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RADIOACTIVITY AND RECOVERY OF THE LAND PLANTS AT ENIWETOK ATOLL, 1954-1957

by

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ABSTRACT

A long-term investigation was conducted at Eniwetok Atoll during 1954-1957 to determine the rate of recovery of land plants damaged by the radiation, shock and heat blast of the Nectar detonation in 1954. During this period the levels of gross beta radioactivity in the plants, the radio-isotopes present in some of the plants and the soil, and the changes in the levels of beta radioactivity in the tissues of the plants, with time after the detonation (decline of radioactivity), also were investigated.

At Belle Island seven plant species were tagged, measured and photographed before the detonation. At approximately monthly intervals after the detonation, for a period of ten months, and again after an interval of six months, the plants were observed and photographed. The first indication of recovery was observed on the eighth day, at which time buds were noticeable on stems of Scaevola and Messerschmidia plants. In a month's time, most of the plants had formed new leaves and some had produced flowers and fruits. In six months, the general condition of the vegetation was similar to that which existed before the detonation. Two plants,

Guettarda and *Portulaca*, which were unhealthy at ten months, had improved by the sixteenth month. Photographs of the recovery of some of the plants are included in this report, as well as a discussion of agents other than radiation which have been reported to cause similar damage to plants of the coral atolls of the Pacific Ocean.

RADIOACTIVITY AND RECOVERY OF THE LAND PLANTS AT ENIWETOK ATOLL, 1954-1957

Since the summer of 1946, the Laboratory of Radiation Biology of the University of Washington has conducted studies at the Eniwetok Proving Ground to evaluate the distribution of radioactivity in aquatic and terrestrial organisms of the atolls of the western Pacific and adjacent areas. These studies were made either shortly after a nuclear device had been detonated or after intervening periods varying from several to many months. The results of the investigations conducted in 1946[7], 1947[1], 1948[2], 1949[3], and 1952[4] indicated the need for a study of the reinvasion or regrowth of organisms in an area contaminated by radiation, as well as a study of the decline of radioactivity in these organisms (changes in the amount of radioactivity of samples collected at various times).

A study of this nature was undertaken following the Nectar detonation at Eniwetok Atoll in the spring of 1954. Facilities were made available at the Eniwetok Marine Biological Laboratory on Elmer (Parry) Island by the Division of Biology and Medicine of the United States Atomic Energy Commission, and logistic support to carry out the sampling program was furnished by Joint Task Force Seven of Operation Castle.

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The study of the land plants was a part of the over-all program of the Laboratory of Radiation Biology. In this report only the results of this portion of the program are presented. The results of the investigations on the following organisms already have been reported: reef fish[24], land crabs[14], invertebrates[8], and algae[20].

The main objective of the land plant program was to determine the length of time required for a plant damaged by a nuclear detonation to resume its normal functions of growth and reproduction while being subjected to chronic radiation. Other objectives were to determine (1) the rate of decline of beta radioactivity in the tissues of land plants growing in radioactive soil during the period starting shortly after detonation of a nuclear device (Nectar) and ending eighteen months later; (2) the gross beta radioactivity of the land plants at several islands of Eniwetok Atoll, and (3) the uptake by the plants of specific radioisotopes from the soil.

The main site of study was Belle Island, 2.7 miles E-SE of the detonation (Fig. 1). This area was estimated to be far enough removed from ground zero that the plants would not be uprooted by physical forces yet would have taken up sufficient radioactivity for the proposed study. Other islands

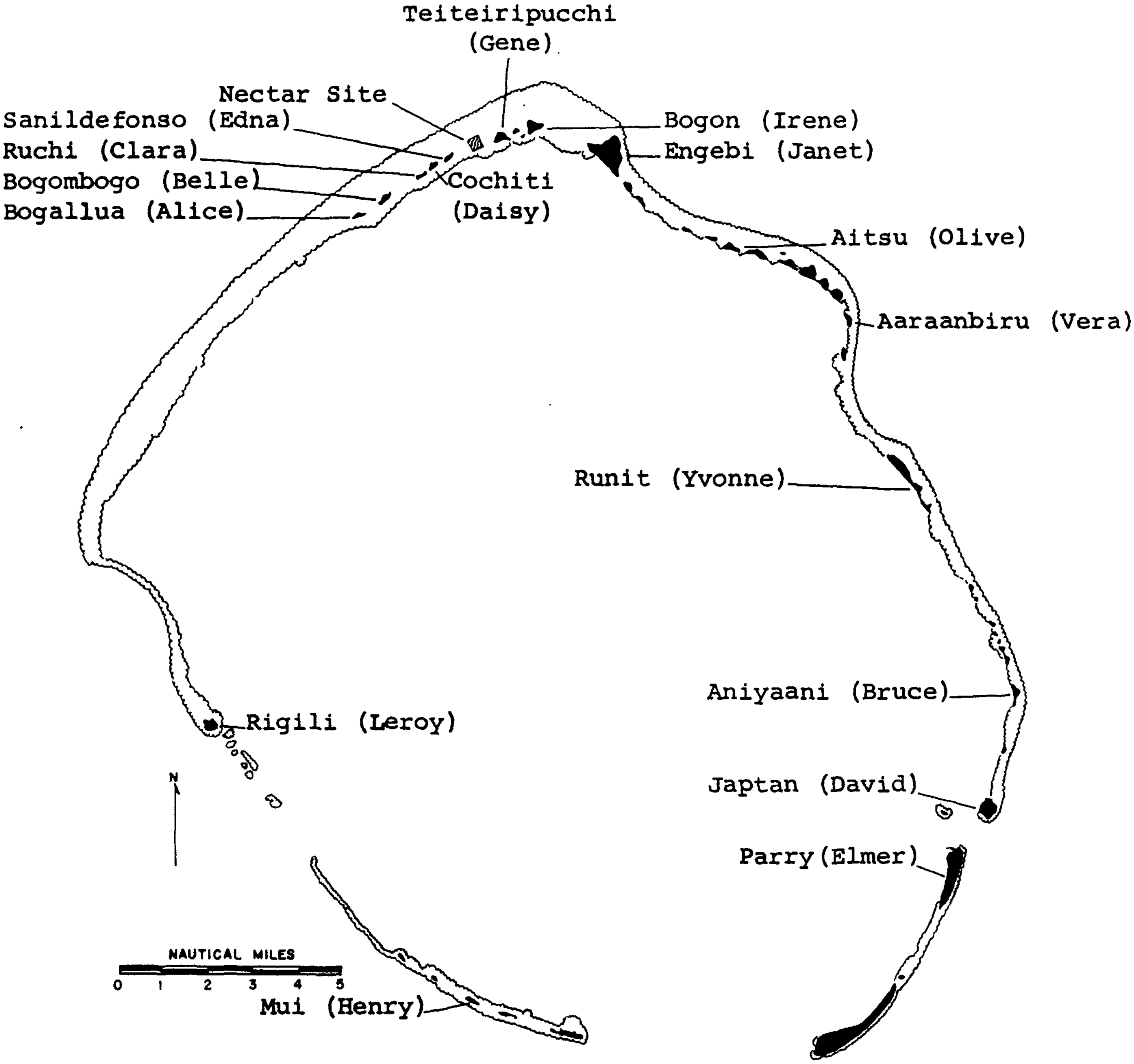


Figure 1. Eniwetok Atoll

included in this study also are shown in Figure 1; the code names of the islands are in parentheses.

