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PROGRESS REPORT IN POSTATTACK ECOLOGY

INTERIM REPORT

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Ecological Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

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ECOLOGICAL SCIENCES DIVISION

PROGRESS REPORT IN POSTATTACK ECOLOGY

INTERIM REPORT

by

S. I. Auerbach
P. B. Dunaway

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PROGRESS REPORT ON POSTATTACK ECOLOGY - FY 1970

S. I. Auerbach P. B. Dunaway

SUMMARY

Cooperative, related studies of movement of fallout simulant; movement of ^{137}Cs through plants, animals, and soils; gamma and beta dosimetry; and effects of chronic and acute radiation on plants and animals are continuing in field facilities.

Gamma-radiation dose rate remains virtually unchanged at heights 0.5-1 m above ground after 21 months postapplication of a ^{137}Cs-tagged fallout simulant in 100 m^2 enclosures. Gamma dose rates near the ground are decreasing while beta dose rate is decreasing with height above ground. In-vivo dosimetry shows that dose to organisms is related to location of the organisms in the contaminated environment.

Interception and loss rates of fallout simulant tagged with ^{137}Cs or ^{86}Rb in six species of plants early after application varied with simulant size, plant species, and meterological conditions. After about one week, loss rates of simulant were slow, and differences in retention rates between species and between particle size were nonsignificant. Vegetation data are presented for retention rates, weathering half-lives, and effective half-lives of the simulants. Soon after fallout simulant was applied, a considerable quantity of ^{137}Cs leached onto vegetation (1.32 and 4.6 μCi/g in living and dead vegetation, respectively). Cesium-137 concentrations continued through time to be higher in dead than in living vegetation. Total loss of ^{137}Cs from the areas via water and erosion was estimated to be ~0.1% per year.

Laboratory experiments with the collembolan Folsomia showed that sensitivity of populations is determined primarily by sensitivity of fertility rates rather than sensitivity of adults. Dose rates estimated to give an LD_{50-30} or LD_{50-60} were more than twice as high as dose rates required to reduce fertility to zero. Analyses of variance showed significant difference between arthropod communities in the nonradioactive and radioactive enclosures. A cross-correlation matrix test was developed for further testing of the arthropod populations. Mortality in laboratory populations of crickets (Acheta domesticus) increased with increasing dose rate up to a point (210 rads/hr), after which further increases in irradiation intensity produced no increases in mortality.

Cesium-137 levels were relatively high (5.65 μCi, whole body) in cotton rats (Sigmodon hispidus) living in the radioactive enclosures during Feb. 1969, decreased regularly from February to October as the fallout simulant moved toward the ground, and then remained relatively constant until the experiment was terminated in April 1970. Measurements of ^{137}Cs in whole body, tissues, and in GI-tract organic matter and fallout simulant in general paralleled each other. Most of the body burden of ^{137}Cs was contained in muscle. About 27% of the whole-body burden was in the GI tract, and of this amount, 79% was in organic matter and 21% was in fallout simulant. No effects of the chronic, low-level radiation environment were found for blood or body weight.

Radioresistance of eggs and larvae of Italian cordovan hybrid bees (LD_{50-4} = 1700 R) was an order of magnitude lower than that for adult workers (LD_{50-5} = 16,300 R). Adults were irradiated at 1000, 2000, and 4000 R; the lifespan of only the 4000 R group (8.9 days) differed statistically from controls (23 days). Bees supplied only with water lived significantly longer at 34°C than at 24 or 40°C (2.8 vs 2.0 and 2.0 days, respectively), and bees fed queen cage candy had significantly different mean lifetimes of 13, 8, and 2 days

at 24, 34, and 40°C, respectively. Colonies of bees were irradiated at doses ranging from 500-4000 R. Mortality increased at higher irradiation levels, and daily number of flights, amount of pollen in honeycombs, number of brood cells, and egg production were decreased at the higher doses.

INTRODUCTION

Research on postattack ecology in Ecological Sciences Division, Oak Ridge National Laboratory, is sponsored by the Office of Civil Defense in cooperation with the Atomic Energy Commission. These continuing, field-oriented studies are concentrated on (1) movement of fallout simulant affected by biotic and abiotic factors, (2) movement of ^{137}Cs through plants, animals, and soils, (3) gamma and beta dosimetry, and (4) effects of chronic and acute radiation on plants and animals.

Efforts during the past year were directed increasingly toward field studies of populations in several areas: the ^{137}Cs-contaminated enclosures, an area for testing fallout behavior on crop plants, two different areas with confined or unconfined honeybee colonies, and uncontaminated areas in the OCD 0800 Area. A class "A" weather station at the 0800 Area provided needed climatological data. An experiment by Weather Bureau personnel is comparing climates in the 0800 Area and a nearby coniferous forest. Resultant data, joined with our data, will be valuable for predicting fallout behavior in contrasting environments.

We have reached a point where the fallout simulant in the enclosures essentially forms an irregular plane source of chronic beta and gamma radiation, and the ^{137}Cs is cycling regularly through soils, plants, and animals. We will be able shortly to characterize both short-term and long-term behavior of fallout and ^{137}Cs in systems similar to ours. However, as we anticipated, effects of chronic irradiation can not be detected readily in adult individual organisms during exposures of a few weeks or months. Consequences of chronic radiation in populations over periods of many months or a few years may be discernible, particularly with respect to reproduction and radiosensitive transformation stages.

Although progress accelerated this year, the OCD budget decrease will necessitate termination of some work. The studies in ^{137}Cs enclosures constitute a comprehensive approach to defining long-term behavior of fallout simulant and ^{137}Cs under natural conditions. We also need to continue these studies to ascertain effects of chronic, long-term radiation. Accordingly, we chose to proceed with this project and terminate the honeybee project.

FALLOUT SIMULANT STUDIES WITH AGRICULTURAL PLANTS*

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

SUMMARY

Five species of agricultural plants were contaminated in the field with two particle size ranges of a quartz

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*This study has been accepted for publication in Health Physics.

fallout simulant containing ^{86}Rb. Initial fallout interception and retention of particles up to 8 weeks was determined. Loss of fallout from foliage due to weathering action of wind and rain (weathering half-lives) and loss due to weathering plus radiological decay (effective half-lives) were determined for all species.

Initial interception of smaller particles (44-88 μ dia.) by foliage was 2.5 times that of larger particles (88-175 μ dia.). Particle interception was correlated with leaf area and varied between species by a factor of 65 in terms of μCi ^{86}Rb/g foliage.

After rapid initial losses of fallout (67% lost the first week after deposition), differences in retention rates between species became nonsignificant. Retention times of the two particle size ranges were also found to be similar.

Introduction

Interception and retention of fallout by plants leads not only to irradiation of plants but also to the entry of fission products into food chains. Since an appreciable portion of the total dose from fallout may be delivered during the first week following a weapon detonation, initial interception and early losses of fallout are critical events in determining dose to contaminated plants. A better understanding of these events should lead to improved evaluation of short-term biological hazards involved in using nuclear devices for peaceful or military purposes.

Previous studies on retention of fallout particles by plants have been made at the Nevada Test Site following nuclear detonations (Romney et al. 1963, Martin and Turner 1966), in Costa Rica following the eruption of the Irazú volcano (Miller and Lee 1966), and with

artificial fallout under field conditions (Johnson and Lovaas 1969, Dahlman and Auerbach 1968, and Witherspoon and Taylor 1969). In most of these studies, however, early losses of fallout from plants due to weathering (wind and rain) were not determined.

The purpose of this study was to determine initial retention and early losses of a fallout simulant by agricultural plants. Five species of plants were selected to represent a wide range of foliage shapes and surface conditions. Two ranges of particle size (44 to 88μ diameter and 88 to 175μ diameter sand) were selected to represent close-in fallout. Moreover, these particle sizes have been used in previous studies under field conditions.

Materials and Methods

Experimental Plots

Two 10- by 10-m seed beds were prepared, and seed were planted the last week of May. Each seed bed consisted of two rows each of squash (*Cucurbita moschata*), soybeans (*Glycine max*), grain sorghum (*Sorghum vulgare*), peanuts (*Arachis hypogaea*), and Korean clover (*Lespedeza stipulacea*). Spacing of plants followed standard agricultural practice. Following seed planting, the plots were fertilized and maintained for weed control until the plants were six weeks old. Plant height at six weeks ranged from 25 cm (lespedeza) to 100 cm (sorghum).

Application of Fallout Simulant

Two fallout simulants consisting of quartz particles 44-88μ and 88-175μ dia. containing ^{86}Rb sorbed at high temperatures (Lane 1968)

were obtained from W. B. Lane of the Stanford Research Institute. The ^{86}Rb concentrations at time of application were 2.04 and 2.81 μCi/g sand for the 44-88μ and 88-175μ sizes, respectively. Solubility of the ^{86}Rb was approximately 2% in distilled water (24 hr contact of 1 g of particles with 100 ml distilled water).

The small particles were applied to one 10- by 10-m plot and the larger size to the other plot by a technique developed at ORNL for fall-out studies in a grassland (Dahlman and Auerbach 1968). In general, this technique consisted of running a modified fertilizer spreader containing the fallout simulant over the plot on a movable track. Figure 1 shows the remote-controlled spreader and part of the overhead track with its supports. Both the speed of the spreader and an internal hopper opening can be controlled such that a desirable mass loading of particles (g/ft^2 soil) can be obtained from calibration operations with nonradio-active sand. The spreader (1.5 m above the soil) covered a strip of ground 1 m wide so that several runs were necessary to cover the entire plot.

Before sanding operations, thirty plastic tubs (18 cm dia. openings) were placed between rows on each plot as a check on mass loading. The simulant was applied between 8:30 and 9:30 p.m. on July 14 under dry conditions (68% relative humidity) with 0-0.5 mph winds.

Sampling

Plant samples were taken the day before simulant application for determination of foliage area and weight per soil area. Immediately following contamination three $0.25m^2$ samples of each species in each plot were randomly selected, clipped, and bagged for radiometric analyses.

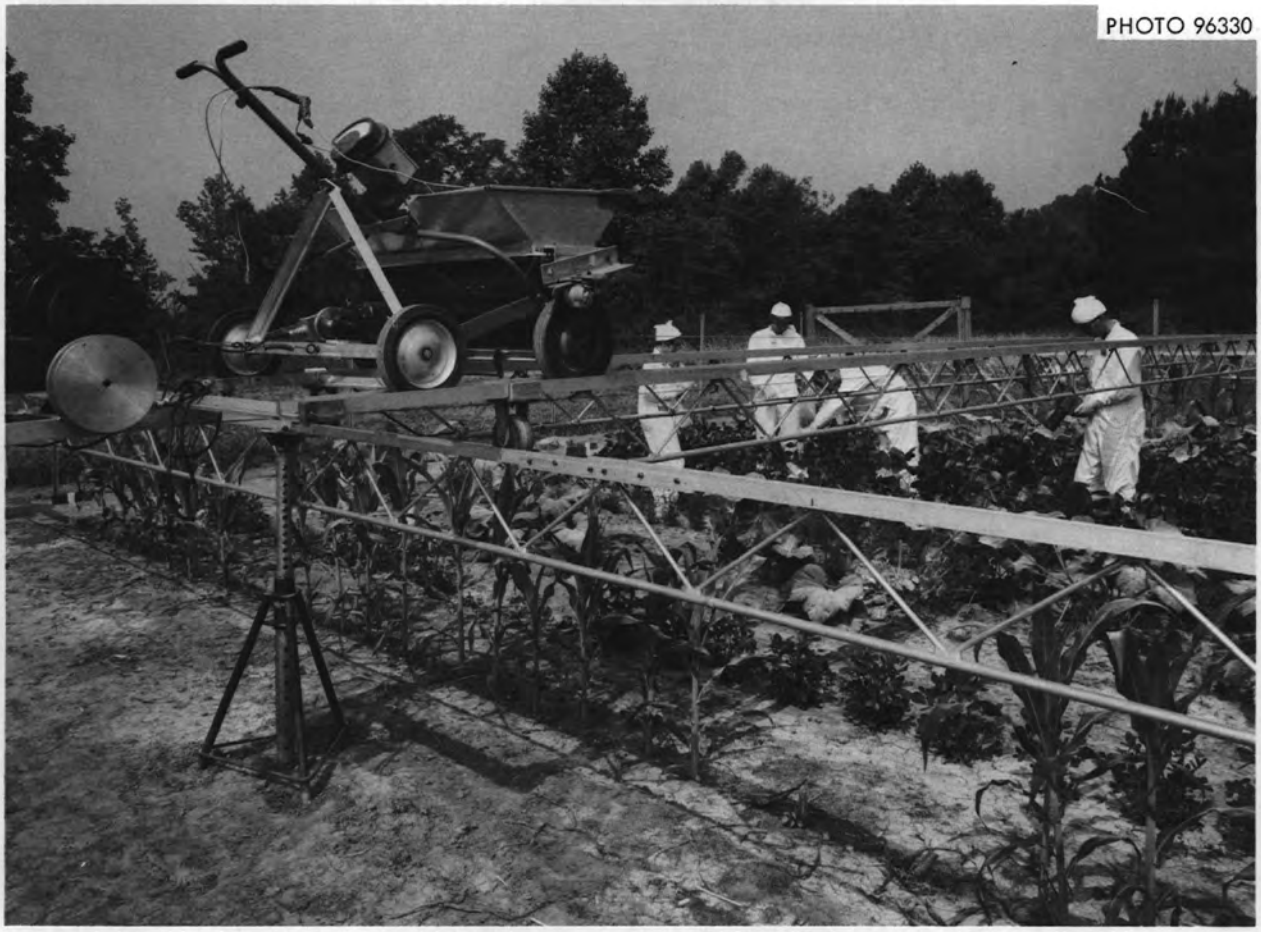

Fig. 1. Remote Control Spreader for Sand Application and Movable Track with Supports. Personnel are sampling plants. The fallout simulant is visible as light-shaded areas on foliage and soil.

These samples were used to determine initial reception of the fallout simulant. Afterwards, three samples per species per plot were collected at intervals of 0.5, 1.4, 7, 14, 21, 28, 35, 42, 49, and 56 days following simulant application. Each sample was oven-dried at 100°C for 24 hr, then the ^{86}Rb activity of foliage was measured in a Packard gamma spectrometer with an Armac scintillation detector.

Weather Data

A small weather station was located 200 m from the experimental plot. Wind speed was recorded at 20-min. intervals by a low-inertia anemometer located 2 m above ground surface. Precipitation was recorded at 20-min. intervals daily from midnight to midnight.

Results and Discussion

Initial Interception of the Fallout Simulant

Initial mass loading, as determined by deposition of particles in plastic tubs, was 5.70 $\pm$ 0.7 g/ft^2 soil (11.6 μCi $^{86}Rb/ft^2$) for the 44-88μ particles and 6.57 $\pm$ 0.6 g/ft^2 (18.4 μCi $^{86}Rb/ft^2$) for the 88-175μ particles. This mass loading was probably lower than that for close-in fallout following a large-yield weapon detonation. Clark and Cobbin (1963) estimated a mass loading of 15.7 g/ft^2 at a distance of 77 miles from a 10^4 KT surface detonation.

Foliage area and biomass at the time of particle deposition are given in Table 1. Three species had a relatively dense foliage coverage such that the ratio of foliage area to soil area exceeded one. Growth habits, however, differ greatly in these species. The large surface area of squash foliage (1.7 m^2/m^2 soil) is due to large individual leaves, and

Table 1. Foliage Area and Dry Weight of Plants at Time of Fallout Simulant Application. Values are mean ± S.E.

Species	Foliage area/soil area (m^2/m^2)	Foliage wt/soil area (g/m^2)
Squash	1.72 ± 0.4	68.59 ± 14.4
Soybeans	3.11 ± 0.4	122.91 ± 11.3
Sorghum	1.25 ± 0.2	57.96 ± 9.0
Peanuts	0.91 ± 0.03	47.87 ± 2.1
Lespedeza	0.51 ± 0.02	20.27 ± 1.0

a relatively prostrate growth habit. The large foliage area (3.1 m^2/m^2 soil) of soybeans is due to its bushy growth habit with many layers of relatively small leaves. Sorghum (1.2 m^2/m^2 soil), like corn, has many broad, lance-shaped leaves and a vertical growth habit.

Following the notation of Miller and Lee (1966), the initial concentration of the fallout simulant on foliage may be expressed by a foliage contamination factor, a_i, such that

$$a_i = C_i^o/m_i,$$

where C_i^o is quantity in μCi of radionuclide initially intercepted per g dry weight of foliage, and m_i is quantity of μCi of radionuclide deposited per ft^2 of open soil-surface area.

The fraction, F, of fallout that is initially intercepted by foliage is given by

$$F = a_i W_1,$$

where W_1 is the dry weight of foliage in g per ft^2 of soil-surface area.

Table 2 gives initial retention values of the fallout simulants for all plants. The F values for 44-88μ particles ranged from 0.07 for the small-leaved lespedeza to 1.2 for squash. For the 88-175μ particles, F values ranged from about 0.02 for lespedeza to 1.1 for soybeans. Values of $F > 1$ were obtained for squash and soybean plants. The area of foliage per unit soil area (Table 1) exceeded unity due to the bush-like form of these plants, and particles had a tendency to fall in at an angle between layers of foliage such that more particles per unit foliage area were intercepted by these species. For all plants, F values for the smaller particles averaged about 2.5 times greater than those for the larger particles. The greatest differences in interception of small

Table 2. Initial Retention of Simulated Fallout Particles by Crop Plants

Species		C_i^o (μCi/g foliage)	m_i (μCi/ft^2 soil)	a_i (ft^2/g)	w_1 (g foliage/ ft^2)	F ($a_i w_i$)	F_B/F_A
Squash	A*	2.568	18.46	0.139	6.37	0.885	1.41
	B	2.275	11.61	0.196		1.248	
Soybean	A	1.876	18.46	0.101	11.41	1.152	0.89
	B	1.047	11.61	0.090		1.027	
Sorghum	A	0.380	18.46	0.020	5.38	0.108	4.53
	B	1.058	11.61	0.091		0.489	
Lespedeza	A	0.180	18.46	0.010	1.88	0.019	3.95
	B	0.460	11.61	0.040		0.075	
Peanuts	A	0.238	18.46	0.013	4.45	0.058	1.69
	B	0.252	11.61	0.022		0.098	
							$\bar{X}$ = 2.49

A* = 88-175μ diameter particles

B = 44-88μ diameter particles

versus large particles were found in lespedeza and sorghum in which interception of 44-88μ particles was about 4-4.5 times greater, respectively, than that of 88-175μ particles. These species have smooth leaves, and it is probable that the larger particles had a greater tendency to roll off during deposition. The least difference in interception of small versus large particles was found in soybeans. The highly layered foliage structure and villous leaf surfaces were slightly more effective in trapping larger particles (F = 1.1) than the smaller (F = 1.0) particles.

Figure 2 illustrates the pattern of 88-175μ particle deposition on the individual leaf types. A slight vee-shape on leaves of sorghum, lespedeza and peanut caused particles to roll in toward the midvein and orient in a line along the length of the leaf. Particle distribution on squash and soybean leaves was more uniform due to small hairs on the surface and along veins.

Plants with large foliage surface areas tended to show smaller interception differences between particle sizes. Figure 3 shows the relationship between F values for the two particle-size ranges and foliage area. Maximum retention differences occurred when the ratio of foliage area to soil area was less than one. This may represent a "bounce" effect where heavier particles, with greater deposition velocities, tend to bounce off of small leaves but fall back on larger leaves. Deposition velocities of the largest particles (175μ) were about seven times greater than those of 44μ particles (Clark and Cobbin 1963), Particles up to about 100μ in diameter would have reached terminal velocities in this case (Slade 1968).

