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STUDIES OF SOILS AND PLANTS IN THE NORTHERN MARSHALL ISLANDS

BY

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CONTENTS

Page

ACKNOWLEDGEMENTS ii

LIST OF FIGURES iii

LIST OF TABLES iv

INTRODUCTION 1

SOILS: GENERAL DESCRIPTION AND METHODS 2
  RONGELAP ATOLL SOILS 11
    Characteristics of Soil Series 11
    Significance of Series Separation 22
    Other Data 22
    Plant-Soil Interrelationships 22
    Litterfall and Litter Decomposition 27
    Nitrogen and Phosphorus Content of Litter and Soil 27
    Total Nitrogen in Soil 30
    Fungi and Algae 30
  SOILS AND PLANTS OF ENEWETAK AND BIKINI ATOLLS 32
    1964 Condition 32
      Disturbance Class 32
      Chemical Analyses 35

PLANT PHYSIOLOGICAL STUDIES 35
  PLANT NUTRITION 35
    Pot Tests Using Atoll Soils 35
    Plant Tissue Analyses 39
    Growth Response to Coconut Fertilization 48
  WATER RELATIONS 50
    General Aspects 50
    Salinity and Ionic Composition of Ground Waters 51
    Osmotic Relations of Strand Species 51

GENERAL ATOLL ECOLOGY 53

  INTRODUCTION 53

  PLANT COMMUNITIES 53

  QUANTITATIVE DESCRIPTION OF A SCAEVOLA-GUETTARDA COMMUNITY 59
  WEIGHT OF VEGETATION (BIOMASS) 62

  VEGETATION GROWTH RATES 62

NATURAL AND MAN-MADE CHANGES IN THE VEGETATION 63

CONCLUDING REMARKS 67

LITERATURE CITED 68

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LIST OF FIGURES

		Page
Figure 1	Map of the Northern Marshall Islands	5
Figure 2	Map of Rongelap Atoll	6
Figure 3	Map of Bikini Atoll	7
Figure 4	Map of Enewetak Atoll	8
Figure 5	Map of the Northeastern Part of Rongelap Island Showing Locations of Soil Pits	15
Figure 6	Map of Kabelle Island, Rongelap Atoll, Showing Locations of Soil Pits	16
Figure 7	Rongelap Gravelly Sand: Typical profile and vegetation	17
Figure 8	Gogan Series: Typical profile and vegetation	18
Figure 9	Lomuilal Sand: Typical profile and vegetation	19
Figure 10	Beach Ridge Sand: Typical profile with buried horizons	20
Figure 11	Kabelle Sand: Profile and vegetation	21
Figure 12	Maize in pot cultures in experimental shelter at Enewetak	40
Figure 13	Vegetation Map of the Northeastern Part of Rongelap Island	54
Figure 14	Map of Kabelle Island showing vegetation types	56

LIST OF TABLES

Page

Table 1. More Common Plants Found in the Northern Marshall Islands 3

Table 2. Characteristics of Rongelap Gravelly Sand, Representative Profile, Pit 22, Rongelap Island 12

Table 3. Characteristics of Gogan Sandy Loam, Representative Profile, Pit 4, Kabelle Island 12

Table 4. Characteristics of Lomuilal Sand, Representative Profile, Pit 8, Rongelap Island 13

Table 5. Characteristics of Beach Ridge Sand, Representative Profile, Pit 2, Rongelap Island 13

Table 6. Characteristics of Kabelle Sand, Representative Profile, Pit 6, Kabelle Island 14

Table 7. Bulk Density of Soil Cores from Enewetak, Bikini, and Rongelap Atolls 14

Table 8. Nutrient Levels, and Soil Reaction in the A_1 Horizon of the Five Most Extensive Soil Series 23

Table 9. Dry Weight and Nitrogen Content of Vegetation Litter, Rongelap Atoll 23

Table 10. Elemental Composition of Contrasting Rongelap Atoll Soil Profiles 24

Table 11. Weight Loss of Leaf Litter from Three Species of Rongelap Atoll Trees in a Decomposition Study 28

Table 12. Dry Weight of and Nitrogen Content of Humus Under Two Tree Species on Rongelap Atoll 28

Table 13. Average Nitrogen and Phosphorus Contents of Litter and Soil Under Different Plant Species, Rongelap Atoll 29

Table 14. Total Nitrogen Content of Selected Soil Profiles, Rongelap Atoll 31

Table 15. Estimates of Fungi in some Rongelap Soils 31

Table 16. Soil Disturbance Classification by Islets for Bikini And Enewetak Atolls (1964) 33

Table 17. Elemental Analyses of Contrasting Bikini and Enewetak Soils 36

Table 18. Maize Grown in the Greenhouse on Rongelap Well Soil 38

Table 19. Methods Used for Plant Tissues Analyses 38

Table 20. Yield, Chemical Composition, and ^{90}Sr and ^{137}Cs Activities in Maize Grown in Pot Cultures at Enewetak Atoll 41

Page

Table 21. Analyses of Foliage of *Tournefortia* (*Messerschmidia*) Plants from Rongelap Atoll 43

Table 22. Analyses of Foliage of *Tournefortia* (*Messerschmidia*) Plants on Bikini and Enewetak Atolls Collected in August 1964 44

Table 23. Analyses of Foliage of *Scaevola*, *Guettarda*, and Squash Plants Collected on Rongelap Atoll 45

Table 24. Analyses of Coconut Palm Foliage Collected on Rongelap Atoll 46

Table 25. Mean Nitrogen Concentrations in Wood, Bark and Leaves of Woody Plants of Rongelap Atoll 49

Table 26. Height Growth of Seedling Coconuts with Fertilization 49

Table 27. Ionic Composition of Rongelap and Bikini Ground Waters 52

Table 28. Air Dry Weight of Total Vegetation and Litter for Bikini Island Clearing Area 64

Table 29. Diameter and Diameter Growth Rates of *Tournefortia* Trees on Kabelle Island, Rongelap Atoll 64

Table 30. Diameter and Growth Rates of *Pisonia* Trees on Kabelle Island, Rongelap Atoll 65

Table 31. Total Height and Height Growth Rates of Native Shrubs on Kabelle Island, Rongelap Atoll 66

STUDIES OF SOILS AND PLANTS IN THE NORTHERN MARSHALL ISLANDS

BY

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INTRODUCTION

During the period 1958-1964, the authors undertook soil and vegetation studies in the northern Marshall Islands as part of the University of Washington Radiation Biology Laboratory surveillance team. This team was responsible for monitoring levels of radiation in various components of the island environment and any effects on plant and animal life. The authors of this report were charged with the soils and vegetation components but assisted with collections in the aquatic ecosystems and some food plant materials. Collections and measurements were made during relatively short term visits to the islands with sample processing and analysis performed during intervening periods. Much of the field and laboratory work was done by graduate students in the College of Forest Resources and the Department of Botany, with results reported in theses, but generally not in the open press. Therefore, we use some of this material in the report, together with unpublished material from our files.

The emphasis of field collection of both soils and plants was to establish levels of radiation across the range of island environments and exposure levels and to monitor these over time. For this reason, sampling points were generally marked for return collections. This made possible a variety of studies of the soils and plants, which are presented in this paper. Effort was initially expended on an inventory of soils and plant associations on the islands so that these could form a basis for sampling. All identified soil series were sampled throughout the profiles and chemical and physical analysis made. Special collections were made to study distribution of radionuclides, and lysimeters were used to study movement of nuclides as well as major cations and anions. Plant and litter samples were studied to assess absorption and cycling of mineral elements, with special emphasis on ^{137}Cs. Because ground water is important on some of the islands the ground water lens was also sampled to the extent feasible.

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Much of the material and information collected had not been published because of the termination of contracts with the University of Washington. The authors were given the opportunity to revisit some of the collection sites on Bikini and Rongelap Atolls in 1986 and reinventory some of the older work. This led to the decision to make the material available for other researchers. Although we were never able to carry out complete ecosystem studies, we believe that what we present will be of current interest, and useful in any future investigations.

For orientation, a map of the Northern Marshall Islands is included (Figure 1), as well as more detailed maps of the atolls on which observations were made: Rongelap (Figure 2), Bikini (Figure 3) and Enewetak (Figure 4). Also to aid readers with respect to atoll plants, a list of the common plant species is included (Table 1). Identification of plants was made using Taylor (1950) and Baker (1959).

SOILS: GENERAL DESCRIPTION AND METHODS

General Characteristics. Soils of Pacific atolls on which these studies took place are dominated by the environment in which they have developed and by the parent materials. They have originated from the detritus of corals and other marine life cast slightly above high tide, and then stabilized by plants. Consequently, mineral materials, so common in continental land masses, are absent from these atoll soils, except for small amounts of pumice. Topographic variations are slight so that factors of drainage, erosion and mass earth movements play only a minor role in the subsequent course of soil development. The nature of the materials and soil development has been described by Fosberg and Carroll (1965) and Porter (1966). Also Morrison (1990) has recently discussed the chemical properties, mineralogy, and classification of atoll soils with a few comments on the northern Marshall Islands.

The marine origin of the soils means that they are dominated by carbonate parent materials, largely calcium carbonate, but magnesium carbonate also plays a role. This original marine detritus must change in order to be a hospitable substrate for plant growth and plant community development. Certain essential elements have to be added to the soil system, and the development and maturity of the soil in this island system seem to be largely functions of such additions. Studies on Rongelap, Bikini and Enewetak atolls indicate that accumulation of nitrogen plays a major role in the maturation and general improvement of soils. Fresh marine debris, largely coralline in nature, has little nitrogen, but in this warm, humid environment, nitrogen fixation and accumulation is rapid, far exceeding that found in temperate regions. Therefore, in terms of nitrogen status, a soil can change from rather sterile lime sand to a reasonably fertile substrate within a matter of ten to twenty years.

As a result of these various influences on soils, any given atoll is likely to have soils of several ages, fertility, and productivity on the different islands. Some of the small islets give the appearance of having just emerged from a salt water environment, and

Table 1. More Common Plants Found in the Northern Marshall Islands[a].

Species	Family	Habitat Notes
Tree Form		
Bruguiera conjugata	*Rhizophoraceae*	Tidal or wet areas
Cocos nucifera	*Palmaceae*	Village areas; plantations
Cordia subcordata	*Boraginaceae*	Occurs in thickets; poorer soils
Neisosperma oppositifolia (formerly Ochrosia parviflora)	*Apocynaceae*	Wooded central areas
Pandanus sp.	*Pandanaceae*	Widely distributed over islands
Pisonia grandis	*Nyctaginaceae*	Good soils in island centers
Soulamea amara	*Simarubaceae*	Scattered trees
Terminalia litoralis	*Combretaceae*	Scattered behind beach or shore rocks
Tournefortia argentea (formerly Messerschmidia)	*Boraginaceae*	Disturbed soil; wide occurrence
Tree-Like to Shrubby		
Dodonaea viscosa	*Sapindaceae*	Thickets in disturbed areas
Guettarda speciosa	*Rubiaceae*	Very common; beaches to interior
Morinda citrifolia	*Rubiaceae*	Near villages and coconut plantations
Pemphis acidula	*Lythraceae*	Behind fringe vegetation; in rocky intertidal areas
Pluchea odorata	*Compositae*	In disturbed areas near villages
Scaevola frutescens (= *S. sericea*)	*Goodeniaceae*	Very abundant; forms fringe vegetation at beaches and thickets over many areas
Suriana maritima	*Surianaceae*	On windward beaches
Tournefortia argentea	*Boraginaceae*	Disturbed soil; common
Shrubs		
Clerodendron inerme	*Verbenaceae*	Near settlements or coconut plantations
Pseuderanthemum atropurpureum	*Acanthaceae*	Village areas
Sida fallax	*Malvaceae*	Clumps near coconut groves
Understory Plants		
Boerhaavia spp.	*Nyctaginaceae*	Often under Pisonia; shaded areas; variable soil
Portulaca spp.	*Portulacaceae*	Poorer soil; in the open
Tacca leontopetaloides	*Taccaceae*	Good soil under coconuts
Triumfetta procumbens	*Tiliaceae*	Spreading stoloniferous cover; open areas; beaches
Vines		
Ipomea alba (= I. macrantha)	*Convolvulaceae*	Spreading vine in many areas; disturbed sites
Cassytha filiformus	*Lauraceae*	Parasitic; vine-like over other plants
Canavalia microcarpa	*Leguminosae*	Spreading under coconuts

Table 1, continued.

