THE ECOSYSTEM STUDY ON RONGELAP ATOLL

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Abstract—**During the 1950's and 1960's, the Laboratory of Radiation Biology at the University of Washington carried out an intensive study of this Atoll, which was contaminated with radioactive fallout from the "Bravo shot" in 1954. This study involved many aspects of the environment and the plant and animal life: soils, land plants, marine life, birds, geology and hydrology, and human diets as well. In much of the research, the fortuitiously present radioactive isotopes, especially ^{137}Cs and ^{90}Sr, were tracers. Although the term "ecosystem study" was not in vogue at that time, it is clear that this was an early use of the ecosystem approach. Soil types and their development, the distribution of mineral elements in plants and soils, including predominant radionuclides, distribution and growth of native terrestrial plants in relation to topography and salinity, some aspects of the human diets, micronutrient nutrition of the coconut palm, island and islet development and stability, were given attention in the studies. Some of the findings in the various areas of study will be presented and discussed.**

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INTRODUCTION

ALTHOUGH the first studies of the effects of atomic testing had concentrated on Eniwetok and Bikini atolls, the fallout from the "Bravo shot" in 1954 was substantial on Rongelap Atoll (this incident and the fallout distribution were described by Hines 1962). This led to intensive observational and research efforts on this atoll by the Laboratory of Radiation Biology (later Radiation Ecology) of the University of Washington, under the leadership of Lauren Donaldson, and other groups over the next twenty or more years (Hines 1962). In March 1958, the University of Washington group, upon request from the Division of Biology and Medicine, U. S. Atomic Energy Commission, and with special encouragement by John Wolfe, one of its program directors, started a comprehensive program of ecological studies including most aspects of the plant and animal life and their environment: soils, land plants, algae, fish, birds, invertebrate animals, geology and hydrology. The diet of the resident human population, which returned in 1957 three years after evacuation, was included as well. Such an inclusive approach would now be called an ecosystem study, although the term was not widely used at that time. The nature of the studies and some findings of investigations in a number of these areas will be covered below.

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SOILS

Soil classification

Some background information was available on atoll soils (Stone 1951, 1953; Fosberg 1954), but little specific information on Rongelap soils. Over several years, Gessel and his associates made extensive field observations and collections on most of the islands of the atoll, followed by substantial laboratory studies of the samples.

They recognized five soil series (Kenady 1962), based primarily on the vegetation and on significant differences in the surface (A_1) horizon in the percentages of coarse material, organic matter, and total nitrogen, in phosphorus, and in cation exchange capacity (Table 1). Also there are sharp differences between the series deeper down in the profiles, as shown by the comparison between a Gogan soil from a *Pisonia* grove in the center of Kabelle Island and a Beach Ridge Sand developed under pioneer shrubs near the lagoon on Rongelap Island (Table 2). Organic matter, nitrogen, exchange capacity, and especially phosphorus are higher in the upper layers of the Gogan soil. These calcareous soils contain no clay, so exchange capacity is derived solely from organic matter. Our Gogan series may be a younger stage of the Jemo series described on Arno Atoll in the southern Marshall Islands (Stone 1951) and by Fosberg (1954) for the northern Marshall Islands. More complete discussions of atoll soils are given in Fosberg and Carroll (1965) and Morrison (1990), but were published after our studies.

Soil development

With age and stability, and the steady contribution of litter from the vegetation, soil organic matter and fertility increase. Both the amounts of litter and the nitrogen and phosphorus contents vary with the species growing on a site. *Pisonia* stands drop more litter than stands of pioneer species (*Scaevola* alone or *Scaevola* together with *Tournefortia* and *Guettarda*), and the *Pisonia* litter also has a much higher nitrogen content (Table 3), although in part this reflects the guano from

Table 1. Properties of the A_1 horizons of the five principal soil series.[a]

Soil series→	Rongelap Gravelly Sand	Gogan Gravelly Sandy Loam	Lomuilal Sand	Beach Ridge Sand	Kabelle Sand
Soil property ↓					
% Material > 2 mm	46.	10.	0.0	8.0	8.0
% Nitrogen	0.57	1.71	0.26	0.09	0.14
% Organic matter	16.7	35.6	6.4	4.5	7.7
Exchange capacity[b]	22.2	37.7	12.6	3.7	5.7
Potassium[b]	1.95	1.80	0.79	0.37	0.46
Magnesium[b]	4.19	11.1	3.21	2.55	1.92
Sodium[b]	3.36	4.01	2.68	1.16	1.52
Phosphorus[c]	81.7	985	54.2	32.8	32.1
pH	8.1	7.8	8.4	8.6	8.6

[a] Data from Kenady (1962). The A_1 horizon is the top layer of mineral soil, dark in color because of its organic matter.
[b] Exchangeable cations in centiequivalents per kg of oven dry soil (2 mm fraction)
[c] Parts per million phosphorus extracted by bicarbonate (Olsen et al. 1954).

Table 2. Comparison of Gogan Gravelly Sandy Loam and Beach Ridge Sand.[a]

Sample depth (cm)	% > 2 mm	%N	%O.M.	Exchangeable cations (centieq kg^{-1})[b] Ca	Mg	K	Na	Capacity	P	pH
Beach Ridge sand										
0–5	8	0.08	3.8	2.63	2.07	0.39	1.29	2.8	18.1	8.4
5–12.5	16	0.13	3.9	3.48	2.61	0.50	1.06	4.6	14.1	8.4
12.5–22.5	10	0.07	3.2	2.26	2.49	0.23	0.85	2.1	10.0	8.6
22.5–30	12	0.15	5.3	3.50	1.51	0.38	1.96	7.0	10.1	8.3
30–45	32	0.09	3.7	3.13	1.21	0.26	1.31	2.4	8.0	8.5
45–92.5	7	0.03	1.9	2.76	1.67	0.23	1.09	0.8	9.0	—[c]
92.5–110	14	0.03	1.3	2.81	1.51	0.18	1.06	1.0	26.0	9.0
110+	21	0.01	1.1	2.63	1.51	0.21	1.28	0.1	10.0	8.5
Gogan Gravelly Sandy Loam										
—[d]	10	1.54	21.4	10.3	7.0	—[c]	2.0	20.5	1330	7.4
0–2.5	20	1.96	—[c]	—[c]	7.4	—[c]	3.0	43.6	893	7.1
2.5–12.5	20	0.42	5.9	14.1	4.0	—[c]	0.8	17.9	416	7.9
12.5–30	27	0.18	6.8	6.2	2.2	—[c]	0.4	7.2	216	8.2
30–50	39	0.07	2.6	7.7	1.2	—[c]	0.4	2.6	151	8.6
50–65	56	0.05	2.6	7.8	1.1	—[c]	0.4	1.7	25	8.8

[a] Data from Kenady (1962).
[b] Soil analyses performed on the 2 mm fraction; exchangeable cations determined by flame spectrophotometry after extraction with ammonium acetate; the adsorbed ammonium was displaced from the samples, then assayed to attain exchange capacity; phosphorus was determined in the sodium bicarbonate extract according to Olsen et al. (1954). *Note:* The total of exchangeable cations may exceed the capacity because of dissolving of carbonates in the extracting solution.
[c] Analysis not available.
[d] Organic layer above the mineral soil.

birds which favor *Pisonia* for roosting (Gessel and Walker 1992). *Pisonia* litter is also relatively high in phosphorus (Billings 1964). Litter decomposes rapidly in this warm environment, with half or more of its weight reported lost in 6 mo in a litter bag decomposition study (Gessel and Walker 1992).