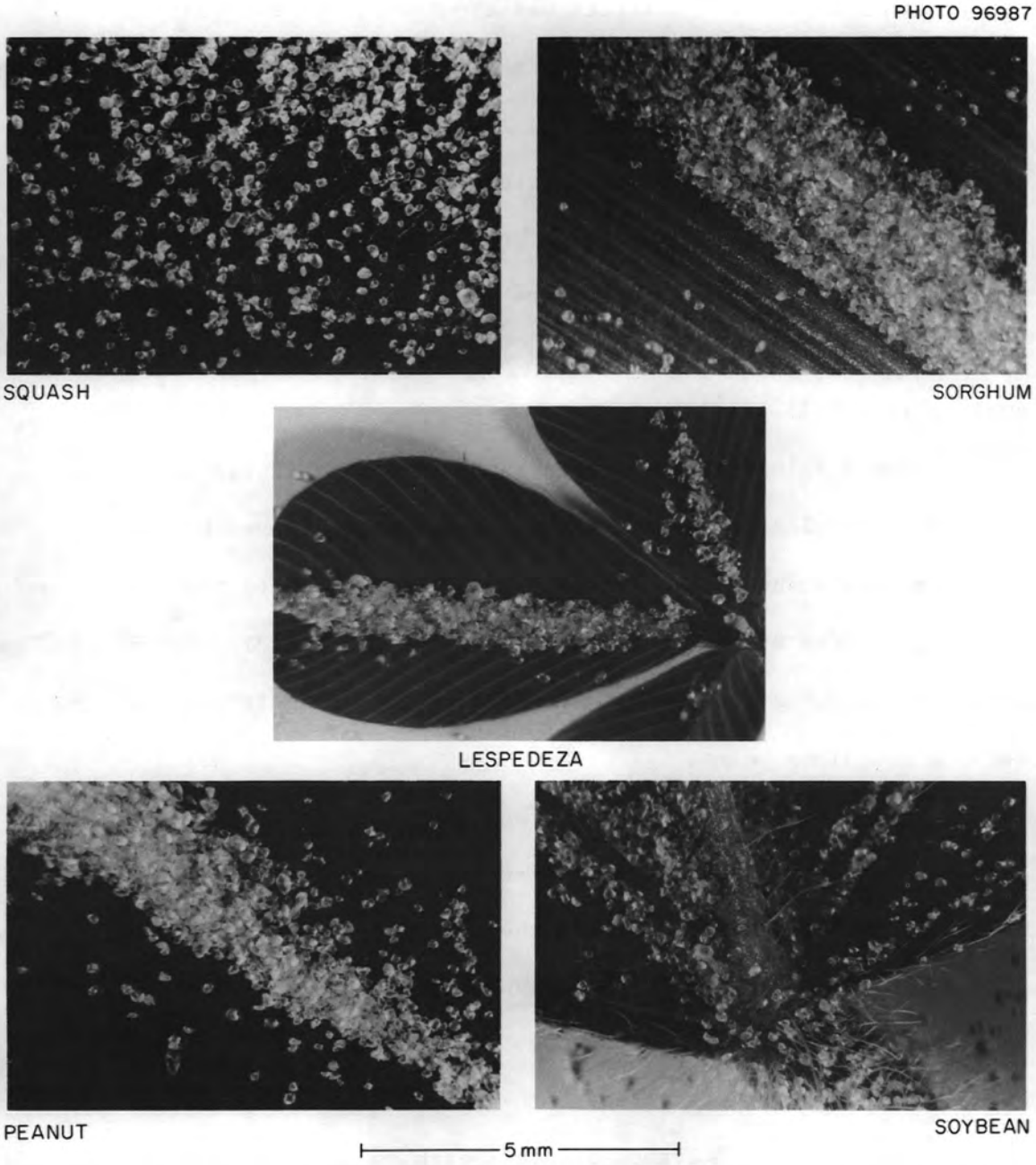

Fig. 2. Detailed Photo Showing Initial Orientation of 88-175μ Particles on the Different Types of Foliage. Note the troughing effect in sorghum, lespedeza, and peanuts.

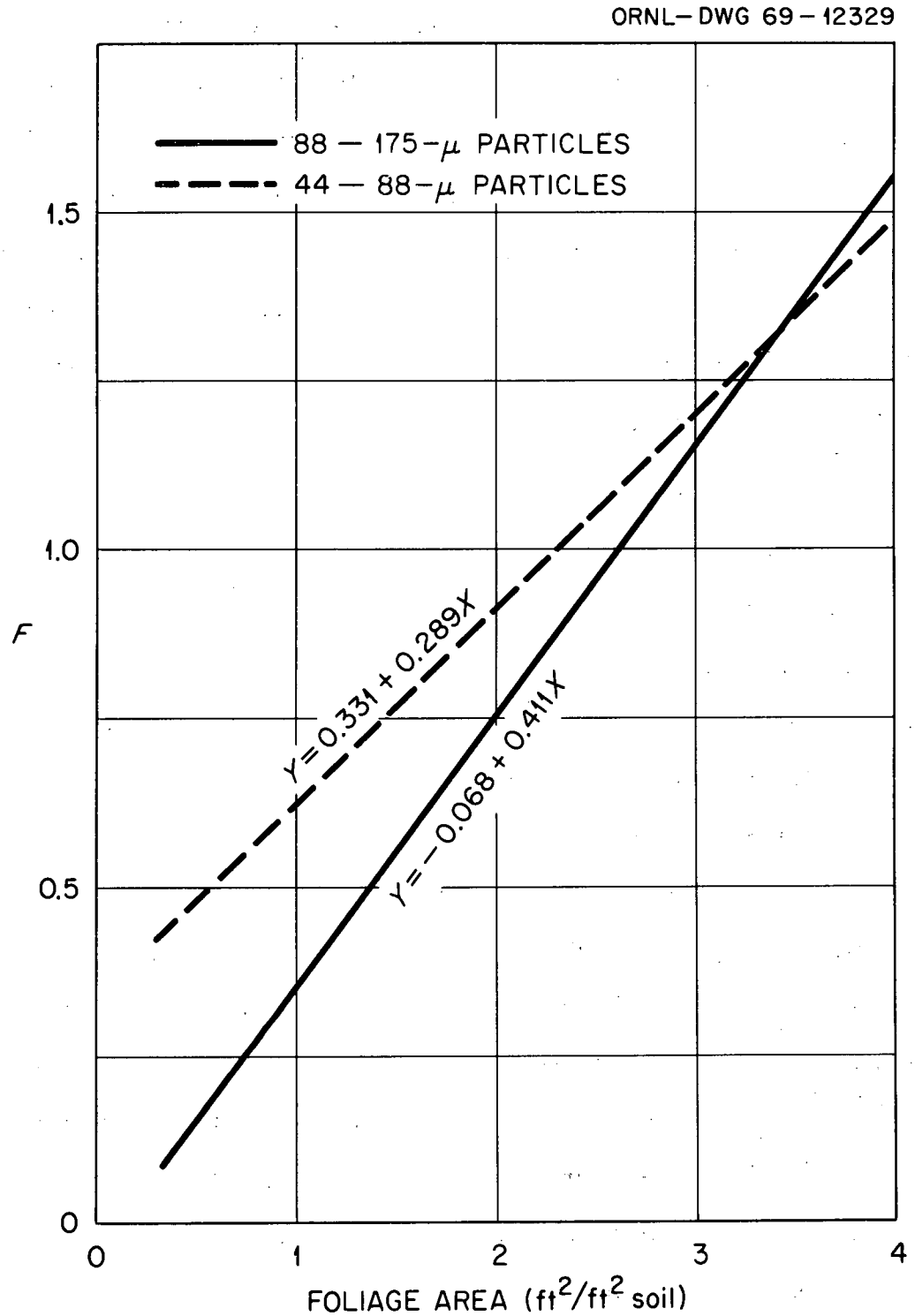

Fig. 3. Linear Regressions of F, Fraction of Fallout Initially Intercepted, on Foliage Area.

The average F value for 88-175μ particles in the case of these crop plants was 1.5 to 2.2 times greater than values for small oak and pine trees under similar deposition conditions (Witherspoon and Taylor 1969). The foliage-contamination factor, a_i, ranged from 0.01-0.19 in this study. These values are higher than reported values from NTS fallout fields (Miller and Lee 1966). Samples for the latter, however, were usually collected several days after initial contamination or after some loss of particles due to weathering.

Retention of the Fallout Simulant

No rain occurred for six days following application of the fallout, so the samples taken at 12 and 36 hr after deposition reflected losses due to wind only. Figure 4 shows average retention of particles by all plants and average wind speeds up to 36 hr after initial deposition. During the first 12 hr (overnight), the plants lost an average of 18.5% of the initial contamination. Wind speed averaged 0.5 mph over this period. Losses for the next 24-hr period also averaged 18.5% with an average wind speed of 1.1 mph. In terms of particle size, losses from plants from 0-12 hr ranged from 3-35% ($\bar{X}$ = 21.1%) for 44-88μ particles and 9.5-26% ($\bar{X}$ = 15.8%) for 88-175μ particles. For the 12-36 hr period, losses ranged from 1.2-33.5% ($\bar{X}$ = 15.4%) for smaller particles and 7.7-34.0% ($\bar{X}$ = 21.6%) for larger particles. Thus, during the first 12 hr when wind speed averaged only 0.5 mph, average loss of small particles was greater than loss of large particles by a factor of 1.3. For the 12-36 hr period, when wind speed averaged 1.1 mph, average loss of large particles was 1.4 times greater than loss of small particles.

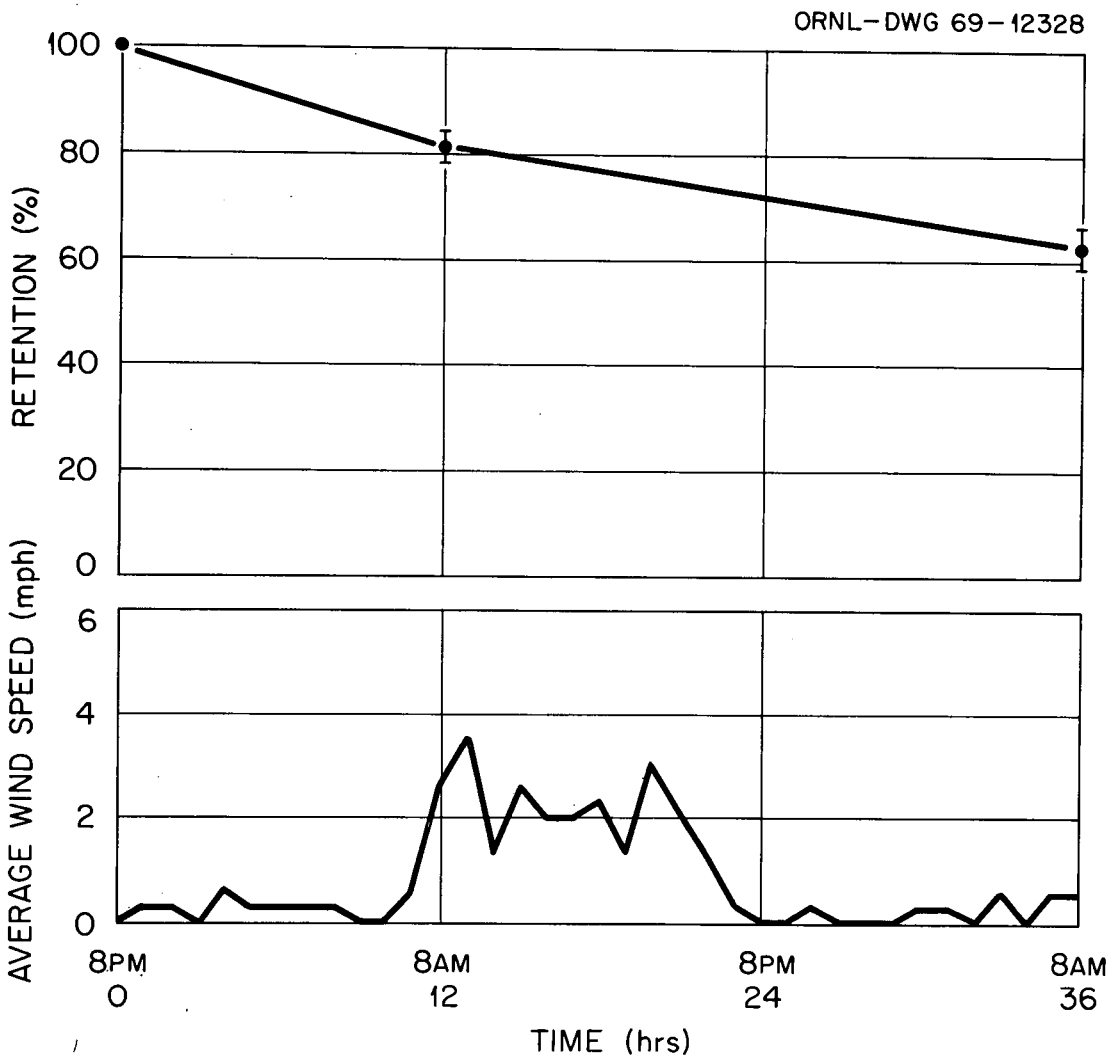

Fig. 4. Percent of Initial Fallout Reception Retained and Wind Speeds for 36 hr Following Fallout Application. Retention values are averages for all plant species.

It apparently took a windspeed between 0.5 and 1.1 mph to remove some of the larger particles in the 88-175μ range.

Concentration of a radionuclide on fallout-contaminated foliage, C(t), as a function of time after fallout is usually approximated by

$$C(t) = C_i^o e^{-\lambda pt},$$

where λp is the effective decay constant for the radionuclide and is equal to $0.693/T_p$. The effective half-life, T_p, of the radionuclide on foliage is given by

$$T_p = T_r\ T_w/T_r + T_w,$$

where T_r is the radioactive half-life (18.7 days for ^{86}Rb) and T_w is the weathering half-life due to the action of wind and rain.

Retention curves, however, can not be adequately expressed in terms of a single effective half-life. Rapid particle loss rates during the first week and subsequent rate changes due to weathering imply that retention data should be compartmentalized into appropriate time components for half-life analyses.

In this study four time components were used for calculation of half-lives. Linear regression analyses were performed on ^{86}Rb concentrations on foliage through time periods of 0-1.5, 1.5-14, 14-28, and 28-56 days. Weathering half-lives, T_w, were estimated from these linear expressions. Effective half-lives were then determined.

Figure 5 shows average retention by all plants of the fallout simulant. Both particle size ranges were included. This curve approximates the shape of individual retention curves for each species and each particle size range. Amount and time of rainfall during the study are also shown in Fig. 5. Eleven rain periods were recorded, and total

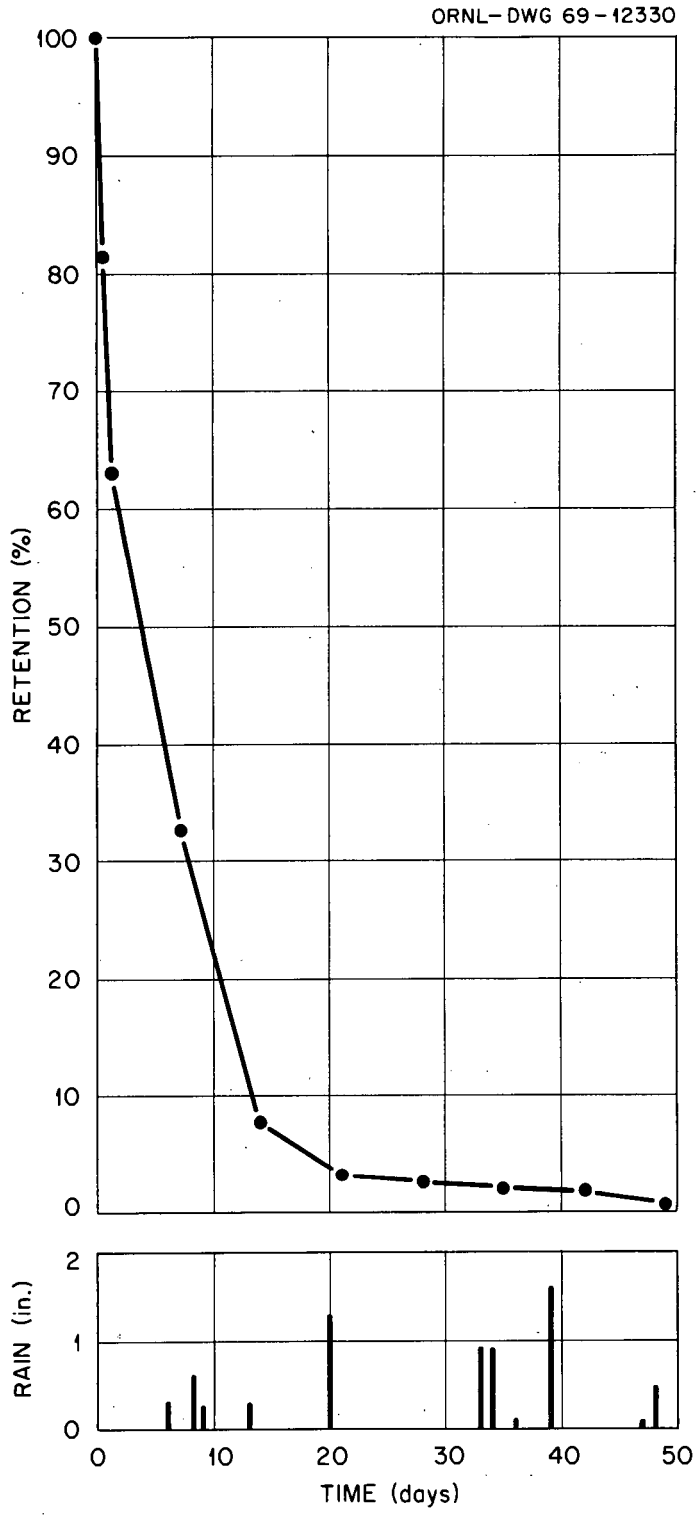

Fig. 5. Percent of Initial Fallout Interception Retained and Amount of Rainfall up to 49 Days Following Fallout Deposition. Retention values are averages for all plant species.

rainfall was 6.96 in. The initial drop to 64 ± 3% at 1.5 days in the retention curve is due to loss of particles only by wind action. Wind speeds up to 6 days, time of the first rain, averaged 1.7 mph (7 mph max) during the day and 0.3 mph (2 mph max) during the night. It is likely that maximum losses due to wind action occurred during the first 2 or 3 days following deposition and that most of the loss of particles from 1.5-7 days was due to a 0.25-in. rain on the sixth day. After the second week, and three rains totaling 1.08 in., average retention was 7.9 ± 1.6%. One intense rain (1.4 in.) on the twentieth day caused another sharp drop in retention down to 3.3 ± 1.0%. After the third week the loss rate became relatively constant, and subsequent rains had little effect on the quantity of fallout remaining on foliage.

Weathering half-lives for each species, each particle size range, and for the four time components are given in Table 3. When plant species were averaged, there was no statistically significant difference between T_w values for individual species. For example, sorghum foliage was very effective in trapping 44-88μ particles which funnelled down the angular leaves into leaf axils. This resulted in large T_w values for this species after two weeks. The hairy leaves of squash and soybeans were also relatively effective in retaining the smaller particles during this period. Species differences in T_w values of the 88-175μ particles were less pronounced. Sorghum foliage, for example, was not as effective in retaining this particle size range.

The T_w values for the 14-28 day component averaged between 16 and 26 days in this study. Martin and Turner (1966) reported T_w values of 28 days (^{89}Sr) and 13-17 days (^{131}I) for Sedan fallout on plants from

Table 3. Weathering Half-lives (T_w days) for Simulated Fallout Particles on Crop Plants

Time component (days)	Squash	Soybean	Sorghum	Peanuts	Lespedeza	$\bar{X}$ all Plants
	44-88μ Particles					
0- 1.5	2.46	2.09	2.77	5.06	1.40	2.76 ± 0.71
1.5-14	7.21	7.29	6.62	8.43	8.36	7.58 ± 0.35
14-28	42.00	17.51	35.29	17.71	18.12	26.13 ± 4.71
28-56	39.00	45.66	272.76	32.11	32.68	84.44 ± 46.28
	88-175μ Particles					
0- 1.5	1.62	1.47	4.10	1.33	2.88	2.28 ± 0.53
1.5-14	7.36	7.19	7.43	15.71	7.55	9.05 ± 1.64
14-28	15.06	15.97	19.43	16.07	14.07	16.12 ± 1.03
28-56	56.50	34.72	38.36	29.46	38.33	39.47 ± 5.20

5-30 days following detonation. Weathering half-lives of simulated fallout (^{134}Cs) on oak and pine trees were 25 and 21 days, respectively, during a period of 7-33 days after deposition (Witherspoon and Taylor 1969). Thus, it appears that T_w values for many different kinds of vegetation, in different geographical regions, may be quite similar after rapid initial losses during the first week or two.

When effective half-lives, T_p's, are compared (Table 4), differences between species become even smaller. The relatively short T_r of ^{86}Rb (18.7 days) compared to some of the long T_w values reduced differences between species to nonsignificance.

Effective decay constants (Table 5) reflected only slight differences between particle size ranges and between species. Again, low λp values for sorghum reflected the ability of this species to retain particles. Relatively smaller λp's for peanuts and lespedeza during the 1.5-14 day component were due to a foliage phenomenon common to legumes. From late afternoon until morning, leaves of these species close up. This closure tended to reduce particle losses induced by wind and rain during this period.

It is obvious that concentrations of radionuclides on fallout-contaminated plants can be expected to decrease at rates significantly faster than would be predicted on the basis of radiological decay. This is especially true during the first day or two after deposition. Although large differences in initial interception existed between species and between particle size ranges, they became nonsignificant after about 1 week of exposure to wind and rain. Plants with grass-like foliage, such as sorghum, with an efficient particle-trapping mechanism may be exceptions.

Table 4. Effective Half-lives (T_{eff} days) for Simulated Fallout Particles on Crop Plants

Time component (days)	Squash	Soybean	Sorghum	Peanuts	Lespedeza	$\overline{X}$ all Plants
	44-88μ Particles					
0- 1.5	2.17	1.88	2.41	3.98	1.30	2.35 ± 0.51
1.5-14	5.21	5.25	4.89	5.81	5.78	5.39 ± 0.17
14-28	12.94	9.57	12.22	9.09	9.20	10.60 ± 0.72
28-56	12.64	13.27	17.50	11.82	11.89	13.42 ± 1.09
	88-175μ Particles					
0- 1.5	1.49	1.36	3.36	1.24	2.49	1.99 ± 0.41
1.5-14	5.28	5.19	5.32	8.54	5.38	5.94 ± 0.64
14-28	8.34	8.61	9.53	8.64	8.03	8.63 ± 0.29
28-56	14.05	12.15	12.57	11.44	12.57	12.56 ± 0.50

Table 5. Effective Decay Constants (λ_p day^{-1}) for Simulated Fallout Particles on Crop Plants

Time component (days)	Squash	Soybean	Sorghum	Peanuts	Lespedeza	$\bar{X}$ all Plants
	44-88μ Particles					
0- 1.5	.319	.368	.287	.174	.533	.336 ± .07
1.5-14	.133	.132	.142	.119	.120	.129 ± .004
14-28	.053	.072	.057	.076	.075	.067 ± .004
28-56	.054	.052	.039	.059	.058	.052 ± .004
	88-175μ Particles					
0- 1.5	.463	.508	.206	.559	.278	.404 ± .06
1.5-14	.131	.133	.130	.081	.129	.121 ± .01
14-28	.083	.080	.073	.080	.086	.080 ± .002
28-56	.049	.057	.055	.060	.055	.055 ± .002

The particle-size distribution over the size ranges used was not known. The 88-175μ particle-size range may have contained a large percentage of particles in the lower portion of this range. This would tend to minimize differences in retention values between the two size ranges used in this study.