Species	Family	Habitat Notes
Grass; Grass-like		
Cenchrus echinatus	Poaceae	Village areas; plantations
Chloris inflata	Poaceae	Coconut areas
Eleusine indica	Poaceae	Shade of coconuts
Eragrostis amabilis	Poaceae	Woodland glades
Fimbristylis cymosa	Cyperaceae	On poorer areas
Lepturus repens	Poaceae	Poorer disturbed areas
Thuarea involuta	Poaceae	Shaded, wooded areas
Ornamental-Food		
Artocarpus altilis	*Urticaceae*	Trees in village areas
Carica papaya	*Caricaceae*	Village areas
Cocos nucifera	*Palmaceae*	Plantations; village areas; otherwise scattered groves
Crinum asiaticum	*Amaryllidaceae*	Settled areas; cemeteries
Hibiscus tiliaceus	*Malvaceae*	In villages
Plumeria rubra	*Apocynaceae*	Village areas

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[a] Botanical names follow Taylor (1950); with some modifications from Fosberg (1988)

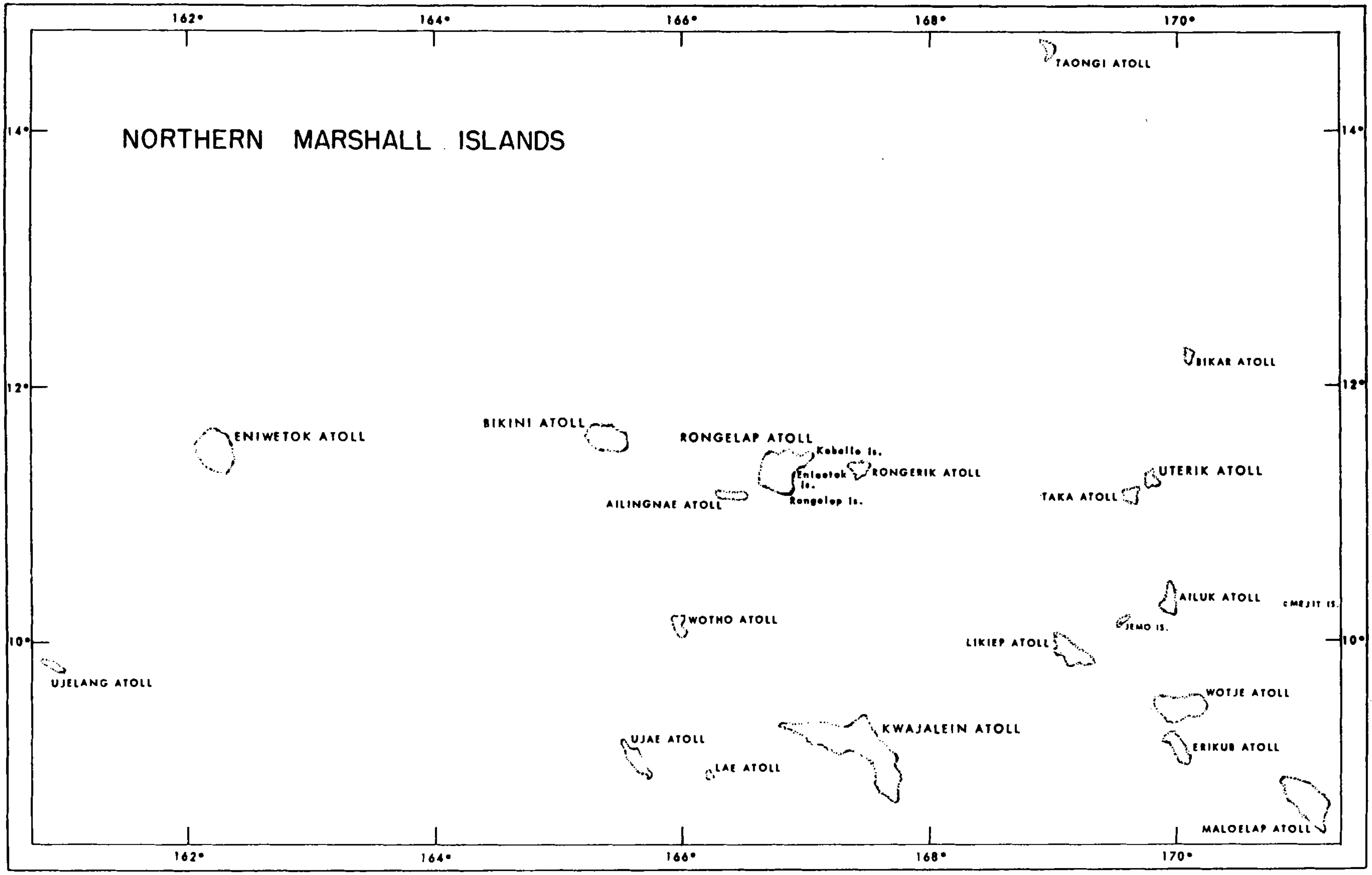


Figure 1. Map of the Northern Marshall Islands

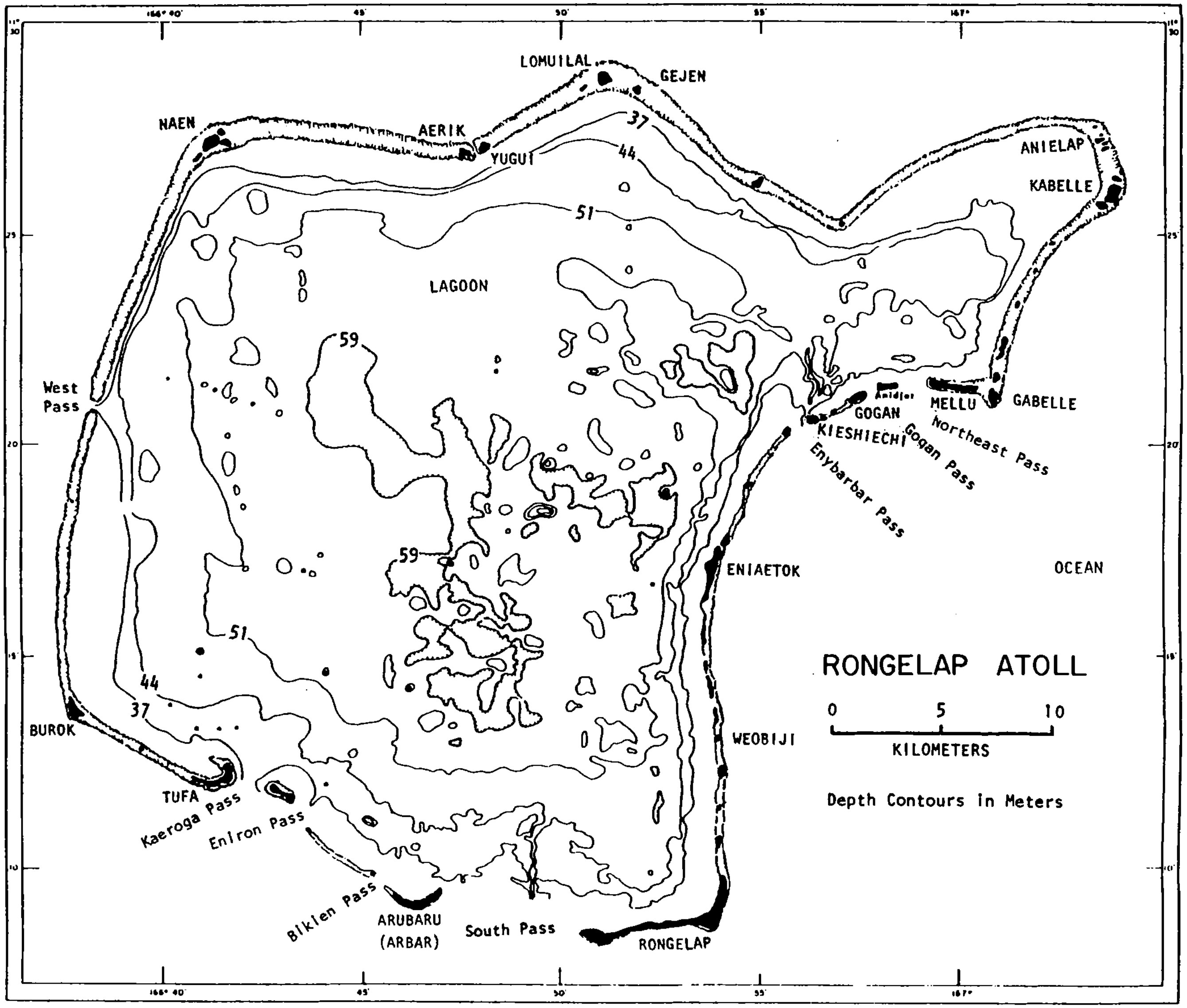


Figure 2. Map of Rongelap Atoll

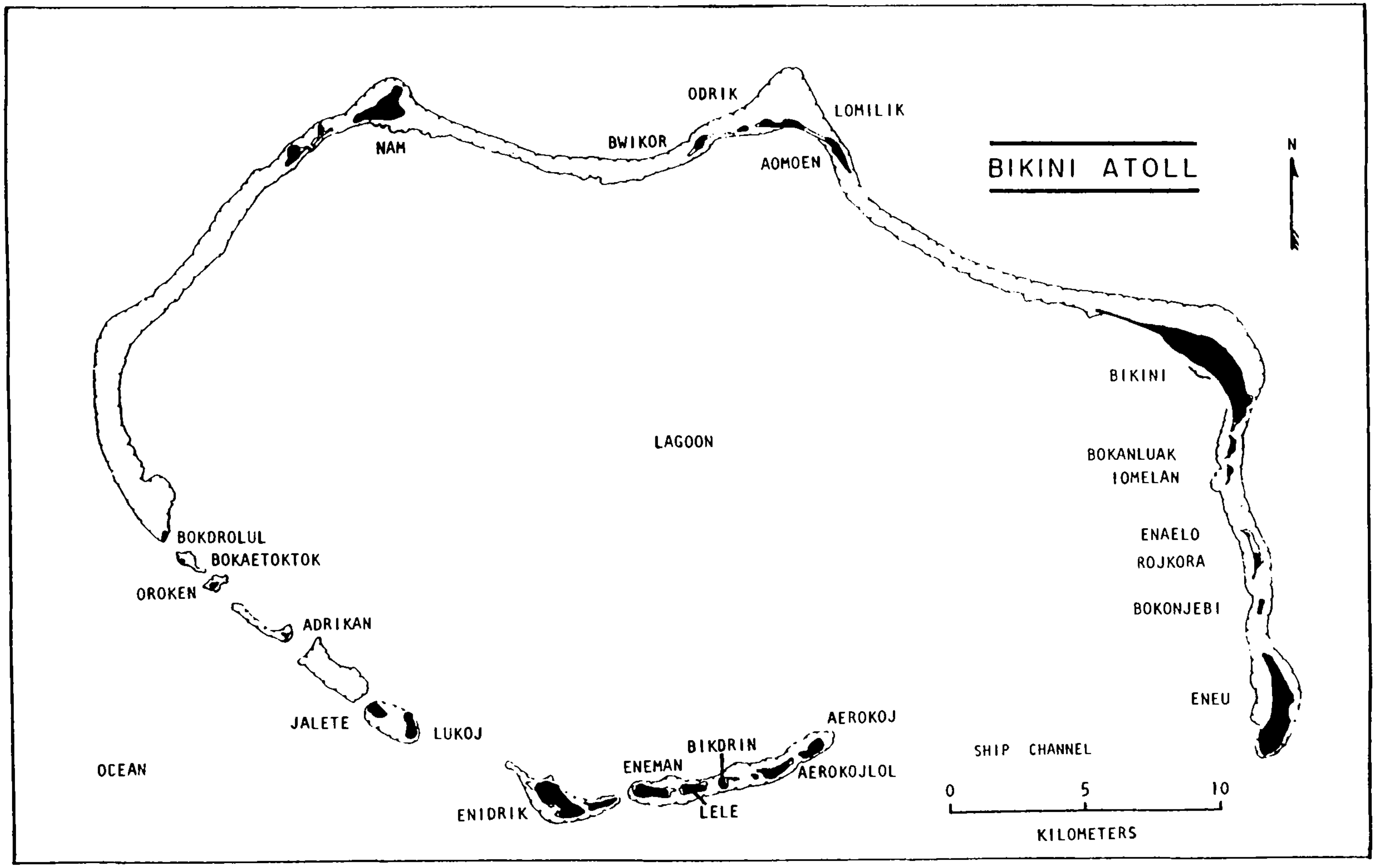


Figure 3. Map of Bikini Atoll

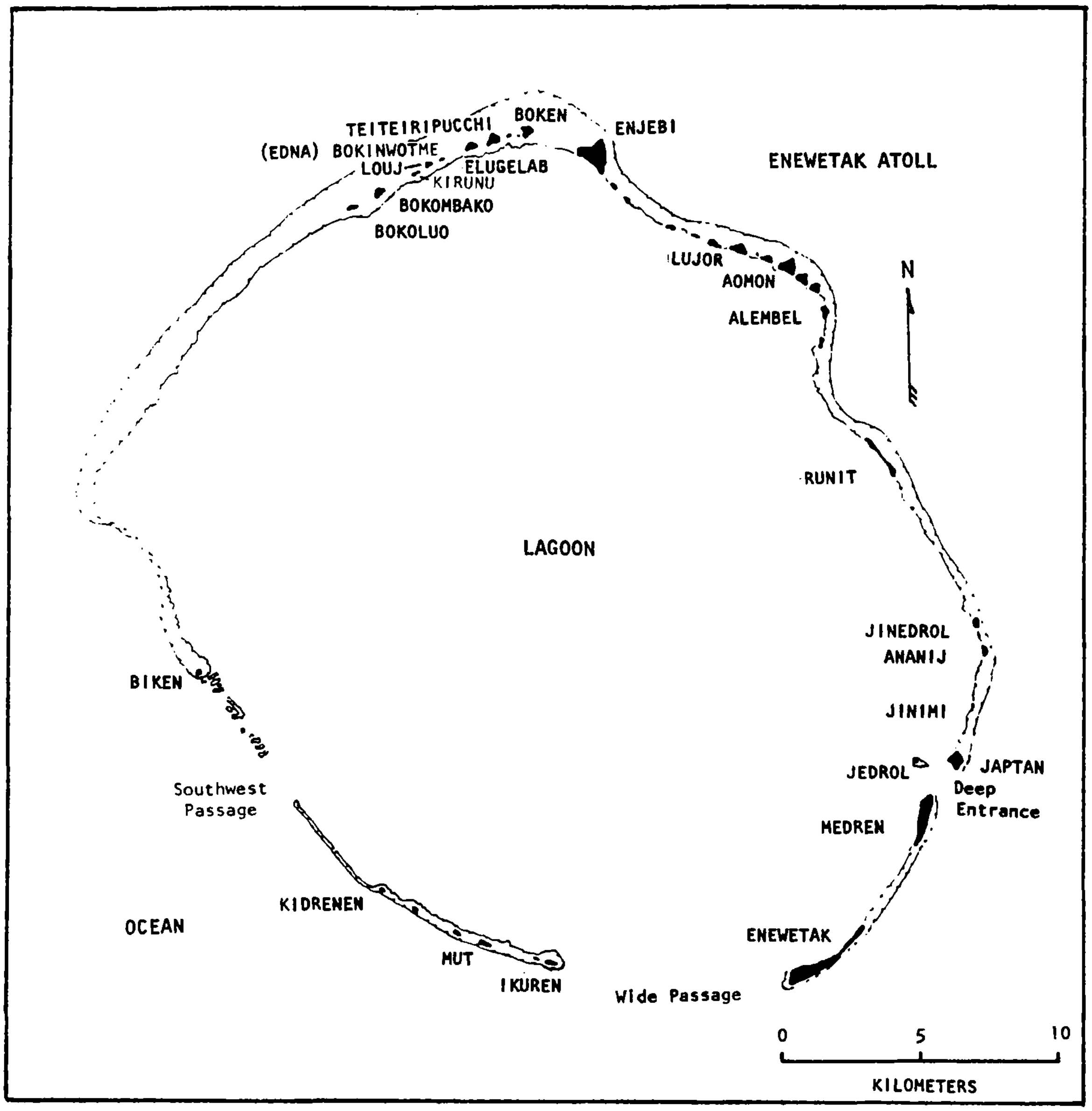


Figure 4. Map of Enewetak Atoll

vegetation and soil development is at an early stage. Larger islands, particularly if they are more than a few hundred meters wide, have areas of very well developed and fertile soils. These more mature soils are high in organic matter, nitrogen, and phosphorus to a depth of 30 to 45 cm. Native vegetation is lush on these soils, and many such areas have been cleared for coconut production. They contrast with the white coral sands of young soil areas of either the same or adjacent islands. Foliage color, as well as chemical composition of the plants, is related to the general state of development and organic matter accumulation of the soil.

Our evidence also shows that certain other elements, particularly those needed only in small amounts, such as iron, zinc and manganese, are at critically low levels even for native plant growth. Factors which tend to concentrate or add these elements to the system therefore become important to the development of fertile soils.

The invasion and succession of plants in the island environment also relates to soil development. Some of the plants have an ability to grow in sea water or in only small dilutions of sea water. These plants can extract elements from the sea and place them into a cycle which is part of the land mass life cycle. Similarly, certain sea birds which nest in island vegetation can contribute. They carry small fish to their young, and through residues from this feeding operation, as well as from the excrement of the total population, large quantities of elements necessary for plant growth are introduced. Kenady (1962) quoted an estimate of 2 metric tons/ha/yr of guano for Kabelle Island on Rongelap Atoll. Again our evidence suggests that major additions of nitrogen, phosphorus, zinc, manganese, copper and other elements occur in this manner.

There are certain destructive forces acting in this environment which have an impact on both vegetation and soil. Repeated visits to certain islands over a period of a few years have shown definite changes in shorelines and beach areas. Over long periods of time major storms have entirely covered most of the islands at some time with salt water and new marine detritus. Evidence in deep soil pits suggest that this process has been repeated many times (see Fig. 10), even in the northern Marshalls, which have typhoons less frequently than do atolls farther south. Well developed buried A_1 soil horizons have been found as deep as 200 cm (80 inches) below the surface of existing stable land areas. All atolls and islets we have investigated show evidence of periodic inundation. This fits in with the observations that major island features in the atolls are formed or destroyed by typhoons (Fosberg and Carroll, 1965).

Soil Sampling

Sampling procedures provided for taking appropriate types of soil samples for radionuclide status, nutritional level, series characterization, and bulk density. At selected locations, a standardized set of soil samples was taken within a 15x15 cm area and at 2.5 cm depth increments. At some locations samples were taken in duplicate as well as different depth sequences. All material within this volume was placed in plastic containers for transport to the ship laboratory. It was oven dried at 105°C and then shipped to Seattle. Eventually, the samples were re-dried at 105°C, sieved through a 2 mm sieve, and both components weighed. Bulk densities were calculated from the volume and weight data. The fine portion passing the 2 mm sieve was further pulverized and then used for radionuclide determination, as well as elemental analyses. Radionuclide analysis of some of the coarse fractions was also made. After soil series were mapped, a type soil pit was established in each series and all horizons were sampled (Kenady 1962). Plant materials were collected and plant growth conditions recorded at all pit sites.