Two features of the soils—organic matter contents, and the presence of buried horizons—are obvious in micromonoliths, prepared by impregnating samples, which were removed at increasing depths in soil pits, with plastic resins (Held et al. 1965a). Fig. 1 illustrates the differences between typical profiles of the different series as represented in micromonoliths. The buried horizons indicate that repeatedly in the past, especially at the unstable margins of islands, the growth of vegetation and the consequent development of soils occurred, only to be covered over by raw sand deposits in catastrophic storms, so that soil development had to start anew.

Retention and movement of ions

The differences described above between the soil series, reflecting primarily the ages of the soils and the amounts of organic matter accumulated, are also of importance in their retention of radioactivity and the movement of the elements and their isotopes. Since the exchange capacity is directly related to organic matter content, the adsorption of ions is on this organic matter and on the algal crust, which is common on the recently developed "young" sandy soils near the lagoon beaches. The distribution of the predominant radionuclides in the profiles of four soils is given in Table 4. The differences in the radionuclide levels can be understood in terms of

Table 3. Dry weight and nitrogen content of the vegetation litter above the mineral soil.[a]

Location	Species	No. Samples	Litter weight[b]		Nitrogen[b]	
			$g\ m^{-2}$	$kg\ ha^{-1}$	$g\ m^{-2}$	$kg\ ha^{-1}$
Various Islands	*Tournefortia* *Guettarda* *Scaevola*	11	1,074	10,740	6.7	67
Wash area Kabelle Is.	*Tournefortia*	19	1,340	13,400	7.3	73
Soil Pit 6 Kabelle Is.	*Pisonia*	20	1,610	16,100	20.7	207
Rongelap Is.	*Pisonia*	20	1,900	19,000	45.3	453

[a] Data from 1959–1963 collections (Gessel and Walker 1992).
[b] Mean values.

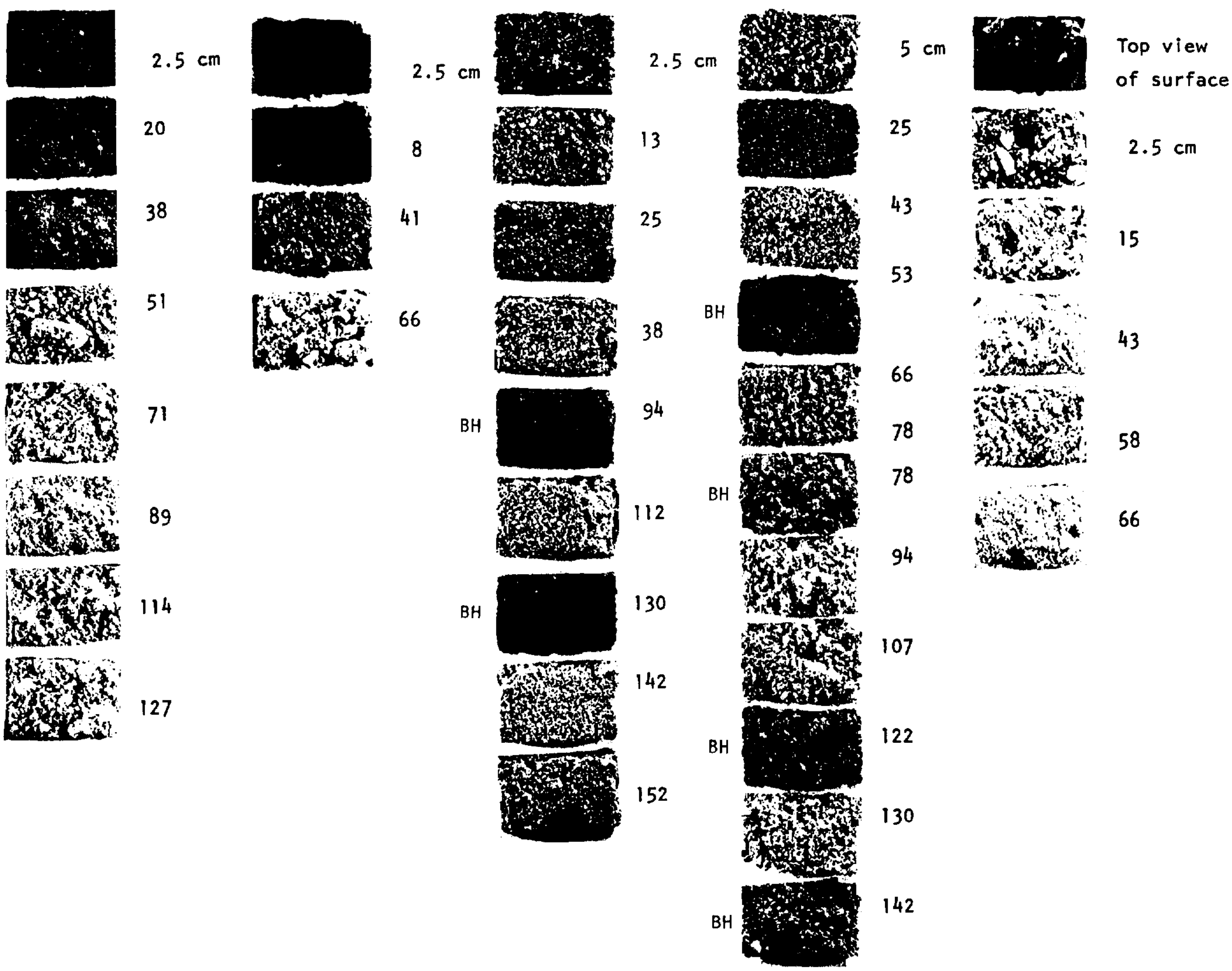

Fig. 1. Comparison of the micromonolith profiles of the principal soil series. Left to right: Rongelap gravelly sand; Gogan Gravelly Sandy Loam; Lomuilal Sand; Beach Ridge Sand; Kabelle Sand. BH means buried horizon.

the soil characteristics, and in relation to the at least fourfold greater fallout from the Bravo shot, which was received in the more northerly islands (Hines 1962). In general, the radionuclides decline with depth, reflecting the original deposition on the surface, the relatively high exchange capacities in the top layer of the soils, and the slowness of migration downward over time. An exception to this is seen with the Beach Ridge sand on

Table 4. Predominant radionuclides in several soil profiles (1974 collections[a]) (Bq g^{-1}, dry).