In 1956 another series of nuclear tests (Operation Redwing) was conducted at Eniwetok Atoll. During this series, plant samples were collected from various islands of the atoll as well as in July 1957, one year later. The gross beta radioactivity of these samples is presented in the Appendix Table B. The results of gamma spectrum analyses for specific radioisotopes present in some of the samples collected in 1956 were reported in 1957 by Lowman, Palumbo and South[16].

METHODS

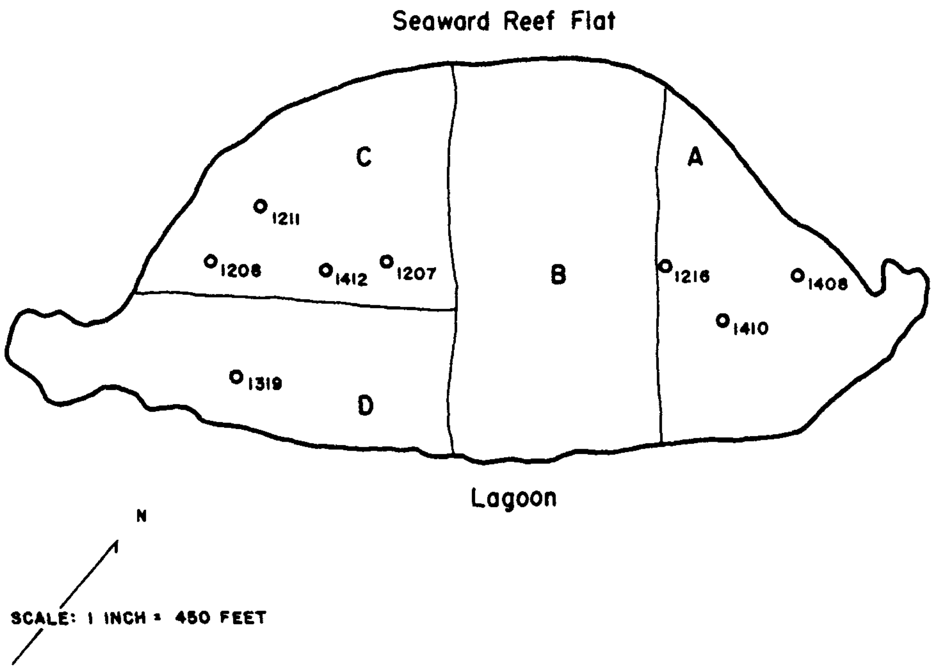
The beach magnolia (Scaevola sp.*) was chosen as the principle plant for study because of its widespread occurrence in the central Pacific Islands; six other species also were studied. In order to establish the levels of radioactive contamination from previous tests, samples of plant tissues were collected before the detonation. The plants were staked, labelled, measured and photographed. After the detonation, observations and measurements were made of the plants and photographs were taken. Samples to be used for the determination of radioactivity were taken at approximately monthly

*Probably Scaevola sericea Vahl[9].

intervals starting on May 22, 1954 and continuing to March 1955. The locations of these plants on the island, which was divided arbitrarily into areas A, B, C and D, are shown in Figure 2.

At each collection period at Belle Island, six subsamples of the top two inches of soil near the base of *Scaevola* plant No. 1319 were combined and an aliquot of the combined sample was taken for the measurement of gross beta radioactivity. Gamma survey-meter readings also were taken to determine the gamma dose to which the plants were subjected.

After the plant samples were collected they were put on ice and taken to the Eniwetok Marine Biological Laboratory where they were dissected, weighed, dried, and packaged and later sent to the Laboratory of Radiation Biology in Seattle, Washington, for further processing as outlined in UWFL-33[4]. The samples were dry-ashed in a muffle furnace at 540°C and counted in an internal gas-flow counting chamber. Corrections were made in the counts for geometry, backscatter, coincidence, self-absorption and decay. All counts for the 1954-1955 and April 1956 samples were corrected to the date of collection, the decay factors being based on a soil sample collected May 15, 1954 at Belle Island. For the early collections decay factors as



Area A

1216 *Guettarda speciosa*
1408 *Messerschmidia argentea*
1410 *Lepturus repens*

Area C

1207 *Boerhaavia tetrandra*
1208 *Triumfetta procumbens*
1211 *Portulaca oleracea*
1412 *Cocos nucifera*

Area D

1319 *Scaevola* sp.

Figure 2. Diagram of Belle Island, Eniwetok Atoll, showing the location of the land plant stations and the collecting areas.

high as 16.2 were used, whereas for the last collection a decay factor of only 1.02 was used. The counts for the 1956-1957 samples, which were not corrected for decay, are presented in the appendix tables. The levels of radioactivity for plant tissues other than scorched leaves are based on wet tissue weights; to convert the latter values to a wet weight basis it is necessary to divide them by 6, the approximate dry to wet ratio for this tissue. The values for soils are based on dry weights. All values in the text tables are expressed in μc/kg; values in the appendix tables are expressed in thousands of d/m/g/.

The rate of decline was plotted on a log-log scale because of its similarity to the decay curve of mixed fission products.

The isotopes present in the samples were indicated by the decay curves but in one soil and four plant samples they were specifically identified by radiochemical analysis*.

*Work done by D. J. South

RESULTS

Regrowth of the Land Plants at Belle Island

The gamma survey-meter readings taken at Belle Island during the period of investigation are given in Table 1 and in Figure 3, which includes the theoretical gamma dose rate according to Miller and Loeb[17] and the slope for $t^{-1.2}$. The accumulated total dose from one minute after the detonation to the end of 200 days was calculated to be approximately 400 r.

Before the Nectar detonation, the plants on Belle Island were generally green and healthy-looking. A photograph of the general area taken at this time (Fig. 4a) shows the healthy appearance of the vegetation. In some plants there was yellowing of the leaves and necrosis, especially in *Scaevola* and *Guettarda*, and some reddening of the tops of the grass, *Lepturus repens*. The latter symptom is typical of some species of plants growing in phosphorus-deficient soil, a condition often found on coral atolls and in areas where the top soil has been disturbed or blown away. The Mike detonation of 1952 had removed most of the plants and top soil from Belle Island, resulting in the depletion of some of the elements essential for plant growth. In spite of these deficiencies regrowth of the

Table 1. Gamma dose rates three feet above ground in milliroentgens per hour at Belle Island, Eniwetok Atoll, May 15, 1954 to March 21, 1955.*

Date	Days after 5-14-54	Mr/hr	Date	Days after 5-14-54	Mr/hr
5-15-54	1.4	375	6-10	27	20
5-16	2.2	230	6-11	28	19
5-17	3	180	6-18	35	13
5-18	4	130	6-25	42	12
5-19	5	140	7-1	48	10
5-22	8	70	7-8	55	6.5
6-1	18	30	7-15	62	6
6-2	19	30	8-5	83	5
6-3	20	28	9-7	116	2
6-4	21	27	11-30	200	2.6
6-7	24	22	3-21-55	305	0.8

*Early readings taken with a PDR-39 ionization chamber survey meter and later readings with a Juno AEC Model S1C-17C survey meter.