Soil cores, using a 7.6 cm diameter metal tube approximately 30 cm long and machined with sharp cutting edges, were also taken. A lead brick was used to drive the tubes into the soil. Snug fitting wooden plugs were then sealed at each end of the tube and the entire unit was shipped to the Seattle laboratory. Upon arrival these were oven dried, weighed, and impregnated with plastic according to the method described by Held et al. (1965b). The cores were used for studies of radionuclide distribution, as well as to study soil profile characteristics.

Ground water was sampled by driving a well point of our own design into the water lens wherever possible. Each of these consisted of a length of pipe of interior diameter 1.25 cm, with the point itself a perforated section. Water was extracted from the lens, when encountered, by Tygon tubing evacuated with a hand pump. One to two liters of water were generally collected. At many sample points near shores, it was impossible to contact the water lens because of beach rock layers.

Soil Analyses

For pH determination, subsamples were taken from the bulk samples before drying, then measured in the field laboratory on a 1:1 soil to distilled water ratio using a battery operated glass electrode pH meter.

For all other analyses the bulk samples were oven-dried, then seived through a 2 mm screen. The percentage by weight of material larger than 2 mm is reported in the tables of analyses. In each case, organic material which did not pass through the 2 mm screen was ground in a steel mortar, then combined with the other material which had passed through the 2 mm screen to make up the sample used for nitrogen, phosphorus and exchangeable cation analyses.

Total nitrogen was determined by the Kjeldahl method as described by Jackson (1958). Phosphorus was extracted and determined colorimetrically by the bicarbonate method of Olsen et al. (1954). Exchangeable cations were extracted with ammonium acetate, then determined with a Beckman DU flame photometer. Exchange capacity was measured on the same sample by displacing the adsorbed ammonium with sodium chloride, then distilling and titrating the ammonia (Jackson, 1958).

Organic matter content was determined by difference. The amount of calcium carbonate was calculated from the volume of carbon dioxide given off when the sample was mixed with hydrochloric acid in a closed system. This calculated weight of calcium carbonate was then subtracted from the oven dry weight of the sample to approximate the weight of organic matter present, since no detectable silica was in the samples. Some error is introduced by the presence of some magnesium carbonate, which on a unit weight basis would release more carbon dioxide than calcium carbonate, thus making the calculated organic matter values lower than the true amount. However, if magnesium carbonate is in the range of 10% of the total carbonate as might be expected, this error will not be large.

The total analyses of soils as in Tables 10 and 17 were made by heating samples with 6N HCl, which dissolved all carbonate material and intensively extracted the organic matter. Analyses were made on suitable aliquots of the filtrate from this digest by the following methods: Ca, Mg by EDTA titration; K, Na by flame photometry; B by the curcumin method (Dible et al., 1954); Zn and Cu by the zincon method after anion exchange separation (Sandell, 1959); Mn by the tetrabase method (Sandell, 1959); and Fe by the thiocyanate method (Sandell, 1959).

RONGELAP ATOLL SOILS

Characteristics of Soil Series

In order to provide a basis for systematically sampling soils and making comparisons, the soils of Rongelap and Kabelle Islands were investigated thoroughly in early visits and a soil mapping system developed. This is described by Kenady (1962) in detail. Names assigned to soils identified as definitive units (series) will be used in this report. Similar soil units were recognized on Enewetak and Bikini Atolls in 1964. Summary information on the principal soil series is presented in Tables 2 through 6 along with photographs of typical soil profiles and micromonoliths in Figures 7 through 11, adapted from Kenady (1962). Locations of the soil pits referred to in these figures are given on the maps of the Northeastern part of Rongelap Island (Figure 5) and the map of Kabelle Island (Figure 6). For specific geographic location, the benchmark (BM) in Figure 5 is at latitude 11°8’88" N. and longitude 166°53’35" E. Although Stone (1951, 1953) and Fosberg (1954) had done some studies on northern Marshall Atoll soils and had established some series names, these did not seem to fit the soils we were observing. However our Gogan series may be a younger stage of the Jemo series described by Stone on Arno Atoll in the southern Marshall Islands (1951) and by Fosberg (1954) for the northern Marshall atolls, and referred to recently by Fosberg (1990) and Morrison (1990). Fosberg and Carroll (1965) have a more complete discussion of atoll soils, but done after our studies. For these reasons we will use names originally given to soils based on detailed chemical and physical analyses (see next section).