Sample depth (cm)	^{60}Co	^{125}Sb	^{137}Cs	^{155}Eu	^{241}Am	$^{239,240}Pu$	^{90}Sr
Rongelap Island (near lagoon beach, soil pit #3, Beach Ridge Sand soil series)							
0–2.5	0.013 ± .006	ns[b]	1.56 ± .033	0.018 ± .01	0.041 ± .011	0.012 ± .002	0.29 ± .026
2.5–5.0	0.044 ± .004	0.026 ± .012	1.22 ± .022	0.015 ± .013	0.20 ± .015	0.081 ± .026	0.59 ± .059
5.0–10	0.093 ± .006	0.081 ± .01	1.85 ± .026	0.14 ± .009	0.23 ± .01	0.23 ± .052	0.67 ± .009
10–15	0.03 ± .003	0.067 ± .007	0.70 ± .10	0.034 ± .006	0.059 ± .004	na[b]	na
15–25	0.01 ± .002	0.036 ± .006	0.23 ± .007	0.008 ± .004	0.020 ± .004	na	na
25–35	0.002 ± .001	0.0056 ± .004	0.024 ± .002	ns	0.0089 ± .004	na	na
35–50	0.004 ± .002	0.0070 ± .004	0.011 ± .002	ns	ns	na	na
Kabelle Island (Near cistern, pit #6, open and flat lagoon beach area, Kabelle Sand soil series)							
—[c]	0.33 ± .007	ns	18.1 ± .056	0.48 ± .019	0.67 ± .019	0.41 ± .056	11.1 ± 2.1
0–2.5	0.078 ± .004	0.030 ± .016	6.56 ± .026	0.34 ± .015	0.41 ± .019	0.19 ± .019	8.26 ± .74
2.5–5.0	0.013 ± .003	ns	0.17 ± .007	0.0077 ± .004	0.012 ± .004	0.0063 ± .0019	0.70 ± .067
5.0–10	0.0081 ± .002	0.0048 ± .004	0.067 ± .004	0.0063 ± .003	0.003 ± .003	na	na
10–15	0.0048 ± .001	0.0096 ± .003	0.30 ± .004	ns	ns	na	na
15–25	0.0026 ± .001	0.0014 ± .003	0.015 ± .004	ns	0.005 ± .004	na	na
25–50	0.0019 ± .0015	0.0093 ± .003	0.007 ± .004	ns	ns	na	na
Kabelle Island (Soil pit #7, toward center of island from cistern, Gogan Gravelly Sandy Loam)							
0–2.5	0.11 ± .007	0.070 ± .011	1.15 ± .019	0.56 ± .022	0.70 ± .022	0.19 ± .022	2.56 ± .24
2.5–5.0	0.024 ± .003	0.024 ± .008	1.07 ± .015	0.063 ± .007	0.085 ± .007	0.12 ± .007	1.15 ± .13
5.0–10	0.016 ± .002	0.021 ± .007	0.85 ± .011	0.029 ± .007	0.048 ± .007	na	na
10–15	0.006 ± .002	0.013 ± .008	0.56 ± .011	ns	0.011 ± .006	na	na
15–25	0.004 ± .001	0.006 ± .005	0.21 ± .007	0.014 ± .005	0.011 ± .005	na	na
25–35	ns	ns	0.019 ± .004	ns	ns	na	na
35–40	0.002 ± .0015	ns	0.011 ± .004	ns	ns	na	na
Lomuilal Island (Soil pit #5, Lomuilal Sand soil series)							
0–2.5	0.48 ± .01	0.25 ± .019	10.6 ± .052	1.41 ± .026	2.11 ± .033	2.48 ± .32	16.0 ± 1.41
2.5–5.0	0.17 ± .007	0.13 ± .018	11.0 ± .056	0.41 ± .015	0.67 ± .015	1.37 ± .17	10.6 ± .93
5.0–10	0.037 ± .003	0.036 ± .009	3.22 ± .026	0.056 ± .009	0.10 ± .011	0.078 ± .011	3.89 ± .37
10–15	0.015 ± .002	0.020 ± .007	1.19 ± .015	0.023 ± .007	0.041 ± .008	na	1.93 ± .16
15–25	0.0085 ± .002	0.013 ± .005	0.41 ± .007	0.009 ± .006	0.014 ± .006	na	0.74 ± .089
25–40	0.004 ± .001	ns	0.13 ± .005	0.004 ± .004	ns	na	0.33 ± .041
40–65	0.0015 ± .0007	ns	0.027 ± .002	0.0044 ± .002	0.007 ± .003	na	0.056 ± .011

[a] Data from Nelson (1977); error values for all radionuclides except ^{90}Sr and plutonium were two-sigma, propagated counting errors for a single sample; the error value for ^{90}Sr and plutonium were the two-sigma counting error for a single sample plus an analytical error. Counts adjusted for decay to 1975.
[b] na = not analyzed; ns = not significant, i.e., the net sample count was less than the two-sigma, propagated counting error.
[c] Algal crust on top of the soil.

Rongelap Island. In this soil, exchange capacity is low in the surface 5 cm, so there was apparently migration downward, especially to the 5–10 cm layer, which has somewhat higher exchange capacity. Both the Kabelle Island sand and the Lomuilal Island sand, from the northern part of the atoll, have expected higher radionuclide concentrations than those of the Rongelap Island Sand. In comparing the two soils from Kabelle Island, the sand from the lagoon beach area shows higher concentrations, especially of ^{137}Cs and ^{90}Sr, than the gravelly sandy loam from the interior of the island. This is particularly evident in the prominent algal crust at the beach location. However the gravelly sandy loam shows higher concentrations of ^{137}Cs in lower soil layers, presumably because of the greater exchange capacities at these depths.

Held et al. (1965b) compared the gamma-ray spectra of depth increments from "young" soils such as the Kabelle Sand with those from "older" soils such as the Gogan gravelly sandy loam. They found that ^{137}Cs and ^{125}Sb moved most readily in the older soils, while the principal gamma-emitting radionuclide moving in younger soils was ^{125}Sb. ^{90}Sr moved in both older and newer soils, and a vertical gradient was seen even in the surface 2 cm, but quantitative differences were obscured by the highly variable surface distribution of the radionuclides.

PLANTS

Mineral nutrition of plants

Soil pot experiments. Using atoll soils, plants were grown in pots both in a greenhouse in Seattle and under a wind/rain shelter on Enewetak Atoll, using several different soils, but in all cases ones which we would classify in the Gogan series. The principal objective of these trials was to test the effect of mineral fertilization on the uptake of ^{137}Cs into the plant shoots. For example, in an experiment using squash, fertilization with nitrogen and phosphorus increased yield and decreased the ^{137}Cs in the shoots, but application of potassium was more effective in the reduction of ^{137}Cs uptake (Table 5). The depression of ^{137}Cs uptake was great enough that dilution by increased yield could not be responsible. To test this effect in the field, in August 1958, two plots of 0.005

Table 5. Depression of ^{137}Cs uptake in squash by fertilization with potassium in a greenhouse test with Rongelap Gravelly Sand.[a]

Fertilization[b]	Ave. dry yield (g)	Ave. K in shoots (% dry weight)	Ave. ^{137}Cs in shoots[c] (Bq dry g^{-1})
No fertilizer	4.5	1.16	6.83 ± 0.57
$N_{3.36}P_{4.48}K_0$	8.0	0.69	2.83 ± 0.18
$N_{3.36}P_{4.48}K_{2.24}$	7.4	1.42	2.17 ± 0.23
$N_0P_{4.48}K_{2.24}$	5.5	1.86	2.50 ± 0.23
$N_{3.36}P_0K_{2.24}$	8.4	1.05	2.00 ± 0.27

[a] Data from Walker et al. (1961).
[b] Subscripts refer to equivalent rate of application in hundreds of kg per hectare.
[c] Error given is 95% counting error.

hectare were established in a stand of the grass *Lepturus repens* in a coconut grove on Rongelap Island, one as a control and one fertilized with KCl at the rate of 170 kg ha^{-1}. Grass collected on the plots in March 1959 gave the following analyses: Control = 0.395% K, 1.08 Bq g^{-1} dry ^{137}Cs; Fertilized = 0.645% K, 0.333 Bq g^{-1} dry ^{137}Cs, again showing markedly less uptake of ^{137}Cs with added potassium.