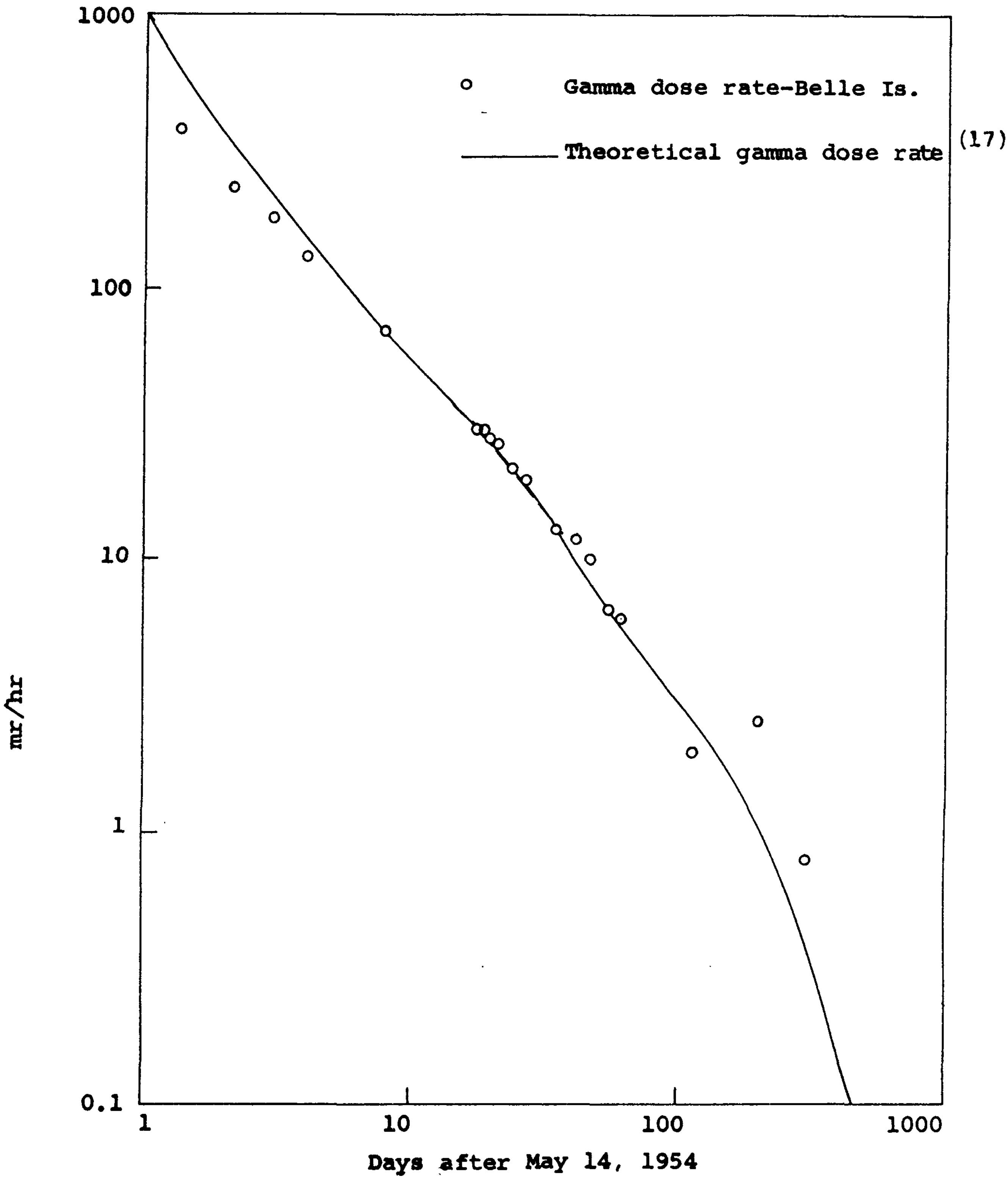


Figure 3. Gamma dose rates at three feet at Belle Island, Eniwetok Atoll, May 15, 1954 to March 21, 1955, compared with the decay of fission products from the slow neutron fission of U^{235} (17).

plants at Belle Island was rapid. In April 1954 some of the Scaevola and Messerschmidia "trees" were up to five feet in height, with a spread of ten feet, and bore many flowers and fruits. Plants of the other species also were well established.

A photograph of Belle Island taken eight days following the Nectar detonation (Fig. 4b) shows the extent of the damage sustained by the plants. From the air the island looked brown and desolate. On closer inspection it was found that most of the plants had been scorched by the heat wave and many of them had been blown over or broken by the shock blast. Two of the previously tagged plants (Cocos and Portulaca) had disappeared or had been dislodged from their original positions; other plants of these species were staked and labelled for study. On the tall shrubs, such as Scaevola, Messerschmidia and Guettarda, the leaves were usually gone or scorched, and the scorched branches and a few persistent leaves were all that remained of the plants. Flowers and fruits were found on some plants, especially in the prostrate plants such as Portulaca (No. 1211), which was located behind a large fallen coconut trunk. Close-ups of examples of damaged plants eight days post Nectar are shown in the foreground of Figures 4b and 5a.

Recovery of the plants was rapid. Heavy rains occurred on the third day. On the eighth day green buds, 1-3 mm in length, were observed on the stems of *Scaevola* and *Messerschmidia* (Fig. 5a) plants. On the thirty-fifth day the shoot leaves were 7 to 15 cm long, covering much of the old stems (Fig. 5b) and giving the plants a green and healthy appearance. By this time many of the other plants had formed new leaves and three species (*Portulaca*, *Triumfetta*, and *Messerschmidia*) had produced new flowers and fruits. The island now had lost its scorched appearance; from the air it looked green rather than brown as it had one month earlier.

In August, three months after the detonation, the plants were growing well (Fig. 6) and some species, such as *Boerhaavia* had produced new flowers. The leaves of most of the species had grown to maximum size, and the branches had grown almost to the pre-Nectar dimensions. This was not the case with the *Guettarda* and *Lepturus* plants, which recovered more slowly than the other species. The new growth on the *Guettarda* plant (No. 1216) consisted of ten small leaves which originated from a new shoot 18 cm tall at the base of the old plant; the *Lepturus* plant (No. 1410) was a mat of dead tops with some new growth forming at the periphery.

In six months the general condition of the vegetation (Fig. 7) was similar to that which existed before the Nectar detonation. In March 1955, approximately ten months post Nectar, the plants appeared to be normal, most of them bearing abundant flowers and fruits, healthy, green leaves, and the usual amount of yellow, older leaves. Plant No. 1216 (Guettarda) however, bore curled, distorted, and unhealthy-looking leaves (Fig. 8a). When observed again in November 1955, it bore about thirty healthy, green leaves, had increased in height and apparently was completely recovered (Fig. 8b). Plant No. 1211 (Portulaca) bore only a few leaves in March 1955, but when observed in November 1955, it had recovered somewhat, bearing abundant flowers and some green leaves.

No other aberrant growth forms were seen in the field observations at Belle Island. At Janet Island, the fasciated stems and the tumorous growths on plants of Ipomoea tuba observed in 1949 by Biddulph[6] were still present in 1957.