The data of Tables 2-6 give a general characterization of the soil series. However some caution is advisable in considering the data. In many instances, the sum of the exchangeable cations exceeds the measured exchange capacity. We believe that some dissolution of solid phase carbonates by the ammonium acetate leaching solution can explain these overruns.

Table 2. Characteristics of Rongelap Gravelly Sand, Representative Profile, Pit 22, Rongelap Island

	Sample Depth—cm						
Property	0-12.5	12.5-30.5	30.5-46	46-66	66-91	91-127	127-168
Percent Material > 2mm	46	50	39	**	28	39	54
Percent Nitrogen	0.99	0.53	0.11	**	0.03	0.02	0.02
Percent Organic Matter	26.5	12.6	4.5	2.6	2.6	1.2	1.9
Exchange Capacity	34.1	12.3	6.3	3.1	0.8	**	**
*Sodium	3.47	1.48	0.91	0.55	0.64	**	**
*Magnesium	4.95	1.59	1.00	0.78	0.70	**	**
*Calcium	**	**	2.95	2.00	1.45	**	**
*Potassium	1.61	0.65	0.30	0.17	0.16	**	**
Phosphorus (ppm)***	85	45	26	6.4	15	5.1	7.1
pH	8.0	8.0	8.1	8.6	8.6	8.8	8.7

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Analysis not available
*** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 3. Characteristics of Gogan Gravelly Sandy Loam, Representative Profile, Pit 4, Kabelle Island

		Sample Depth—cm				
Property	***	0-2.5	2.5-12.5	12.5-30	30-50	50-65
Percent Material > 2mm	10	20	20	27	39	56
Percent Nitrogen	1.54	1.96	0.42	0.18	0.07	0.05
Percent Organic Matter	21.4		5.9	6.8	2.6	2.6
*Exchange Capacity	20.5	43.6	17.9	7.2	2.6	1.7
*Sodium	2.0	3.0	0.8	0.4	0.4	0.4
*Magnesium	7.0	7.4	4.0	2.2	1.2	1.1
*Calcium	10.3	**	14.1	6.2	7.7	7.8
*Potassium	**	**	**	**	**	**
Phosphorus (ppm)****	1330	893	416	216	151	25
pH	7.4	7.1	7.9	8.2	8.6	8.8

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Analysis not available
*** Organic layer above mineral soil
**** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 4. Characteristics of Lomuilal Sand, Representative Profile, Pit 8, Rongelap Island

	Sample Depth—cm				
Property	0-7.5	7.5-25	25-30	30-52.5	52.5-120
Percent Material > 2mm	0	5	18	12	2
Percent Nitrogen	0.29	0.07	0.08	0.04	0.02
Percent Organic Matter	2.8	2.3	2.2	1.9	1.7
*Exchange Capacity	14.2	2.3	2.6	1.1	0.6
*Sodium	2.73	0.73	0.82	0.82	0.84
*Magnesium	4.66	0.84	1.05	0.85	0.83
*Calcium	5.02	1.87	2.50	2.31	2.35
*Potassium	1.09	0.18	0.19	0.16	0.16
Phosphorus (ppm)***	106	15.1	14.1	5.0	5.0
pH	8.4	8.6	8.3	8.8	9.1

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Analysis not available
*** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 5. Characteristics of Beach Ridge Sand, Representative Profile, Pit 2, Rongelap Island

	Sample Depth—cm							
Property	0-5	5-12.5	12.5-22.5	22.5-30	30-45	45-92.5	92.5-110	110+
Percent Material > 2mm	8	16	10	12	32	7	14	21
Percent Nitrogen	0.08	0.13	0.07	0.15	0.09	0.03	0.03	0.01
Percent Organic Matter	3.8	3.9	3.2	5.3	3.7	1.9	1.3	1.1
*Exchange Capacity	2.8	4.6	2.1	7.0	2.4	0.8	1.0	0.1
*Sodium	1.29	1.06	0.85	1.96	1.31	1.09	1.06	1.28
*Magnesium	2.07	2.61	2.49	1.51	1.21	1.67	1.51	1.51
*Calcium	2.63	3.48	2.26	3.50	3.13	2.76	2.81	2.63
*Potassium	0.39	0.50	0.23	0.38	0.26	0.23	0.18	0.21
Phosphorus** (ppm)	18.1	14.1	10.0	10.1	8.0	9.0	26.0	10.0
pH	8.4	8.4	8.6	8.3	8.5		9.0	8.5

* Exchangeable cations in meq per 100 grams of oven dry soil (2mm fraction)
** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 6. Characteristics of Kabelle Sand, Representative Profile, Pit 6, Kabelle Island

	Sample Depth—cm		
Property	0-2.5	2.5-27.5	27.5-95
Percent Material > 2 mm	34	8	2
Percent Nitrogen	0.22	0.02	0.01
Percent Organic Matter	8.1	**	2.6
*Exchange Capacity	6.3	0.3	0.1
*Sodium	1.57	3.01	1.37
*Magnesium	1.37	1.04	1.16
*Calcium	3.01	2.88	2.65
*Potassium	0.57	0.15	0.20
Phosphorus (ppm)***	30.0	12.0	12.0
pH	8.9	9.1	9.2

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Analysis not available
*** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 7. Bulk Density of Soil Cores from Enewetak, Bikini, and Rongelap Atolls (1964).

Core No.	Location	Island	Bulk density g/ml
1	Disturbed area	Runit	1.30
2	Native vegetation	Biken	1.04
3	Disturbed area	Bokombako	1.21
4	Disturbed area	Bokombako	1.27
5	Coconut stand near airfield	Eneu	0.84
6	Open *Scaevola* near airfield	Eneu	1.08
7	*Pandanus*; island center	Bikini	0.92
8	*Scaevola* seaward	Bikini	1.17
9	Under *Guettarda*	Bikini	1.33
10	Seaward reef area	Bikini (Reef)	1.15
11	Near crater	Aomoen	1.14
12	Near crater	Bwikor	1.31
13	*Tournefortia*	Nam	1.18
14	Crater area	Nam	1.06
15	Undisturbed area	Bokdrolul	1.31
16	Crater area	Eneman	1.12
17	*Tournefortia*	Bikdrin	1.20
18	Disturbed dock area	Aerokoj	1.20
19	*Pisonia* area	Kabelle	1.01
20	Open area	Bokinwotme	1.28
21	*Tournefortia*	Bokinwotme	1.21

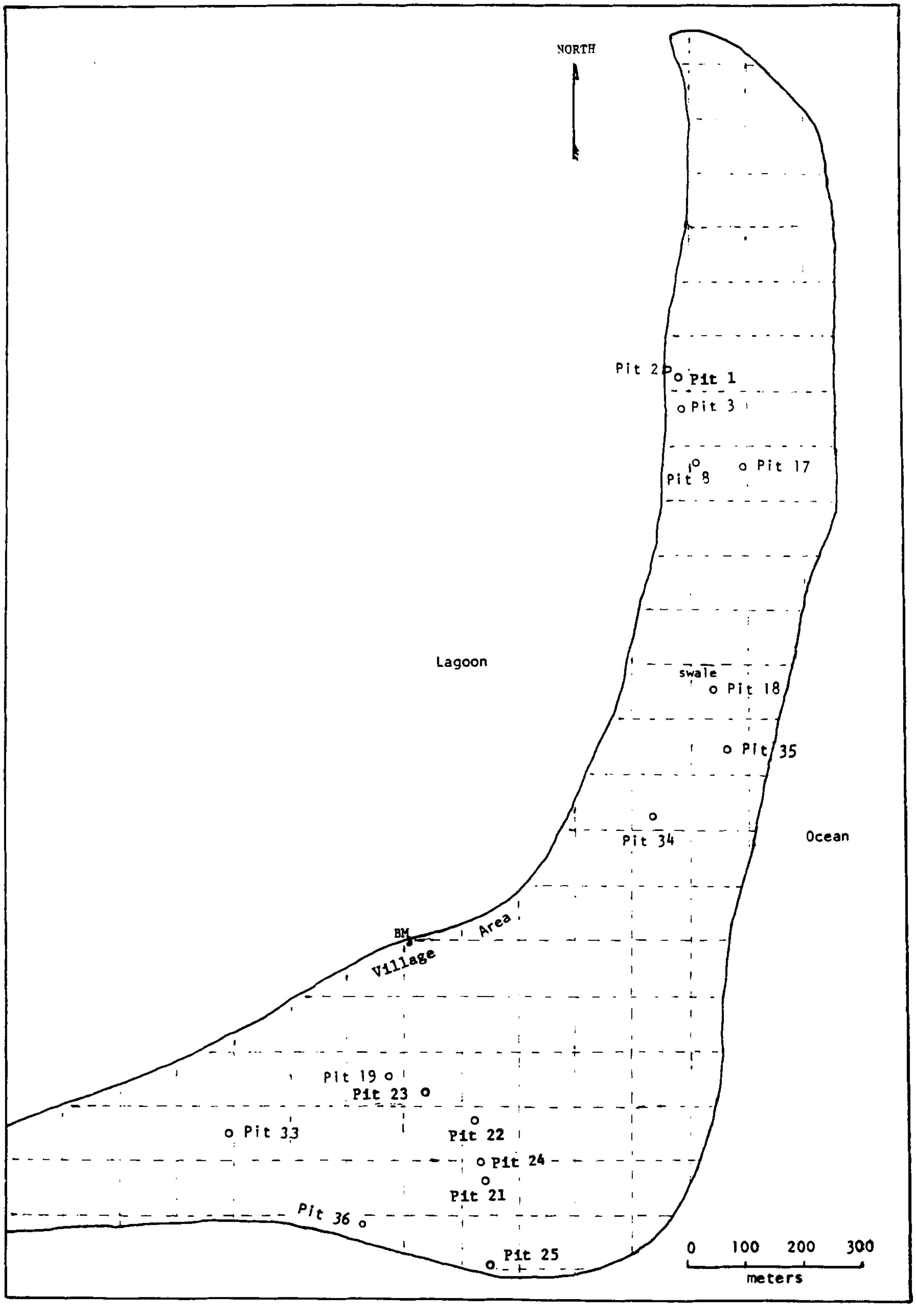


Figure 5. Map of the Northeastern Part of Rongelap Island, Showing Locations of soil Pits.

