Earlier studies were unsuccessful in quantitatively correlating the long component of excretion with metabolism (Wangersky 1963, Orr 1967, and Baker and Dunaway 1969). In retrospect, it seems logical that the early components of radionuclide excretion curves should reflect metabolic rates better than the long components because, ipso facto, the tissues and organs most active in releasing elements during early excretion, in general, are those which are most active metabolically in excreting unincorporated materials. Whatever the reasons for the more rapid excretion of ^{54}Mn and ^{60}Co from the free-ranging pine voles, an obvious consequence is reduction in internal irradiation dose.

If ^{137}Cs enters the diet primarily through material deposited on vegetation, internal dose will be proportional to retention of the fallout. If, however, the isotope is incorporated predominately through the root systems of plants, the dose will be proportional to the total amount of isotope in the soil, assuming root uptake as a function of radionuclide pool size in soil. Regardless of the mechanism of incorporation of radioisotope, one of the major consequences of fall-out is the creation of a contaminated food source which subsequently circulates through food chains. Contamination transfer in the eco-system will not cease at the vegetation-cotton rat link in the food chain. Trophic level increase ratios for the predator-prey relationships were found to be 2.0 for the gray fox and cotton rat and 6.9 for the bobcat/cotton rat relationship (Jenkins 1969). Since the same predator-prey relationships of gray fox-cotton rat and bobcat-cotton rat presumably exist in and around Oak Ridge, contamination levels can be predicted for the gray fox and bobcat. In February 1969, when radioactivity in cotton rats was highest (0.04 $\mu Ci/g$), radioactivity in gray fox and bobcats would have been about 0.08 and 0.28 $\mu Ci/g$, respectively. In November 1969 when cotton rat radioactivity was lowest (0.007 $\mu Ci/g$),