The measurements and observations made on one of the plants, Scaevola (No. 1319), during the course of the study are presented in Table 2. Notes for the remainder of the plants are given in Appendix Tables A and B.

Table 2. The regrowth of Scaevola sp. (Plant No. 1319) at Belle Island, Eniwetok Atoll, from May 22, 1954 to March 15, 1955 following the detonation of May 14, 1954 at a site two and one-half miles away.

Date	Appearance	Height (cm)	Over-all diameter (cm)	Length of larger leaves (cm)	Remarks
4/15/54	Healthy; green flowers and fruits present	75	90	16	
5/22	Plant badly damaged, stems naked and broken; some burned and green leaves persist at terminals	45	40	7.5	A few plants observed with persistent floral parts.
6/19	New leaves on stems; branches still scrawny-looking	65	75	15	No flowers observed on this plant.
8/12	Most leaves green and healthy; plant not as bushy as in April	75	75	16	Flowers present on Scaevola Plant No. 1209 Area C
9/14	Plant as healthy and bushy as in April	75	90	20	Flowers present on Scaevola Plant No. 1209 and No. 1213 Area A, and others.

Table 2. (continued)

Date	Appearance	Height (cm)	Over-all diameter (cm)	Length of larger leaves (cm)	Remarks
11/2/54	Growth normal in every respect; small flowers present	75	90	20	
11/30	Plants healthy, larger than in April, many flowers	78	95	20	
3/15/55	Yellowing of oldest leaves only; plant healthy, no flowers or fruits	100	125	20	Some *Scaevola* plants 2 meters in height.

Levels and Decline of Gross Beta Radioactivity at Belle Island

Plants

The amount of radioactivity in the samples of Scaevola plant No. 1319 collected during the study is given in Table 3. The amounts for the other species are given in Table 4.

The highest amounts of radioactivity, pre-Nectar, were found in the leaves (20 μc/kg) of a young coconut plant collected in the western part of the island in Area C and in the roots (18 μc/kg) and tops (13 μc/kg) of a grass plant in the same area. The lowest amount was found in the stem (0.35 μc/kg) of a Messerschmidia plant at the eastern end of the island.

In Scaevola, the levels of radioactivity three days post Nectar were higher than the pre-Nectar levels by factors of 500 (leaves) and 30 (stems) (Table 3). The basal leaves of a Scaevola plant in area C contained the highest level (29,000 μc/kg) of all of the plant samples collected at Eniwetok Atoll during this study.

The amounts of radioactivity of eight tissues of Scaevola plant No. 1319 were compared to determine whether some tissues contained more radioactivity than others. In

Table 3. Gross beta radioactivity of Scaevola sp., plant No. 1319, at Belle Island, Eniwetok Atoll, April 14, 1954 to April 26, 1956, expressed in $\mu c/kg$ of wet tissue at time of collection.

Collection	Leaves				Stems			
date	Scorched*	Basal	Terminal	Shoot	Entire	Bark	Internal	Flowers-Fruits
4-14-54			2.0		1.1			1.3
5-17	12,000	2,200	1,000		36	76	120	
5-18	10,000	1,000	740		150	540	26	2,700.
5-19	11,000	930	90		68	120	32	620
5-20	2,000	660	49		34	130	30	2,200**
5-21	6,700	380	61		65	1,100	44	530
5-26	3,300	33	26		97	790	38	170
5-28	4,600	12	17	44	14	29	5.9	34
6-1	910	12	10	26	46	100	10	
6-7		5.6	5.0	22	110	220	18	
6-11	390	3.4	3.3	16	2.1	5.9	0.73	
6-19		5.9	2.5	23	86	110	14	
6-25		2.5	1.7	2.2	12	16	2.2	
7-1		2.8	1.3	5.0	17	59	5.9	
7-8		2.4	1.8	10	6.6	12	1.1	
7-15		1.9	1.5	4.5	1.3	1.8	1.2	
7-22		1.2	1.4	2.6	1.1	2.0	0.40	
7-29		1.7	0.84	1.4	4.2	9.4	2.4	
8-5		2.0	0.99	4.4	0.73	1.2	0.62	
8-12		1.5	1.2	1.2	0.88	1.0	0.83	
8-19		1.0	1.2	0.70	0.76	1.2	0.32	
9-7		0.92	0.77	0.82	0.76	0.94	0.66	

* $\mu c/kg$ of dry tissue

** partly scorched

Table 3. (continued)

Collection date	Leaves				Stems			
	Scorched*	Basal	Terminal	Shoot	Entire	Bark	Internal	Flowers-Fruits
10-5		1.5	0.81		1.4	1.6	1.7	0.77
11-2		0.64	0.28		0.30	0.50	0.067	0.44
11-30		1.0	0.84	0.65	0.47	0.70	0.38	0.71
1-18-55		1.0	1.0	0.48	0.51	0.82	0.96	0.52
2-9		0.32	0.76			0.48	0.57	0.48
3-15		0.54	0.39		0.38	0.34	0.21	0.18
11-1		0.79			0.77			
4-26-56***		0.31					0.24	0.22

***From several plants including No. 1319

Table 4. Gross beta radioactivity of six species of land plants collected at Belle Island, Eniwetok Atoll, April 14, 1954 to April 26, 1956 expressed in uc/kg of wet tissue at time of collection.

Collection date	Leaves				Stems			Flowers and Fruits	Roots	Tops
	Scorched*	Basal	Terminal	Shoot	Entire	Bark	Internal			
A. *Messerschmidia argentea*										
4-14-54			0.60		0.35			0.64		
5-22	4200	130	43		560	1800	110	920		
6-1				17						39
6-19		4.6	2.8	4.4	26			54		
8-5		1.5	1.2	1.4	0.64	0.81	0.44			
9-7		0.43	0.31	0.34	2.1	2.1	0.48	0.57		
10-5	16	0.52		0.05	0.58	0.82	0.42	0.61		
11-2	0.23	0.20		0.13	0.12			0.23		
11-30		0.62			0.18	0.20	0.092			
1-18-55		0.20	0.17	0.19	0.14	0.18	0.92	0.53		
2-9		0.24		0.16		0.13	0.077			
3-15		0.27		0.28		0.26	0.10	0.40		
11-1		0.48			0.40					
4-26-56		0.42					0.50	0.32		

*μc/kg of dry tissue

Table 4. (continued)

Collection date	Leaves			Stems			Flowers and Fruits	Roots	Tops
	Scorched*	Basal	Terminal Shoot	Entire	Bark	Internal			
B. *Cocos nucifera*									
4-14-54		20							
5-22		790							
6-19	700	0.48							
8-5		7.3	1.8						
9-7		0.52							
10-5		1.5	0.76						
11-30		0.27	0.64						
1-18-55	1.7	0.19							
2-9		1.1	0.21						
3-15		0.21	0.16						
C. *Portulaca oleracea*									
4-14-54		0.86		6.4					
5-22		110		230			180		
6-19		0.11		2.5			1.6		
8-5		0.45		0.47	0.48	0.36			1.5
9-7		0.41		0.47			0.52	17	1.5
10-5		0.40		0.56			0.64		
11-2		0.37		0.28			0.28		
11-30		0.41		0.48			0.61		
1-18-55		0.63		0.36					
2-9		0.50		0.43					
3-15		0.65		0.76	0.58	0.40			