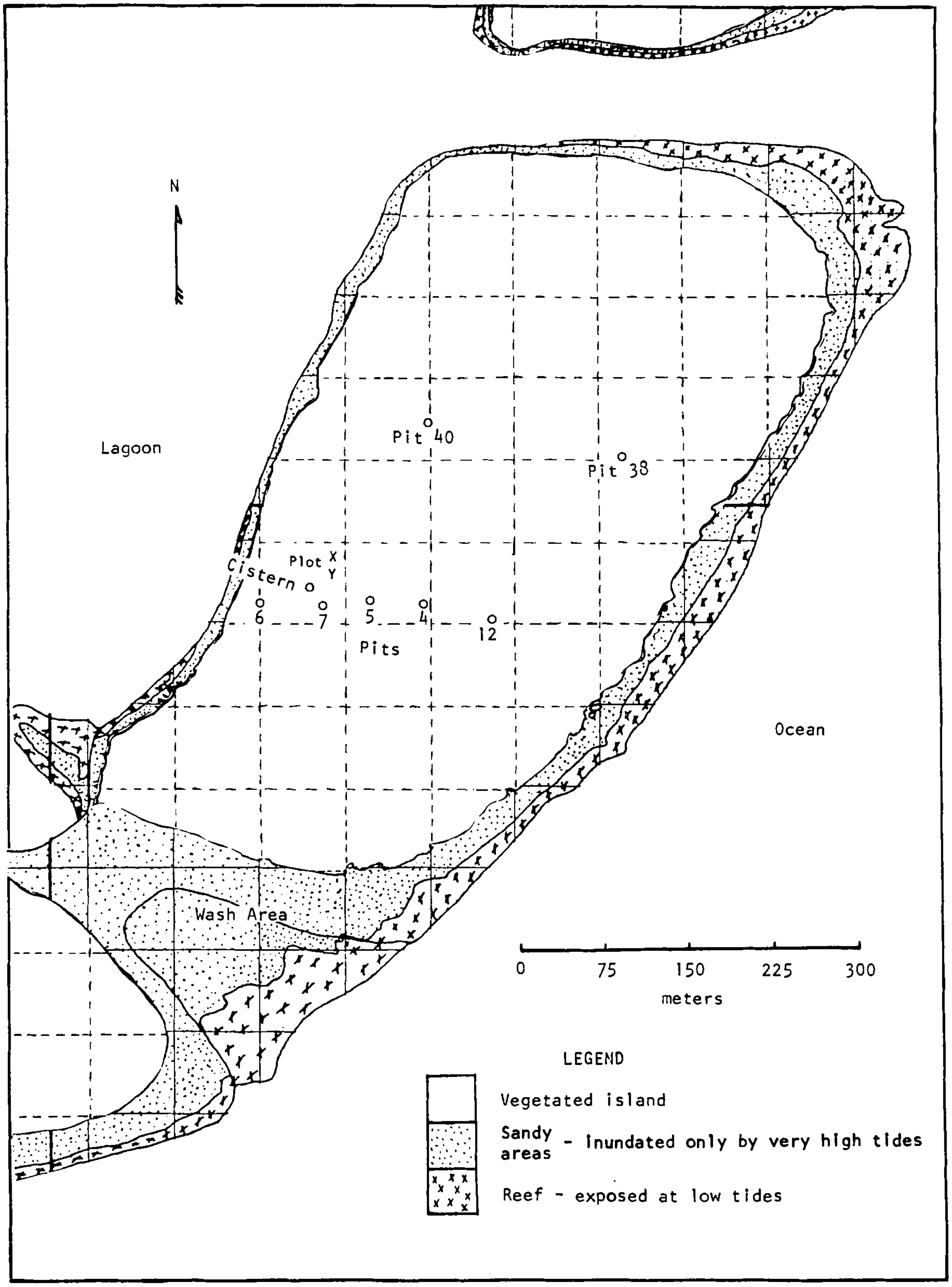
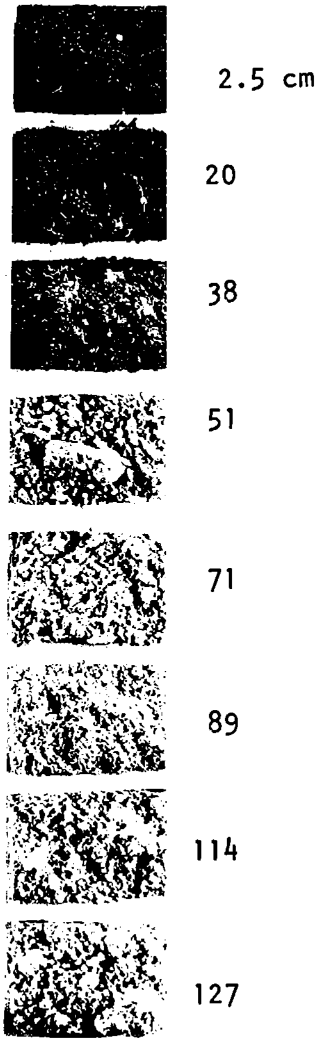
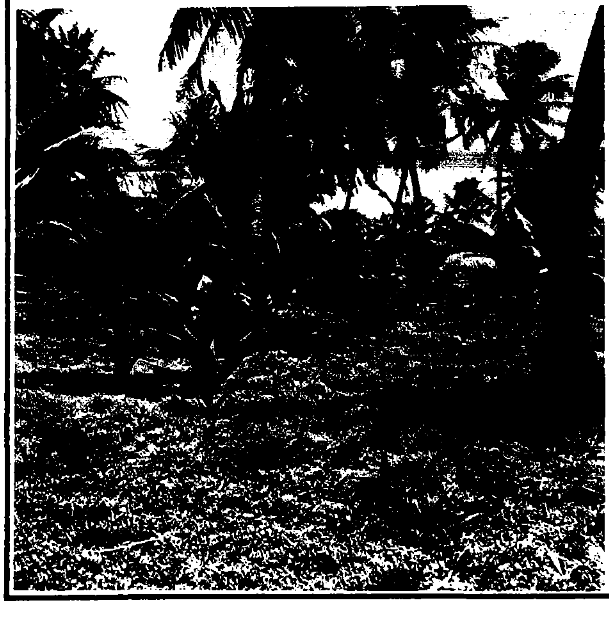


Figure 6. Map of Kabelle Island, Rongelap Atoll, Showing Locations of Soil Pits

Pit 7 under coconut trees on Kabelle Island, with Triumfetta growing below and the compound-leafed Tacca above.



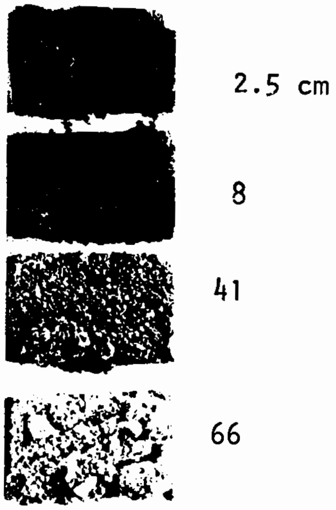
Micromonolith, Pit 22 on Rongelap Island



Coconut grove near Pit 22

Figure 7 Rongelap Gravelly Sand: Typical profile and vegetation

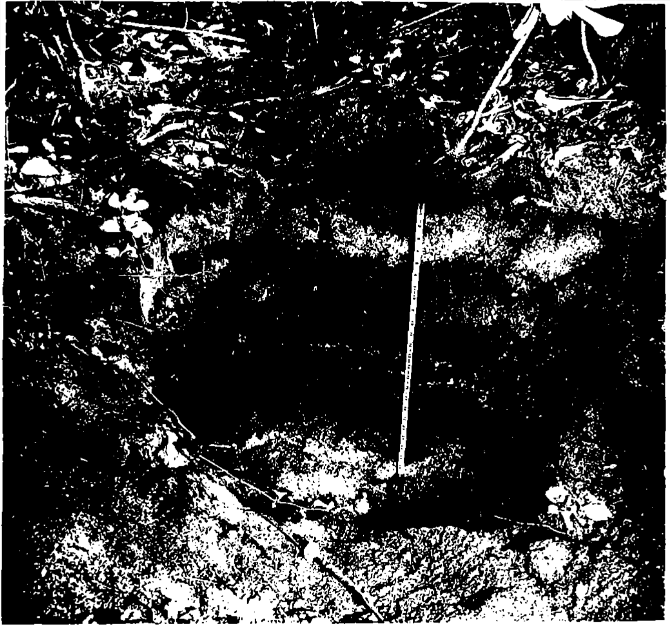
Pit 4 on Kabelle Island, under Pisonia trees, with Boerhaavia ground cover. Note the well point for obtaining ground water.



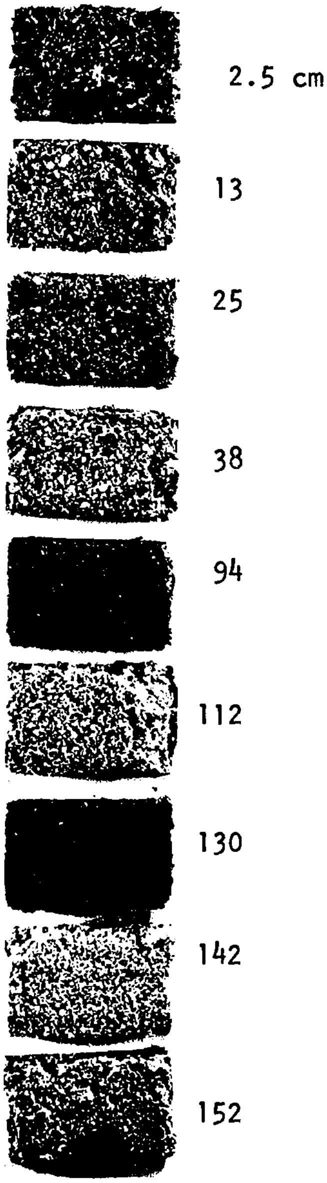
Micromonolith of Pit 38

Stand of Pisonia grandis in the Pit 38 area, Kabelle Island

Figure 8 Gogan Series: Typical profile and vegetation



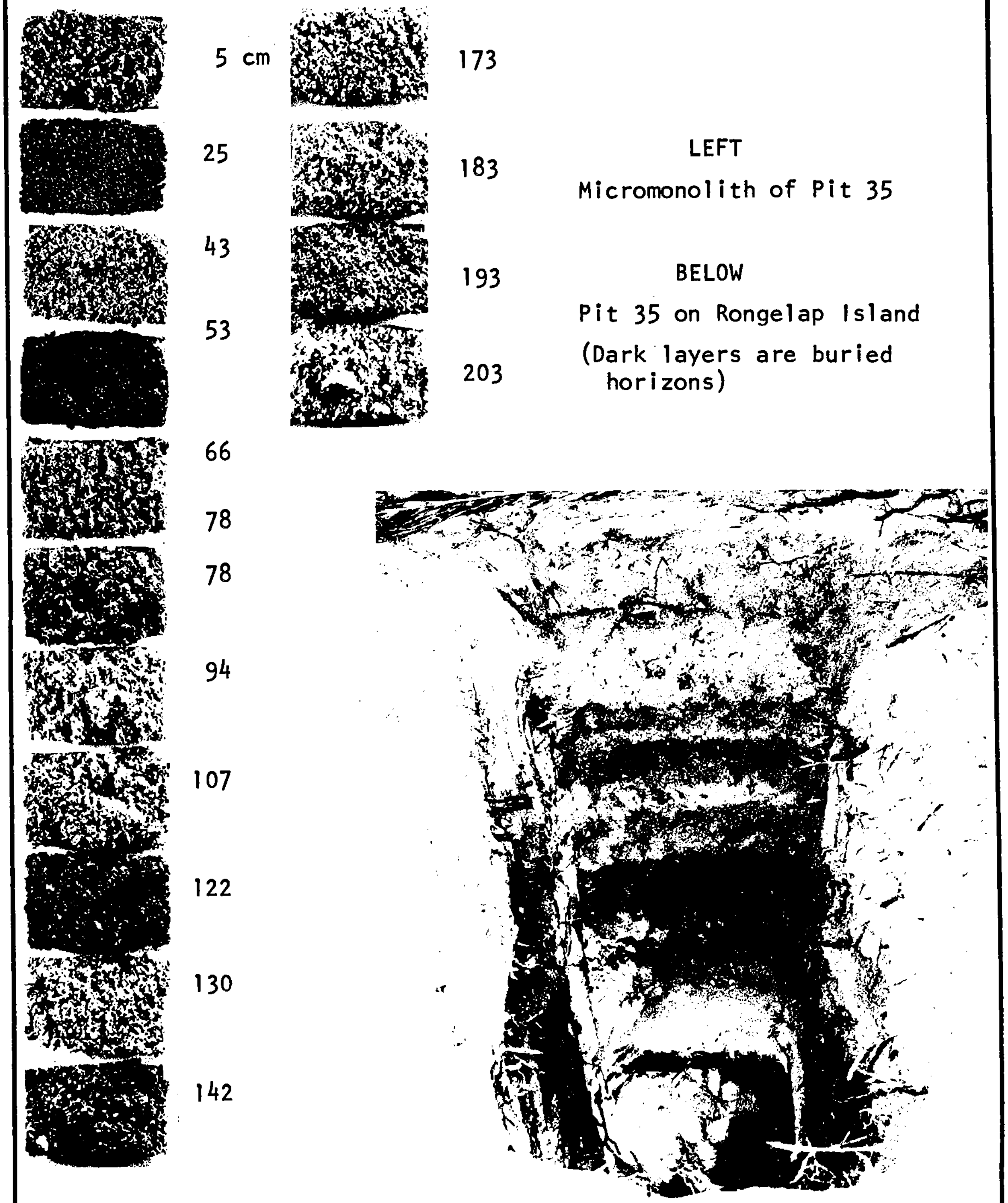
Pit 12 on Kabelle Island
(Dark strata are buried horizons)



Micromonolith
of Pit 21 on
Rongelap Island

Tournefortia argentea near Pit 12
(Boerhaavia spp. cover the ground)

Figure 9 Lomuilal Sand: Typical profile and vegetation

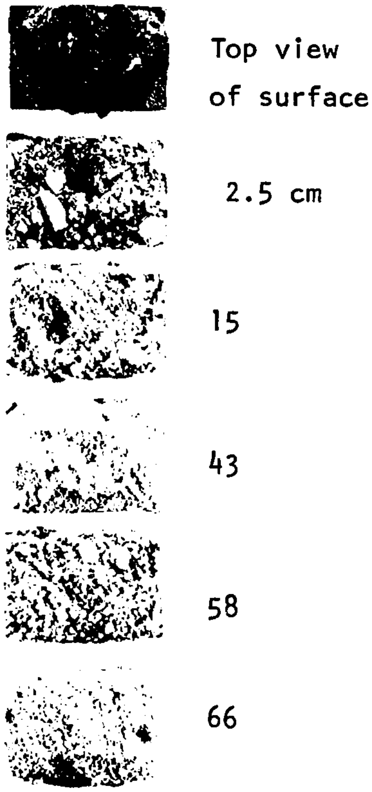


LEFT
Micromonolith of Pit 35

BELOW
Pit 35 on Rongelap Island
(Dark layers are buried horizons)

Figure 10 Beach Ridge Sand: Typical profile with buried horizons

Soil Pit 6 on Kabelle Island. The black areas are crusts formed by algae.