Mineral composition of foliage of woody plants. Many samples of foliage were collected on the different expeditions to Rongelap, especially of *Scaevola, Tournefortia, Guettarda,* and *coconut palm.* These samples were dried, carried to Seattle, then analyzed for the contents of various mineral elements. Table 6 gives representative data for mineral analyses of samples of leaves of these species. A general evaluation of these, with respect to the individual elements follows (see relations with radionuclide uptake in the next section:

- *Calcium:* The contents in the dicotyledenous species (as compared with coconut palm, a monocot) were high, as might be expected on the calcium carbonate substrate, and in most cases higher in lower than in upper leaves, characteristic of an element immobile in the phloem. In palm the contents were lower, to be expected in a monocotyledenous plant.
- *Magnesium:* The contents of this element are appreciable, and in most cases higher in lower than in upper foliage, indicating a more than adequate supply for the plants. Palm sometimes showed more magnesium than calcium in the leaves.
- *Potassium:* For all species the upper leaves showed fairly good levels of this element, but the lower leaves were almost always lower and sometimes very low, indicating a limiting supply.
- *Sodium:* The sodium contents of the dicotylenous species were high, as might be expected near the sea, but also because these species have a halophytic tendency (Walker and Gessel 1991). On the other hand, palm foliage was much lower in this element.
- *Nitrogen:*Contents of nitrogen were often low, especially in plants growing on the beaches, and often less in lower than in upper leaves, indicating a short supply of this mobile element.

Table 6. Analyses of the foliage of pioneer shrubs and coconut.[a]

		% of Dry weight						Parts per million		
Island/location	Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	^{137}Cs (Bq g^{-1}, dry)
Tournefortia argentea										
Rongelap-Pit 25	UL[b]	2.14	0.62	1.30	2.74	1.84	0.23			2.77 ± .083
	LL[b]	3.48	0.86	0.26	4.73	0.88	0.21			1.73 ± .083
Kabelle-Pit 6	UL	3.96	0.52	2.13	1.99	2.50	0.23			4.96 ± .055
	LL	6.78	0.64	0.60	3.45	1.13	0.17			3.29 ± .152
Kabelle-cistern	UL	3.28	0.63	1.24	5.60	—	0.21	48	23	
	LL	5.25	0.77	0.35	4.30	—	0.16	43	16	
Scaevola sericea										
Rongelap-Pit 25	UL	1.41	0.64	1.33	1.34	—	0.20			1.27 ± .069
	LL	2.27	1.24	0.48	1.34	—	0.26			1.73 ± .083
Kabelle-cistern	UL	2.69	0.62	1.90	1.37	2.01	0.29	48	37	
	LL	2.99	0.75	1.25	1.89	1.45	0.32	33	28	
Guettarda speciosa										
Kabelle-cistern	UL	1.37	0.34	1.21	0.53	1.47	0.19	30	5.8	
	LL	2.21	0.43	1.04	0.72	0.59	0.18	21	33	
Cocos nucifera (coconut palm fronds)										
Kabelle-Tree #39[c]	UL	0.32	0.50	1.49	0.75	1.47	0.18	35	9.8	
(Lagoon beach)	LL	1.09	0.73	0.49	0.70	1.25	0.16	18	4.8	
Kabelle-Tree #21[d]	UL	0.20	0.28	1.69	0.57	0.85	0.11	11	19	
	LL	0.44	0.37	0.50	0.47	0.85	0.11	8.1	9.1	

[a] Data from Gessel and Walker (1992); ^{137}Cs activity adjusted for decay to 1975.
[b] UL = upper leaves; LL = lower leaves.
[c] Both upper and lower leaves green; had been sprayed with iron chelate solution.
[d] Both upper and lower leaves yellow; soil had been fertilized with Fe-Mn-Zn mixture.

- *Phosphorus:* These values vary widely, probably reflecting the amount of soil organic matter as well as the spotty nature of additions of bird droppings, which are high in this element, to the soils.
- *Iron and Manganese:* As might be expected on calcium carbonate dominated soils with pHs of 7 to 8, the uptake into plants was low to very low. This correlated with the widespread chlorosis in young coconut trees, although chlorosis was absent in older coconut trees and in the native shrubs and trees. Perhaps this can be attributed to more extensive rooting with age in coconut, and the very extensive fibrous root systems of the native woody species.

Radionuclides in the foliage of woody plants. Plants will absorb to some extent all mineral elements that are present in the soil solution, including of course the radionuclides found in the Rongelap soils. Indeed traces of all of those listed for the soils in Table 4 were detectable in many plant samples. However, among these only ^{137}Cs and ^{90}Sr were consistently present in appreciable concentrations, which is not surprising because these elements are absorbed by plant roots in a manner comparable to that for potassium and calcium, which are chemically similar elements required in plant metabolism. Also ^{40}K was a predominant isotope in plant samples collected on Rongelap, even though it is mostly a naturally occurring isotope and was not a predominant radionuclide in the soils. This can be explained by the ability of plants to absorb potassium from very low external levels and concentrate it in their tissues. Consequently, ^{40}K is included along with ^{137}Cs and ^{90}Sr in Table 7, which lists their concentrations in samples of foliage of several woody species collected from a number of islands in the atoll.

Although there are some exceptions, in general the radionuclide concentrations are higher in samples collected on the more northerly islands (Kabelle, Lukuen, Naen) than those collected on the more southerly islands (Rongelap, Eniaetok). This is consistent with the higher levels in the soils in the northerly islands as seen in Table 4. For the *Pandanus* samples from Rongelap Island, there seems to have been a greater decrease in ^{137}Cs activity in the leaves than can be attributed to isotopic decay (all values in the table are adjusted to 1975). This may indicate that the soils are declining in ^{137}Cs levels over time through leaching to the ground water.