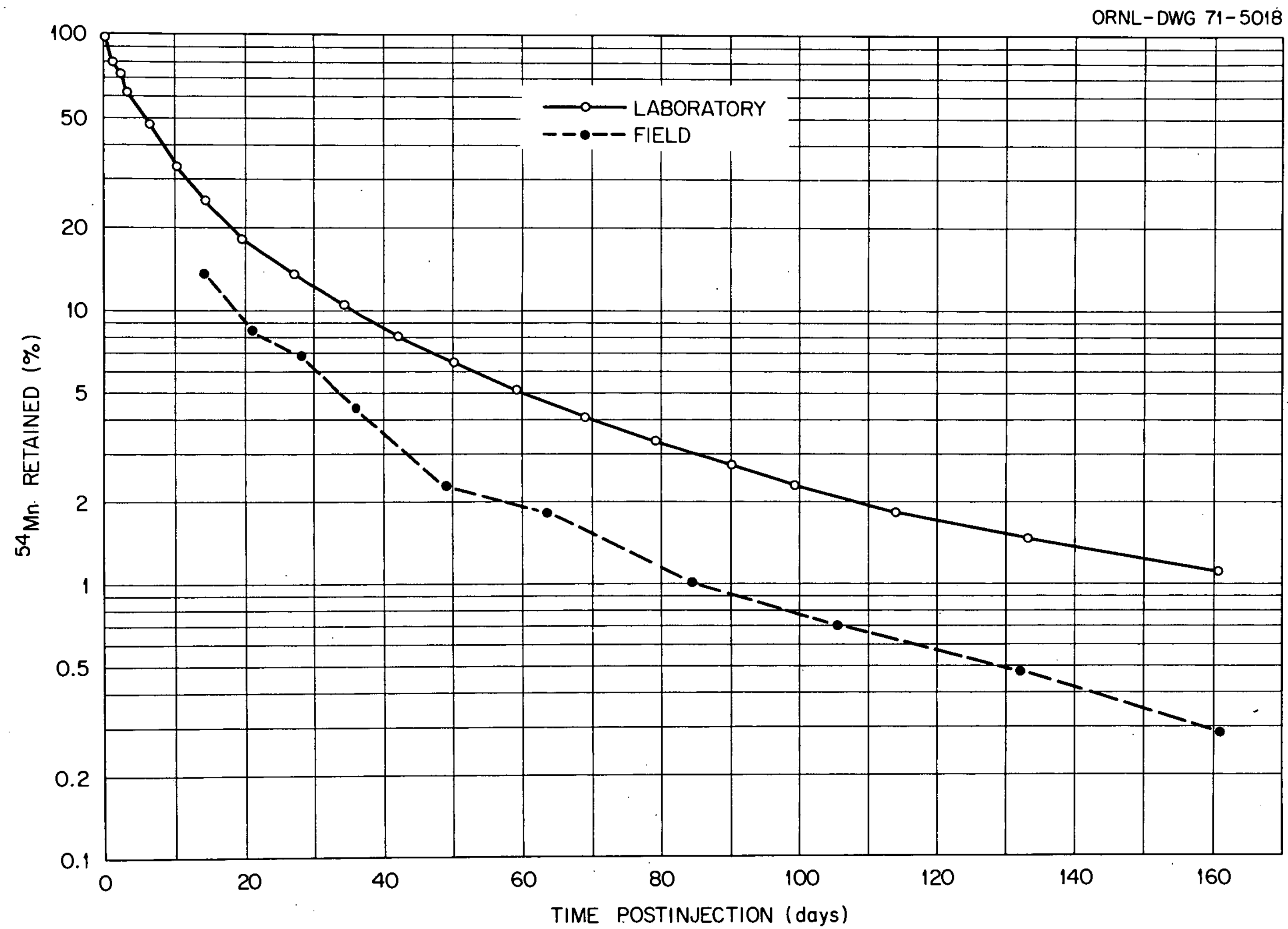

Fig. 13. Retention of ^{54}Mn by field and laboratory populations of <u>Microtus</u> <u>pinetorum</u>.