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RETENTION OF SIMULATED FALLOUT PARTICLES BY FESCUE GRASS

Roger C. Dahlman

SUMMARY

Large (44-177μ) fallout-simulant particle retention by dense fescue grass approached 50% initially, and from 1 hr to 1 day later, weathering processes decreased retention to 10%. A modified negative exponential function characterized particle weathering over a 2-3 week period. Half-time for early weathering loss was 3-4 days, but retention approached an asymptotic level after 2-3 weeks, the time at which 2% of the ground surface deposit remained on vegetation. Particle deposits on leaf blades were readily removed by slight wind (< 1 mph) and phytotaxic movements of the foliage. Axillary deposits, however, were not readily removed by wind and rain.

Introduction

Surface nuclear detonations produce both world-wide and local fallout materials which may be hazardous to biological organisms. Precise definition of different kinds of fallout is difficult because many variables influence formation processes and distribution patterns. The properties of local* fallout from a given detonation depend on the kind of materials drawn into the firefall, cloud-arrival time, particle size distribution resulting from condensation of vaporized materials, and character of initial ejecta. Rather than distinct zonation, the

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*Conceptually a local deposit is regarded as a layer of particulate material which can be seen with the unaided eye.

deposits exhibit a gradation of particle size and radioactivity properties as a function of distance from formation. The variable nature of local fallout notwithstanding, there are certain consistent characteristsics of the materials which have been deposited in the vicinity of 7-30 KT test shots (Baurmash et al., 1958). Deposits of 50-150μ material were recorded 50 to 140 miles distant from ground zero. At least 50% of total fallout was in the 44-177μ size class, and an appreciable quantity of the radioactivity was fixed to this fraction.

Fallout deposits from nuclear testing traditionally have been reported in terms of radiation intensity contours rather than mass loads, although the latter parameter would be more useful for the experimental determination of particle behavior and radiation exposure in specialized situations. Mass load has been estimated indirectly from mass contour ratios, fallout specific activity and intensity contour ratios (Clark and Cobbin 1963; Miller and Yu 1967), but these parameters are often unavailable, a factor which increases the difficulty of characterizing local fallout deposit. Assuming that volcanic eruptions produce particle clouds somewhat similar to those of nuclear detonations, Miller (1966, 1967) and Miller and Lee (1966) evaluated the deposition characteristics downwind from the Costa Rican volcano, Irazu. There, as much as 8 $g/ft^2/day$ was deposited 25 miles downwind, and 90% of the particles were in the 44 to 175μ size class. These measurements of particle travel and mass load represent minimal magnitudes because the cloud dimensions were somewhat smaller than those recorded for 7-30 KT surface tests.

Accumulations of local fallout are important radiologically because subsurface biological tissues may receive a considerable beta dose from surface deposits. The meristematic regions of plant apices which reside

within several millimeters of the surface will be particularly sensitive to the beta component. That biological effects to plants were manifested by beta radiation from local deposits is unclear according to field observations associated with projects Sedan, Palanquin and Cabriolet. Damage from local fallout was attributed to the physical effect of dust in the Sedan test (Beatley 1965), but plant effects at Palanquin and Cabriolet (Rhodes et al. 1969) were greater than would be expected from either dust deposits or cumulative gamma dose. Plants exhibited damage when the total beta dose was less than 200 rads. A mantle of dust covered the plants where effects were manifested, but mass load of the deposit was not reported.

According to a damage-assessment analysis, Brown and Pilz (1969) calculated beta/gamma dose ratios of 2 to 4 for average-dimensioned plant meristems at 1 m height. At 1 cm height the dose ratios were 10 to 20 depending on time of arrival. However, these calculations were based on uniform deposition which ignores the specialized cases of particle retention and concentration; e.g. collection in plant crevices, a phenomenon which has been observed frequently (Miller 1966, Dahlman et al. 1969, Johnson and Lovaas 1969 and Witherspoon and Taylor 1970). The specific morphological characteristics not only affect particle concentration and dose to local tissues, but they also influence the magnitude of initial interception and the degree of retention as a function of time.

Despite intensive efforts to characterize initial retention of fallout ash by plants (Miller 1966, Miller and Lee 1966 and Miller 1967) and long-term contamination from nuclear fallout debris (Baurmash et al. 1958,

Romney et al. 1963, Beatley 1965, Martin and Turner 1966 and Rhodes et al. 1969), there is limited information on the behavior of fallout materials in the relatively short interval after deposition (several hours to 1 week). Additional data on retention phenomenology would be useful for estimating plant contamination and species vulnerability to beta radiation. Reported herein are the results of initial retention and short-term coefficients of loss for simulated fallout deposits in a tall fescue (Festuca arundinacea Shreb) meadow community. Mass load and particle diameter were consistent with the above-described requirements for local fallout in the vicinity of 7 to 30 KT nuclear tests and for reported deposition of fallout from a volcanic eruption. Evaluations for this magnitude of detonations obviously are very conservative relative to what might be expected from MT-size explosions. Particle travel, mass load, and area coverage would be considerably different from MT-size detonations.

Procedures

Experimental Area

Extraneous plant material (litter and weeds) was removed from a 4-year-old stand of tall fescue 6 weeks prior to applying a fallout simulant to the vegetation. A homogeneous cover of fescue grass developed by late July at which time the plant density* was 17.4 g/ft^2 $\pm$ SE 2.3, and average canopy height was 30 cm. Two areas (each 2.5 x 5 m)

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*Plant density is expressed in terms of dry weight per area rather than in conventional terms of units of individuals per area.

were located for treatment, and a 1-meter-wide border zone extended around each plot. Walkways were established in this zone to avoid disturbing the contaminated plants during later sample collection. When the experiment was terminated after 3 weeks, plant density was 20.2 g/ft^2 $\pm$ 1.9, and the quantity of grass for intermediate dates of sampling was estimated by interpolation. Meterological data (temperature, rainfall, dewpoint, wind velocity, and direction) were recorded continuously at a nearby (200 m distant) weather station.

Simulant Characteristics and Application

A fallout simulant was fabricated at the Stanford Research Institute by fixing low-level ^{86}Rb on two size classes of quartz sand. The simulant possessed physical characteristics similar to local fallout (Lane 1965, 1968 and 1969), and the ^{86}Rb label expedited the measurement of sand retention and loss by the grass. Rubidium-86 was used because its half-life (18.7 days) and gamma (1.07 MeV) emission were convenient for following short-term particle movement on vegetation. Minimal occupational exposure and field-site contamination hazards resulted from the use of this isotope. Leachability was low (2% over 24 hr at 1-to-100 particle-to-water ratio) because high temperatures during fabrication fused the isotope to the quartz. Two particle size classes (44-88 and 88-177μ dia)* were used in the experiment in order to determine differential retention and loss parameters for both fine and coarse fractions associated with

*Hereafter, the 44-88μ and 88-177μ size classes are respectively designated as fine and coarse particles.

local fallout debris. At the time of simulant application, the ^{86}Rb activity density was 1.56 and 2.07 μCi/g for fine and coarse particles, respectively.

The simulant was released from a hopper-spreader apparatus which traveled on elevated girders at least 1 meter above the vegetation canopy. At this height the particles approached maximum falling velocity before contact with the canopy. Rate of travel and simulant release were controlled remotely to minimize hazard to personnel during application. Uniformity and effectiveness of simulant application from such an apparatus has been reported elsewhere (Dahlman et al. 1969 and Witherspoon and Taylor 1970). Two separate areas were contaminated with fine and coarse simulant particles during calm conditions in late afternoon. Ambient temperature averaged 89°F ± 1 and relative humidity was 78% ± 0.8 in the plant canopy.

Sampling and Radioassay

Particle mass load on an area basis was determined gravimetrically from randomly positioned plate collectors which were placed above the canopy. Similar plates were placed beneath the grass canopy and initial grass retention at t_o was determined by difference. Collecting dishes from beneath the canopy were recovered immediately after application, prior to weathering and redistribution of intercepted particles.

Short- and long-term particle retention characteristics were determined by radioassay of randomly-collected subsamples of grass. To minimize accidental particle loss during the sampling procedure, a plastic bag was gently placed over small clusters of tillers and was tightly

gathered around the tussock base before the plants were clipped. Ten replications were taken from each area at the respective sampling dates. Remaining inside the plastic collection bag, the samples were placed in uniform-geometry cartons and assayed with a 3 x 3 in. crystal and Packard MCA-115. Only the 1.07-Mev gamma peak of the radiation spectrum was evaluated in the radionalysis. Counting efficiency and physical decay were determined from a 1.05-μCi ^{86}Rb standard of similar geometry which was obtained independently from the ORNL Isotopes Division.

Results and Discussions

Mass Deposit and Initial Retention

The initial mass deposit of particles over open ground area was 11.0 g/ft^2 $\pm$ 0.5 and 9.2 g/ft^2 $\pm$ 1.0 for fine and coarse particles, respectively. This mass load approximates the quantity of surface deposit which could be expected in the form of local fallout for intermediate weapon yield according to predictions from mass-contour models (Clark and Cobbin 1963) and measurements of volcanic ash debris (Miller and Lee 1966). Initial retention at t_o as determined by difference of particle deposit above and below the grass canopy, is given as 5.0 and 1.8 g/ft^2 (Table 6) for the fine and coarse size classes, respectively. A substantial fraction (45% fine and 20% coarse) was retained in the grass canopy during this short time interval, but the quantity had diminished by a factor of 3 for both size classes 1 hr later (Table 6). These data indicate substantial particle loss from vegetation shortly after contamination, and the timing of the first observation greatly influences the magnitude of initial retention values.

Table 6. Mass, ^{86}Rb Activity, and Sand Retention by Fescue Following Contamination with Fine (44-88μ) and Coarse (88-177μ) Fallout Simulant

Time	Fescue Mass[1]	Fine Particles				Coarse Particles				Average Retention[3]		Cumulative Precipitation
		^{86}Rb activity		Retention		^{86}Rb activity		Retention				
(days)	(g/ft^2)	(μCi/g)	(μCi/ft^2)	(g/ft^2)	(%)	(μCi/g)	(μCi/ft^2)	(g/ft^2)	(%)	(g/ft^2)[4]	(%)	(in.)
0.0	17.4 ± 2.3[2]	-	-	5.0	45.4	-	-	1.8	19.6	3.4	33.7	0.0
0.042 (1 hr)	17.4 ± 2.3	0.153 ± .013[2]	2.65	1.7	15.4	0.071 ± .006[2]	1.24	0.60	6.5	1.15	11.4	0.0
0.75	(17.5)	0.117 ± .022	2.05	1.35	12.3	0.069 ± .005	1.21	0.61	6.6	0.98	9.7	0.0
1.83	(17.7)	0.062 ± .008	1.10	0.75	6.8	0.061 ± .006	1.08	0.56	6.1	0.66	6.5	0.53
2.88	(17.9)	0.074 ± .006	1.32	0.94	8.5	0.037 ± .002	0.67	0.36	3.9	0.65	6.4	0.80
5.85	(18.3)	0.018 ± .002	0.34	0.27	2.4	0.030 ± .001	0.55	0.33	3.6	0.30	3.0	1.03
6.88	(18.5)	0.015 ± .001	0.28	0.23	2.1	0.025 ± .001	0.46	0.29	3.2	0.26	2.6	1.03
17.0	20.2 ± 1.9	0.009 ± .001	0.18	0.22	2.0	0.010 ± .0007	0.21	0.19	2.1	0.20	2.0	2.42

[1] Oven dry weight. Initial and final quantities measured. Intermediate quantities (in parentheses) estimated by interpolation.

[2] Plus or minus 1 standard error of mean.

[3] Average retention includes data for both fine and coarse particle fractions.

[4] Unadjusted average of columns 5 and 9.

Nearly 50% retention has been observed here (Table 6) and elsewhere (Johnson and Lovaas 1969) when measurements are made immediately after deposition. However, approximately 10% retention on grass has been reported when measurement is delayed 1 hr to 1 day after deposition. Specific examples are 11% for fescue at 1 hr (Table 6), 9% for sorghum at 12 hr (fine particles, Witherspoon and Taylor 1970), and 11% average for primary volcanic deposit on Costa Rican grasses (Miller and Lee 1966). Operationally, it seems advisable to distinguish between absolute t_o and delayed retention (1-12 hr postcontamination). Herein, initial retention and/or weathering are designated as the phenomena occurring from absolute t_o to 1 hr, and effective retention as that which occurs from 1 hr to several weeks.

The reader is reminded that retention data of different size class particles (Table 6) is based on slightly dissimilar simulant application rates, 11.0 vs 9.2 g/ft^2 for fine and coarse material, respectively. Strict comparison of absolute retention would require adjustment of one set of data, e.g. the coarse size class values x $\frac{11.0}{9.2}$, thereby increasing coarse retention by 20%. Average retention (Table 6, column 12) would increase by less than 6%. The aforementioned adjustment was not performed, however, because the effect on subsequent evaluations of relative retention would be negligible.

Continuous Function Weathering

A continuous weathering function is an important parameter used in generalized mathematical models of landscape contamination (Miller and LaRiviere 1966 and Martin and Turner 1966). Although often an over-simplification of retention phenomenology, such functions describe the transitory foodstuff contamination and potential radiation hazard in

extensive agricultural systems. For the 17-day interval, the best fit of the composite fescue data was to a negative exponential model (Figure 6a) of the form,

$$Y = \alpha+(1-\alpha)e^{-\lambda t}. \qquad \text{Eq. 1}$$

In effect the α parameter is a weighting function which dominates the expression of retention during the early period of weathering (small t's) but which exerts less influence as time passes (large t's). High α values portray considerable deviation from the normal negative exponential model ($y = ae^{-\lambda t}$), and indicate multicomponent weathering processes, the individual components of which will be discussed below. Other retention data on sorghum (Witherspoon 1970) are also fitted to the same model (Fig. 6b), and the α and λ parameters for fescue, sorghum, and composite grass are given in Table 7. Relatively low standard errors for the α and λ parameters indicate that the continuous function model adequately describes partial retention for fescue grass. Higher SE's for sorghum and composite grass reflect a less satisfactory fit of the model to the data. High variance of the α parameter indicates that a zero value could be expected within the limits of error of the estimate; thus for these cases, the best fit deviates little from an unmodified negative exponential model. The λ parameters, however, were less variable in all test cases. Since the λ's are similar for different species of grass, and the α parameters appear to be species-dependent, then the generalized model (Eq. 1) could be applied in the widespread evaluation of particulate fallout retention on grass if an experimentally determined array of α values could be provided as input data for vulnerability assessments. Additionally, by employing different species-related α and λ parameters, the model could also describe the time-dependent retention phenomena for vegetation types other than grass.

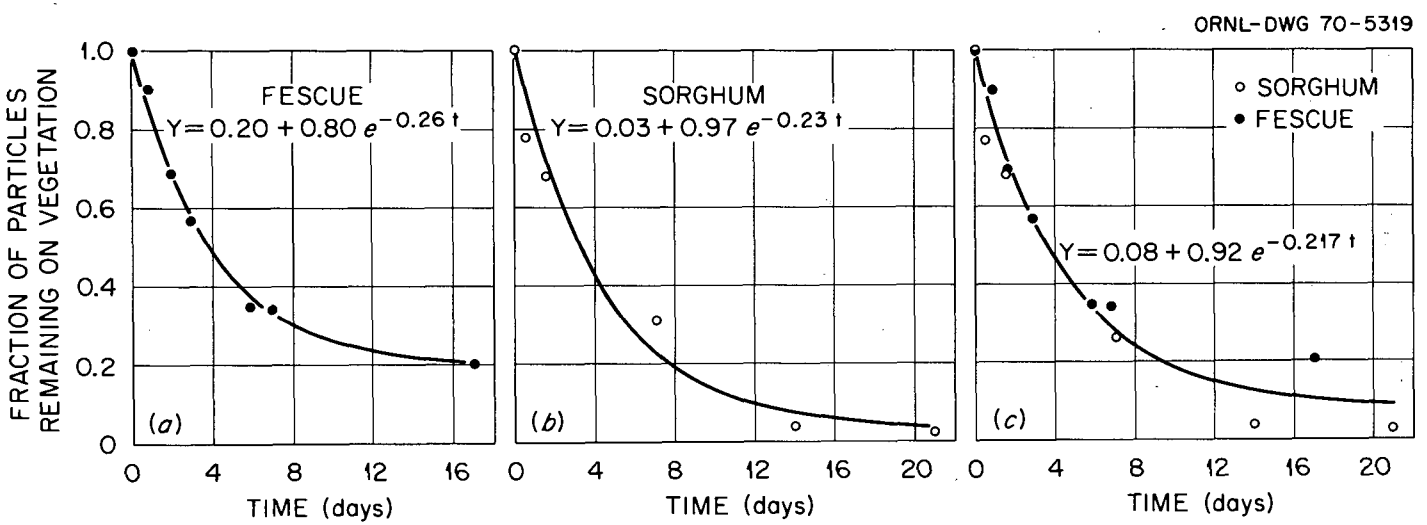

Fig. 6. Average Effective Particle Retention by Fescue and Sorghum Grasses. Data normalized to express t + 1 hr as initial retention. Sorghum data provided by Witherspoon (1970).

Table 7. Comparison of α and λ Parameters for Different Sets of Data Evaluated by the Continuous Function Weathering Model (Eq. 1), Negative Exponential Particle Retention

Test data	α	λ
Fescue	0.195 ± .02[1]	0.261 ± .02
Sorghum[2]	0.029 ± .07	0.227 ± .06
Composite grass	0.081 ± .05	0.217 ± .03

[1] Standard error of the parameter estimates.

[2] Sorghum data compliments of Witherspoon (1970).

Multicomponent Weathering

Component loss of fallout particles from plants is evaluated when there is reason to believe that several factors independently influence retention. For example, weathering of particles from grass plants is different when particles initially are retained on leaf-blade surfaces than when retention is in axillary crevices. Although the exact details of independent weathering processes are not well understood, several distinct components are evident for the fescue data (Fig. 7). Fitting the data to a semilogarithmic regression model of the form

$$\log_{10} Y = a + bX, \qquad \text{Eq. 2}$$

two log normal equations (Fig. 7, Eq. b and c) were derived which described effective retention for days 0-6 (in practice here, the t + 1 hr value is considered day 0) and days 6-17. The loss-rate coefficients (b) were 0.098 and 0.014 for early and late time intervals, respectively. The factor-of-7 difference in the loss rate for early and late intervals strongly indicates that dissimilar mechanisms affect retention on fescue and sorghum. No outwardly apparent effects were caused by moderate rainfall and low wind velocity, thus particle retention is influenced by a complex of environmental and vegetative factors which presently are poorly understood.

Extremely rapid weathering during the first hour (3.4 $g/ft^2 \rightarrow 1.2$ g/ft^2; Fig. 7) characterizes the initial component of loss. Described in log-normal terms, the loss-rate parameter ([b], Eq. a, Fig. 7) was 11, a value 2 to 3 orders of magnitude greater than those derived for effective retention. However, one should place only limited confidence

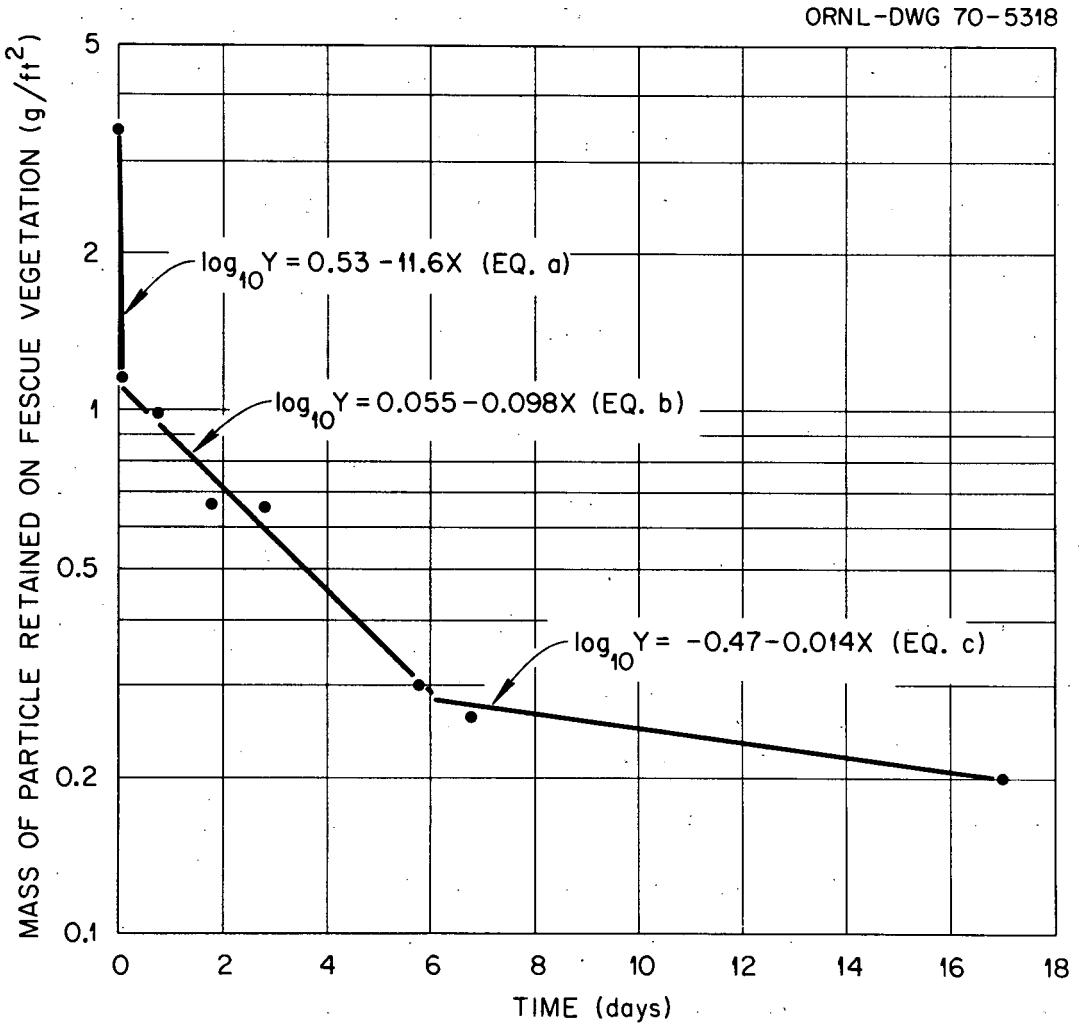

Fig. 7. Log Normal Regression Equations Describing Component Particle Retention by Fescue.

in this parameter of the initial weathering interval because the function is described from merely 2 data points.