Water relation of plants

General aspects. The annual precipitation at Rongelap Atoll is about 125 cm, with a pronounced dry

Table 7. Predominant radionuclides in leaves of plants collected on Rongelap Atoll.[a,b]

Island/Location	Year collected	No. of samples	Radionuclide concentration (Bq g^{-1}, dry)		
			^{40}K	^{137}Cs	^{90}Sr
Pandanus sp.					
Rongelap Is.	1958	9	na	2.93	0.63
Rongelap Is.	1959	19	na	2.26	na
Rongelap Is.	1961	16	na	2.74	na
Rongelap Is.	1963	13	na	1.96	0.44
Rongelap Is.	1971	3	na	0.52	na
Rongelap Is.	1974	1	na	0.48	0.41
Rongelap Is. #3	1976	1	0.27 ± .052	2.17 ± .022	0.54 ± .029
Kabelle Is.	1958	4	na	9.22	1.19
Kabelle Is.	1961	1	na	4.19	na
Kabelle Is.	1963	1	na	6.00	1.48
Lomuilal/Lukuen Is.	1974	2	na	1.59	1.46
Naen Is. #1	1976	1	0.81 ± .081	4.53 ± .033	na
Eniaetok Is. #2	1976	1	0.27 ± .059	1.27 ± .018	na
Scaevola sericea					
Rongelap Is. Pit #3	1974	1	0.23 ± .085	0.78 ± .026	na
Lukuen Is. Site 5	1974	1	0.56 ± .10	0.52 ± .011	0.96 ± .11
Artocarpus sp. (breadfruit leaves)					
Rongelap Is. Pit #3	1974	1	0.28 ± .070	1.00 ± .015	na
Eniaetok Is. village	1976	1	0.48 ± .067	0.51 ± .015	na
Cocos nucifera (coconut fronds-central leaflets)					
Rongelap Is. Pit #3	1974	1	ns	0.16 ± .007	0.078 ± .011
Rongelap Is. Site #5	1976	1	0.19 ± .044	2.21 ± .025	na
Eniaetok Is.	1976	1	0.09 ± .059	0.21 ± .014	na
Lukuen Is.	1974	1	ns	0.31 ± .015	0.36 ± .030
Lomuilal Is.	1974	1	0.059 ± .026	0.67 ± .004	0.37 ± .019
Naen Is. Site #1	1976	1	0.21 ± .044	1.52 ± .018	0.34 ± .029

[a] Data for 1958–1971 collections are from University of Washington, Laboratory of Radiation Ecology (unpublished). Data for 1974 and 1976 are from Nelson (1977, 1979). All counts adjusted for decay to 1975.
[b] na = not analyzed. ns = not significant, i.e., the net sample count was less than the two-sigma, propagated counting errors for a single sample. The error values for all radionuclides are two-sigma, propagated, counting errors for a single sample.

season from January to May. The mean annual temperature is 27°C, with afternoon highs reaching to over 30°C. This regime causes high evapotranspiration, especially during the dry season.

Thus with the very coarse coral sand as the rooting substrate, water stress is a major influence on the survival and growth of plants. This is attested to by the relatively sparse vegetation on this atoll in comparison with the lusher plant growth in the more southerly atolls such as Majuro. Salinity adds to this water stress through osmotic effects. Such effects are always present, but become extreme during storms, with the blowing of salty spray over the plants or even inundation of the root systems in lower lying areas. Thus all plants growing on the atoll have some tolerance of salinity, and those inhabiting the beach and sand spit areas must be very salt resistant.

From the above, it will not be surprising that plants such as the native *Scaevola* and *Pisonia* often show some temporary wilting in the afternoons during the dry season. Perhaps a rise in leaf temperature, which would increase transpiration as well as reduced water uptake, may explain this wilting, which commonly disappears overnight.

Ground water and the fresh water lens. An important feature of atoll islands, especially the larger ones, is the presence of a lens of fresh or brackish water in the coral sand matrix, beginning a meter or so below the surface and extending downward as much as several meters. We sampled these ground waters from several islands of the atoll, by driving galvanized steel pipes down into the lens of water, which was commonly reached at depths of 1.5 to 4 m, then drawing up samples with plastic tubing. Some samples were almost as saline as sea water [electrical conductivity (EC) = 50 mMhos cm^{-1}], but those from the interior of islands were typically brackish [such as EC = 28 at Pit #4 near the center of Kabelle Island), but just slightly salty (EC = 2.6) in the well in the interior of the larger Rongelap Island]. The ionic proportions were similar to those in sea water. Also, some data on soil solutions were gathered; they were not very saline, having electrical conductivities of about 1.5 to 2.0 mMhos cm^{-1} (Walker and Gessel 1991).

Osmotic relations of species growing along beaches. Walker and Gessel (1991) also reported on osmotic potentials (Ψ_π) and sodium contents of leaf samples collected on Rongelap, and grew several woody atoll species in the greenhouse using culture solutions with varying levels of added salt. The Ψ_π of the field-collected leaves ranged from −1.9 to −3.1 M Pascals, compared with that of sea water at −2.7 M Pa; sodium contents were high in the tissues, usually 1 to 3% of the dry weight. In culture solutions, seedlings of four shrubby species (*Cordia subcordata, Guettarda speciosa, Scaevola sericea,* and *Tournefortia argentea*) and an atoll variety of squash (*Cucurbita pepo*) all grew well at a salinity of about 1/10 that of sea water, but were depressed to about 50% yield at salinity of about 1/6 that of sea water. The woody species declined to about 10–20% yield at salinity of about 1/2 that of sea water, and survived but grew very little in solutions with salinity equal to sea water. We were unable to obtain viable seed of *Pemphis acidula*, a tree often observed to grow directly in sea water on Rongelap, for greenhouse trials. However one sample of field-collected foliage of that species had an osmotic potential of 3.1 M Pa, which would have permitted absorption from sea water.

The studies just described show that seedlings of the species which occur on or near the atoll beaches, can endure exposures of the roots to osmotic concentrations equal to that of sea water, but do not grow much at such high salinity. Nonetheless, these species often grow well in nature close to both the lagoon and seaward shores. Ground waters in such locations are usually considerably less saline than sea water, and the plants have root systems which penetrate to considerable depths. These species can tolerate the salinity of most of the ground waters and probably absorb much water from them, especially during the dry season.

GENERAL ATOLL ECOLOGY

Introduction

Some time ago Fosberg (1953) summarized the general nature of Pacific atoll vegetation, and more recently wrote a description of the vegetation of Bikini Atoll, which has relevance also to Rongelap Atoll (Fosberg 1988). The following sections are based on observations made on Rongelap Atoll, especially during the period 1958–1964, by Ralph Palumbo, Mark Behan, James Kimmel, and the authors. In 1986, we had the opportunity to visit Rongelap again for several days, and made comparisons with the notes from the earlier years (Gessel and Walker 1987, 1992). These and previous observations were generally in good agreement with those of Fosberg just cited.

Non-vascular plants

Reef building algae are important, along with corals, in the geo-biotic structure of the atoll. Nitrogen fixation by algae in the crusts on top of young soils are very beneficial in the establishment of pioneer plants (Léskó 1968). Phytoplankton are not very abundant in the lagoon, being about 0.00825 g dry m^{-3} (Mathisen 1964), but nonetheless support some fish.

Vascular plant communities

Kimmel (1960) described seven plant communities occurring on the northern half of Rongelap Island. These were also characteristic of all of the larger islands of the atoll in the 1950's. During the 1960's, coconut planting decreased the areas of these plant communities somewhat, but all could still be recognized in 1986. Since the atoll has been mainly uninhabited since that time, there has probably been substantial regrowth of native woody species. The seven plant communities are briefly described below.