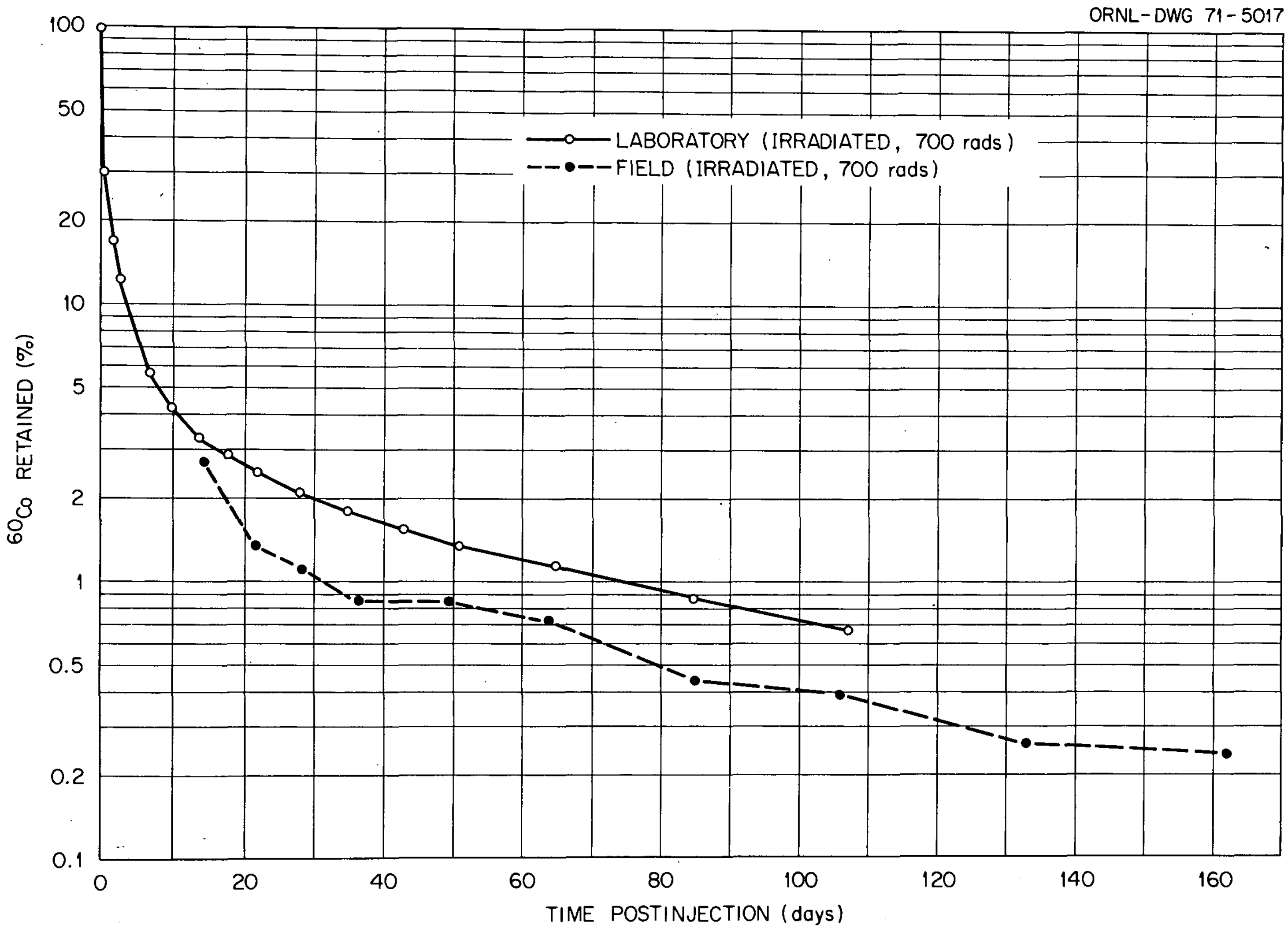

Fig. 14. Retention of ^{60}Co by field and laboratory populations of <u>Microtus pinetorum</u>.

radioactivity in gray foxes and bobcats would have been about 0.014 and 0.048 μCi/g, respectively. During November 1969, a 5000-g gray fox could accumulate 70 μCi, while a bobcat weighing 7000 g could accumulate 336 μCi.

Differing levels of radiocesium uptake in the tissues mean that food-chain transfers to predators from small prey species such as cotton rats should differ according to feeding habits of the predators. Preliminary results of a study conducted in the summer of 1970 indicate that trophic-level magnification of ^{137}Cs may indeed depend upon the feeding habits of the particular secondary consumer. Cesium-137 and ^{60}Co-tagged white pine seeds were used as the base food supply in studying the transfer of the isotope from the food base to the primary consumer (white-footed mouse - *Peromyscus leucopus*) to a secondary consumer (short-tail shrew - *Blarina brevicauda*). Based on the whole-body equilibrium concentration (μCi/g), the concentration factor for ^{137}Cs movement from *Peromyscus* to *Blarina* was 0.76. Additional data analysis may show that, when the concentration factor calculation is based on the levels of ^{137}Cs in the tissues most often eaten by the shrews, an increase in ^{137}Cs from one trophic level to another does occur.

Radiation Effects

Radionuclides in fallout debris enter vertebrate populations primarily by ingestion and inhalation of the particles and by ingestion of foods contaminated with nuclides leached or weathered from the particles. Incorporation and accumulation of these radionuclides by mammals depends on ingestion of the nuclides, absorption of the nuclides within the gastrointestinal tract, and finally the physiological importance of the nuclides. Internal radiation doses to vertebrates from fallout thus result from two pathways of exposure. First, ingested radioactive particles essentially are point sources of irradiation while in the gastrointestinal tract. Second, radionuclides leached from fallout particles or from contaminated vegetation may be incorporated into tissues. The effect of internal and external radiation from the simulant was measured in the contamination pens. External gamma irradiation contributed the major portion of the dose to the whole-body. Internal beta irradiation contributed more to both the whole-body and GI tract total dose rate than did internal gamma because of the more complete absorption of the beta energy.