In terms of potential radiation damage to plants from local fallout, one can expect extremely rapid weathering of the early arriving, highly radioactive, but promptly decaying products. Rapid exponential loss of particles, coupled with the substantial early radioactive decay, would minimize the contact beta dose to sensitive plant parts. Approximately 10% of the fallout, however, may be effectively retained 1 hr post-deposition; and the loss rate of this fraction diminishes more slowly throughout a several-week period, thereby allowing appreciable beta exposure to plant parts in direct contact with the particles.

Differential particle weathering can be attributed to the combined effects of meterological factors (wind, rain), leaf morphology (pubescence) and plant habit (crevices, niche). Wind-induced weathering was considered nominal in this experiment because of atmospheric calms during application, and because wind speeds in the grass canopy (h = 20 cm) were very low during the 17-day period. Wind speeds ranged from 0 to 1.5 mph and averaged 0.3 mph $\pm$ 0.3 based on extrapolations from wind-profile data obtained 10 cm above the vegetation.

The low-magnitude wind speeds probably were effective in the initial dislodgment of particles from horizontally-positioned leaf-blades immediately following interception. Thereafter wind-induced weathering was negligible because particles had become trapped in the axillary crevices of the grass shoot. Neither were loss rates affected appreciably by moderate quantities of rainfall which occurred as light showers. One-inch cumulative precipitation over days 2 to 4 caused no

significant deviation from the established trend of particle loss for the composite data (Fig. 7). An additional 1.4-in. shower at day 12, the midregion of the slow loss component, did not enhance particle removal.

Vegetation Influence

Long-term retention of fallout particles is strongly influenced by plant-habit and leaf-surface features (Romney et al. 1963, Miller 1966 and Witherspoon and Taylor 1970). The junction of blade and sheath in grasses is a particularly effective collector (Dahlman et al. 1969) because the V-shaped leaf-blade structure channels particles into a crevice. Rainfall and wind-induced flexing movements further impact the particles within the sheath. The principal mode of removal is associated with growth and development of internal leaf tissue where adhering particles are carried upward by the elongating central axis. It follows, then, that particle retention would be directly related to growth, perhaps as a mirror image of the generalized exponential growth function. Retention results herein (Fig. 6) indeed suggest such a negative exponential loss rate under circumstances when particle loss was not conspicuously related to moderate meterological events. While central-axis growth rate was not measured in the present study, perhaps in future retention experiments it would be advisable to examine the correlation between central-axis elongation and fallout-particle decontamination, expecially for maize and cereal-grain crops.

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CESIUM-137 DYNAMICS IN A FESCUE MEADOW

R. C. Dahlman

SUMMARY

Early incorporation of ^{137}Cs into foliage was largely by contact assimilation because appreciable uptake had occurred before the simulant had reached soil surface. Two loss rates (0.04 and 0.003), derived from linear regression analysis, described ^{137}Cs decrease in living foliage. The fast component characterized nuclide loss during the first month. Subsequent loss due to the slower component was an order of magnitude less than the fast rate. When evaluated over a longer time interval; i.e., 1 year, ^{137}Cs content of living foliage was expressed by a modified negative exponential, $Y = \alpha+\beta e^{\lambda t}$. Asymptotic concentration in foliage in the second growing season indicated equilibration of ^{137}Cs in the vegetative component.

Introduction

One important consequence of a surface nuclear detonation is the fallout of radioactive particles downwind from the blast. For shots in the KT yield range (Teapot Series [Nishita and Larson 1957]), 100 μ median diameter particles were carried at least 140 miles downwind. Obviously, fallout would travel greater distances and cover larger areas from explosions in the MT range; the yield capability of today's devices. At Oak Ridge National Laboratory (ORNL), long-term response of plants, animals, and insects to chronic radiation is being investigated in the regime of chronic radioactivity in the local fallout zone.

Our specific objectives were to observe the effects of radiation and the behavior of radioactive particles under conditions resembling a local

fallout situation within approximately 50 mi of the explosion. To provide for a first approximation to these postattack conditions it was necessary to achieve certain design advantages, and these included: (1) uniform particle mass load, and (2) chronic beta-gamma dose rate somewhat comparable to that of residual fallout. This paper also reports first-year results following particle application and radionuclide assimilation by plants in a subhumid climate.

Methods

Simulant Characteristics

The local fallout simulant was synthesized at NRDL from silicate sand and ^{137}Cs. This radionuclide is an important long-lived component of fallout, and from it emits both beta (0.52 and 1.18 Mev) and gamma (0.66 Mev) radiation. Approximately 100 μCi ^{137}Cs/g was fixed on sand to achieve the desired dose for a particle mass load of 25 g/ft^2, the fallout deposit for the outer fringes of the local fallout zone (Lane 1965). Controlled temperatures during the fusion process impart desired leachability to the simulant which is somewhat similar to that possessed by local fallout particles. Leachability in this case was defined as percent of ^{137}Cs dissolved in an aqueous system in 24 hr, which was 15 $\pm$ 0.6% for the material used in the experiment. Although the particle-diameter fraction (88 to 177 μ) approached upper limits of the size observed to be effectively retained by foliage, it was selected for the ease with which it could be manipulated safely during application to vegetation.

Simulant Application

Simulant was applied to an established fescue community inside rodent-proof enclosures. Released from a hopper-type spreader elevated ca. 70 cm above the grass canopy, the simulant fell directly to the vegetation. Lateral movement due to wind turbulence was negligible because of calm atmospheric conditions. Spreader travel was regulated by remote control to minimize exposure to personnel. Simulant was applied in two stages and in criss-cross directions to assure uniform coverage of the area below. Each of four 100 m^2 areas was tagged with 2.2 curies (Ci) of ^{137}Cs radioactivity. Particle mass load was approximately 22 g/ft^2.

Vegetation Measurement

Random plant samples were collected from each contaminated area for radioassay at different intervals following tagging to determine quantity of radioisotope assimilated by foliage. Sand particles first were removed from grass leaves by vacuum-cleaning; then the vegetation was assayed for activity in a single-channel spectrometer. Standing dead plant materials were prepared in the same fashion.

Quantity of living and dead dry matter in the contaminated areas was determined from nondestructive sampling methods based on a regression of mass on capacitance and an estimate of standing dead material (Van Dyne *et al.* 1968). Regression equations were derived from measurements in uncontaminated areas, and then were used to predict mass of living and dead material in the radiation zones.

Runoff Measurement

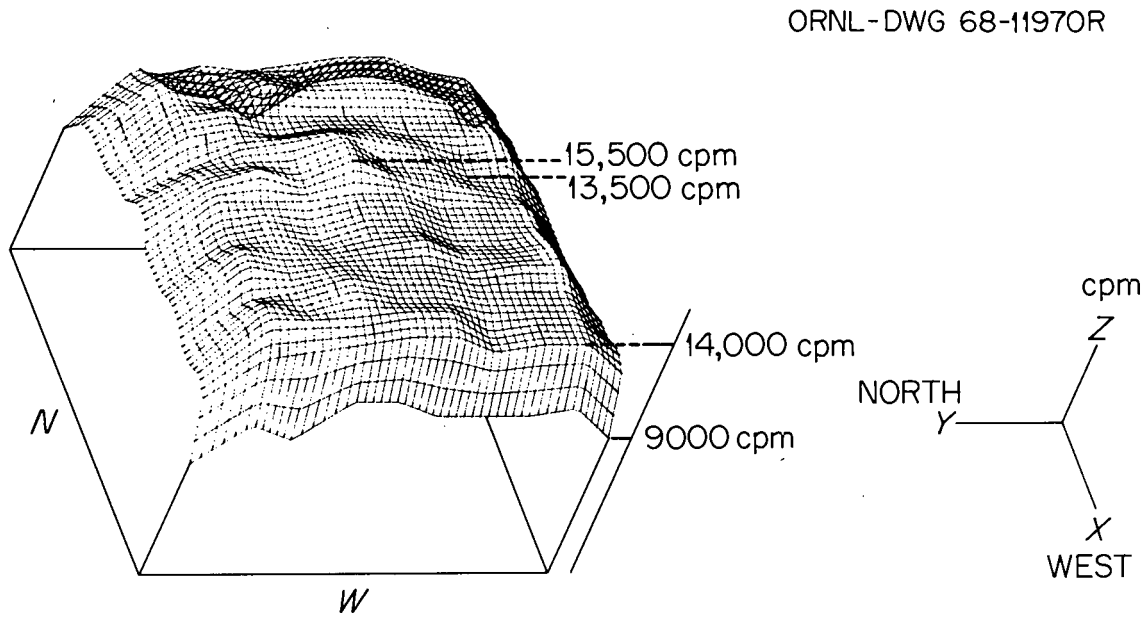
Average rainfall in this region of eastern United States is 125

cm/year, and occassionally there is significant surface water runoff during intense storms. The magnitude of radioactivity redistribution in these instances is determined by radioassay of soil and water collections and by measuring the quantity of materials carried in runoff.

Results and Discussion

Application

The ^{137}Cs fallout simulant was successfully applied to the fescue grass community. Radiation intensity was 100 and 200 mr/hr at 1 m near the edge and center, respectively, allowing 30 to 60 min/week for personnel to work in the radiation areas. There was uniform distribution of simulant in each plot according to the scan surveys (Fig. 8). The response surface shows even activity intensity over the 100 m^2 area, and maximum difference between trough and peak is 12% of the average intensity. This level of activity represents a condition when some particles still were scattered throughout the vegetation canopy. Although particles later became dislodged and incorporated into the soil, data from successive scans showed little decrease in gamma intensity, indicating a slow weathering rate of particulate fallout in this community. The extent of lateral redistribution of particles to surface depressions thus far is negligible as determined from sequential analysis of response surfaces. It has been demonstrated that the scanning instrument is sufficiently sensitive to detect intensity changes which may result from redistribution, because the locations of minor spills during simulant application agree with peaks in the response surface.



PEN 7
0800 AREA
AUG 1968

Fig. 8. Radioactivity Response Surface 1 Meter above Ground Level.

Vegetation Dynamics

A dense stand of fescue grass existed when the areas were contaminated with the simulant. Approximately half the 1200 g/m^2 (1200 kg/ha) of fescue was living and half was dead. Relative proportions of live and dead vegetation influenced whole body radioactivity of cotton rats (DiGregorio et al., this report) and cycling processes related to biological segments of the ecosystem (e.g., radionuclide redistribution to deeper horizons by roots, assimilation by consumer organisms). Quantities of dead and living vegetation remained relatively constant during the first month of the experiment, after which the living mass decreased with onset of the dormant season. Quantity of dead vegetation increased at this time, reflecting organic transfer from one compartment to another. Decomposition of dead material and organic redistribution to roots probably are responsible for the late season decreases in total quantity of above-ground vegetation.

Particle Interception and Retention

The dense grass significantly affected particle behavior because the closed canopy intercepted appreciable quantities of falling simulant (Fig. 9). Many particles remained at the site of impact for 3 or 4 days after which time those on horizontally positioned leaf blades became dislodged but were subsequently intercepted again by dead and living plant parts in the understory layer. Particles often concentrated in the crevice formed at the junction of leaf-blade and sheath, and they remained here until rainstorms washed the particles to ground surface 4 to 6 weeks later. Circular voids evident in the leaf deposit (Fig. 9) were caused by

Fig. 9. Distribution of 88-177 μ Silica Sand Particles on Plant Surfaces 2 to 3 Days Following Application. Note the concentration of particles at the junction of leaf-blade and sheath.

raindrops from a very brief shower shortly after particle application. Retention of this size particle (88 to 177 μ dia.) was unexpected, based on reports of size fraction interception by plants surrounding surface detonations (Romney et al. 1963), where 44 to 80 μ was the largest particle class collected from foliage. The seemingly higher retention in our experiments may be a function of the subhumid micro-environment caused by actively transpiring vegetation and by nightly dew deposits. In this moist environment water films developed between particles and plant parts, which enchanced particle retention and provided an aqueous medium for leaching of ^{137}Cs from particles and for transfer of nuclide to vegetation.

We recognize that particle application in this experiment was very different from deposition processes associated with surface nuclear detonation. Particle-falling velocity, air turbulence, and locally drying conditions would be important factors which were not evaluated in this situation. For example, the parameters in Miller's (1967) contamination factor equation "all depend on wind speed."

Dynamics of Radiocesium in Vegetation

The tagged particles effectively contaminated the vegetation. Initial activity (Table 8) was 1.32 ± 0.16 μCi/g and 4.6 ± 0.59 μCi/g for cleaned living and dead foliage, respectively. The ^{137}Cs content represents the quantity assimilated metabolically or adsorbed to surfaces, but presumably it does not include sand particles, because plant parts were thoroughly brushed and vacuumed before radioassay. The differential uptake (1.32 vs 4.6 μCi/g) may be attributed to several factors. Dead material was collected from sites inside the canopy where nonliving parts overlap to

Table 8. Radiocesium Content of Living and Dead Vegetation

Date	^{137}Cs of living		^{137}Cs of dead		Total ^{137}Cs of plant component
	$\mu Ci/g$[a]	$\mu Ci/m^2$	$\mu Ci/g$	$\mu Ci/m^2$	mCi/m^2
16 Aug.	1.32 ± 0.16	840	4.62 ± 0.59	2587	3.48[b]
23 Aug.	1.05 ± 0.15	672	-	-	-
5 Sept.	0.52 ± 0.05	335	4.12 ± 0.48	2390	2.72
3 Oct.	0.49 ± 0.04	223	3.15 ± 0.22	1922	2.14
17 Oct.	0.38 ± 0.02	126	3.73 ± 0.30	2324	2.45
13 Dec.	0.16 ± 0.01	45	0.57 ± 0.09	428	0.47
15 Jan.	0.155 ± 0.006	33	0.19 ± 0.02	146	0.18
2 Mar.	0.18 ± 0.009	-	0.29 ± 0.03	-	-
29 Apr.	0.008 ± 0.001	-	0.22 ± 0.03	-	-
30 June	0.019 ± 0.006	-	0.28 ± 0.03	-	-
9 Aug.	0.014 ± 0.003	-	0.29 ± 0.06	-	-

[a]Dry Matter

[b]Summation of columns 3 and 5

form a closed layer above the soil and litter, and this zone may have trapped particles more effectively than living foliage. Also, because of the modified microenvironment in this layer there were better moisture conditions on vegetation surfaces, thus enhancing the leaching of ^{137}Cs from particles and adsorption to dead plants. Diurnal moistening and drying cycles in association with morning dew deposits may have been responsible for the magnitude of ^{137}Cs transfer from particles to vegetation.

Three factors would tend to reduce ^{137}Cs content in living foliage relative to dead vegetation. Except in axillary crevices, the time of initial particle contact with dead vegetation was approximately twice that of living (8 vs 3 to 4 days). This would allow for greater leaching and diffusion of ^{137}Cs from particles to vegetation in the case of standing dead materials. Secondly, new growth in the 8-day period between contamination and sampling would have diluted finitely absorbed amounts of radiocesium. But growth rates were not of a magnitude to account for a three-to-fourfold dilution in activity. Thirdly, internal redistribution of assimilated radiocesium to other plant parts would reduce the quantity present in foliage. Results of laboratory experiments (Fig. 10) show that approximately 20% of assimilated radiocesium will be transported to the root system within 8 days. This process definitely would reduce ^{137}Cs content of live foliage, but not to the extent of observed differences between living and dead vegetation. Conceivably a combination of factors (shorter particle residence time on living foliage, dilution due to new growth, transport to the root system) could account for the observed differences in ^{137}Cs content in living and dead plant parts.

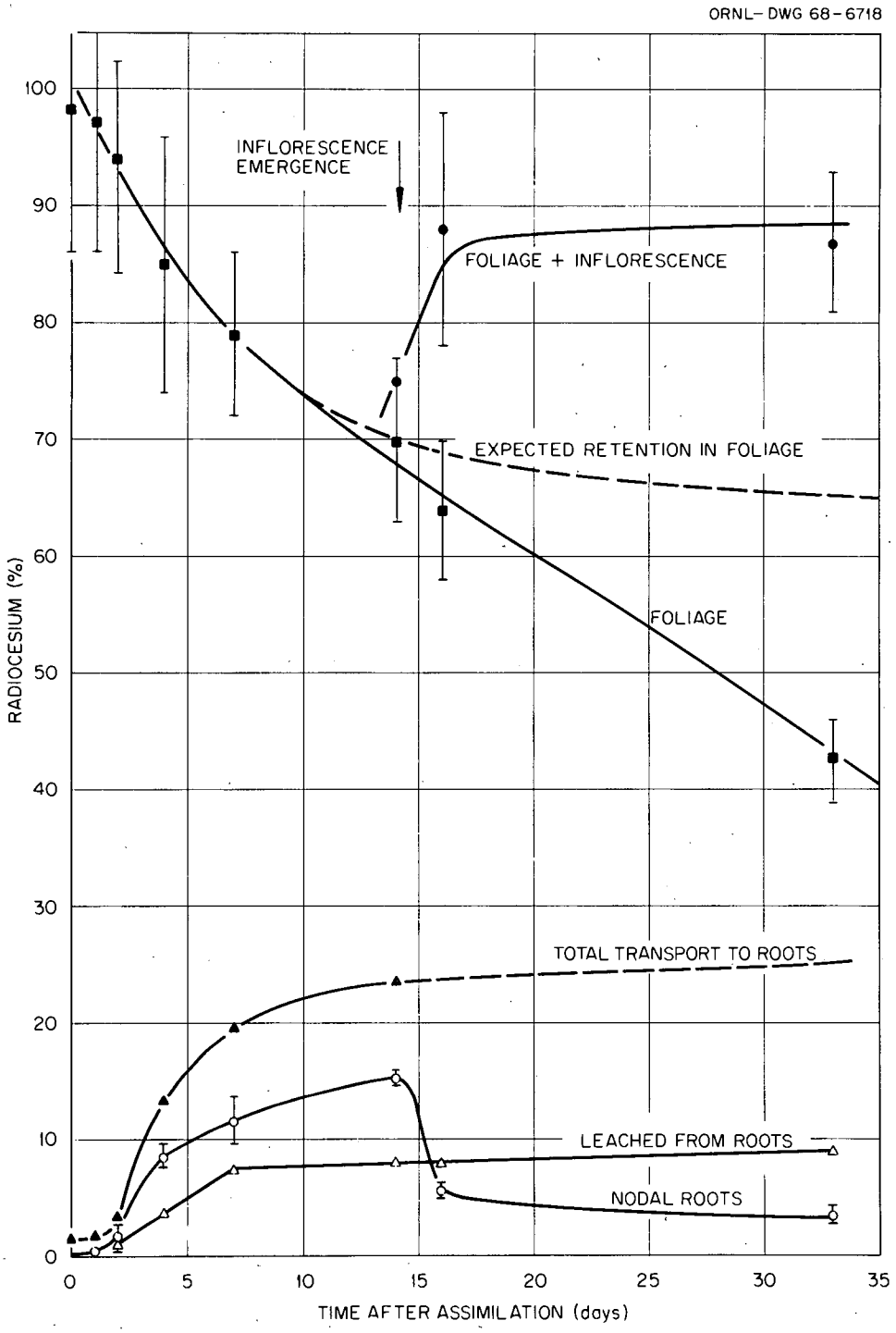


Fig. 10. Distribution of Radiocesium in Fescue Following Foliar Assimilation.

Results of a laboratory experiment in which grass foliage was contaminated (Fig. 10) show the magnitude of intraplant transport of radiocesium. Approximately 25% of assimilated radiocesium moved to the root system in 14 days. Then there was redistribution to the inflorescence which emerged shortly thereafter. Extensive radiocesium mobility in plants has been well-documented (Waller and Olson 1967 and Levi 1966), and its movement to reproductive structures presents an added dimension of hazard to man and other herbivores. Accumulation of the long-lived nuclide in edible plant parts could increase appreciably the intake of body burdens of man and other animals which selectively feed on seeds and fruits.