***Scaevola-Guettarda* community.** This is the most prevalent community along the beaches, where typically it is wedge-shaped, with the shrubs taller with increasing distance from the shoreline. "Fingers" of sand may penetrate the shrubby vegetation, with the grass *Lepturus repens* frequently present there.

***Suriana* Society.** Pure stands of *Suriana maritima* form small communities along the seaward shores of some islets. *Suriana* also occurs occasionally in the interior of islands, in places where there is evidence of overwashing with sea water.

***Pisonia-Tournefortia* Community.** *Pisonia grandis* is a very large tree by atoll standards, rising to a height of as much as 20 m and forming a dense closed canopy in the wet season. During the dry season the canopy thins by shedding of many leaves. Although not as tall and often recumbent, scattered old specimens of *Tournefortia argentea* are usually present also. The trailing vine *Boerhaavia* is common as a ground cover.

Ochrosia (*Neiosperma oppositifolia*) Community. In 1959, there were several small but dense communities of this large leafed species on Rongelap Island, with the trees 6 to 9 m tall. By 1986, these had all succumbed to clearing for coconut planting.

***Cordia* Community.** *Cordia subcordata* communities occur in boulder areas and are best developed on Rongelap Atoll on the seaward sides of Mellu Island and Aniclap Islet. Here the large-trunked trees form a tangled vegetation among boulders.

Coconut Plantation Community. The coconut trees are usually spaced 3 to 6 m apart, with a ground cover of the grass *Lepturus* and sometimes other herbaceous plants. In a well kept plantation there are no shrubs present.

Coconut Grove Community. This consists of three layers: first, a canopy of coconut fronds 10–13 m high; next, a layer .5 to 4 m high, consisting of coconut seedlings, a few *Pandanus* seedlings, *Tacca* (arrowroot), and occasional other shrubs; the third layer is a ground cover of grasses, the sedge *Fimbrystilis*, and scattered individuals of other small plants.

Mixed Forest Community. This is composed of a variety of trees, none of which is dominant. The 7 to 9 m tall canopy usually consists of *Pisonia*, coconut, and *Terminalia* or Cordia, with *Morinda*, *Guettarda*, *Tournefortia*, and *Scaevola* forming somewhat lower layers.

***Pemphis* Community.** Finally, there is a *Pemphis* community, which was not described by Kimmel (1960) because it does not occur on the northern part of Rongelap Island where he worked. This community is best developed on the leeward, lagoon shore of Mellu Island, where *Pemphis acidula* grows to a height of 4 to 6 m among the boulders and beach rock high in the intertidal zone. Both at Mellu and elsewhere, *Pemphis* trees can be seen standing in sea water at high tide.

Distribution of seeds

A conspicuous feature of the shores is the presence of seedlings of the pioneer species *Scaevola sericea* and *Tournefortia argentea*. The fleshy fruits of *Scaevola* are eaten by birds, especially curlews, and the hard seed-containing stones are deposited along the beaches after passing through the guts of the birds. *Tournefortia* seeds float in sea water and are not only unharmed by this soaking, but their germination is stimulated by the exposure to sea water (Léskó and Walker 1969). From the considerable amounts of seeds deposited on shores, an occasional seedling establishes (Léskó 1968).

Development of Vegetation on Islets and Islands

It is interesting to speculate on the development of plant life on islets newly formed from storm action, or on parts of larger islands which have been modified by typhoons. Evidence for the repeated development of vegetation and its obliteration is seen in the buried organic horizons depicted in Fig. 1.

A substantial part of our work on Rongelap Atoll was centered on Kabelle Island, which has an area of about 25 hectares, has been little disturbed by humans since it is remote in the atoll and is visited infrequently, and has only a few coconuts trees. We made a rough map of the vegetation on this island in 1958 (Fig. 2), and found that it had changed very little by 1986. From this distribution of plants and from observations of pioneer *Tournefortia* and other shrubs establishing along the beaches on various islands, we can propose a scenario for colonization of Kabelle Island. A feature of special interest is the presence of very large and obviously old *Tournefortia* trees in the center of this island. The hard solid trunks of these trees, which are often partially or completely recumbent, have diameters up to almost 1 m. Perhaps *Tournefortia* seedlings established on the island when it was small, newly formed after a major storm, and persisted as the island accreted and enlarged. Eventually birds carrying the sticky seeds of *Pisonia* could have led to the establishment and flourishing of this species in the central part of the enlarged island, but with the long-lived old *Tournefortia* still present. Such a scheme seems to fit with the presence of these old slow growing trees in the *Pisonia* groves of Kabelle Island, and perhaps such a development might have taken place on other islands as well.

The most fertile soils of the atoll (Gogan Series) are found in the *Pisonia* stands. Litter deposition is heavy, and a thick humus layer is often present. Fertility is enhanced by birds, since these stands are favorite nesting areas for both fairy and noddy terns. The late Frank Richardson estimated that some 1,400 terns, frequenting

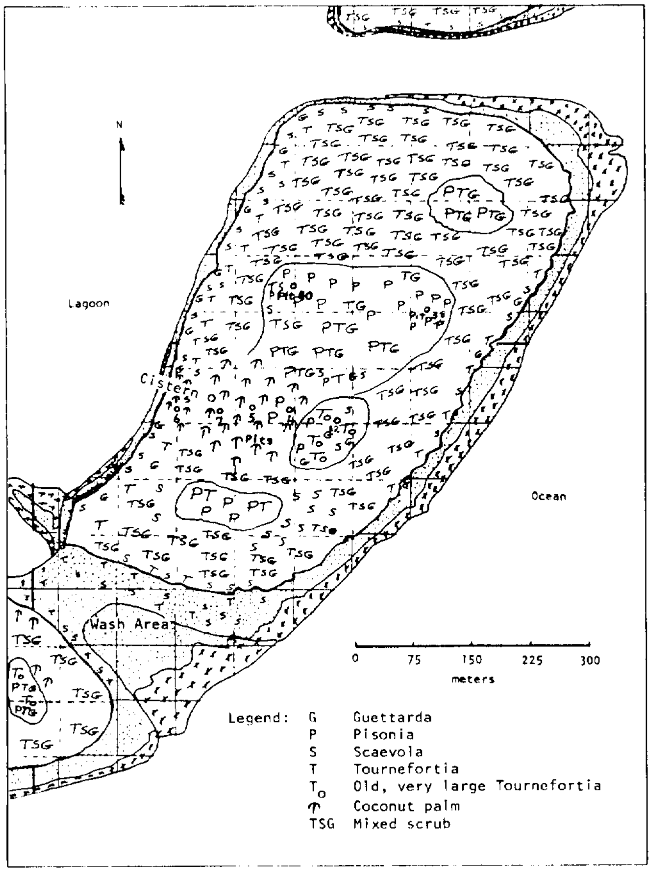

Fig. 2. Map of Kabelle Island, showing the distribution of vegetation (Charted in 1959, but little changed in 1986).

and nesting in a *Pisonia* community of about 0.25 hectare on Kabelle Island, consumed about 48 tons of fish per year, thus bringing large amounts of nitrogen, phosphorus, and other mineral nutrients from the sea to the island. On the larger islands the *Pisonia* areas with their relatively fertile Gogan Series soils have been largely converted to coconut plantations.