Average gamma dose rates from both external and internal sources in cotton rats ranged from 3.84 rads/day in February 1969 to 2.35 rads/day in November 1969 (Fig. 11). Regression analysis showed that from February to July dose rates decreased by 0.008 rad/day per day, but from July 1969 to April 1970 there was no significant change. The initial decrease in dose rate was due to changing geometry of the radiation fields in pens as the fallout simulant descended through the vegetation to the ground. Most of the fallout simulant has now reached ground level, forming an irregular plane source and resulting in a relatively stable dose rate of approximately 2.46 rads/day. No effects of the ^{137}Cs radiation on either body weight or peripheral blood of cotton rats was apparent (Table 6). Any slight changes in body weight or general blood measurements probably resulted from seasonal variations in the general environment, since similar measurements were obtained for both control and experimental animals. For cotton rats, general environmental fluctuations may be of more immediate consequences than low-level irradiation. Consequently, it is likely that a relatively large number of rats living for many months or a few years on the areas would be required to detect effects of irradiation at the low dose rates present. Such an experiment was not possible with the facilities available. Previous studies with cotton rats showed that relatively high acute doses of radiation were required to affect body weight (Dunaway _et al_. 1969b) and blood (Kitchings _et al_. 1970). In January 1970, the experimental animals were exposed to several days of 0°F temperatures and precipitation. After 30 days, only 3 of 8 experimental and 2 of 8 control animals were recovered alive. Similar mortality in free-ranging cotton rats during cold weather has been reported (Dunaway and Kaye 1961).

The problem of predicting consequences to free-ranging mammal populations exposed to environmental contamination, whether by radioactive fallout or other chemical pollutants should be approached from two viewpoints. Consideration must be given to the immediate lethal effects, such as the level of external radiation received by the organism from the initial encounter with the source material. If wild species' responses to acute doses of radiation vary significantly during the course of a year, then knowledge of the environmental factors responsible is necessary for prediction of radiation-induced consequences in natural populations.

Seasonal Changes in Radiation Effects on White-Footed Mice

White-footed mice were trapped during the first of each month from June 1969 to May 1971, given 1050 rads, and caged in the outside environment. The dose of 1050 rads was the LD_{50-30} for the mice in the laboratory (Dunaway _et al_. 1969b). Cotton bedding (10 g) was provided for each mouse and food (Purina Lab Chow) and water were provided _ad libitum_.

Mortality was relatively low from May through September (42.5 to 55.0%), high during November and December (90.0%), and ranged from 59 to 72.5% during the remaining months. Mean survival time declined from a high of 8.3 days in June to a low of 5.3 days in November. Mean survival time of _P. leucopus_ in the laboratory at this dose was 8.2 days. It was anticipated that the caged animals would be exposed to lower average temperatures in winter than those experienced by free-ranging

Table 6. Hematological Values of Cotton Rats in Control Enclosures and in ^{137}Cs Fallout Simulant Contaminated Enclosures