Table 4. (continued)

Collection date	Leaves				Stems			Flowers and Fruits	Roots	Tops
	Scorched*	Basal	Terminal	Shoot	Entire	Bark	Internal			
D. *Lepturus repens*										
4-14-54									18	13
5-22									790	1800
6-19									120	4.5
10-5									4	2.9
11-2									25	2.6
1-18-55									0.18	0.34
2-9									1.6	0.81
3-15									18	1.1
E. *Boerhaavia tetrandra*										
4-14-54		11			5.9					
5-22		1400			3100					
6-19		2.8			2.1			5.4		
8-5		0.81			0.43		1.2			
9-7		1.3			0.54			1.5		
10-5		1.4			0.76			0.99		
11-2		1.4			0.60			1.3		
11-30		0.83			0.59				2.6	4.3
1-18-55		1.4			0.65					
2-9		1.4	2.5		0.37					
3-15		0.21	0.16							

Table 4. (continued)

Collection date	Leaves				Stems			Flowers and		
	Scorched*	Basal	Terminal	Shoot	Entire	Bark	Internal	Fruits	Roots	Tops
F. *Triumfetta procumbens*										
4-14-54		3.2			0.87					
5-22	4300	1400			920					
6-19	80	5.1			5.1					
8-5		2.1	1.1		0.72	0.91	0.52			
9-7		0.70	4.4		0.35			1.1	2.3	
10-5		2.4	1.2		1.0			0.83		
11-2		1.7			1.9			0.96		
11-30		1.8	1.4		1.4			1.2		
1-18-55		0.61			0.65			0.42		
2-9		0.70			0.52			0.62		
3-15		0.60			0.61			0.34		
4-26-56		0.48						0.25		

49 of 54 comparisons the scorched leaves contained the highest levels of radioactivity. The chi-square test shows that this difference is highly significant. Since the scorched leaves were unable to absorb nutrients by metabolic means they must have accumulated the radioactive material by physical adsorption. A similar test showed that the internal portion of the stem contained the lowest amounts of beta radioactivity, which is not surprising, because the internal portion of the stem is the only tissue sampled in which there would be no surface contamination. No marked differences in levels of radioactivity were noted among the other six tissues.

Comparisons of the relative amounts of beta radioactivity among the tissues of plant species collected at Belle Island (Table 4) showed that the plants with a prostrate growth habit, such as that found in *Triumfetta* and *Boerhaavia*, and the forms with limited growth, such as the grass (*Lepturus*) and the purslane (*Portulaca*), contained higher levels of radioactivity than the plants with a taller growth habit, such as *Scaevola* and *Messerschmidia*.

With increased time after the Nectar test the levels of radioactivity of the different plant parts declined at different rates. In *Scaevola* the rate of decline of the basal and terminal leaves was rapid ($t^{-2.2}$) for about 50 days post Nectar, then when the pre-Nectar level was reached, it was much slower ($t^{-0.4}$) for the remainder of the study. The decline of radioactivity of the terminal leaves is shown in Figure 9. In the flowers, adventitious shoot leaves, and scorched leaves, the rate of decline was rapid ($t^{-2.0}$) for the entire period (for flowers see Figure 10). The differences in the rates of decline of radioactivity of these tissues may be due to the fact that the terminal leaves were protected by older leaves and were not exposed to fallout to the same degree as the flowers and scorched leaves. This difference in rate of decline may reflect the uptake of longer-lived fission products by the protected leaves. In the stems the rate of decline was less rapid than in other tissues. Figure 11 shows the decline of radioactivity of the entire stem. In each of these figures the decay of mixed fission products according to Hunter and Ballou[15] is included for comparison.

In *Messerschmidia* there were also three types of decline, these tissues having the same type of radioactive decline as the *Scaevola* tissues (Figs.9-11). In the other species, however, the decline was the same for each tissue; for example, in *Portulaca*, *Triumfetta* and *Boerhaavia*, the rate of decline for

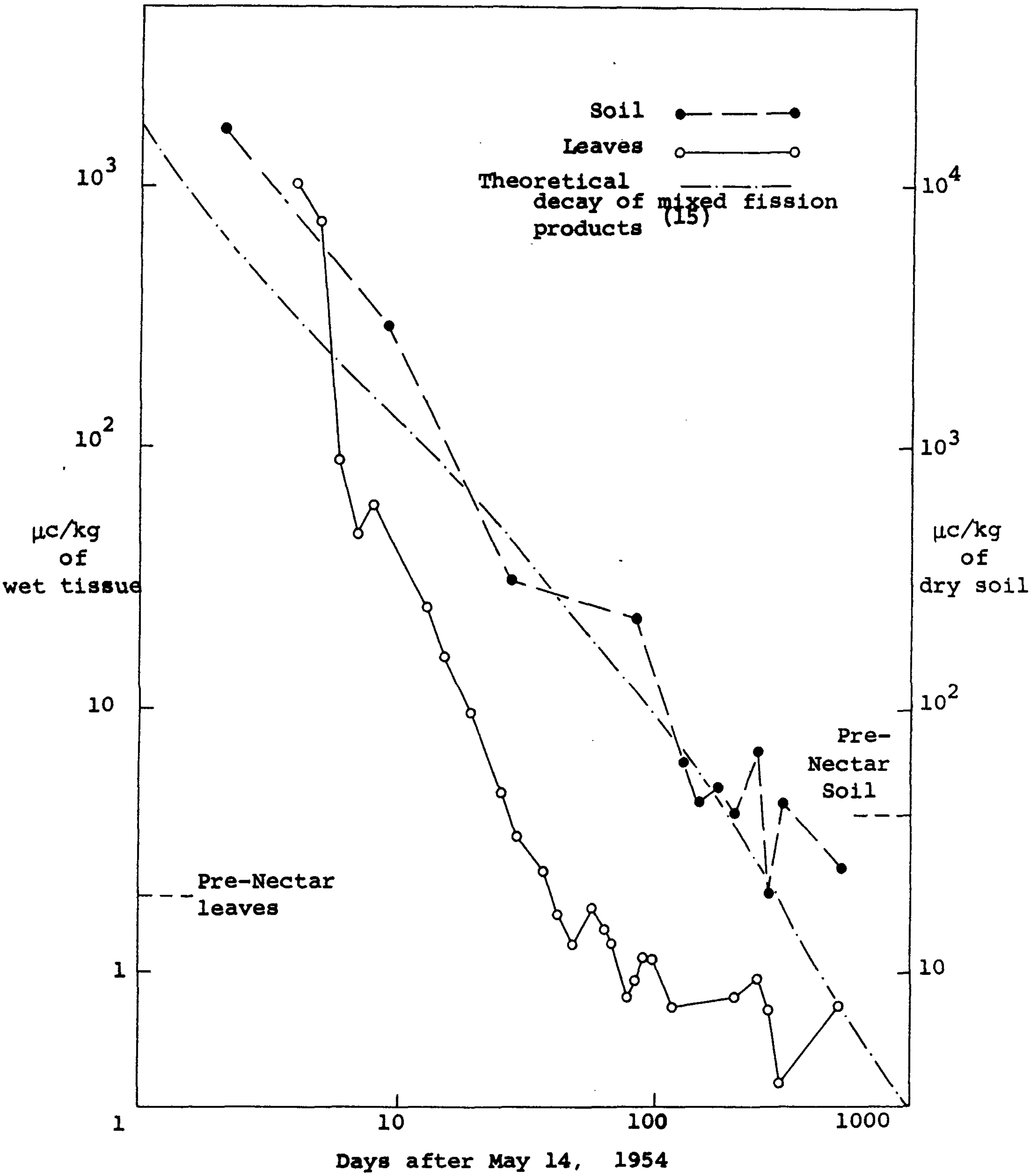


Figure 9. Decline of radioactivity of the terminal leaves of <u>Scaevola</u> sp. and of the soil at Belle Island, 1954-1955, compared with the theoretical decay of mixed fission products (15).