Total radioactivity accumulation in biological organisms constitutes one major hazard of environmental contamination. The fraction of radioactivity that transfers from fallout particles to plants constitutes the base level in foodstuffs which will be consumed directly or indirectly by man. Knowledge of fallout deposition, particle characteristics, and the quantity of vegetation per unit area was used to estimate the ^{137}Cs transfer coefficient (simulant particles to vegetation). Total activity in all vegetation was determined as 3.4 mCi/m^2 (Table 8, last column) 8 days after particle deposition. This value represents 15% of ^{137}Cs deposited on the area (22 mCi/m^2). Although greater than expected, the estimated transfer (15%) was consistent with results of simulant leachability (15%, 24 hr in water). Tamura (1968) reported that nearly all radiocesium sprayed on field plots initially was associated with vegetation. Apparently radiocesium is first fixed by the vegetation when there is suitable contact by means of an aqueous carrier. Plant material

seems to behave as a sponge as it soaks up the radionuclide. To effect 15% transfer to vegetation it would have seemed necessary for nearly all the particles to have remained on plant parts for at least 1 day, but some fell to the ground at the time of initial application. Apparently optimal moisture conditions existed for those which remained on the vegetation, and this enhanced the radionuclide movement to fescue vegetation.

These results cannot be applied directly to local fallout situations because the radionuclide leachability of the simulant particles (15%) is somewhat greater than most values given for actual fallout (usually 1 to 5% and 20% maximum [Lane 1965]). Also, our simulant contained only one radionuclide, ^{137}Cs, and it is highly mobile when in contact with biological systems. Ultimate tests with fallout simulant should include mixed isotope preparations possessing various leachability properties, and particles should be tested in different climatic and environmental situations.

First-year decrease of ^{137}Cs in live fescue is described by a negative exponential function, $Y = 0.27 + 1.59\ e^{-0.32t}$, where Y = μCi/g and t = days (Fig. 11). Activity decreased by an order of magnitude within 4 months after application of the simulant, and later seasonal fluctuations were relatively minor. A significant doubling of activity density in June, 1969 (.08 μCi/g to .18 μCi/g) may be attributed to increased root feeding associated with the early season flush of new growth. Thereafter, the activity density of living and dead vegetation became stabilized as the ^{137}Cs approached a new equilibrium in the plant-soil system.

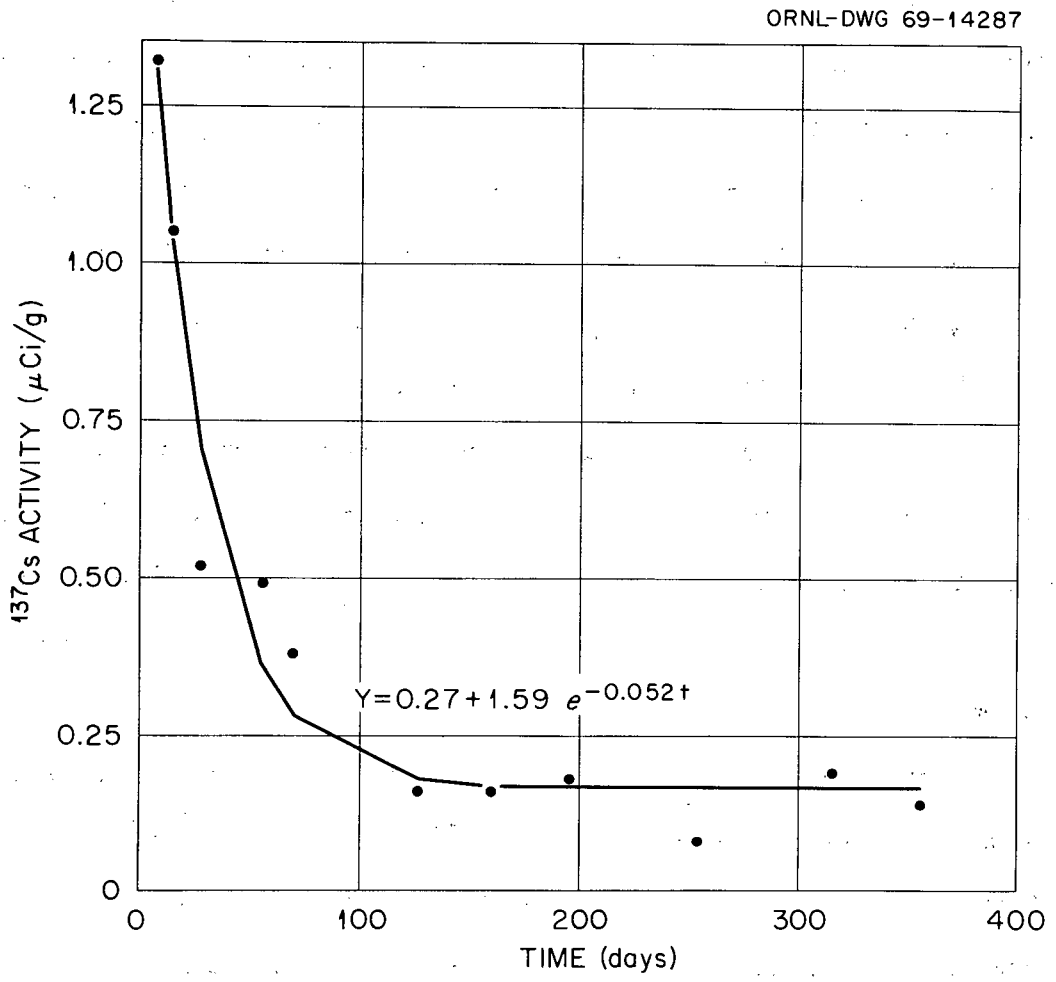


Fig. 11. Radiocesium Activity of Fescue Vegetation After Contamination by Fallout Simulant Particles.

Weathering Loss of Foliage ^{137}Cs

Weathering processes remove particles and dissolved radionuclide from contaminated materials, and the weathering half-life of ^{137}Cs was calculated from daily loss rates of the fraction which had been incorporated by plant tissue. Values in Table 9 are the half-life times per unit mass or area. The short-term component for living vegetation had a 3-week half-life, and it was the same whether activity was expressed per unit mass or per unit area. Weathering half-life of the living long-term component and that of dead vegetation was approximately 80 days. Surprisingly, the weathering half-life was shorter during the initial 4-week interval of no measurable rainfall. The results expressed herein indicate that there are complex interactions between fallout particles and vegetation, and that there are important factors other than rainfall which affect weathering.

Redistribution of Contaminant by Rainfall

Lateral movement of the contaminant over the ground surface can be assessed from sequential examination of scan surveys, and from measurement of surface water runoff. No redistribution has been detected from changes in the response surface of the scan data, and only a small quantity of ^{137}Cs was carried from the contaminated area in runoff.

Prior to fallout simulant application the magnitude of ^{137}Cs transfer in runoff was predicted from a simple compartmental model (Fig. 12), which was based on physical characteristics of simulant and soil, and on rainfall-runoff relationships observed during the preceding year (Dahlman and Auerbach 1968). According to the model only 0.13 mCi of ^{137}Cs (0.006% of that present) would move from the area in runoff for each significant

Table 9. Weathering Half-life[a] of Radiocesium in Vegetation

	Expressed in days per unit of	
	Mass	Area
Live vegetation		
Fast component	20	21
Slow component	106	74
Combined	76	65
Dead vegetation		
Single component	81	87
All vegetables	-	76

[a]Half-life is defined as the days for loss of half the ^{137}Cs assimilated by the foliage. Calculations were made from linear regression equations ($r^2 > .9$) of activity values on time.

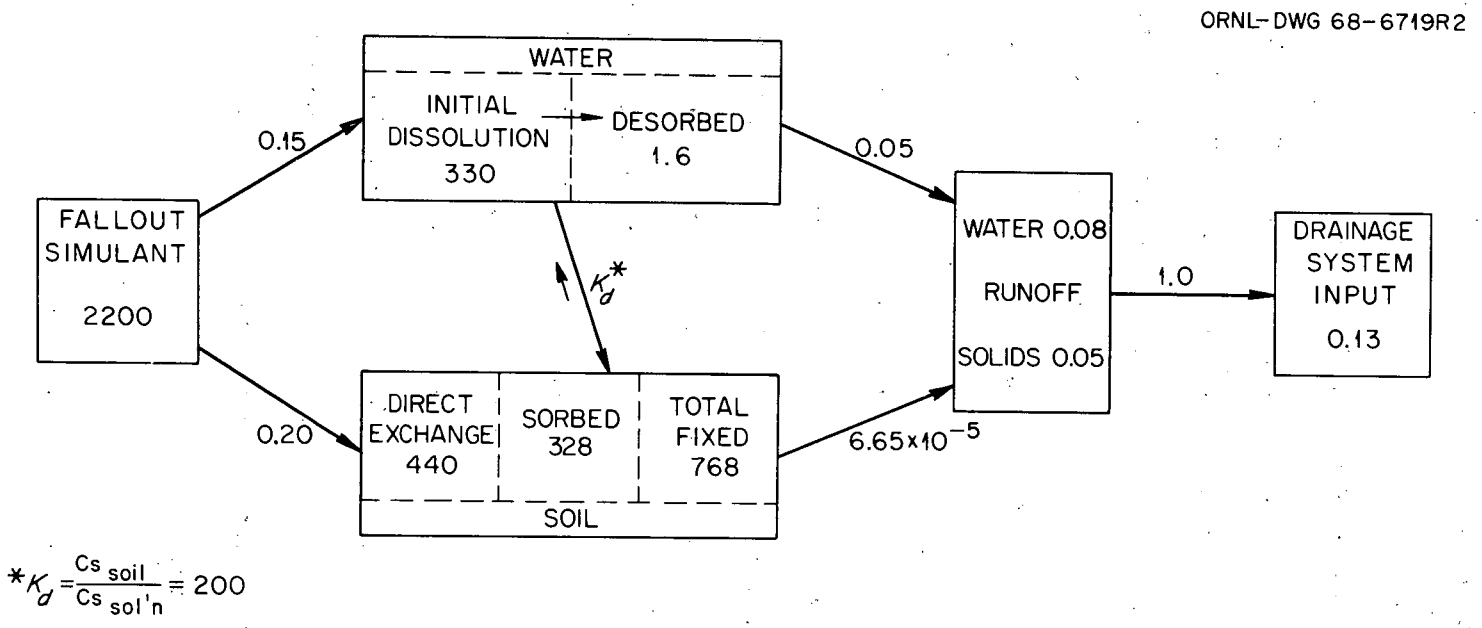


Fig. 12. Predicted Movement of Radiocesium from One Contaminated Plot ($100m^2$) Shortly After Application of Fallout Simulant. Numbers in compartments represent mCi of ^{137}Cs/plot and other values indicate fractional transfer between compartments. Multiply compartment values by 100 to express activity in mCi/ha.

precipitation event (one in which >2% of the input occurs as runoff). Because of a distribution coefficient (K_d) of 200, it was estimated that approximately one-third of the activity would be fixed to soil and the remainder dissolved in water. The actual results for 4 measurable runoff events are presented in Table 10. Two events, each occurring in mid-winter of 1969 and 1970, produced a significant quantity of runoff which removed 0.12 and 0.18 mCi of ^{137}Cs, respectively. The measured quantity was in surprisingly good agreement with the predicted value based on the model (0.12 and 0.18 vs 0.13 mCi). There was poor agreement, however, between the predicted and observed relative proportions of ^{137}Cs in soil and water. Practically all the activity was present in the water, a probable consequence of the unusually small quantity of eroded soil (approximately 1 g for each current event vs 80 g/event for equivalent runoff based on precontamination observations). Obviously, the dense vegetation prevents soil erosion, and it also restricts soil-water mixing, a process which influences the magnitude of cesium sorption by soil. That removal of radiocesium was greatest in the aqueous phase supports the contention of high ^{137}Cs mobility during the initial period of the investigation. In this case approximately 15% of the radiocesium was leached from particles, temporarily absorbed by vegetation, then partially removed in surface-water runoff. A significant quantity was still in a transient state after 5 months because it had not yet been immobilized by the soil.

Our preliminary results indicated that only a negligible quantity of ^{137}Cs (0.006%/runoff event) would move from a contaminated area to the natural drainage system. Less than 20 such events would be expected

Table 10. Runoff, Erosion, and ^{137}Cs Movement from an Area Contaminated with Fallout Simulant

Event	Runoff		Erosion		Total activity in runoff
	Quantity (ℓ)	^{137}Cs (μCi)	Quantity (g)	^{137}Cs (μCi)	(mCi)
Jan. 20	2	1	0.06	0.2	0.001
Feb. 3	400	117	0.5	1.3	0.118
Feb. 4	2	0.8	0.3	0.1	0.001
Dec. 28	860	143	1.2	42	0.185

annually, and total loss would be approximately 0.1% per year. An average of only 2 events per year, however, has been observed since 1968, indicating very limited movement of contaminant from a vegetated meadow ecosystem. The low order of magnitude movement would represent a lower limit of radioactivity redistribution for larger landscape areas. The maximum expected could be considerably greater on tilled and fallow fields because Tamura (1968) observed an average annual loss of approximately 20% when the isotope was sprayed on fallow soil. In this case practically all the movement was via soil erosion, approximately 26 metric tons/ha/yr. Research on problems of environmental contamination has provided these guidelines for estimating magnitude of radioactivity redistribution from meadow and fallow landscape units. On a long-term basis our continuing efforts will furnish additional results on the effect of chronic radiation on yield, which in turn could influence radionuclide movement in the environment due to changes in quantity or composition of plant cover.

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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 are being investigated in (1) short-term laboratory studies on interactions of fallout radiation with population dynamics of selected species, (2) long-term field observations on interactions of simulated radioactive fallout with seasonal changes in arthropod community composition and structure, and (3) studies of the biological and physical dosimetry of beta and gamma radiation in the fallout area. Data on the exposure of Folsomia (Collembola) to beta radiation from ^{90}Sr-^{90}Y fallout indicate that the sensitivity of the population is determined primarily by sensitivity of fertility rates rather than by sensitivity of adults. Dose rates estimated to given 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. A sequential three-way analysis of variance on data from a study of the effects of simulated radioactive fallout on an old field arthropod community indicated significant differences between dates and between taxa. There was no significant difference between two field enclosures before application of the fallout, but a significant difference between the control and contaminated pens did appear four months later. Lithium fluoride microdosimeters attached to grasshoppers and crickets in the fallout field indicate that these two closely related organisms receive highly significantly different radiation doses.

Introduction

Information on responses of arthropod communities to ionizing radiation as it interacts with other environmental parameters is needed for predicting patterns of ecological response to a nuclear attack and for planning postattack agricultural procedures. Responses of arthropod communities to gamma radiation are not well known, and information is especially meager on the role of beta radiation as an environmental parameter. 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 are being conducted: (1) short-term, intensive laboratory studies on interaction of fallout with population dynamics of selected species, (2) long-term, extensive field observations on interactions of fallout simulant with seasonal changes in arthropod community composition and structure, and (3) biological and physical dosimetry in the fallout area.

Effect of Chronic Beta Radiation on Folsomia sp. (Collembola)

Many agricultural situations may be upset by effects of radioactive fallout on insect populations (Wong 1967). In particular, fallout beta radiation may be a hazard to small insects and insects that pass developmental stages in soil and litter. Collembola are among the most numerous microarthropods in the soil fauna, and they are important in soil formation. The objective of this study is to assess effects of chronic beta radiation on a collembola population.

Albite sand grains (44 to 88 μ in diameter) coated with $^{90}Sr + ^{90}Y$ were suspended in glycerol and painted onto charcoal-calcium sulfate

substrates. Nonradioactive sand grains in glycerol were used to prepare control culture jars. Dose rates of 3.3 to 341.7 rads/hr were determined using 0.5 x 6.0-mm LiF dosimeters (Harshaw Chemical Co. TLD-100 extruded crystals). Groups of 8 to 12 adult Folsomia sp. were placed in 10 control and in 19 experimental culture jars. The cultures were maintained at 20°C, and the substrates were kept saturated with water. The Collembola were fed brewer's yeast, and numbers of adults, juveniles, and eggs were scored biweekly for 98 days.

Survival and reproductive ability of Collembola were reduced by all dose rates. The LDR_{50-30} for adults was estimated by least-squares regression to be 174.5 rads/hr; the LDR_{50-60}, 38.1 rads/hr. The LT_{50} control populations was estimated at 183.7 days. The effects of chronic beta radiation on fecundity rates (Fig. 13) could not be anticipated from studies (Styron 1969, O'Neill and Styron 1968) of the effects of acute irradiation on this parameter. Following an acute dose of ionizing radiation, fecundity rate of each population was reduced to a new rate. Under chronic irradiation conditions, however, all fecundity rates were initially at control levels and were reduced through time as total doses were accumulated. Change in fecundity rates under chronic irradiation conditions must therefore be represented as the slope of a regression line rather than as a point. Fecundity rates approached zero very rapidly at dose rates greater than 5 rads/hr. Egg mortality (Fig. 14) was greatly increased by radiation 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 grew into adults, but they were sterile.

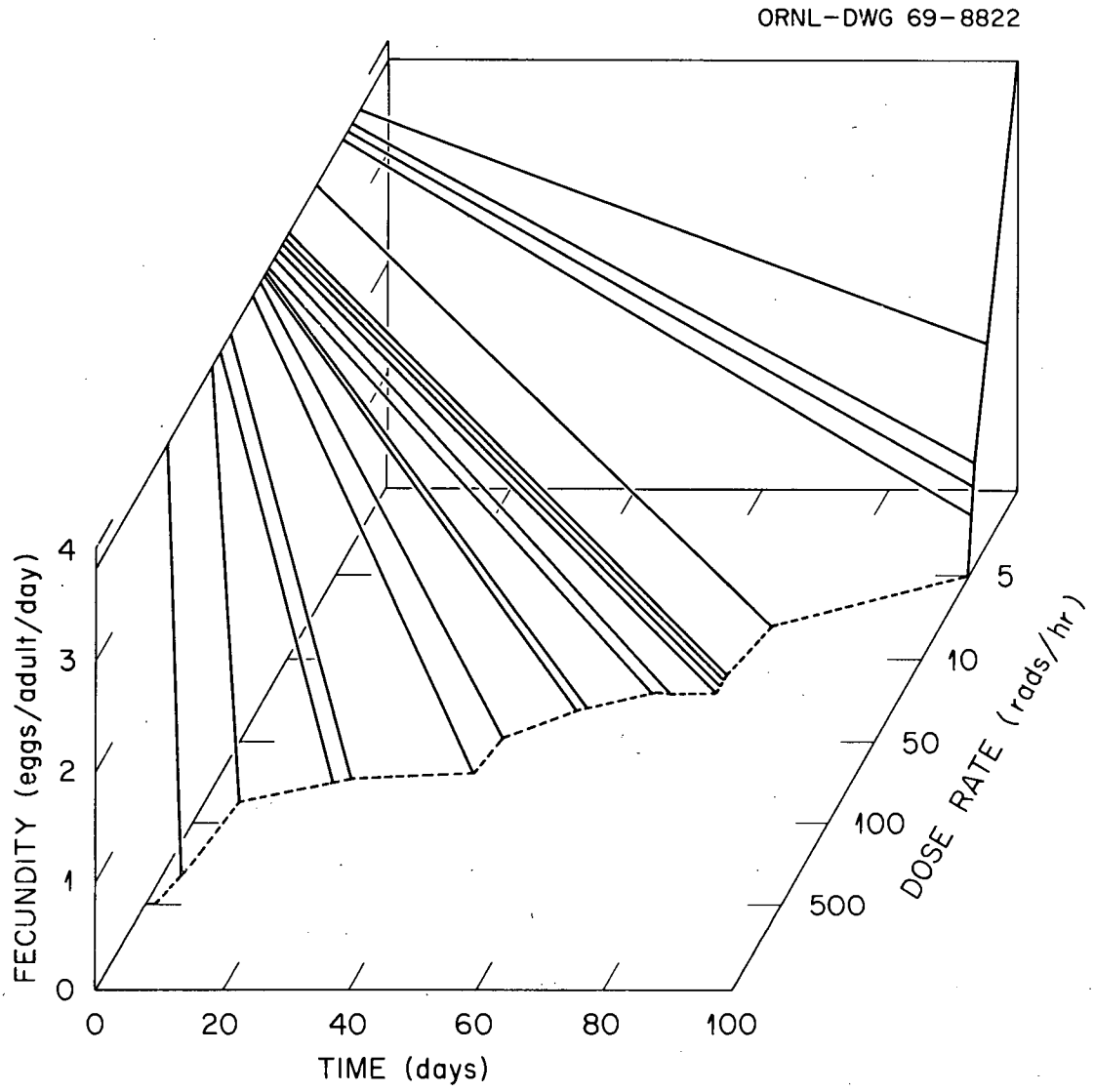

Fig. 13. Isometric Projection of Fecundity in Eggs per Adult per Day on Time in Days and $^{90}Sr + ^{90}Y$ Beta Radiation Dose Rate for Folsomia sp. The fecundity rates for each dose rate are presented as a regression on time, since the fecundity of each population changed as the total doses of radiation were accumulated.