Rate of plant growth

In a tropical environment the diameter growth is difficult to follow because there are not well defined annual growth rings. We marked a large number of specimens and measured their diameters and heights each time we visited over a period of several years (Gessel and Walker 1992). In good situations, *Tournefortias* increased in diameter about 1 cm per year, and the medium sized shrubs grew about 17 cm in height per year. *Pisonias* averaged about 0.4 cm of diameter increase per year in general, but on a good site in the center of Kabelle Island they increased 1.3 cm per year. Medium-sized *Scaevolas* averaged about 21 cm of height growth per year. Although fragmentary, these data give some idea of the growth of these plants in an environment favorable in temperature but stressful with respect to mineral nutrient and water relationships.

Plants as food for humans

The principal plants eaten are coconut, breadfruit, pandanus, and arrow-root (*Tacca*), which are available in relative abundance. Together with fish and shellfish, these made up the bulk of the traditional diet. Coconut crab was considered a delicacy, although it is now rare on the inhabited islands. Also very limited amounts of squash, banana, and papaya were grown. Chakravarti and Held (1961) assessed the amount and composition of typical daily rations of Rongelapese individuals in 1959. Although there was a strong component of the native plant foods and fish, imported flour and rice as well as canned meat were also major components. As might be expected, they reported measurable amounts of radioactivity in the foods, with higher levels of ^{137}Cs and ^{90}Sr in diets which included coconut and local fruits. Table 8 gives the levels of the predominant radionuclides in samples of foodstuffs collected on Rongelap in 1974–1975 (Nelson 1977, 1979). The inclusion of ^{40}K reflects again the avid absorption of potassium by plants from low concentrations in the environment. A much more detailed study of the Rongelap Atoll foods and their radionuclide levels has been published recently by the Lawrence-Livermore Laboratory (Robison et al. 1994).

ANIMALS

Vertebrate animals

Sea birds are a very important component of the atoll ecosystem, and there are also some shore and land birds.‡ Certainly the sea birds, present in large numbers, make a vital link in the movement of minerals from the sea to the land.

The small field rat (*Rattus exulans*) is the only endemic mammal on the atoll, although the Rongelapese kept some pigs for food. Reptiles are represented by skinks, geckos, and a blind snake, and occasionally the giant sea turtle (*Chelonia*) is encountered.

Fish are of course the most varied and numerous of the vertebrates associated with the atoll, there being over 700 species in the lagoon and nearby waters. Welander (1958) collected many of these species and determined their uptakes of radionuclides. Some data on the radionuclides in fish are included in Table 8.

Invertebrate animals

Insects are few, both in number of species and individuals, except for the numerous house flies. Land crabs are common, the most spectacular of these being the coconut or robber crab, *Birgus latro*, which grows to large size and was a favorite food of the Rongelap people (Chakravarti and Held 1960; Held 1960) (see Table 8 for radionuclide levels in the collections of this species from 1957–1976). In contrast with the low number of terrestrial forms, there is a rich variety of invertebrate species

‡ Richardson (1959, unpublished) surveyed the birds of Rongelap, identifying the species and estimating the sizes of the populations, especially of the most common ones: the fairy tern, *Gygis alba*, and the noddy terns, *Anous stolidus* and *A. tenuirostris*.

Table 8. Predominant radionuclides in some human foodstuffs collected at Rongelap Atoll.[a,b]

Island/location	Year collected	No. of samples	Mean radionuclide concentrations (Bq g^{-1}, dry) ^{40}K	^{137}Cs	^{90}Sr
Coconut meat (fresh:dry ratio = 1.6)					
Rongelap Is. Site #5	1976	1	0.13 ± .052	0.91 ± .014	<0.0043
Eniaetok Is. Site #1	1976	1	0.34 ± .059	0.47 ± .01	<0.007
Lukuen Is. Site #6	1974	1	0.14 ± .041	0.48 ± .011	<0.004
Lomuilal Is. Site #7	1974	1	0.144 ± .056	1.59 ± .019	0.007 ± .002
Naen Is. Site #1	1976	1	0.22 ± .052	1.27 ± .011	0.0065
Coconut milk (fresh:dry ratio = 37.5)					
Rongelap Is. Site #5	1976	1	ns	12.9 ± .51	<0.08
Eniaetok Is. Site #1	1976	1	2.00 ± 1.78	1.96 ± .22	na
Lukuen Is. Site #6	1974	1	0.122 ± .009	0.022 ± .001	0.152 ± .056
Lomuilal Is. Site #7	1974	1	ns	0.056 ± .002	0.133
Naen Is. Site #1	1976	1	na	12.6 ± .58	<1.16
Coconut crab muscle (fresh:dry ratio = 4.5)					
Rongelap Is.	1957–58	12			4.85
Kabelle Is.	1957–58	14			16.3
Arbar Is.	1974	2	0.32 ± .052	1.21 ± .017	0.045 ± .008
Tufa Is.	1976	2	0.30 ± .083	0.47 ± .016	0.047 ± .008
Busch Is.	1974	2	0.34 ± .076	1.29 ± .020	0.10 ± .012
Mellu Is.	1974	1	0.41 ± .059	1.96 ± .015	0.126 ± .011
Kabelle Is.	1974	3	0.318 ± .063	2.28 ± .031	0.179 ± .016
Kabelle Is.	1976	2	0.32 ± .071	1.67 ± .023	0.13 ± .010
Lomuilal Is.	1974	1	na	na	0.29 ± .048
Lukuen Is.	1974	1	0.34 ± .052	2.11 ± .022	0.10 ± .015
Naen Is.	1976	2	0.28 ± .062	5.63 ± .033	0.25 ± .035
Fishes (eviscerated whole)[c]					
Rongelap Is. (goatfish)	1974	1	0.44 ± .015	0.001 ± .0007	<0.003
Rongelap Is. (convict surgeon)	1974	1	0.32 ± .044	ns	<0.003
Kabelle Is. (mullet)	1974	2	0.26 ± .056	0.009 ± .002	0.0044 ± .007
Lukuen Is. (mullet)	1975	1	0.37 ± .037	0.003 ± .002	<.005

[a] Data from Nelson (1977, 1979).
[b] Counting procedures were the same as indicated for Table 7. All counts adjusted for decay to 1975.
[c] Fresh:dry ratios for fishes (eviscerated whole): goatfish, 3.64; convict surgeon, 3.89; mullet, 3.41.

in the lagoon and off shore waters, and in many cases very large numbers of individuals are present. Corals are dominant forms which played an essential role in the formation of the atoll and continue to be vital in the maintenance of reefs and shores. Among the invertebrates, some of the most numerous and often attractive in appearance are the Tridacnid clams, the wide variety of sea snails, and the sea cucumbers (*Holothuria, Stichopus*). Bonham and Held (1963) made a detailed population study of the very abundant *Holothurias*.