Micromonolith of Pit 6

View of the Pit 6 area, with its shrubby open strand vegetation.

Figure 11 Kabelle Sand: Profile and vegetation

Significance of Series Separations

The five principal soil series were examined by analysis of variance to test for the significance between levels of nitrogen, organic matter, exchange capacity and soil reaction. These levels were means from three replicate samples of A_1 horizons. Table 8 shows the basic data for these comparisons.

Of the four factors studied, differences in total nitrogen and exchange capacity were statistically significant at the 0.1 percent level, organic matter was significant at the 1.0 percent level, and pH was nonsignificant. These results indicate that based on essential chemical properties, the soil series are distinct and separate units and that sampling based on these units was reasonable for the studies.

Other Data

A great deal of information on gravel content of the soils and bulk density is given in the theses of Kenady (1962) and Billings (1964) and more exists in unpublished files (available from the authors). Typical bulk densities from the 30 cm soil cores are in Table 7. Bulk densities of the surface 2-3 cm are lower, typically about 0.5 g/ml. During the various expeditions to Rongelap from 1958 to 1964 some of the established soils pits used to represent the soil series, and study radionuclide deposition and movement, were sampled in 2.5 cm increments to a depth of 37.5 cm. In most cases the sampling was in duplicate. A September 1963 sampling of this kind was also used for a complete chemical analysis. Because these data could be of interest in plant growth and nutrition studies they are presented in Table 10. Pits 4 and 38 are in the interior of Kabelle Island under the influence of Pisonia trees and sea birds. Pits 1 and 22 are under coconut plantings on Rongelap Island and these soils are used for island food production. Pit 6 is a young soil on the lagoon beach of Kabelle Island under vegetation struggling to become established. The wash area samples are essentially new deposits of sand, occasionally washed by sea water. Nitrogen and phosphorus distribution in the profiles clearly reflects the seabird contributions and organic matter accumulation. Calcium and magnesium show the coral origin of the soils but also the dilution by organic matter and weathering. There is considerable variation in the elements in some of the profiles, some of which is due to buried horizons or other depositional features. The micro-element data are more limited but show low levels of manganese through all soils and low levels of iron, zinc, and copper in the young and emerging soils. Also considerable data was published on the behavior of the soil solution from tension lysimeter studies (Cole et al. 1961), with the most noteworthy feature being the pronounced stimulation of leaching of all ions by fertilizer additions of nitrogen or potassium.

Plant-Soil Interrelationships on Rongelap Atoll

The single source of soil parent material, the few plant species and associations, and the distinctive age groupings of soils and plants allowed for soil and vegetation sampling over an age range. Single individuals or specific stands of the dominant plant species were selected on what we judged to be young or more mature soils. On a

Table 8. Nutrient Levels and Soil Reaction in the A_1 Horizon of the Five Most Extensive Soil Series

Soils Series	Rongelap Gravelly Sand	Gogan Gravelly Sandy Loam	Lomuilal Sand	Beach Ridge Sand	Kabelle Sand
Percent Nitrogen	0.57	1.71	0.26	0.09	0.14
Percent Organic Matter	16.7	35.6	6.4	4.5	7.7
*Exchange Capacity	22.2	37.7	12.6	3.7	5.7
*Sodium	3.36	4.01	2.68	1.16	1.52
*Magnesium	4.19	11.1	3.21	2.55	1.92
*Potassium	1.95	1.80	0.79	0.37	0.46
Phosphorus (ppm)**	81.7	985	54.2	32.8	32.1
pH	8.1	7.8	8.4	8.6	8.6

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)

** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 9. Dry Weight and Nitrogen Content of Vegetation Litter, Rongelap Atoll

				Litter Weight*		Nitrogen*	
Area	Year	Species	No. Samples	g/m^2	kg/ha	g/m^2	kg/ha
Various islands of the Atoll	1961	*Tournefortia* *Guettarda* *Scaevola*	11	1,074	10,740	6.7	67
Wash. Area Plots Kabelle	1961	*Tournefortia* *Guettarda* *Scaevola*	19	1,343	13,430	7.3	73
Weobiji	1961	*Pisonia*	9	1,185	11,850	21.6	216
Weobiji	1962	*Pisonia*	20	981	9,810	17.8	178
Pit 6-Kabelle	1963	*Pisonia*	20	1,614	16,140	20.7	207
Rongelap Isl.	1964	*Pisonia*	20	1,904	19,040	45.3	453
Rongelap Isl.	1961	*Scaevola*	1	587	5,870	4.4	44
Rongelap Isl.	1961	*Tournefortia*	1	1,001	10,010	6.7	67
Pit 38-Kabelle	1961	*Scaevola*	1	1,000	10,000	7.5	75
Pit 38-Kabelle	1961	*Tournefortia*	2	1,114	11,140	7.5	75
Pit 38-Kabelle	1961	*Tournefortia*	1	1,549	15,490	14.7	147
Pit 38-Kabelle	1961	*Scaevola*	1	839	8,390	6.3	63

* Mean values

Table 10. Elemental Composition[1] of Contrasting Rongelap Atoll Soil Profiles

Depth cm	Pit 1	Pit 4	Pit 38	Pit 22	Pit 6	Wash Area Kabelle Is.
Nitrogen—Percent						
0.0 - 1.25	1.21	3.58	4.71	0.80	0.15	0.04
1.25 - 2.5	0.69	1.88	4.78	0.62	0.03	0.03
2.5 - 5.0	0.43	0.60	4.61	0.59	0.03	0.02
5.0 - 7.5	0.31	0.38	1.73	0.42	0.02	0.02
7.5 - 10.0	0.19	0.37	0.43	0.34	0.02	0.02
10.0 - 12.5	0.25	0.29	0.25	0.26	0.02	0.02
12.5 - 15.0	0.20	0.22	0.18	0.25	0.02	0.02
15.0 - 17.5	0.17	0.22	0.18	0.21	0.02	0.02
17.5 - 20.0	0.21	0.21	0.21	0.15	0.02	0.01
20.0 - 22.5	0.31	0.19	0.20	0.14	0.02	
22.5 - 25.0	0.15	0.18	0.17	0.12	0.02	
25.0 - 27.5	0.12	0.13	0.17	0.10	0.02	
27.5 - 30.0	0.10	0.14	0.14	--	0.02	
30.0 - 32.5	0.09	0.12	0.11	0.09	0.02	
32.0 - 35.0	0.08	0.10	0.13	0.09	0.02	
35.0 - 37.5	0.07	0.08	0.10	0.08	0.02	
Phosphorus—ppm						
0.0 - 1.25	2912	5187	6060	5394	409	394
1.25 - 2.5	2156	3842	2000	5248	348	392
2.5 - 5.0	2006	2543	1776	4890	298	370
5.0 - 7.5	1087	1719	6575	4295	33	388
7.5 - 10.0	967	1524	5939	4072	270	327
10.0 - 12.5	1062	1165	3430	3785	315	363
12.5 - 15.0	1006	925	3600	1910	349	333
15.0 - 17.5	859	950	3275	3879	335	312
17.5 - 20.0	822	875	624	4152	360	
20.0 - 22.5	1250	731	2124	4781	312	
22.5 - 25.0	603	625	2188	4030	266	
25.0 - 27.5	862	830	1876	--	300	
27.5 - 30.0	375	830	848	3394	315	
30.0 - 32.5	443	631	1336	--	290	
32.5 - 35.0	381	449	1351	2790	275	
35.0 - 37.5	379	506	1212	2921	248	
Calcium—Percent						
0.0 - 1.25	14.2	8.9	4.6	33.1	26.7	
1.25 - 2.5	22.9	17.4	3.0	35.1	35.5	
2.5 - 5.0	18.8	32.0	3.0	35.9	37.7	
5.0 - 7.5	16.0	17.8	18.3	--	41.6	
7.5 - 10.0	27.2	26.6	26.2	35.7	39.5	
10.0 - 12.5	22.8	35.3	24.5	35.6	41.5	
12.5 - 15.0	31.7	25.7	29.5	35.9	38.2	
15.0 - 17.5	25.4	40.4	37.5	34.2	39.6	
17.5 - 20.0	27.9	16.3	15.9	33.1	46.3	

Table 10. continued.

Depth cm	Pit 1	Pit 4	Pit 38	Pit 22	Pit 6	Wash Area Kabelle Is.
Calcium—Percent						
20.0 - 22.5	29.4	32.9	21.4	36.7	26.0	
22.5 - 25.0		15.1	20.3	40.1	37.6	
25.0 - 27.5		36.1	26.7	--	24.5	
27.5 - 30.0		33.7	--	37.0	42.1	
30.0 - 32.5		19.1	24.8	--	29.0	
32.5 - 37.0		31.8	26.9	37.8	37.4	
37.0 - 37.5		31.9	31.4	40.1	--	
Magnesium—Percent						
0.0 - 1.25		5.59	0.71	4.44	6.79	
1.25 - 2.5	0.23	6.51	1.57	1.22	3.32	
2.5 - 5.0	1.08	1.17	0.49	2.00	3.06	
5.0 - 7.5	0.49	7.38	1.34	--	3.01	
7.5 - 10.0	0.39	2.38	0.93	2.40	2.35	
10.0 - 12.5	1.62	2.04	1.82	1.59	3.24	
12.5 - 15.0		2.87	1.31	4.34	4.32	
15.0 - 17.5	0.62	2.24	0.39	5.12	3.71	
17.5 - 20.0	0.08	--	1.16	3.07	1.87	
20.0 - 22.5		5.11	0.39	7.29	5.59	
22.5 - 25.0		3.67	1.08	1.44	0.62	
25.0 - 27.5		3.72	1.85	--	2.84	
27.5 - 30.0		6.67	0.62	1.47	3.30	
30.0 - 32.5		7.26	2.55	--	5.33	
32.5 - 35.0		2.18	3.43	2.13	3.20	
35.0 - 37.5		1.19	2.55	1.49	--	
Iron—ppm						
0.0 - 1.25	100	40	170	65	18	
1.25 - 2.5	68	38	115	--	10	
2.5 - 5.0	26	36	125	39	1.3	
5.0 - 7.5	30	33	140	19	1.3	
7.5 - 10.0	31	26	55	15	2.5	
10.0 - 12.5	45	43	38	15	7.5	
12.5 - 15.0	35	24		15	7.5	
15.0 - 17.5	35	30		30	7.5	

Table 10, continued.