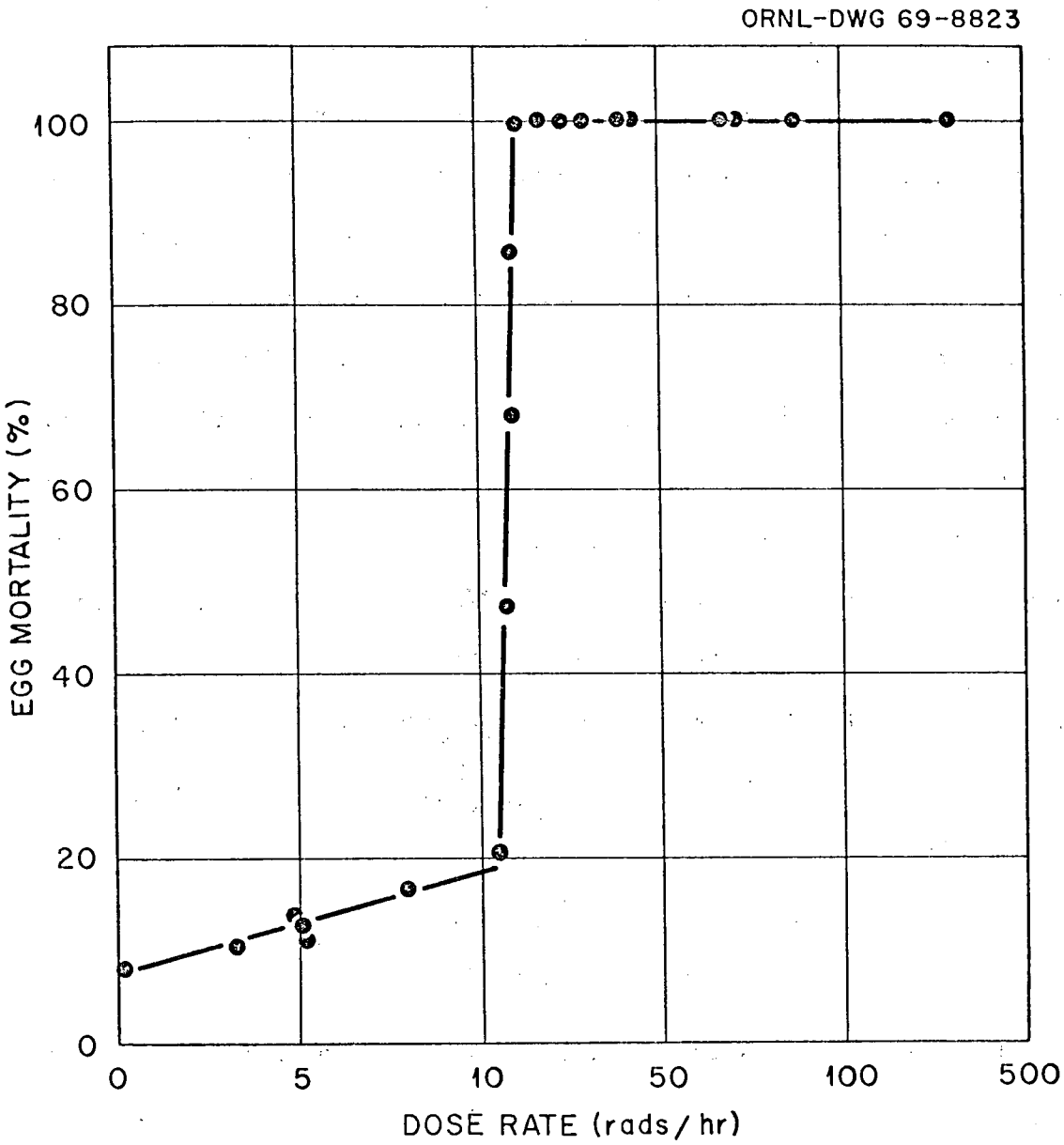

Fig. 14. Egg Mortality Plotted Against $^{90}Sr + ^{90}Y$ Beta Radiation Dose Rate for Folsomia sp. The point at 0 rads/hr represents the mean of 10 control populations.

These data demonstrate that the sensitivity of a population of Folsomia to beta radiation is determined primarily by sensitivity of fertility rates (number of eggs surviving) rather than by sensitivity of adults. Dose rates estimated to give an LD_{50-30} or LD_{50-60} for adults are more than twice as high as dose rates required to reduce fertility to zero. Sensitivity of fertility rates to acute irradiation has been demonstrated for another collembolan (Sinella) population (Styron 1969). For the acute irradiation regime, however, substantial recovery occurred several weeks following irradiation. If a natural population of these insects were subjected to acute irradiation during a seasonal 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 could thus be masked by seasonal cycles in reproduction. This situation would not be expected for populations under chronic irradiation conditions, since recovery cannot occur.

Effects of Simulated Radioactive Fallout on an Old Field Arthropod Community

There are practically no experimental data available on ecological responses of arthropod communities to chronic beta and gamma radiation within the context of an entire ecosystem. A project has been initiated at the 0800 Ecology Research Area to assess effects of beta and gamma radiation from simulated radioactive fallout on an old-field ecosystem. The study of responses of the arthropod community is a continuing one, and this report will cover the first year's observations and development of analytical techniques.

Simulated radioactive fallout, 2.44 Ci of ^{137}Cs on silica sand grains (Dahlman and Auerbach 1968, Auerbach 1969), was applied in July and August, 1968 to a 100-m^2 pen in an old-field ecosystem dominated by Festuca elatoir. Three sites in the field--one fenced with sheet metal, one fenced and contaminated with fallout, and one merely roped off--were sampled bimonthly during the first year and are now being sampled monthly. The roped area was established for comparison with the uncontaminated pen to detect possible effects of the fencing itself. Sampling was begun four months prior to application of fallout simulant. Seventy-eight arthropod taxa are being sorted from samples collected with pitfall traps, soil cores, and biocoenometers.

A sequential three-way analysis of variance has been applied to data from 14 sampling periods as a means for detecting significant changes in structure of the arthropod community. Variance between sites, taxa, and sampling dates was first calculated using the seven sampling dates prior to application of the fallout simulant. An F-test indicated significant differences between dates ($P \leq 0.01$) and taxa ($P \leq 0.01$), but not between the two pens or between either pen and the roped area. Difference between sampling dates would be expected because of seasonal responses of the arthropod community, and difference between taxa would also be expected because the taxa normally occur at different population densities. Lack of a significant difference between the arthropod communities of the two pens before application of the fallout lends support to the use of either pen as a control following the application. An analysis of all 14 sampling dates confirmed the differences between dates ($P \leq 0.01$) and between taxa ($P \leq 0.01$) as well as the lack of a

significant difference between sites. However, when the initial sampling dates were sequentially deleted and the analysis of variance repeated after each deletion, a significant difference ($P \leq 0.05$) between the control and the contaminated pens appeared four months (six sampling dates) after application of the fallout simulant.

The following compartment model of the arthropod community has been developed for analysis of effects of ionizing radiation on model parameters. The 78 arthropod taxa have been grouped into six compartments: herbivores and carnivores in the soil, in the litter, and in the standing grass. Changes in the herbivore compartments are described by equation (1); changes in the carnivore compartments, by equation (2):

$$\frac{dH_i}{dt} = r_i H_i \left(1 - \frac{1}{k_{H_i}} H_i - \frac{a_i}{k_{H_i}} C_i \right) - e_i(t) H_i, \qquad i = 1,2,3; \qquad (1)$$

$$\frac{dC_i}{dt} = r_i C_i \left(1 - \frac{1}{k_{C_i}} C_i - \frac{a_i}{k_{C_i}} H_i \right) - e_i(t) C_i, \qquad i = 1,2,3; \qquad (2)$$

where r_i = intrinsic rate of increase (birth - death),

k_i = environmental carrying capacity,

a_i = coefficient of interaction, and

$e_i(t)$ = environmental stress parameter.

Parameters in these equations, r_i, k_i, a_i, and $e_i(t)$, will be quantified for both the control and experimental sites. The data will be fitted to the model by a random-search method which is presently under development. The value of this model is that not only will it be possible to state whether a significant change in structure of the

arthropod community has taken place, but it will also be possible to identify parameters or aspects of community dynamics that have been modified by the simulated radioactive fallout.

Considerable efforts have been devoted to studies of energy transfers through ecosystems and the associated pathways. Use of radioactive tracers in studies of community dynamics has greatly extended such investigations, but in some experimental situations the use of radioactive tracers may be either undesirable or impracticable. As a case in point, the experimental design of this project on effects of radioactive fallout on an arthropod community does not permit the introduction of additional radioactive isotopes into the system. Techniques of cross-correlation (Mott 1966) have been suggested as a possible alternative method for studying predator-prey and competition relationships in an arthropod community.

In the cross-correlation analysis the total catch of each taxon, X, for each sampling period, 1 to N, was used. Covariances of $x_1x_2 \ldots x_1x_n \ldots x_{n-1}x_n$ were calculated from the equation

$$\mathrm{cov}(x_i x_j) = \sum_{k=1}^{N} (X_{ik} - \overline{X}_i)\ (X_{jk} - \overline{X}_j).$$

Resulting covariance values were strongly biased by number of each taxon that was caught. It was thus difficult to compare hundreds of aphids with scores of grasshoppers or dozens of crickets. Covariance values, then, were normalized with the partial correlation equation

$$r_{ij} = \sum_{k=1}^{N} \frac{(X_{ik} - \overline{X}_i)\ (X_{jk} - \overline{X}_j)}{\sqrt{\Sigma\ (X_{ik} - \overline{X}_i)^2}\ \sqrt{\Sigma\ (X_{jk} - \overline{X}_j)^2}}\ .$$

Significant correlations may appear in the arthropod community for two reasons. Populations may vary in response to one common environmental parameter, such as temperature, or in response to several correlated parameters. Populations of Collembola, for instance, achieve their maxima at different seasons. An analysis of this response would yield a large negative value, indicating competition even though the two populations are not active during the same season. Significant correlation values would also be expected for populations varying in response to one another. A high positive value may suggest a predator-prey relationship; a large negative value, competition.

As a means of evaluating this technique, several taxa were selected, based on their documented relationships or responses to environmental conditions. These documented relationships were then compared with relationships predicted from values in a correlation matrix (Table 11). High positive correlation between the cricket Pteronemobius and lycosid spiders was expected since these spiders are known to feed on adult crickets. High correlation between Pteronemobius and the thomicid spiders appears to have resulted from predation of young crickets. Low correlation values between Drosophilidae and Entomobrya, Pteronemobius, Carabidae, Lycosidae, and Thomicidae would be expected because of their diverse feeding habits. There are also low correlation values between the Mycetophilidae and Entomobrya, Paederus, Formicidae, and Thomicidae. The large negative correlation between Lycosidae and Carabidae suggests competition between these two arthropod predators. The high positive correlation between Paederus and Pteronemobius is less easily explained.

Table 11. Cross-Correlation Matrix for Ten Arthropod Taxa

Taxa	Correlation values									
	Entomobrya	Pteronemobius	Carabidae	Paederus	Formicidae	Mycetophilidae	Drosophilidae	Aphididae	Lycosidae	Thomicidae
Entomobrya	1.00									
Pteronemobius	0.14	1.00								
Carabidae	0.36	−0.33	1.00							
Paederus	0.29	0.83	0.00	1.00						
Formicidae	0.50	0.00	−0.25	0.50	1.00					
Mycetophilidae	0.07	−0.17	−0.17	0.07	0.07	1.00				
Drosophilidae	0.07	0.00	0.00	0.29	0.36	0.17	1.00			
Aphididae	−0.07	−0.17	−0.17	−0.07	−0.07	0.25	0.07	1.00		
Lycosidae	0.50	0.67	−0.58	0.21	0.29	0.17	−0.07	0.17	1.00	
Thomicidae	−0.07	1.00	0.00	−0.07	0.07	−0.08	0.00	0.17	0.29	1.00

Since both the rove beetle and cricket dwell in litter, however, it is likely that the populations differ in response to a common environmental parameter.

Agreement of expected relationships with those suggested by this analysis lends support to its use in investigations of community dynamics. It should be possible, for instance, to establish relationships in an arthropod community before an experimental treatment and then follow changes in these relationships through seasons.

Applications of LiF Crystals in Ecological Radiation Dosimetry

Radiation levels in contaminated areas are usually determined with ionization chambers, scintillation counters, G-M counters, or silver-activated metaphosphate glass dosimeters. Serious difficulties must be overcome when any of these methods are used in long-term field situations where the radiation levels are low. Expense and inability of electronic equipment to withstand harsh environmental conditions are obvious, and the metal shielding of most sensors obviates their use in measuring beta radiation. Glass rod dosimeters have overcome many of these disadvantages for dosimetry in the field, but they are fragile and light-sensitive, their response is for all practical purposes limited to a minimum absorbed dose of 1 rad, and for beta radiation their response is energy-dependent.

In ^{137}Cs-tagged plot studies at the 0800 Ecology Research Area, measurements of beta as well as gamma dose rates are needed. Beta radiation may be a primary factor in the survival of organisms ingesting, carrying externally, or living in contact with fallout. Surface beta dose rate is considered to be 40 times the gamma dose rate (Brown 1965), and this is delivered in close proximity to sensitive tissues such as plant meristems

and developing insect eggs in soil. Several mathematical models are available for predicting beta and gamma radiation dose rates from the quantity of fallout present, but these models are rendered inadequate for ecological situations by restrictions in geometry; for example, surface conditions, presence of grass, and movement of fallout. Thermoluminescent dosimeter materials were selected for this study since they are mechanically rugged, available in several geometries and small sizes, and insensitive to light. Cleaved crystals (1 mm^3) and extruded crystals (0.5 x 6.0 mm) of LiF (Harshaw Chemical Company TLD-100) were used, because this material is essentially energy-independent for beta and gamma radiation and it can measure doses as low as 5 millirads.

Beta and gamma point dosimetry was begun with the first application of fallout simulant. Extruded crystals of LiF were suspended at several heights above the ground. Some dosimeters were unshielded, while others were contained within nylon capsules which absorbed more than 95% of the ^{137}Cs beta radiation. Gamma and gamma-plus-beta radiation dose rates integrated over the first week in the middle of Pen 3 (Fig. 15) can be used to estimate the beta radiation dose rate by subtraction. As a consequence of the short range of ^{137}Cs beta particles in air and vegetation, beta dose rates can be used to estimate the vertical distribution of fallout for the point at which the series of dosimeters was suspended. Beta radiation dose rates during the first week following application indicated that 45 to 50% of the simulant was present in the litter layer and 25 to 30% was on the ground surface. Eleven weeks after first application

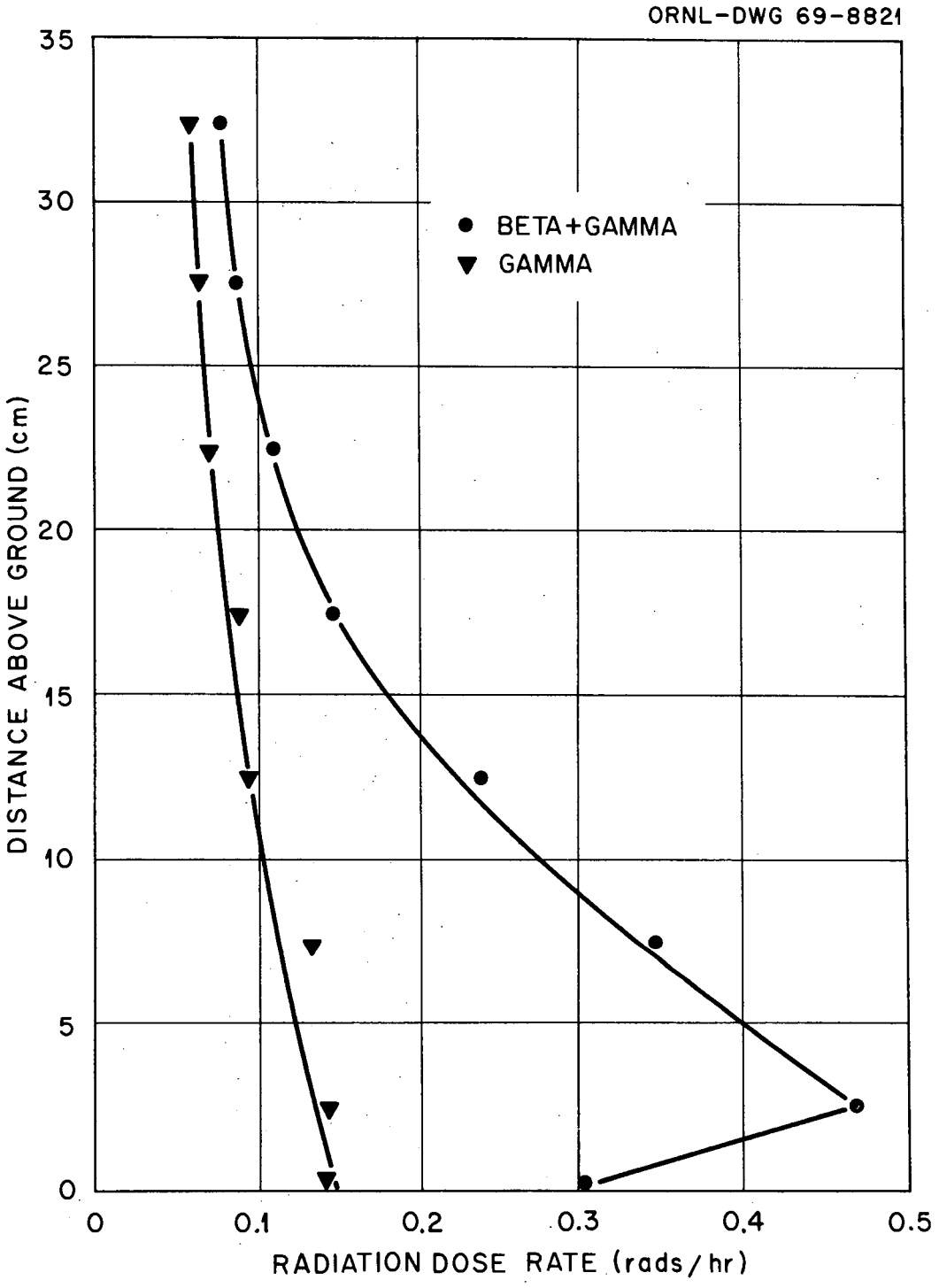

Fig. 15. Distance Above Ground Plotted Against Gamma and Beta-Gamma Radiation Dose Rates in the Middle of Site 3 at the 0800 Ecology Research Area During the First Week After Application of Simulated Radioactive Fallout. The distance between the two dose rate lines represents the beta radiation dose rate.

and eight weeks after second dosing of simulant (Fig. 16), 50 to 55% of the beta dose appeared on the ground surface, 25 to 30% was delivered in the litter layer, and less than 10% could be accounted for at the height of leaf surfaces (20 to 30 cm).

Microdosimeters have also been placed on and in grass stems and on insects. The attached dosimeters integrate the dose received by an insect as it moves through various dose rate levels and thereby eliminate disadvantages of estimating total dose from purely physical measurements. Results of a typical emplacement of extruded crystals during the eleventh week after the first application of simulated radioactive fallout (Fig. 16) show that most of the intercepted simulant had been washed from leaf surfaces but that some remained trapped in leaf axils. Beta-gamma dose rates in axils ranged from 931 to 1145 mr/hr, as compared with air dose rates at the same height above ground of 200 to 250 mr/hr. Grasshoppers (Melanoplus) and crickets (Acheta domesticus) with cleaved crystals attached to their thorax and abdomen were released in Pen 3 during the same week. Differences between dose rates to thorax and abdomen of the insects (Table 12) were not significant, but there was a significant difference ($P \leq 0.01$) between exposure rates of the grasshoppers and crickets. These two insects are closely related taxonomically but occupy different habitats. Crickets dwell primarily on and in litter, where they are exposed to more beta radiation, and grasshoppers dwell higher on blades of grass. Thus any attempt to predict ecosystem responses to radioactive fallout based on different radiation sensitivities must also deal with the problem of differential radiation exposures.