Enclosure Treatment	Sample Number	Sex	Day Sampled	Wgt.	RBC	HGB	HCT	MCB	WBC
Control	8	M	0	114.2 ± 9.5	7.3 ± 0.1	17.1 ± 0.3	46.5 ± 0.8	64.0 ± 0.7	5.3 ± 0.4
Control	4	M	30	96.9 ± 5.9	6.7 ± 0.1	15.1 ± 0.2	39.8 ± 1.2	59.8 ± 2.6	2.9 ± 1.1
Control	4	M	60	117.4 ± 2.2	6.5 ± 0.3	14.8 ± 0.1	38.5 ± 1.3	59.0 ± 1.5	4.7 ± 0.9
Contaminated	8	M	0	114.5 ± 7.0	7.1 ± 0.3	16.6 ± 0.7	46.0 ± 1.9	65.0 ± 0.5	7.6 ± 1.8
Contaminated	6	M	30	108.4 ± 7.6	6.5 ± 0.3	14.8 ± 0.4	40.0 ± 1.9	61.7 ± 1.0	2.6 ± 0.3
Contaminated	4	M	60	108.7 ± 2.2	6.6 ± 0.3	16.0 ± 0.9	37.9 ± 1.2	57.5 ± 1.9	4.3 ± 0.3
Control	8	F	0	115.0 ± 7.0	7.4 ± 0.1	16.4 ± 0.3	46.9 ± 0.4	63.0 ± 0.4	7.3 ± 0.7
Control	7	F	30	115.4 ± 6.8	6.4 ± 0.2	15.1 ± 0.6	40.5 ± 1.5	63.9 ± 0.6	3.5 ± 0.4
Control	3	F	60	133.7 ± 9.2	7.2 ± 0.1	16.7 ± 1.1	41.2 ± 0.6	57.0 ± 1.5	3.0 ± 0.9
Contaminated	8	F	0	118.1 ± 8.1	7.9 ± 0.2	17.2 ± 0.5	48.1 ± 0.9	61.0 ± 0.8	6.6 ± 1.3
Contaminated	6	F	30	116.1 ± 5.8	7.3 ± 0.2	15.8 ± 0.5	43.2 ± 1.0	59.5 ± 1.3	2.8 ± 0.3
Contaminated	5	F	60	132.8 ± 4.9	7.7 ± 0.2	17.0 ± 0.6	44.6 ± 1.1	58.0 ± 2.4	3.6 ± 0.7

mice, which had access to well-insulated burrows and nests and which could huddle in groups to conserve heat. It was expected that the highest mortality and shortest survival time would occur in winter (Newson and Kimeldorf 1961). Instead, such results as highest mortality and shortest survival time in November and December indicate that some factor or factors were more important than temperature alone as determinants of mortality and survival times. Environmental conditions and/or endogenous factors certainly acted synergistically with radiation during most of the year because mortality was usually greater and survival time shorter than for this species in the laboratory.

As a companion to the previously mentioned ^{54}Mn and ^{60}Co metabolism study in a wild pine vole population, a preliminary effort was undertaken to test (1) radiation effects in adult voles and (2) feasibility of analyzing radiation effects on reproductive success by injecting trace amounts of radioisotopes into females and then whole-body counting the young from these females. One group was irradiated and injected with ^{60}Co while the other group, which was not irradiated, was injected with ^{54}Mn. The males were grouped similarly, with one group being irradiated and the other receiving no radiation; however, no males were injected with radioisotopes.

Fewer irradiated than unirradiated male voles were caught during the first two trapping periods, but eventually as many irradiated as unirradiated individual males were caught. Captured irradiated females also were fewer than unirradiated females during the first two trapping periods. However, the total number of irradiated females caught during the entire study was only 50.8% that of unirradiated females. The total of recaptures for irradiated females (33) was significantly less (<0.01) than total recaptures of nonirradiated females (65), but recaptures of irradiated males (35) were not significantly different from recaptures of nonirradiated males (40).

Effects of irradiation on reproduction could not be judged in terms of young appearing in the population. Although irradiated females were pregnant or lactating 9 times out of 20 captures from day 28 to 106 and nonirradiated females showed signs of reproductive activity in 19 out of 36 captures; only two young voles were captured that contained either of the radionuclides. The percentage (47.4) of irradiated females exhibiting reproductive activity from day 28-106 was not significantly different from the nonirradiated females (55.5%). On day 28 one nonirradiated female, found dead in a trap, had two near-term fetuses; this ^{54}Mn-injected female was counted, and the fetuses were removed and counted. The fetuses accounted for 2.9% of the total body burden of the female. No such isotopic transfer from mother to young occurred in a ^{60}Co-injected and irradiated female which was counted on day 63 and bore one young while being held overnight in the lab. This new-born vole was counted on day 64 and no ^{60}Co was detected.