GEOLOGIC STUDIES

From the studies of soils and vegetation described above, some indications of the influences of the sea, especially during storms, could be envisaged. The presence of buried soil horizons high in organic matter and the size and age of pioneer plants on beaches, islets, and sand spits gave some indications of the unstable nature of the land areas.

Porter (1966) reported on geologic observations made on Rongelap in 1963. From these observations and from the literature, he drew a number of tentative conclusions:

a) Most islands along the windward side of the atoll show evidence of lagoonward migration within the recent past, with beachrock pavements extending outward from the modern beaches;
b) Erosion of windward coasts has been accompanied by sedimentation on leeward coasts;
c) From world-wide sea level changes, atoll islands may be no older than about 3,000 y;
d) Beachrock formation and history seem to be related to water tables rather than to sea water influences; and
e) The present rate of deposition of atoll sediments appears to be greater than the rise of sea level, which permits accretion of reef detritus on atoll margins to form emergent land.

A study of lagoon bottom sediments was made by Anikouchine (1961).

CONCLUSION

This study of the Rongelap Atoll ecosystem was incomplete, because the scientific expeditions were of necessity short and infrequent. Nonetheless, valuable data was accumulated on many aspects of the ecosystem: the physical environment, soils, plants, vertebrate and invertebrate animals, and human nutrition. The long lived isotopes ^{137}Cs and ^{90}Sr were useful as tracers in studying mineral uptake from the soils into plants and animals. An earlier evaluation of the distribution of isotopes in different components of the atoll was made by Held (1963), and a recent detailed assessment was made by the Lawrence-Livermore Laboratory (Robison et al. 1994).

REFERENCES

Anikouchine, W. A. Bottom sediments of Rongelap Lagoon, Marshall Islands. Seattle: University of Washington; 1961. Thesis.

Billings, R. F. A description of nitrogen and phosphorus distribution in some Rongelap Atoll land ecosystems. Seattle: University of Washington; 1964. Thesis.

Bonham, K.; Held, E. E. Ecological observations on the sea cucumbers *Holothuria atra* and *H. leucospilota* at Rongelap Atoll, Marshall Islands. Pacific Sci. 17:305–314; 1963.

Chakravarti, D.; Held, E. E. Potassium and cesium-137 in *Birgus latro* (coconut crab) muscle collected at Rongelap Atoll. J. Marine Biological Assoc. of India II:75–81; 1960.

Chakravarti, D.; Held, E. E. Chemical and radiochemical composition of the Rongelap diet. J. Food Sci. 28:221–228; 1961.

Fosberg, F. R. Vegetation of Central Pacific Atolls, a brief summary. Atoll Res. Bull. 23:1–26; 1953.

Fosberg, F. R. Soils of the Northern Marshall Atolls, with special reference to the Jemo series. Soil Sci. 78:199–207; 1954.

Fosberg, F. R. Vegetation of Bikini Atoll, 1985. Atoll Res. Bull. 315:1–28; 1988.

Fosberg, F. R.; Carroll, D. Terrestrial sediments and soils of the Northern Marshall Islands. Atoll Res. Bull. 13:1–156; 1965.

Gessel, S. P.; Walker, R. B. Marshall Island vegetation and the United States nuclear weapons program. Univ. of Washington Arboretum Bull. 50(1):20–24; 50(3):18–23; 1987.

Gessel, S. P.; Walker, R. B. Studies of soils and plants in the Northern Marshall Islands. Atoll Res. Bull. 359:1–70; 1992.

Held, E. E. Land crabs and fission products at Eniwetok atoll. Pacific Sci. 14:18–27; 1960.

Held, E. E. Qualitative distribution of radionuclides at Rongelap Atoll. In: Schulz and Klement, eds. Radioecology. New York: Reinhold Publishing Co.; 1963:167–169.

Held, E. E.; Gessel, S. P.; Mattson, L. J.; Billings, R. F. Autoradiography of sectioned soil cores. In: Proc. Symposium on Radioisotope Sample Measurement Techniques in Medicine and Biology. Vienna, Austria: IAEA; 1965a: 553–560.

Held, E. E.; Gessel, S. P.; Walker, R. B. Atoll soil types in relation to the distribution of fallout radionuclides. Washington, D.C. U. S. Atomic Energy Commission, Division of Tech. Information (Biology and Medicine TID-4500); 1965b.

Hines, N. O. Proving ground: an account of radiological studies in the Pacific, 1946–1961. Seattle: University of Washington Press; 1962.

Kenady, R. M. The soils of Rongelap Atoll, Marshall Islands. Seattle: University of Washington; 1962. Thesis.

Kimmel, J. D. Plant communities of the northeastern half of Rongelap Island, Rongelap Atoll, Marshall Islands. Columbus: Ohio State University; 1960. Thesis.

Léskó, G. L. Some ecological aspects of coral atoll beach colonization by *Messerschmidia* and *Scaevola*. Seattle: University of Washington; 1968. Dissertation.

Léskó, G. L.; Walker, R. B. Effect of sea water on seed germination in two Pacific atoll beach species. Ecology 50:730–734; 1969.

Mathisen, O. A. Determination of plankton biomass in Rongelap Atoll, Marshall Islands, by the use of a multi-net plankton pump. Verh. Internat. Verein. Limnol. 15:735–734; 1964.

Morrison, R. J. Pacific atoll soils: chemistry, mineralogy, and classification. Atoll Res. Bull 339:1–25; 1990.

Nelson, V. A. Radiological survey of plants, animals and soil at Christmas Island and seven atolls in the Marshall Islands: Progress report for 1974–1975. Seattle, WA: University of Washington, Laboratory of Radiation Ecology; NVO-269-32; 1977.

Nelson, V. A. Radiological survey of plants, animals, and soil at five atolls in the Marshall Islands: September–October 1976. Seattle, WA: University of Washington, Laboratory of Radiation Ecology; NVO-269-36; 1979.

Olsen, S. R.; Cole, C. V.; Watanabe, F. S.; Dean, L. A. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U. S. Dept. Agric. Circular 939; 1954.

Porter, S. C. Geomorphology of windward islands, Rongelap Atoll, Marshall Islands. Proc. Cordilleran, Sect., Geol. Soc. Amer., Abst.; Boulder, CO; 1967.

Robison, W. L.; Conrado, C. L.; Bogen, K. T. An updated dose assessment for Rongelap Island. Livermore, CA: Lawrence Livermore National Laboratory; UCRI-LR-107036; 1994.

Stone, E. L., Jr. The soils of Arno Atoll, Marshall Islands. Atoll Res. Bull. 5:1–56; 1951.

Stone, E. L., Jr. Summary information on atoll soils. Atoll Res. Bull. 22:1–6; 1953.

Walker, R. B.; Held, E. E.; Gessel, S. P. Radiocesium in plants grown in Rongelap Atoll soils. Recent Advances in Botany, Section 12:1363–1367; 1961.

Walker, R. B.; Gessel, S. P. Osmotic relations of some plants of the Northern Marshall Islands. Pacific Sci. 45:55–62; 1991.

Welander, A. D. Radiobiological studies of the fish collected at Rongelap and Aelinginae Atolls, July 1957. Oak Ridge, TN: Technical Information Service; 1958.

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