Depth cm	Pit 1	Pit 4	Pit 38	Pit 22	Pit 6	Wash Area Kabelle Is.
			Manganese—ppm			
0.0 - 1.25	1.56	0.52	0.18	1.56	0.03	0.41
1.25 - 2.5	1.75	0.44	0.50	0.94	0.12	0.22
2.5 - 5.0	1.00	0.75	0.31	1.11	0.18	0.35
5.0 - 7.5	1.03	0.78	0.18	0.65	0.21	0.29
7.5 - 10.0	0.87	0.72	0.06	0.75	0.18	0.20
10.0 - 12.5	0.66	0.25	0.12	0.81	0.12	0.28
12.5 - 15.0	0.37	0.22	0.25	1.04	0.12	0.37
15.0 - 17.5	1.15	0.31	0.38	1.22	0.10	0.49
17.5 - 20.0	0.87	0.03	0.00	0.65	0.38	0.39
20.0 - 22.5	3.00	0.18	0.50	0.40	0.21	
22.5 - 25.0	0.68	0.00	0.50	0.38	0.08	
25.0 - 27.5	0.10	0.00	1.44	--	0.38	
27.5 - 30.0	0.15	0.00	0.00	0.25	0.06	
30.0 - 32.5	0.20	0.00	0.88	--	0.06	
32.5 - 35.0	0.11	0.00	0.44	0.18	0.12	
35.0 - 37.5	0.20	0.00	0.31	0.06	0.25	

Other elements

	Pit 38		Pit 22		Pit 6	
Depth cm	Zn	Cu	Zn	Cu	Zn	Cu
0.00 - 1.25	145	23	10	27	9	32
1.25 - 2.5	47.5	24	--	34	3	
2.5 - 5.0	95	21	7	27	0	
5.0 - 7.5	--	--	--	--	2	
7.5 - 10.0	8.3	6	34	0	-	
10.0 - 12.5	5.3	--	5	28	2	
12.5 - 15.0	1.5	0	2	24	3	
15.0 - 17.5	4.5	--	8	23	0	
17.5 - 20.0	4.0	21	7	22	-	
20.0 - 22.5	--	27	52	26	0	
22.5 - 25.0	2.5	21			6	
25.0 - 27.5	1.5	24			0	
27.5 - 30.0	0.0	22			2	
30.0 - 32.5	2.0	19			2	
32.5 - 35.0	1.0	21			1	
35.5 - 37.5	1.5	20			2	

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[1] Nitrogen by Kjeldahl. Other elements based on HCl digest (see p. 11 for Methods).

specific area basis, collections were made of current litter, humus layers if they existed, and soils at three depth increments to a total depth of 30 cm. At some isolated locations, litter trays were also set out, with litterfall collections at each visit to the area. Information from these collections has not been presented previously so detailed summary tables are given in this report along with short discussions of the data.

Litterfall and Litter Decomposition

Weight and nitrogen contribution of litter from the principal plant species are given in Tables 9 and 13. The species seem to produce about the same amount of litter as associations, or as individual shrubs, with ranges between 1000 to 1500 g/m^2 yr. Lowest values are on the youngest soils with the most harsh environment. The greatest amount of both litter and nitrogen contribution is under the well developed *Pisonia* forest on Kabelle Island. Nitrogen return by litter is up to ten times greater under *Pisonia* than under the poorest *Scaevola.* Some of this nitrogen contribution is from sea birds, as their excrement is ubiquitous on the litter. One litter site on Bikini island under a mixed cover of *Scaevola* and *Dodonaea* averaged about 1200 g/m^2 in weight but we have no nitrogen analysis (Table 28).

Because of the favorable conditions for decomposition, humus accumulation on the soil surface was not a common soil feature. Exceptions are under some *Pisonia* forests, occasional *Tournefortia* stands and *Bruguiera* swamps. In most soils the litter decomposes and residual products are incorporated into the surface horizons. In order to get some concept of rate of litter decomposition we collected leaves from three species and set them out in trays under the species of collection for a 6 month period. Results are given in Table 11. These show up to a 75 percent weight loss over the March to September period which encompasses the end of the normal dry season and the summer wet season. *Cordia* and *Tournefortia* leaves decomposed slower than *Scaevola* but there are not enough samples to attach a statistical significance.

Although humus layers are not a normal component of Rongelap Atoll soils and do not approach those described for Arno Atoll by Stone (1951) they are present in some situations. We sampled these under two species and found amounts ranging from 1000 to over 4000 g/m^2, with up to 175 g/m^2 of nitrogen. Humus under *Tournefortia* was much less in amount, but these plants were on a young soil (Table 12).

Nitrogen and Phosphorus Content of Litter and Soil

The nitrogen and phosphorus contents of litter and soils under a number of species over a range of soil ages is summarized in Table 13. Although the soil classification of "young" or "moderate" age was based on general observations and not substantiated by any measurements, the results show pronounced differences in both nitrogen and phosphorus when the same plant is compared on the two age classes of soils. For example *Tournefortia* litter and surface soil have nitrogen values of 1.72 and 0.70 percent respectively in the "moderate age" soil with 0.67 and 0.22 for similar locations in the "young" soil (Table 13). Species differences are also apparent in both age classes with

Table 11. Weight Loss of Leaf Litter from Three Species of Rongelap Atoll Trees in a Decomposition Study[1]

Species	Initial Dry wt.[2] g	Final Dry wt.[2] g	Loss g	% loss
Scaevola	81.0	19.7	61.3	75.6
Scaevola	89.0	30.8	58.2	65.4
Tournefortia	75.0	36.4	38.6	51.5
Tournefortia	74.8	36.3	38.5	51.4
Cordia	109.0	61.7	47.3	43.4
Cordia	68.2	34.1	34.1	50.0

[1] Decomposition period—3/4/59 to 9/4/59
[2] Weights determined by oven drying subsamples

Table 12. Dry Weight and Nitrogen Content of Humus Under Two Tree Species on Rongelap Atoll

				Total Weight		Nitrogen[1]	
Area	Year	Species	No. Samples	g/m^2	kg/ha	g/m^2	kg/ha
Pit 4	1961	*Pisonia*	1	4,196	41,960	172	1,720
Pit 38	1961	*Pisonia*	8	2,690	26,900	110	1,100
Pit 38	1986	*Pisonia*	1	4,304	43,040	177	1,770
Wash area	1963	*Tournefortia*	3	1,022	10,220	6.1	61

[1] Ave N content *Pisonia* humus—4.11%
Ave N content *Tournefortia* humus—0.60%

Table 13. Average Nitrogen and Phosphorus Content of Litter and Soil under Different Plant Species, Rongelap Atoll[1]

Species	No. Samples for N	Nitrogen (Percent) Soil Depth (cm)				No. Samples for P	Phosphorus (ppm) Soil Depth (cm)			
		Litter	0-2.5	2.5-15.2	15.2-30.5		Litter	0-2.5	2.5-15.2	15.2-30.5
		Moderate Age Soils								
Scaevola	7	1.01	1.12	0.32	0.12	4	500	82	34	8
Tournefortia	8	1.72	0.70	0.25	0.10	1	335	273	35	13
Guettarda	10	1.47	0.95	0.36	0.12	8	179	102	14	10
Pisonia	7	2.57	1.94	0.49	0.22	3	924	206	62	42
Cordia	3	1.27	2.02	0.98	0.50					
Neisosperma (=Ochrosia)	3	1.44	1.04	0.28	0.08	1	1662	1198	35	13
Pandanus	2	1.24	1.11	0.47	0.09	1	66	65	8	8
Pemphis	2	1.44	0.33	0.26	0.11	1	193	146	52	14
Lepturus	2	--	0.45	0.23	0.09	--				
		Young Soils								
Scaevola	3	0.72	0.12	0.07	0.05	1	154	45	29	23
Tournefortia	15	0.67	0.22	0.08	0.03	1	352	141	23	14
Guettarda	7	0.99	0.44	0.21	0.07	1	50	50	36	15
Cordia	1	1.08	0.20	0.06	0.03	1	270	92	35	26

[1] Nitrogen was Kjeldahl; Phosphorus is bicarbonate extractable

Pisonia having the highest values. *Cordia* soils of moderate age are also high in nitrogen. In areas not ordinarily disturbed by humans these species and *Tournefortia* are utilized by sea birds for nesting. As many of the samples came from remote islands the high values of the moderate age samples may reflect a sea bird influence on both nitrogen and phosphorus.

Total Nitrogen in Soils

In order to compare total nitrogen in contrasting soils we utilized bulk density and nitrogen content to estimate total nitrogen in the soil to a depth of 25 cm (Table 14). Some nitrogen exists at greater depths but a 25 cm depth accounts for at least 90 percent of the total in the soil. Pit 6 which represents a young soil on Kabelle Island has only 403 kg/ha of nitrogen, while the *Pisonia* forest area at Pit 38 has almost 13,000. In addition it would have up to 1,500 kg/ha of nitrogen in a humus layer making a total of about 14,500 kg/ha in the soil system. Pit 22 which is in the Rongelap Island coconut plantations is intermediate with 4,500 kg/ha. It does not have a humus layer, but does have some nitrogen in litter form.

Fungi and Algae

Although no systematic survey of soil micro-organisms was undertaken by any of the study groups, some information was collected through cooperative efforts. Selected soil samples collected in September 1959 were sent to Dr. William Bridge Cooke, then at the U.S. Public Health Laboratory at Cincinnati, Ohio. Results of his plate counts of fungi are given in Table 15. Surface soils and well-developed soils have more fungi than at depth in a profile or in open sandy areas. He reported that *Trichoderma viride* was ubiquitous in the samples.

Algal crust layers were sent to Dr. L. W. Durrell (Colorado State University) who identified the following species:

Chroococcum dispersus
" *turgidus*
" *pallidus*
Nostoc commune
" *punetiporme*
Plectonema radiosum

Phormidium subcapitatum
" *retzii*
" *papyraceum*
" *tenue*
Mesotaenium macrococcum
Merismopedia glauca
Nodularia spumigena

Table 14. Total Nitrogen Content (Kg N/ha)of Selected Soil Profiles, Rongelap Atoll

Source	0-2.5 cm	2.5-15.2 cm	15.2-25.5 cm	0-25.5 cm Depth
Pit 6 Kabelle	97	204	102	403
Pit 38 Kabelle	2,280	8,620	2,070	12,900
Pit 22 Rongelap	1,660	1,820	1,120	4,590

Table 15. Estimates of fungi in some Rongelap soils[a].

Soil Location	Description	Colony count per ml sample (estimated average of 5 plates corrected for dilution)
Pit No. 1	Surface Soil	55,800
Pit No. 1	0-2.5 cm	95,200
Pit No. 1	38-40 cm	3,000
Pit No. 1	Side of Soil Pit	50,000
Pit No. 34	0-1.3 cm	67,400
Pit No. 34	43-45 cm	2,000
Sand Spit, Rongelap Is.		1,000
Pit No. 36	0-2.5 cm	5,000
Pit No. 36	25-30 cm	7,000
Pit No. 35	0-2.5 cm	21,600
Pit No. 35	56-58 cm	1,000
Pit No. 35	170 cm	1,200

[a] Counts made by Dr. William Bridge Cooke
Soil samples collected September 1959, and sealed in plastic bags; received by Dr. Cooke 4 Dec. 1959; plated 7 Dec. 1959; counted 14 Dec. 1959.

SOILS AND PLANTS OF ENEWETAK AND BIKINI ATOLLS

Bikini and Enewetak atolls were more impacted by the weapons testing program than Rongelap, as they served as the locations for tests. Therefore the principal objective of soil and plant sampling on these atolls was for radioactivity status. Although the subject is dealt with in some parts of this report (see Tables 18 and 19) the authors were not heavily involved in these studies. Interested readers who want to review this subject are referred to the following publications: Chakravarti and Held, 1961; Donaldson, et al., 1955; Held, 1963; Held, et al., 1965a; Palumbo, 1961; Welander, et al., 1966; Nelson, et al., 1977; Robison, et al., 1987, 1991.

In this section we give results of the chemical analysis of soils in relationship to the condition of the collection areas in 1964, several years after the testing program. We first describe conditions in 1964 by setting up some general disturbance classes. This classification of collection areas should provide readers with a basis for judging impact of the tests as well as vegetation recovery by 1964. No attempt to classify soils of Bikini or Enewetak was made.