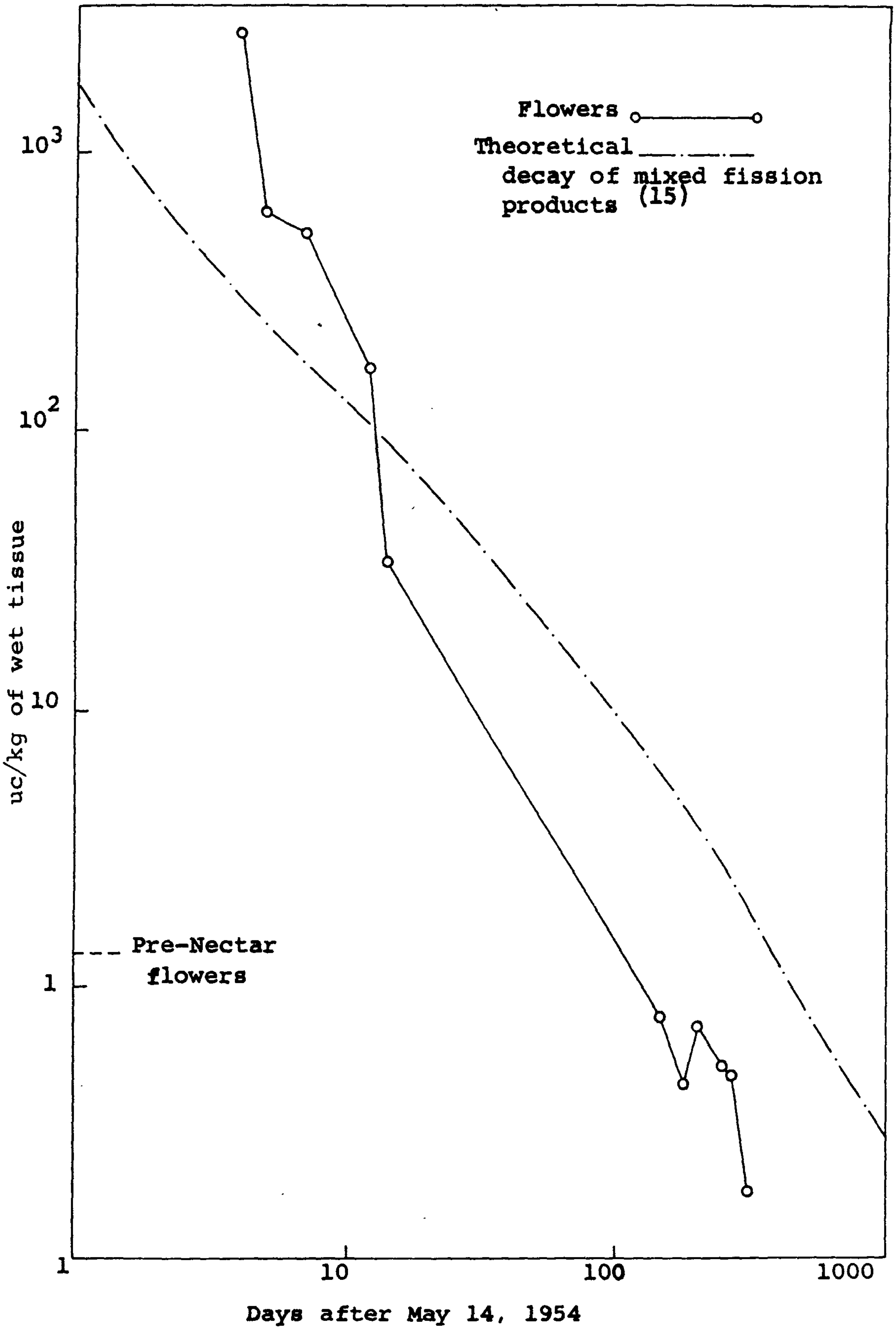


Figure 10. Decline of radioactivity of the flowers of *Scaevola* sp. at Belle Island, 1954-1955, compared with the theoretical decay of mixed fission products[15].