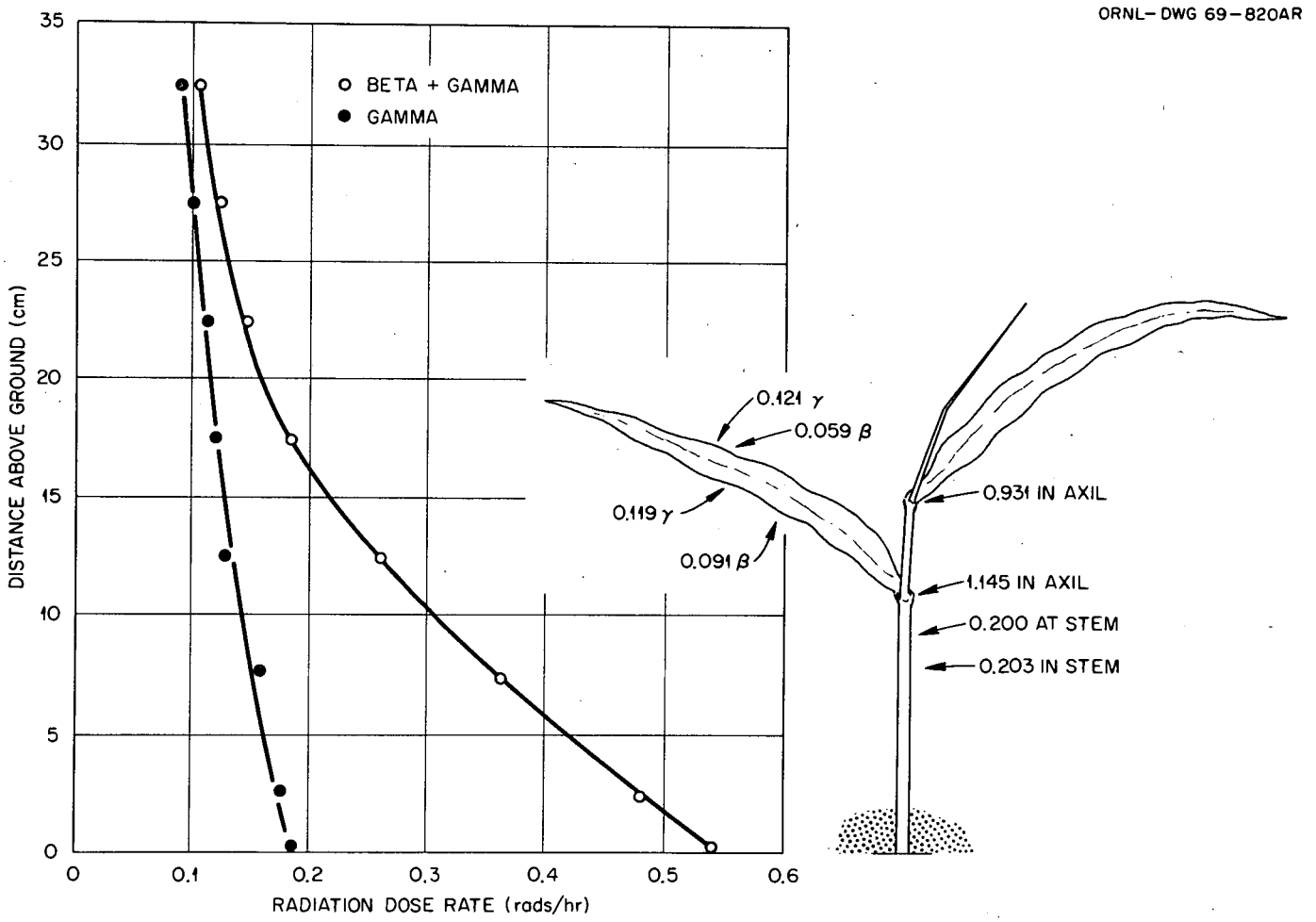

Fig. 16. Distance Above Ground Plotted Against Gamma and Beta-Gamma Radiation Dose Rates in the Middle of Site 3 at the 0800 Ecology Research Area During the Eleventh Week After the First Application and the Eighth Week After the Second Application of Simulation Radioactive Fallout. The distance between the two dose rate lines represents the beta radiation dose rate. Beta, gamma, and the combined dose rates observed for a fescue plant are also presented.

Table 12. Dose Rate (rads/hr) to Grasshoppers (*Melanoplus* sp.) and Crickets (*Acheta domesticus*) from Simulated Radioactive Fallout in Pen 3 of the 0800 Ecological Research Area

Organism	Thorax	Abdomen
Acheta domesticus, living	0.222	0.307
Melanoplus sp., living	0.090	0.095
Melanoplus sp., phantom	0.112	0.203

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GAMMA IRRADIATION OF ARTHROPOD POPULATIONS

R. I. Van Hook, Jr., and Gladys J. Dodson

SUMMARY

Effects of 5000 rads gamma radiation delivered at five different dose rates on the survival of young adult crickets, Acheta domesticus, were determined. Significant differential mortality occurred as the dose rate was varied. Lower dose rates resulted in reduced mortality. Mortality increased with increasing dose rate up to a point above which further increases in irradiation intensity produced very similar mortality rates.

Introduction

Predictions of arthropod population responses to ionizing radiations such as those produced by fallout from a nuclear burst are based in great part on laboratory studies with acute doses. For these studies to be relevant to fallout situations, variations in dose rate should be carefully considered. Ideally, dose rates used in the laboratory should be the same as those encountered in fallout fields. However, this is impractical in instances where fallout radiation dose rate is substantially less than that available from laboratory sources. In these instances, it becomes necessary to assume that there is no dose-rate effect present and the effect observed from the high laboratory dose rate is identical to the effect expected from the low dose rate of fallout. A recent experiment was initiated to determine presence or absence of a dose-rate effect on survivorship of crickets which were given an LD_{50-20} dose of ^{60}Co radiation.

Methods and Materials

Adult crickets (Acheta domesticus) were obtained from stock laboratory cultures maintained at 28° C and ca. 50% RH. Three replicates (25 animals each) were irradiated at each of the following dose rates: 30 rads/hr, 70 rads/hr, 210 rads/hr, 2500 rads/hr, and 23,800 rads/hr with ^{60}Co sources. Total dose received was 5000 rads, the LD_{50-20} gamma dose for Acheta (Menhinick and Crossley 1968). Silver metaphosphate glass rods were used for dosimetry measurements. All crickets were maintained in plastic cages at 28° C and ca. 50% RH with food and water added ad lib. Cricket survivorship was recorded daily and corrected for control mortality. Resulting data were analyzed in a 2 x 2 factorial analysis of dose rate against time.

Results and Discussion

Table 13 shows mean net percent mortality after 20 days for adult A. domesticus after being irradiated with ca. 5000 rads of gamma at five different dose rates. It is evident that there is a dose-rate effect which becomes apparent at the lower dose rates. A similar result was reported by Banham (1962) for the confused flour beetle, Tribolium confusum. He found that survival of adult beetles at 4000 rads/hr was much reduced compared to that at 2000 rads/hr for a given total dose. Jefferies and Banham (1966) reported a reduction in mortality at lower dose rates for a given dose for the grain pests Tribolium, Oryzaephilus, and Sitophilus. Nair and Subramanyam (1963) deomonstrated reduction of fertility in Tribolium castaneum with increasing dose rate. Zakladnoi (1966) and each of the aforementioned authors reported a leveling-off

Table 13. Mean Net Percent Mortality in 20 Days for Adult *Acheta domesticus* after Irradiation with ~5000 Rads Gamma

Dose rate rads/hr	Mean net % mortality*	Estimated total dose**
23,800	52.4 a	5000 ± 250
2,500	54.4 a	5098 ± 281
210	50.3 a	4997 ± 359
70	44.2 a	4637 ± 149
30	9.9 b	5002 ± 387

*Means followed by the same lower case letter are not significantly different ($P < 0.05$).

**Means ± one standard error; N = eight glass rod dosimeters.

of the dose-rate-effect curve above certain dose-rate levels. Similar results are shown in Table 13 with the leveling-off of the effect beginning around 200 rads/hr. Analysis of variance demonstrated no significant differences between the dose rates 23,800, 2500, 210, and 70 rads/hr ($P < 0.05$). However, a difference was detected between each of the above dose rates and 30 rads/hr ($P < 0.05$). These results suggest that, when mortality is used as a biological endpoint, similar arthropod species may be irradiated at relatively high dose rates to achieve an effect that would be expected from exposure of that arthropod population to fallout radiation where the dose rate would be somewhat less than that of the laboratory study. This would be particularly true when applying the results of a laboratory study to conditions that would exist during the first week after fallout deposition. During this time the dose rate is undergoing a rapid exponential reduction, and the range of dose rates would fall within those found to be not significantly different in laboratory studies. The primary advantage of using high dose rate in irradiation studies is that the confinement period for the animals during treatment is greatly reduced, thereby eliminating effects of crowding, cannibalism, etc. In addition, more animals may be irradiated in a given time period, which would tend to reduce some of the effects due to time.

Future Studies

Results obtained from the dose-rate study will be utilized in designing experiments to determine radiosensitivity of each life stage of a laboratory population of grasshopper (Melanoplus sanguinipes) to gamma radiation and to ascertain the effects of an acute dose of gamma

radiation on field populations of *M. sanguinipes* confined in nonradioactive and ^{137}Cs-contaminated areas.

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CESIUM-137 ACCUMULATION, DOSIMETRY, AND RADIATION EFFECTS IN COTTON RATS

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J. T. Kitchings, III, and L. E. Tucker

SUMMARY

Cesium-137 accumulation, dosimetry, and radiation effects were determined in cotton rats living in their natural environment contaminated with ^{137}Cs labeled sand. Cesium-137 levels were relatively high 6 months after the application of the fallout simulant, but decreased as the simulant descended toward the ground. Radioactivity levels in organs and tissues, in general, paralleled that of the whole body. Dose rate to cotton rats paralleled radioactivity levels in the whole body. No effects on the peripheral blood or body weight due to irradiation were observed in this study.

Introduction

Mammals living in an environment contaminated with nuclear fallout debris will be subjected to both internal and external irradiation. Both types of irradiation need to be evaluated to ascertain total doses animals will receive. Information concerning effects of acute and chronic irradiation on caged mammals is abundant. Likewise, metabolism of several radionuclides in caged mammals has been studied in great detail. However, radionuclide turnover and effects of chronic internal/external irradiation in mammals in natural environments have not been investigated to much extent.

One of the major radionuclides in fallout is cesium-137. We studied radiation effects and radionuclide accumulation in cotton rats living in

their natural environment contaminated with ^{137}Cs. Of primary concern were in-vivo dosimetry, whole-body radioactivity, internal organ/tissue radioactivity, gastrointestinal-content radioactivity, and effects on hemopoietic system.

Materials and Methods

Two of the four ^{137}Cs-contaminated pens in the OCD 0800 Area were used to contain experimental cotton rats. Two uncontaminated pens were also used as controls. Each pen was covered with a nylon net and equipped with an electrically charged wire over the 24-in. sides. Escape and predation were prevented by this procedure.

Adult cotton rats (Sigmodon hispidus), both wild and laboratory-born, were used in this experiment. Two weeks before being placed in the pens, animals were weighed and bled. Details of our hematological methods have been described elsewhere (Lewis and Dunaway, 1965). Three to four days before rats were placed in the pens, glass-rod dosimeters encased in nylon capsules were injected subcutaneously (one dorsally and one ventrally in each rat).

Four animals were released into each pen at various times during the year and trapped 30 to 60 days later. All animals were bled, weighed, assayed for whole body radioactivity in a Packard Armac Liquid Scintillation detector, and dosimeters were removed.

Internal organs (heart, liver, spleen, and kidneys) of the radioactive rats were weighed and counted in the whole-body counter. The gastro-intestinal (GI) tract was excised from the terminal end of the esophagus to the anus and separated into four components: stomach, small intestine,

caecum, and large intestine. These components were cleared of contents with 1N sodium acetate buffer solution, weighed, and counted for radioactivity. Gastrointestinal contents were assumed to be comprised of two components, fallout simulant and organic matter. Separation of these contents was based on this assumption. Contents of each GI component were triturated and washed with 30% hydrogen peroxide. Organic matter rose to the top of the hydrogen peroxide, while fallout simulant settled to the bottom. Both components were then counted as described above.

In the spring and fall of 1969, half of the animals trapped at the 30-day sample were released into the pens to be recaptured for a 60-day sample.

In-vivo dosimetry was determined with Toshiba low-Z glass rods (1mm x 6mm) read on a Toshiba Fluoro Glass Dosimeter, Type FGD-3B, using National Bureau of Standards standards.

Results and Discussion

Average dose rates for cotton rats in contaminated pens ranged from 3.84 rads/day in Feb. 1969 to 2.35 rads/day in Nov. 1969. Figure 17 shows a decrease of 0.008 rads/day from Feb. to July, but virtually no change from July 1969 to April 1970. The initial decrease in dose rate is probably due to the changing geometry of radiation fields in pens as the fallout simulant descended through the vegetation to the ground. Most fallout simulant is now on the ground, forming an irregular plane source and resulting in a relatively stable dose rate of approximately 2.46 rads/day.

We have seen no effects of the ^{137}Cs environment on either body weight or the hemopoietic system. Any slight changes in body weight or general blood measurements probably are a result of seasonal variations in the

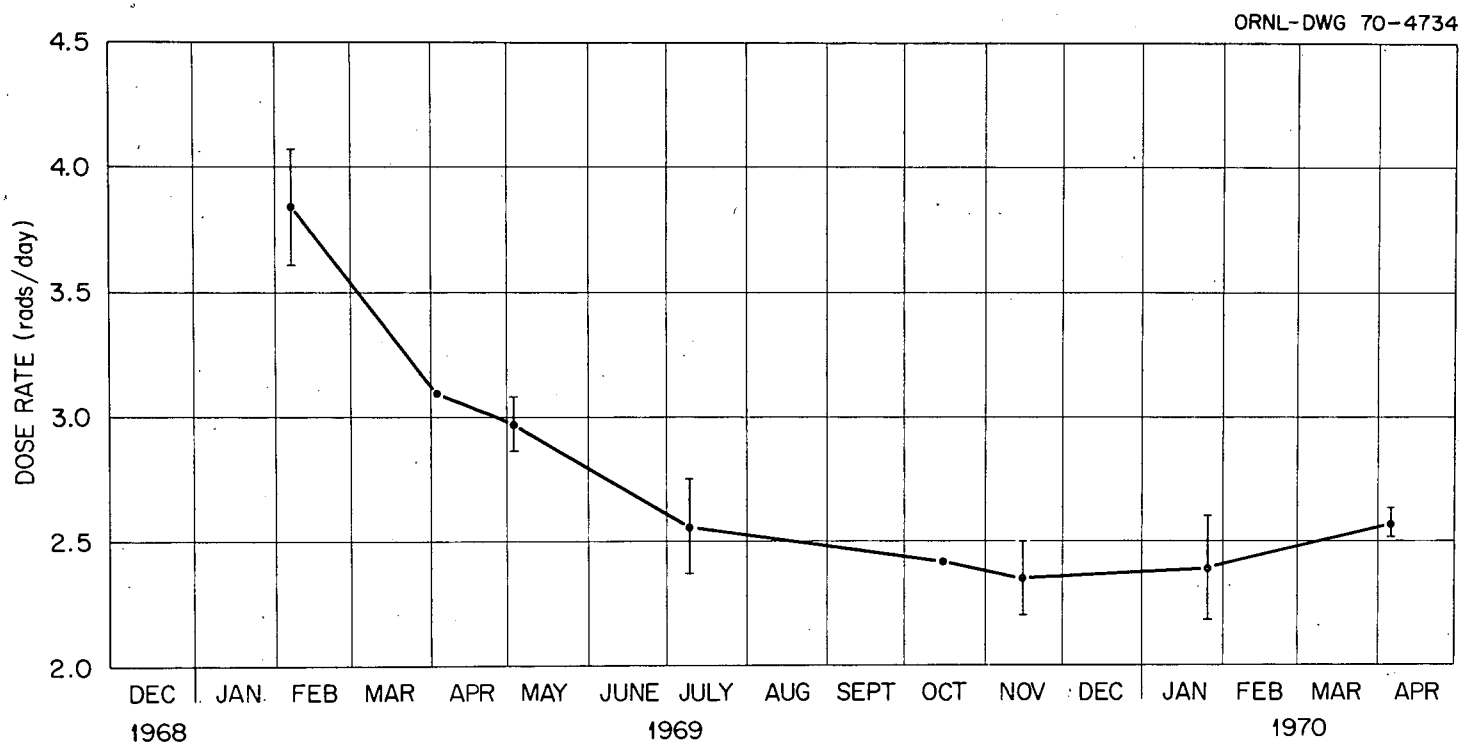

Fig. 17. Dose Rate to Cotton Rats Living in ^{137}Cs-Contaminated Enclosures from February 1969 to April 1970. Points represent means of dorsal and ventral dosimeters. Vertical lines represent standard error of mean. Absence of vertical lines denotes standard error too small to plot.

general environment, since similar measurements were obtained for both control and experimental animals. For cotton rats, general environmental fluctuations may be of more immediate concern than low-level irradiation and radioactivity. Previous studies with cotton rats show that relatively high acute doses of radiation are required to affect body weight and blood (Dunaway et al. 1969a; Kitchings et al. 1970). In January 1970, our 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. Dunaway and Kaye (1961) reported similar mortality in free-ranging cotton rats during cold weather. Percent recovery during the present study was considerably better in favorable weather.

Radioactivity in cotton rats is shown in Fig. 18. The four measurements (whole body, total tissue, organic matter, and fallout simulant), in general, parallel each other. Radioactivity in all four measurements increased from December 1968 to February 1969, after which time it began to decrease. The initial rise in cotton rat whole-body radioactivity from December 1968 to February 1969 was probably influenced by the relative proportions of living and dead vegetation in their diet. Choice of food in midwinter was influenced by the diminution of living vegetation. As living vegetation decreased, rats foraged closer to the ground; hence, their diet consisted of increasing amounts of dead vegetation. Dahlman et al. (1969) and Dahlman (this report) showed that radioactivity was considerably greater in dead vegetation than in live vegetation. Therefore, this change in food and the descent of the fallout simulant, resulting in its availability for ingestion, helps to explain the high whole-body radioactivity in cotton rats during midwinter 1969.

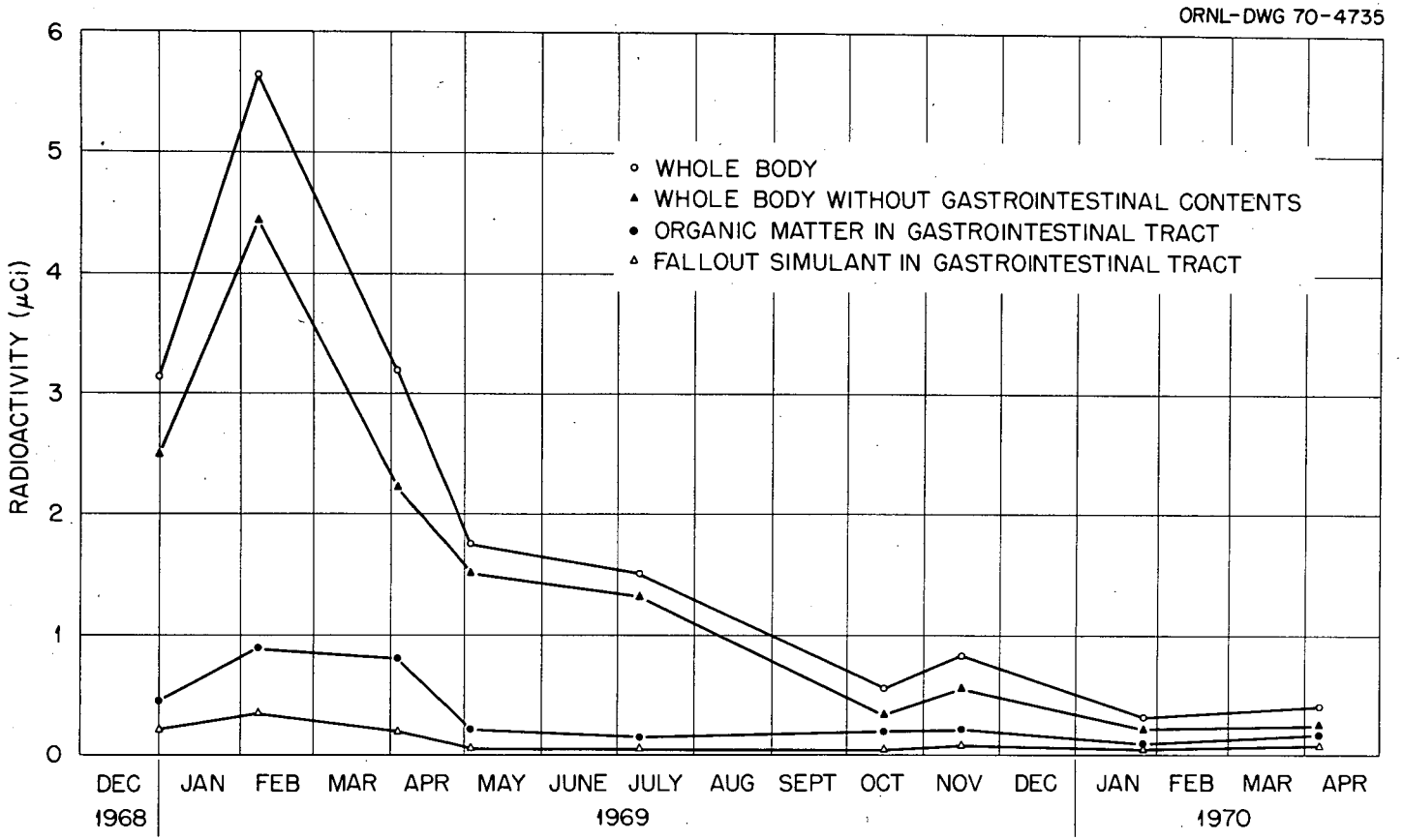

Fig. 18. Total Radioactivity (μCi) in Cotton Rats After Chronic Ingestion of ^{137}Cs-Contaminated Fallout Simulant and Vegetation for 30 or 60 Days.

As time progresses, however, radioactivity of living and dead vegetation approach each other, resulting in a relatively constant body burden in cotton rats. The descent curves of these measurements parallel that of the dosimetry and, again, reflect movement of fallout simulant toward the ground. Whole-body radioactivity has remained relatively constant from Oct. 1969 to April 1970, while GI-content radioactivity has remained relatively constant from May 1969 to April 1970.

Figure 19 shows the 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. These percentages include both 30- and 60-day samples. We found no significant increase or decrease from 30 to 60 days, suggesting that ^{137}Cs equilibrium was reached prior to 30 days. In December 1968, whole-body radioactivity reached a maximum level three weeks after animals were placed in the pens (Dunaway _et al_. 1969b). Kitchings _et al_. (1969) in a laboratory study determined equilibrium at 544 hr (22.7 days) after beginning chronic feeding with ^{134}Cs-tagged lettuce. In March 1970 we trapped cotton rats 7 and 10 days after placing them in contaminated pens. Whole-body radioactivity was 0.3620 and 0.3579 μCi, respectively. These values are not significantly different from 0.3790 μCi determined on day 30. By 30 days then, we feel that cotton rats had reached ^{137}Cs equilibrium and that gain or loss would be negligible for at least 60 days.

Radioactivity in the rats was contained mostly in the residual carcass (Fig. 19). The two major compartments of residual carcass are muscular and skeletal which comprise, respectively, about 49% and 7% of the total body weight (O'Farrell _et al_. 1966). Cesium concentrates in muscle.