The 700-rad dose caused graying of fur on voles in both the laboratory and field experiments, but graying occurred faster in the field population. Graying by days 105-106 in five out of seven irradiated field animals ranged from "slight graying on head, back, and flanks" to "moderate graying all over." In contrast, irradiated voles in the laboratory showed no graying by day 114.

The significantly fewer recaptures of irradiated female pine voles may not have been a reflection of irradiated death per se. The LD_{50-30} of males and females in the laboratory was, respectively, 883 and 1004 rads (Dunaway et al. 1969b), and none died within 30 days at a dose of 700 rads during that study or in the laboratory part of this study. "Radiation sickness" would be expected at 700 rads, however, and the fewer captures of both irradiated sexes during the first two trapping periods may have resulted from effects of radiation sickness. The continuing absence of irradiated females may have resulted from loss of territory by the females because of inability to defend their territory during this time.

Pelage graying is a common phenomenon in mammals irradiated with substantial but sublethal doses (Dunaway et al. 1969b and Chase 1949). This graying results when damaged follicles replace molted pigmented hair. The more rapid graying of the animals in the field than in the laboratory may have reflected normal molting of the field animals in response to natural environmental cues, whereas in the laboratory the environment was unchanging. Graying seemed not to increase predation rate on the voles in the free-ranging population, although evidence that has been compiled (Cott 1957) suggested that such prey species with pelage contrast with their environments would be more vulnerable to predators. Survival of semifossorial species such as the pine vole after graying may be different from other species more exposed to view of predators, but the data of O'Farrell et al. (1971) indicate that grayed pocket mice (*Perognathus parvus*) survived in natural populations about as well as pocket mice with normal pelage.

Recommendations for Future Research

1. A review by Reichle et al. (1970) indicates that both intrinsic biological and extrinsic environmental factors affect turnover and concentration of radionuclides in food chains. Characterization of the environmental parameters that influence radionuclide movement in ecosystems needs to be intensified as it becomes more obvious that nuclear energy will be providing power for much of the world within a few decades. Also, prior knowledge of such radionuclide transfer rates is imperative for protective and ameliorative measures in the event of nuclear war.

2. Since much of the dose received by vertebrates in a contaminated environment will come from radionuclides incorporated in the body tissues or passed through the body via the GI tract, it is necessary to continue work to identify bioenvironmental pathways for the transfer of radionuclides. Of particular importance should be the ones released by operation of any nuclear facility or nuclear weapon.

3. Investigations on the effect of chronic low-level radiation on vertebrate populations should be emphasized. Of particular concern should be the effects on reproduction, blood, and seasonal responses of free-ranging populations. Judging from results obtained in the AEC-OCD field and laboratory facilities here and in other studies, it seems likely that long-term effects from the chronic, low-level radiation field will be manifested in populations of mammals. Delineation of these long-term effects will require (1) additional enclosures to provide population of adequate size for statistical radiation and (2) experiments will have to be truly long-term--many months or a few years.

4. The vegetation studies showed that grazing by cotton rats was an important factor in terms of productivity and effects on plant reproduction. Future studies of a plant-herbivore food chain (e.g., fescue-cotton rat) can provide predictive models of radionuclide dynamics and irradiation effects in a more practical manner and at much less cost than studies utilizing large herbivores and pastures. Small predators (e.g., weasels, cats, shrews) should be used to ascertain whether concentrations of particular radioisotopes increase or decrease to higher trophic levels such as that occupied by man.

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This document contains final progress reports on a number of postattack radioecology studies at Oak Ridge National Laboratory dealing with aspects of the long-term effects of radiation and radionuclides. These studies included the effects of chronic and acute radiation on plants and animals; the behavior of ^{137}Cs in a terrestrial ecosystem; and the retention of ^{54}Mn and ^{60}Co in field rodents (U).

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Abstract

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