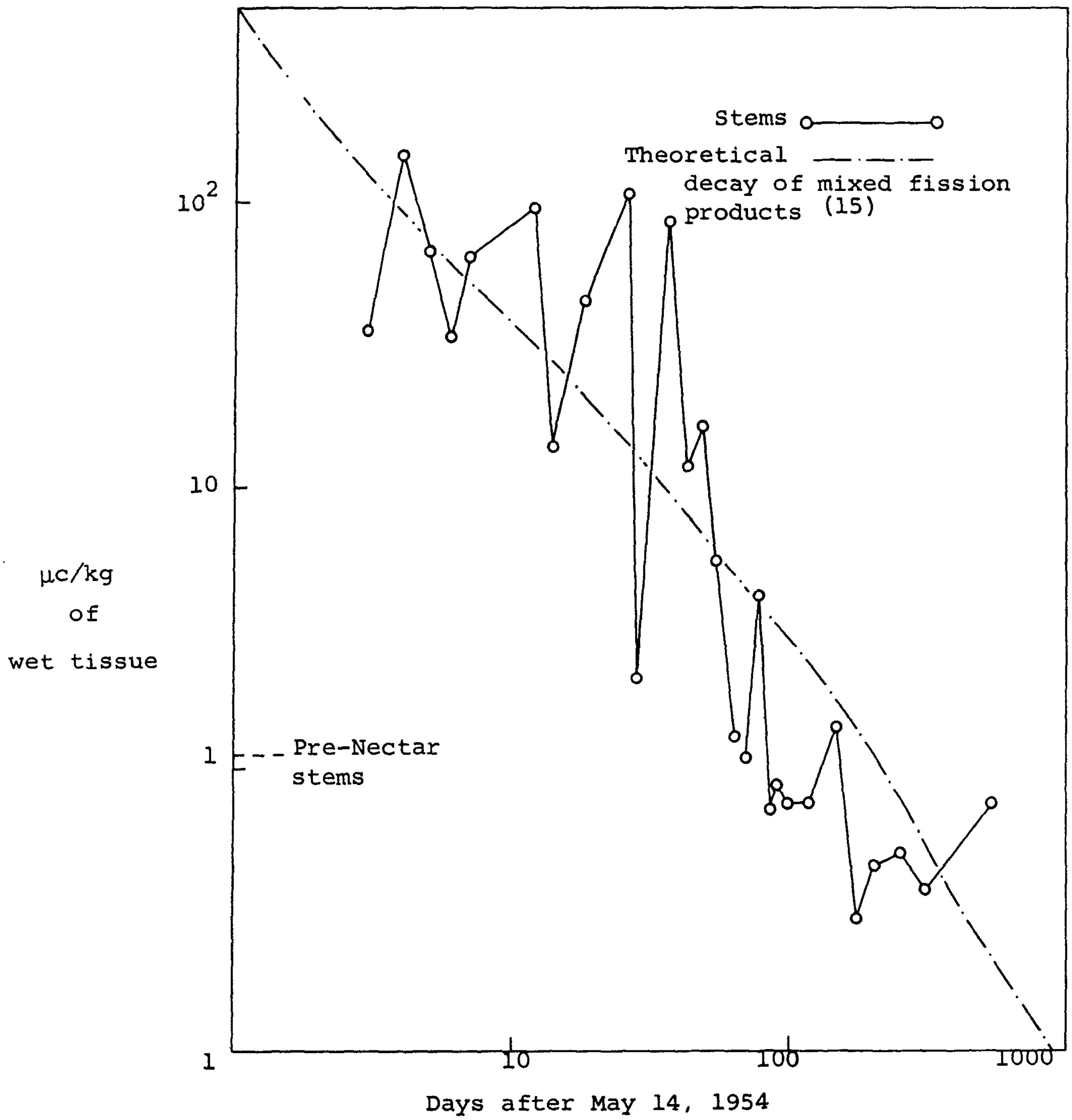


Figure 11. Decline of radioactivity of whole stems of <u>Scaevola</u> sp. at Belle Island, 1954-1955, compared with the theoretical decay of mixed fission products [15].

stems, flowers and leaves was the same. In these tissues the level of radioactivity was high one week after the Nectar test, dropped rapidly, and then leveled off at about 100 days post Nectar, much like the decline of radioactivity in the green leaves of Scaevola (Fig. 9). The radioactivity in the tissues of a coconut (Cocos nucifera) declined at a rapid rate for the entire period, similar to the decline shown in Figure 10. The fluctuations in the plot showing the rate of decline for the bunchgrass (Lepturus) make a comparison with other plants difficult.

Soil

The gross beta radioactivity of the top two inches of soil collected at Belle Island during the study period is given in Table 5 and is presented graphically in Figure 9. The beta radioactivity of the soil after the Nectar detonation decreased to the pre-Nectar level in about 150 days at a rate which approximates the rate of decay of mixed fission products for this period[15]. The rapid decrease in radioactivity of the soil samples was followed by a period of approximately one year in which the radioactivity in subsequent samples decreased at a slower rate. These data indicate that some of the radioisotopes with short half lives

Table 5. Gross beta radioactivity of the soil samples collected in Area D, Belle Island, Eniwetok Atoll, April 27, 1954 to November 1, 1955, expressed in μc/kg of dry weight at time of collection.

Collection date	μc/kg of dry weight: Mean	μc/kg of dry weight: Standard deviation
4/27/54**	40.0*	12.5
5/15	16,100 *	5,910
5/22	2,290 *	403
6/9	322 *	42.8
8/5	239	
9/14	65.9	
10/5	44.3	
11/2	52.3	
11/30	41.1	
1/18/55	71.8	
2/2	20.6	
3/15	46.4	
11/1	26.0	

* See Appendix Table C for individual values

** Area C pre-Nectar

had been leached out of the top layer of the soil and that the longer-lived radioisotopes were still present. This interpretation could account for the deviation observed in the latter portion of the plot for the decay of mixed fission products.

<u>Levels and Decline of Gross Beta Radioactivity at Other Islands of Eniwetok Atoll</u>

The amounts of gross beta radioactivity of the land plants collected at other islands of Eniwetok Atoll from March 1954 to April 1956 are given in Appendix Table D; the values for the plants collected from May 1956 to July 1957 are given in Appendix Table E. Before the Nectar detonation the highest amounts were in the leaves of plants collected at Janet Island on April 4, 1954; the average for eight samples was 149 μc/kg of wet tissue, the range being 8.4 to 384 μc/kg. The lowest amounts of radioactivity were found in two coconut meat (solid endosperm) samples from Henry Island; these samples averaged 0.30 μc/kg. In general the highest levels of radioactivity were found in the plants collected on Janet, Olive and Vera Islands. These levels were significantly higher than those on Belle Island.

On the basis of the increase in background levels of radioactivity at Eniwetok Atoll after the March 1954 tests at Bikini Atoll, and the steep slopes of decay plots of individual plant samples, it is believed that the relatively high amounts of radioactivity in the Eniwetok pre-Nectar samples were due to contamination from the Bikini fallout material.

After the Nectar test the levels of beta radioactivity of land plants at the various islands were directly related to geographical distance from ground zero and to time after detonation.

Uptake of Radioisotopes by the Plants

A comparison of the rates of decline of radioactivity of the soils and plant tissues shows that the radioactivity of some of the land plant tissues declined at the same rate as that of the soil samples. The rate of decline for the first 100 days was similar to the decay of mixed fission products. This similarity indicates that the radioactive material had adhered to the external surfaces of the leaves of the tall plants such as *Scaevola* and *Messerschmidia* during fallout. Splattering of contaminated soil particles on the low plants such as *Triumfetta*, *Boerhaavia* and *Portulaca* may account also for the similarity in the decline of radioactivity of these tissues to that of the soil. After the first 100 days, the rate of decline of radioactivity in all these tissues was slower than that expected by physical decay of mixed fission products, indicating that longer-lived radioisotopes had been taken up by these plants.

The rate of decline of some tissues, however, was different from that of the soil, suggesting that some of the radioisotopes had been taken up by the plants and distributed selectively in the plant tissues. The rapid rate of decline of radioactivity in the adventitious leaves, flowers, and fruits of Scaevola and Messerschmidia indicates the presence of short-lived radioisotopes in these tissues. However, the rapid rate of decline of radioactivity in the scorched leaves, which were incapable of normal metabolic activity, cannot be attributed to a selection process. This apparent anomaly might be explained on the basis of the differential adsorption of fallout particles to the surfaces of living versus dead tissues, on the differences in the foliar absorption of radioisotopes, and on the different rates of removal of radioisotopes by rain water.

The results of the radiochemical analyses of the samples collected during the period of February 1955 to October 1955

(Table 6) show that the plant tissues concentrated the long-lived isotopes Cs^{137} and Sr^{90}, which were present in low amounts in the soil. Ce^{144}-Pr^{144}, present in high amounts in the soil, accounted for only a small percentage of the radioactivity in the plant samples. Analyses were not made of the radioisotopes later shown to be present commonly in plant samples from this area. These isotopes, such as Zr^{95}-Nb^{95}, Ru^{106}-Rh^{106}, $Co^{57,60}$ and Zn^{65}, may account for the radioactivity that was not determined in the analyses.

Radioactive decay curves of individual samples of these tissues show that the radioactivity was decaying at a very slow rate. This observation is in accord with the radiochemical data, since both Sr^{90} (half life 28 years) and Cs^{137} (half life 27 years) accounted for the major portion of the radioactivity analyzed.