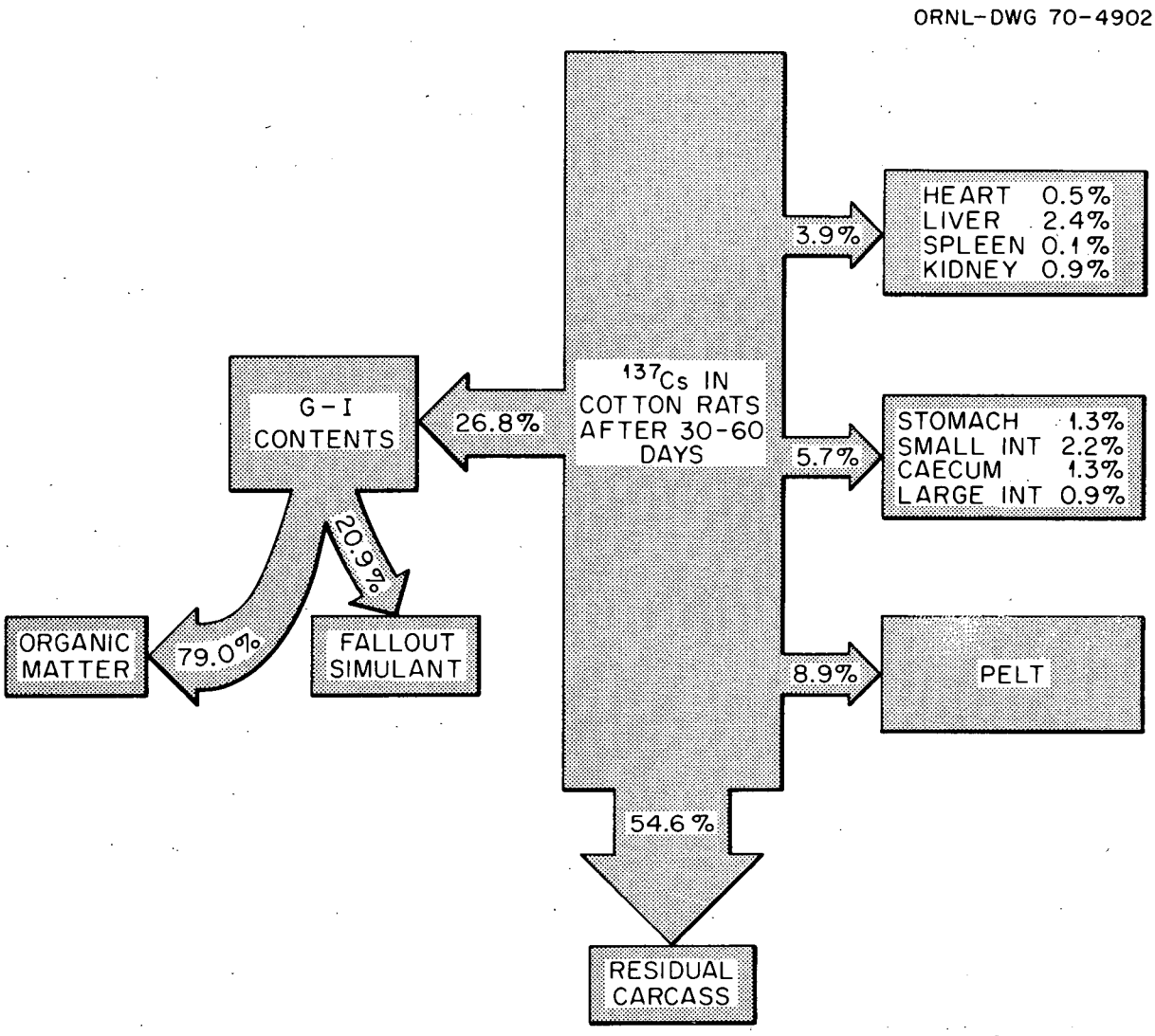

Fig. 19. Percent of Radioactivity in Various Components of Cotton Rats after 30-60 Days Chronic Ingestion of ^{137}Cs-Contaminated Fallout Simulant and Vegetation.

Hamilton (1947) found a low uptake of cesium in the skeleton and relatively high accumulation in muscle. Hood and Comar (1953) and Kereiakes et al. (1961) also showed the high concentration of cesium in muscle relative to bone. Pelt, which includes skin and hair, accounts for 8.9% of the whole body radioactivity. Most of the pelt, in terms of weight, is muscle. Because of both tissue specificity for ^{137}Cs and amount of muscle in the body of mammals, it is apparent that most of the body burden was contained in muscle.

Approximately 27% of the whole body radioactivity in cotton rats was in the contents of the GI tract. Of the total amount of radioactivity in the GI contents, 79.0% 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 what it was in April 1970, our last sample period. Weathering caused leaching of ^{137}Cs from the simulant into the native soil and onto the plants, and the sand particles have settled toward the soil surface. Consequently, ^{137}Cs is still present but is not so readily ingestible in the form of simulant. With increasing time, radioactivity due to simulant should decrease more, and perhaps radioactivity levels in vegetation will increase as ^{137}Cs is taken up from soil. Therefore, future body burdens of herbivores and saprovores living in the contaminated pens will mainly reflect ^{137}Cs levels in living or dead vegetation.

Conclusions

Our results indicate that, in situations similar to ours, we would expect the following for cotton rats.

1. Within a 30- or 60-day time period, neither body weight nor blood will be appreciably affected by chronic radiation from ^{137}Cs. Changes in these measurements will be caused by changes in environmental factors such as temperature.
2. Radioactivity levels for whole body, tissues, and GI contents, in general, will parallel each other. Approximately one year after fallout arrives, whole-body radioactivity will be only about one-tenth of the early levels but will remain at this lower level for a long time, perhaps years.
3. Internal organs such as heart, liver, spleen, and kidneys will accumulate a relatively small amount of ^{137}Cs.
4. Most of the accumulated ^{137}Cs in tissues will be in muscle, because of the relatively high affinity of ^{137}Cs for muscle and the large proportion of muscle in the body.
5. For the first 6-12 months, dose rate will decrease rather sharply. After this initial decrease, equilibrium will be reached and dose rate decrease will be negligible.
6. Although there may be seasonal fluctuations in dosimetry and whole-body radioactivity levels, they will probably be slight.

Projected Research

Interesting and provocative results were obtained in this study, and some questions remain about the possibility of minor seasonal fluctuations in dose and radionuclide turnover, but we feel that our time can be better spent studying small-mammal populations (instead of individuals). Another investigator is now available to work with insects, and we believe that the enclosures presently used for rodent research will be more suitable for the proposed new work with insect populations (Van Hook, this report).

Rodent studies will be shifted to areas outside, but near the present site. Rodent populations will be censused, and animals will be divided by sex and age into two equal groups in each of four areas. One group will be irradiated (700 rads) while the other will be unirradiated. Subsequent samplings will permit analyses of radiation effects in the populations.

Reproduction is one of the most radiovulnerable processes in populations. Tracer amounts of radioisotopes with suitable biological and physical half-lives will be injected into females of the replicated groups so that each group will receive a different isotope. Whole-body counting of young from these females will then reveal reproductive success in various groups. This projected research will simulate a situation where half of a rodent population receives a substantial, acute radiation dose and half of the population is in shielded sites.

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HONEYBEE IRRADIATION STUDIES

A. F. Shinn

SUMMARY

Laboratory populations of Italian cordovan hybrid bees received acute gamma doses of 1000, 2000, and 4000 R; only the 4000-R bees had a lifespan statistically different from controls (8.9 vs 23 days, respectively). Temperature effects on lifetimes were found for laboratory-caged workers supplied with water only (2.8 days at 34°C vs 2.0 days at both 24 and 40°C) and for bees receiving queen-cage candy (13, 8, and 2 days at 24, 34, and 40°C, respectively).

Field colonies were irradiated at 500, 1000, 2000, or 4000 R. Mortality of the 4000-R colonies (200 bees/day) was greater than controls (22 bees/day). Number of flights were less in the 2000-R colonies than in the 500- and 1000-R colonies. Pollen content of honeycomb was reduced in the 2000- and 4000-R colonies.

Nuclei (half-size) colonies were irradiated (1500 and 3000 R) and placed in large outdoor cages. Effects were: brood counts less in irradiated colonies after 10 days; egg production less in the 3000-R colonies by day 12; and reduction in total weight of irradiated worker bees. Radiosensitivity of a mixed sample of eggs and larvae was much greater (LD_{50-4} = 1700 R) than for workers (LD_{50-5} = 16,300 R).

There are no published studies of effects of ionizing radiation on field colonies of honeybees. Ecologically, we are most interested in effects on hive economy and the pollinating activities of bees. Effects of gamma irradiation on daily pollen collection of field colonies and on longevity of both laboratory-caged bees and field colonies were previously investigated.

For the continuation of honeybee studies, Italian cordovan hybrid bees were used, which were supplied from the Genetic Bee Stock Center of the University of California at Davis. Thirty-two of 40 colonies of bees were converted to this type by replacing the queens with the genetically homogeneous cordovan queens. The brightly colored, orange cordovans were easily distinguished from the dark native bees. The cordovans foraged up to 2 miles from the apiary, or over an area of some 8000 acres. No native bees invaded the cordovan colonies.

Laboratory cages of approximately 150 Italian cordovans in each of three replicates were irradiated with 1000, 2000, and 4000 R of ^{60}Co gamma radiation at ~680 R/min and maintained at internal hive temperature (34°C) with sugar syrup as food. Only the 4000-R samples had a mean lifespan (8.9 days) statistically different from controls (23 days). These results are similar to those previously obtained for East Tennessee mixed bees (8.5 days) and Illinois Italian bees (7.7 days), which were irradiated with 5000 R and maintained in the same way a year earlier.

The lifetime of laboratory-caged worker bees was determined at three temperatures (24, 34, and 40°C) for starved bees, and for bees supplied with 66% sugar syrup, water only, and queen-cage candy. The temperatures had no demonstrable effect on the mean lifetimes of unfed bees (1.8 days) or of bees fed 66% sugar syrup (28 days). Bees supplied only with water lived significantly longer at the hive temperature of 34°C than at 24 or 40°C (2.8, 2.0, and 2.0 days, respectively). Bees fed queen-cage candy had significantly different mean lifetimes of 13, 8, and 2 days at 24, 34, and 40°C, respectively.

Our field colonies were sited so as to discourage the drifting of bees from one hive to another (Fig. 20). Colonies were equalized for size and vigor as closely as possible, and those for the several levels of irradiation were chosen at random. Sets of 4 colonies each received 500, 1000, 2000, or 4000 R of ^{60}Co gamma radiation at ~65 R/min in the Variable Gamma Dose Rate Facility of the UT-AEC Agricultural Research Laboratory. They were returned at once to their original position in the apiary along with 8 control colonies which had accompanied them (Fig. 20).

Criteria for effects of ionizing radiation on colonies were: (1) mortality within the hive, (2) quantity of pollen collected daily by a colony, (3) flight activity of a colony, and (4) final status of a colony at end of the observation period of the experiment. Data were obtained during a 37-day postirradiation period.

Table 14 summarizes the data for the first three criteria. The mean daily mortality of the 4000-R colonies (200 bees) was statistically different from controls (22 bees). Mean daily collections of pollen were not statistically different, but the data suggest that more replicates would yield significance. Mean daily number of flights of the 2000-R colonies (36 flights per 2-min period) was less ($P < 0.01$) than the 500- and 1000-R colonies (67 and 61 flights, respectively), but we know of no biological basis for the difference.

Final status of colonies was determined by an inventory of colonies expressed as square centimeters of honeycomb containing honey, pollen, pupae, larvae, and eggs. Inventories of the 500-, 1000-, and 2000-R colonies were statistically different from controls only for pollen

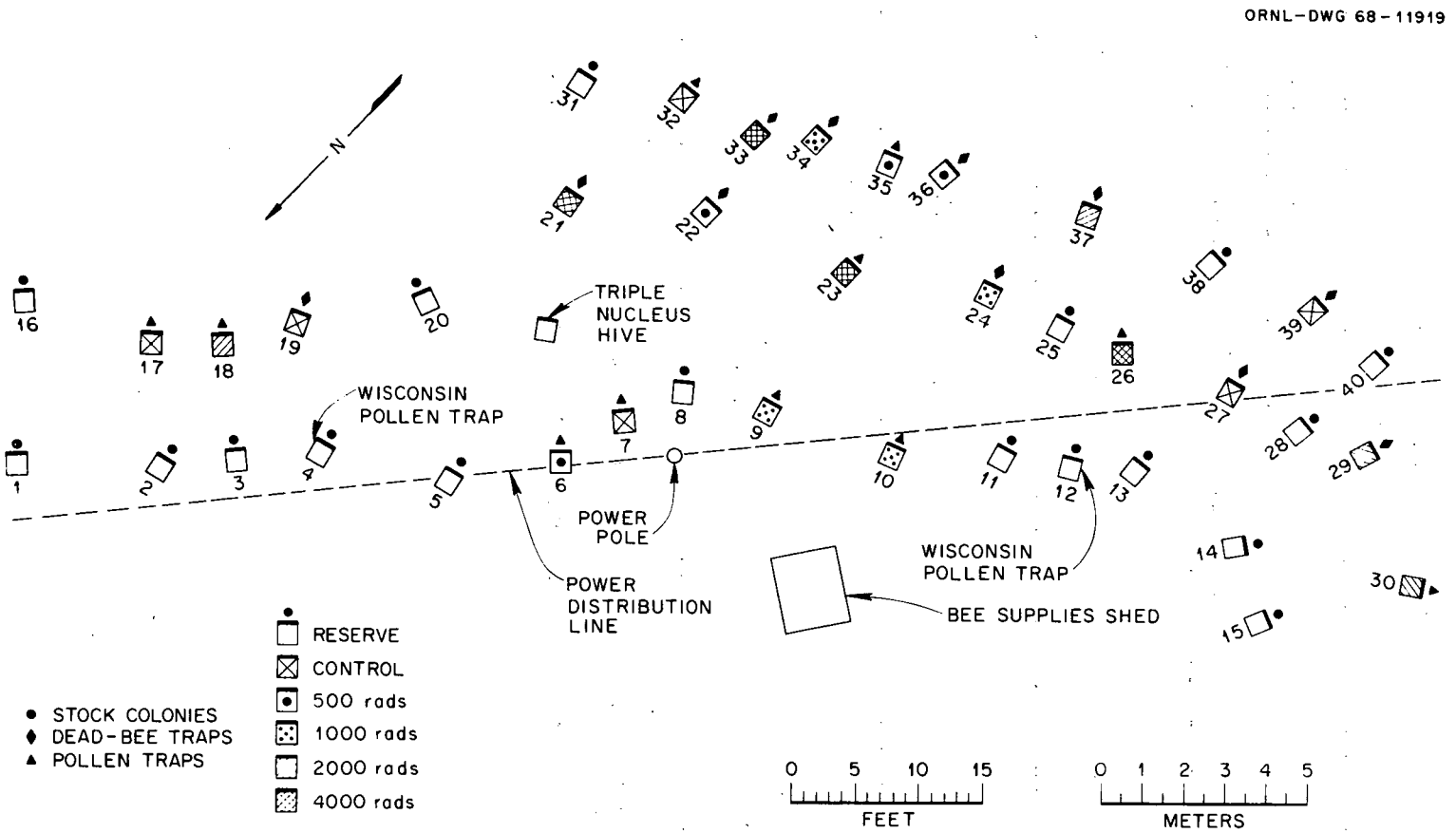

Fig. 20. Apiary of the OCD Honeybee Project, 1968.

Table 14. Mean Daily Values of Effects of Acute Gamma on Entire Cordovan Italian Honeybee Colonies

		Exposure, R			
	Controls	500	1000	2000	4000
Mortality					
Number of dead bees	22.1	18.5	31.1	37.7	200.4[a]
Pollen					
Grams	7.7	17.9	20.9	2.7	0.37
Activity					
Number of flights per 2-min period	48.2	66.6[b]	61.4	35.6	42.9

[a] $P < 0.01$, compared with each other treatment.

[b] $P < 0.05$, compared with controls, 2000, and 4000.

($P < 0.05$); the 2000- and 4000-R colonies had significantly less pollen per colony (297 and 368 cm^2, respectively) than the controls (768 cm^2). The 4000-R colonies were obviously moribund, with two dead at inventory time, and two more almost dead. More replicates would likely have detected differences between controls and the 2000-R colonies. Despite as uniform a genetic composition as current knowledge permits, there was still a large amount of variation among colonies within a given dose level.

Effect of irradiation of nuclei (half-size) colonies of honeybees on their pollination activities was tested by exposure to 1500 and 3000 R of ^{60}Co gamma radiation at the rate of 53 R/min. The 11 replicates of control and dose levels were placed singly at random in 33 cages on a pasture of red clover and fescue grass.

Number of capped brood cells (which contain bees undergoing metamorphosis) in each nucleus was determined from photo inventories which are listed in Table 15. Pre-irradiation counts showed that nuclei of controls and treatments were comparable for number of developing brood cells, but at ten days postirradiation the brood counts of irradiated colonies were substantially less ($P < 0.01$) than controls. A sharp decline in counts occurred by postirradiation day 20 for all colonies, and by postirradiation day 34 no brood was being raised by controls, and very little was present in the 1500-R nuclei. Remarkably, however, the 3000-R nuclei showed a tenfold increase in brood cells ($P < 0.01$). A possible explanation of cessation of brood-rearing in the controls was the exhaustion of the stored pollen in each colony and an inadequacy of pollen supply in the cages for rearing brood. Deaths of

Table 15. Number of Capped Brood Cells Per Nucleus Prior To and Following Irradiation (mean ± standard error)

Sample date and post irradiation day	Controls	1500 R	3000 R
June 18 (Pre-irrad.)	4260 ± 493	3005 ± 545	3998 ± 592
June 30 (PID 10)	2811 ± 354	1579 ± 825**	1552 ± 336**
July 10 (PID 20)	63 ± 45	466 ± 226	56.5 ± 23.0
July 24 (PID 34)	0	241 ± 95	598 ± 145

**Significant at $P < 0.01$.

eggs, larvae, and brood among irradiated nuclei conserved the pollen supply, and brood numbers consequently declined more slowly.

Queens of controls and 1500-R colonies were laying eggs normally (ten of 11 in each case) on postirradiation day 12, but queens of 3000-R colonies were severely affected, with two dead and five nonlaying. By postirradiation day 20, egg-laying was normal for all colonies (eight laying queens among controls, eight among 1500-R, and nine among 3000-R colonies). At the end of the confinement to cages on postirradiation day 34, there was no difference in number of laying queens among controls and irradiated colonies (controls, 6; 1500 R, 10; 3000 R, 8).

Seed yields per cage were determined after 32 days of confinement and were not statistically different among controls and irradiated nuclei (N=24, mean 37.6 $\pm$ S.E. 3.92 g, CV=51%). Differences may have been masked by the unexpected large variability in density of clover blossoms per cage and in their absolute density per cage (N=13, mean 314 $\pm$ S.E. 31, CV=36%). At the end of the experiment, total weight of worker bees per nucleus was less for irradiated nuclei than for controls at $P < 0.01$ (N=11 for each: controls, 0.751 $\pm$ 0.0636 kg; 1500 R, 0.481 $\pm$ 0.0334 kg; 3000 R, 0.355 $\pm$ 0.0587 kg).

Radioresistance of a mixed sample of eggs and larvae less than 3 days old was found to be an order of magnitude lower than that of adult workers (1700 R was the LD_{50-4} for eggs and larvae compared with 16,300 R for the LD_{50-5} for workers).

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13. ABSTRACT

Cooperative, related studies are continuing at Oak Ridge National Laboratory on movement of fallout simulant and ^{137}Cs through plants, animals, soil, and water; areal and in-vivo gamma and beta dosimetry; and effects of chronic and acute radiation.

Gamma-radiation dose rate remains virtually unchanged at 0.5-1 m above ground but decreased near the ground. Beta dose rate is decreasing with height above aground. Doses to organisms are related to locations of the organisms in the contaminated areas.

Interception and loss rates of fallout simulant in six species of agricultural plants early after application varied with simulant size, plant species, and meteorological conditions. Vegetation data are presented for retention rates, weathering half-lives, and leaching of the simulant.

Various experiments with arthropods indicated that (1) sensitivity of populations will be determined by effects on fertility rates or on early life stages rather than by effects on adults; (2) for the same accumulated dose, mortality increases with increasing dose rate up to relatively high dose rates; (3) honeybee mortality, lifespan, number of flights, pollen collection, weight of worker bees, number of brood cells, and egg production were affected at doses of 1500-4000 R; and (4) differences were found between arthropod populations living in nonradioactive or ^{137}Cs-contaminated areas.

Cesium-137 levels were relatively high (5.65 μCi, whole body) in cotton rats in Feb. 1969, decreased regularly from February to October, and then remained relatively constant (~0.5 μCi) until April 1970. Measurements of ^{137}Cs in whole-body, tissues, and in GI-tract organic matter and fallout simulant in general paralleled each other. No effects of the chronic, low-level radiation environment were found in the cotton rats after 30 or 60 days.

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Laboratory and field studies have been underway for two years at ORNL on movement of fallout simulant and Cs-137 through plants, animals, soil, and water. Gamma and beta doses to organisms varied with time and location. Simulant interception, retention, and weathering on plants varied with simulant size, species, and weather. Cs-137 transfers to fescue and cotton rats are reported. Radiation effects in animals depended on species, life stage, fertility rates, dose rate, and dose.

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