DISCUSSION

Previous studies to evaluate the recovery and reinvasion of the flora at the Eniwetok Proving Ground, approximately fifteen months after Operation Sandstone, were made in 1949 by St. John[22] and Biddulph[6]. They reported morphological abnormalities in ten species of plants growing

Table 6. Radiochemical analyses of plant and soil samples from Eniwetok Atoll, February to October, 1955 expressed as percentage of total beta radioactivity at time of analysis, March 1956.

Sample	Island	Collection date	Total beta activity d/m/g wet	Per cent of total radioactivity					
				Ca^{45}	Ce^{144}-Pr^{144}	Cs^{137}	Sr^{89}	Sr^{90}	Not determined
Scaevola, leaves	Belle	3/15/55	2,550	3	<1	28	0	3-4	64
Messerschmidia, leaves	"	"	1,340	2	3	*	0	27	68
Island soil	"	2/9/55	50,000**	<1.3	46	<1	0	5.2	47
Messerschmidia, stems, buds, flowers	Edna	3/8/55	930	*	*	40	*	*	60
Sida, leaves, stems, bark	Janet	10/17/55	470	*	2	66	0	21	17

* Analysis not made

** d/m/g of dry soil

on islands where atomic detonations had taken place, and where radiation levels were undoubtedly higher than those on Belle Island during the Nectar survey. These abnormalities included flattening, shortening, thickening and spiral torsion of stems, severe "die-back" of leaves and stems, chlorosis, asymmetry, shrivelling, crumpling and twisting of leaves, chromatism of stems, proliferation and enlargement of inflorescences, abnormal proliferation of stems, and sterility of plants. St. John reported finding a mutant of Guettarda speciosa on Runit Island but did not describe it. Biddulph reported spiralling and splitting of fronds on several coconut palms on Aitsu (Olive) Island, which is located between two of the "shot" islands.

On the "shot" islands, the plants closest to the bomb crater centers (where radiation levels were highest) were most severely affected. In areas where radiation levels were lower, the "disturbance of ecological habits" was reported to be more important in excluding plants from these areas than the radiation effects from the bombs[6]. Undoubtedly many of the abnormal plants started their growth after the nuclear detonations had occurred, in impoverished soil lacking inorganic nutrients and organic matter. These conditions are known to cause nutrient deficiencies which can sometimes be identified by the appearance of the plant. For example, nitrogen deficiency is often accompanied by yellowing and drying of the leaves and calcium deficiency is often followed by blackening and death of the plant (die-back). In coral atolls where the top soil has been removed the retention of rain water in the surface layer of soil would be slight, resulting in the curling, drying, and ultimate death of the shallow-rooted plants. On the basis of these observations it may be concluded that some of the abnormalities observed could have been caused by factors other than radiation. Therefore, it would be impossible to ascertain all of the causes of damage to plants in an area where radiation and nutrient deficiencies both exist. In areas of high radiation levels, much of this damage could be attributed to the radiation, because it has been shown in controlled field experiments, with several plants, that chronic doses of gamma radiation of 13 to 37 r per day for two to five months can cause plant abnormalities of various kinds(12), similar to those found at the Eniwetok Proving Ground. The total gamma dose delivered in these experiments ranged from 780 r to 5550 r. In more recent studies with conifers Sparrow[21] observed that doses as low as 3 r and 4 r per day caused death of *Pinus rigida* after six years of exposure (total cumulative dose, about 8000 r). Many plants, however, were dead or dying at doses much below this cumulated dose, and some visible damage was observed at doses below 3 r per day.

Observations made in February 1956 in the Marshall Islands by Fosberg[9,10] also suggest possible radiation damage to plants twenty-three months after an incidence of high level radioactive fallout. He found severe damage in the land plants (*Guettarda speciosa*, *Cocos nucifera*, *Suriana maritima* and others) at Gegen Island, Rongelap Atoll, where the "total radiation dose to infinity" was reported to be 3360 r. Where the levels of radiation were 10 to 100 times lower, little or no damage was observed. However, some species (*Guettarda*, *Lepturus repens*, and *Fleurya ruderalis*) appeared to be normal at Kabelle Island where the radiation level was high (total dose 1824 r). Other species (*Suriana*, *Cordia subcordata*, *Cocos nucifera* and *Pisonia grandis*) were abnormal in appearance at islands where the levels of radioactivity were lower. Fosberg suggested that some species of plants were more susceptible to radiation than others.

On the other hand many of the abnormalities reported by Fosberg, St. John and Biddulph have been reported from coral atolls where no radioactive fallout has occurred. For example, defoliation and death at the tips of branches of Cordia, Pisonia and Tournefortia (Messerschmidia) were reported on Wake Island in April 1952 after a period of drought by Fosberg(11). Taylor(23) reported that the vegetation at Bikini Atoll in March and April 1946 (before Operation Crossroads) was unhealthy-looking and that Pisonia plants bore only scanty foliage, improving later in the year. Records of rainfall in the northern Marshall Islands show that the dry period prevails from December to April, the months of January and February getting the least rainfall(5). As shown by the observations of Fosberg and Taylor, one would expect to find the plants at their worst during the dry period.

Some abnormalities found in the plants on coral atolls have been caused by insects. Taylor reported that the leaves of Suriana were clipped as if by insect attack, and Fosberg reported that Bauhinia was chlorotic and badly eaten by insects. Niering(19) reported that on Kapingamarangi Atoll the leaves of Scaevola were attacked by a leaf miner and new shoots and buds of Calophyllum sp. and Barringtonia asiatica were "infested to the point of disrupting the normal growth pattern." On Onotoa Atoll, Moul[18] observed that several insects were found on Guettarda plants. These included wasps, moths, stink bugs, and butterflies. Moul reported also that leaves of Pisonia trees were so badly damaged by leaf cutting bees that he could not find a perfect specimen of foliage. At Rongelap Atoll members of this Laboratory noted infestations of a lepidopteran larva causing deformed leaves on Guettarda plants. They also reported that insects caused defoliation and bud damage in plants of Terminalia sp. and Pisonia.

The bird population also is a factor in the production of unhealthy plants. Niering reported that at Kapingamarangi Atoll the leaves of Asplenium, Nephrolepis, Guettarda and Pisonia were turning brown and dying because of the fecal droppings of the white-capped noddy tern (Anous minutus marcusi). He reported that the breadfruit tree also is damaged by these birds. On Canton Island the suggestion was made that the native birds were chiefly responsible for the dead or dying conditions of the forest and scrub vegetation[13].

Other agencies also have been reported to cause chlorosis, die-back, slow growth, aberrant growth forms, and other kinds of plant abnormalities. Some causes not mentioned previously are salt spray, wind, storms, flying gravel, soil conditions and land crabs.

In ascribing the cause of damage to plants in a region where radioactive fallout has occurred, not only the radiation but also the other factors mentioned above must be considered. The recovery of the plants at Belle Island following their almost complete destruction by the Nectar detonation is remarkable. The slow recovery of two of the plants investigated might be attributed to other changes associated with the detonation rather than to the initial or residual radioactivity.

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