1964 Condition

The effect of the nuclear weapon testing on soils and plants is related to the nature of the soil at the time of the test. This is especially true for rate of recovery. Palumbo (1962) considered some of these aspects in discussing recovery of vegetation on Enewetak Atoll. Islets made up mainly of young, sterile soils were more severely damaged and recovered more slowly from the same intensity of test.

Several distinct contrasts were readily apparent in the condition of both soils and vegetation on Bikini and Enewetak in 1964. We therefore used four disturbance classes (Table 16) and attempted to sample across the range of the classes. Descriptions of the classes follow:

Disturbance Class

A. Relatively undisturbed except by construction activities or those effects related to visitation by relatively large numbers of people. Several islands at both Bikini and Enewetak could be cited as examples of this category. The condition of soil and vegetation ranges from mature to immature. Japtan on Enewetak Atoll represents an island of relatively deep mature soils which suffered no major changes during the testing period. Flora and fauna could be said to be somewhat normal and certain areas of undisturbed soils were found, and indeed sampled.

To a limited degree Eneu Island at Bikini could be placed in the same category. Of course, relatively large areas were changed by airfield construction and activities of a large number of personnel. However, some areas had mature coconut trees as of 1964, and seemed to have experienced little soil disturbance. Also, a number of small islets represent soils and vegetation in the younger stages of development, which had suffered

Table 16. Soil disturbance classification by Islets for Bikini and Enewetak Atolls (1964)[a]

Disturbance Class	Island
Bikini	
A	Bokdrolul (Boro) Eneu
B	Bikini
C	Nam
D	Aomoen (George) Lomilik (Fox) Bwikor (Yurochi, Dog) Odrik (Uorikku, Easy) Eneman (Eninman) Bikdren (Bigiren) Aerokoj (Airukiiji)
Enewetak	
A	Japtan Ikuren (Igurin)
B	Bokombako (Belle)
C	Bokoluo (Bogallua, Alice)
D	Runit Enjebi Bokinwotme (Edna)

[a] Marshallese names of the islands are listed first, with in some cases familiar previously used or code names given in parentheses.

no major physical destruction. Bokdrolul (Boro) could be cited as an example, as well as Ikuren and Biken (Rigili) on Enewetak.

B. This is the condition under which the vegetation was largely destroyed, probably by fire, but in which the soil was little affected, except at the surface. The best example of this condition is on Bikini Island. The soils, except for areas involved in construction disturbance, appear to be almost intact and little different from the soil of the productive areas of many of the atolls. Organic matter was high to depths of 45 cm, and the nutrient element supply is apparently good. Core samples collected in 1964 are difficult to distinguish from good soils of other atolls. The net effect of this lack of soil disturbance was an explosive re-development of native vegetation. So much growth had developed that it was practically impossible to move across the island.

One could surmise that this soil could be returned to productive coconut culture by reestablishing the destroyed coconut plantations, but recognizing the problem of retained radioactivity. In fact, Eneu and Bikini islands of Bikini Atoll were successfully replanted about 1970.

C. On Bikini Atoll, Nam island soils represent an intermediate state of destruction and redevelopment. Although the authors did not see Nam before the tests, it is obvious that the soils were deep and well developed and must have supported a luxuriant island vegetation. Inspection and collection in 1964 showed that destructive effects were largely confined to surface soils throughout most of the island. Soils still had high organic matter contents to depths of 30 cm, but showed indication of considerable disturbance and destruction at the surface. However, much of the inherent productive capacity of the soil had been retained and natural vegetation was rapidly returning and flourishing. The general rapid improvement was aided by large numbers of terns nesting in the trees. This assessment was confirmed by the 1986 visit to Nam, when almost entire coverage of the island by vegetation was noted.

D. The extreme destruction of soils and vegetation is represented by such islands as Lomilik (Fox) or Aomoen (George) on Bikini, and Runit (Yvonne)and Bokinwotme (Edna) on Enewetak. In these cases, there was almost complete destruction of soils on relatively small islands. Surface soils were probably either vaporized or completely blown away. This was true for both mature and young soils, so that the entire nature of the islet was changed. Recovery of these areas is very much related to redevelopment of soil, and subsequently vegetation. Soil redevelopment is, in turn, related to two different geologic factors. In cases where surface soil was destroyed down to cemented beach rock, redevelopment was materially slowed, and the ability of plants to re-invade much reduced. In cases where loose coral sand was present, or was being washed in by the sea, invasion and soil development proceeded at a more rapid pace. Our studies showed that on Bokinwotme (Edna), soil profile development occurred rather rapidly under *Tournefortia* plants so that after 6 to 10 years of growth, a surface organic horizon was forming. By and large these heavily damaged islands represent a great variety of conditions, none of which will be rapidly cured. However, some spots are better than others and will continue to improve rapidly as vegetation is re-established and sea birds again inhabit the areas. We have been able to follow a similar sequence of events brought about by natural factors in very young soils on Kabelle Island of Rongelap atoll. Table 16 presents a disturbance classification of all of the islands on both Bikini and Enewetak atolls which we were able to study.

Casual observations which have some bearing on the ability of test areas to again support life are related to the activity of ants and to hermit crabs. Ants of various species seem to be quite abundant in all Marshall Island atolls. We personally observed them in fairly large numbers in even the most severely damaged test areas. They seemed to be normal in all respects.

Hermit crabs were also observed in rather large numbers on the heavily damaged islets. Their major problem seemed to be a shortage of food. As a result, they were observed to be eating bark and leaves of *Tournefortia* trees. In some cases small trees were almost completely girdled.

Chemical Analyses

Chemical analyses of composite soil samples from various islands representing a range of disturbance and from two pits in more detail are given in Table 17. These clearly show the loss of nitrogen and organic matter in severely disturbed soils represented by the crater area samples.

PLANT PHYSIOLOGICAL STUDIES

PLANT NUTRITION

Pot Tests Using Atoll Soils

Pot tests were run in the greenhouse at Seattle and also under a wind and rain shelter at Enewetak. Objectives of these were to ascertain the ability of the soils to supply various mineral nutrients, and the influence of mineral fertilization on the uptake of ^{137}Cs. The depression of ^{137}Cs uptake by fertilization, especially with potassium, had been reported from our earliest trials (Walker, Held and Gessel, 1961), but these experiments confirmed and extended those findings. In the greenhouse in Seattle, maize was grown in a surface soil collected near the well on Rongelap Island. A summary of the principal results is given in Table 18.

Although as in the earlier trials, potassium fertilization depressed ^{137}Cs uptake, an experiment under atoll climate conditions was conducted at Enewetak for additional verification. Surface soil (ca. 20 cm depth) was collected in a coconut grove near the center of the relatively undisturbed small island of Japtan. A total elemental analysis of this soil is included in Table 17. The dark colored soil was sieved through a 1/2 inch mesh at the collection site. At the Enewetak Marine Biological Laboratory, following

Table 17. Elemental Analysis of Contrasting Bikini and Enewetak Soils.[1]

			Percent				ppm					
Island		Dist. Class	N %	P %	Ca %	Mg %	Na	K	Fe	Mn	Cu	Zn
Composite Soils, Surface 15 cm												
	Vegetation											
Ikuren	*Pisonia*	A	0.31	0.34	36.8	0.73	940	70	37.9	1.80	29.4	12.0
Japtan	*Pisonia*	A	0.84	4.38	31.9	0.96	1,040	260	92.2	8.40	10.3	18.1
Runit	Open crater	D	0.01	0.07	36.9	1.21	1,120	70	607.	5.60	26.9	8.8
Eneu	Coconut grove	A	0.42	0.33	36.2	0.80	1,030	90	138.	2.00	29.3	10.4
Bikini	*Pandanus*	B	0.60	0.95	31.7	2.29	1,010	100	73.5	2.90	44.9	12.7
Lomilik	Crater area	D	0.06	0.11	35.6	1.99	980	50	23.9	1.30	19.8	8.7
Nam	*Tournefortia*	C	0.10	0.04	35.2	2.08	1,090	80	35.0	0.80	21.7	20.0
Eneman	Crater area	D	0.02	0.07	38.0	4.38	1,010	60	21.3	0.70	21.6	10.9
Profile Survey												
Soil Pit 11	**Depth cm**											
Bikini	0.0 - 1.25	B	1.15	1.38	27.7	1.73	760	170	139.	4.80	29.5	24.6
Bikini	1.25 - 2.5		0.89	1.27	30.1	2.06	900	110	118.	3.50	35.2	19.9
Bikini	2.5 - 5.0		0.75	1.34	31.3	1.87	890	130	120.	2.00	33.4	19.5
Bikini	5.0 - 7.5		0.35	1.23	34.1	1.97	1,000	100	94.6	1.50	35.7	18.0
Bikini	7.5 - 10.0		0.31	0.72	33.8	1.55	910	80	50.9	0.70	38.0	17.9
Bikini	10.0 - 12.5		0.31	0.65	34.5	1.47	913	71	44.4	0.80	30.4	14.6
Bikini	12.5 - 15.0		0.20	0.91	34.4	0.99	1,060	78	75.9	.080	26.6	13.1
Bikini	15.0 - 17.5		0.15	0.93	33.6	1.28	776	77	50.5	0.60	24.2	12.8
Bikini	17.5 - 20.0		0.20	0.59	33.7	1.73	865	79	40.2	0.60	23.0	14.0
Bikini	20.0 - 22.5		0.12	0.56	34.3	1.25	764	70	37.7	0.80	20.0	15.0

Table 17. (continued)

			Percent				PPM					
Island	Depth cm	Dist. Class	N %	P %	Ca %	Mg %	Na	K	Fe	Mn	Cu	Zn
Bikini	25.5 - 25.0	B	0.12	0.35	35.7	1.22	773	62	26.4	0.60	20.2	12.4
Bikini	25.0 - 30.0		0.08	0.30	32.6	1.53	882	64	23.8	0.50	14.0	14.1
Bikini	30.0 - 37.5		0.10	0.31	34.9	1.29	863	62	26.3	0.60	14.5	13.3
Bikini	37.5 - 50.0		0.07	0.14	34.5	1.90	931	61	15.0	0.30	10.0	13.3
Bikini	50.0 - 65.0		0.03	0.04	34.3	2.78	970	63	11.3	0.50	7.0	12.1
Aomoen	0.0 - 1.25	D	0.04	0.04	34.5	2.18	790	62	48.3	0.50	6.8	12.8
Aomoen	1.25 - 2.5		0.03	0.05	34.1	2.19	871	61	134.0	0.90	11.4	13.0
Aomoen	2.5 - 5.0		0.03	0.04	35.5	2.06	1,000	61	220.4	0.30	8.0	13.8
Aomoen	5.0 - 7.5		0.03	0.04	35.5	2.29	962	56	109.0	0.70	7.2	13.0
Aomoen	7.5 - 10.0											
Aomoen	10.0 - 12.5		0.04	0.04	35.6	1.89	901	56	205.0	0.60	7.0	13.0
Aomoen	12.5 - 15.0		0.03	0.02	35.0	1.81	821	54	11.3	0.10	6.9	13.2
Aomoen	15.0 - 17.5		0.02	0.02	33.8	2.38	841	53	10.0	0.10	5.3	13.5
Aomoen	17.5 - 20.0		0.03	0.02	35.4	1.69	840	52	7.5	-	3.9	11.8
Aomoen	20.0 - 22.5		0.01	0.03	35.4	1.98	740	50	6.3	-	4.1	10.7

[1] Nitrogen by Kjeldahl; other elements from acid digest (see page 11)

Table 18. Maize Grown in the Greenhouse on Rongelap Well Soil (Expt. 59-471)

Fertilization*	Ave. Dry yield (g)	Ave. K in Shoots (%)	Ave ^{137}Cs in Shoots (becq/g)
$N_{4.48}$ $P_{4.48}$ K_0	2.00 ± 0.30	1.96	0.150 ± 0.027
$N_{4.48}$ $P_{4.48}$ $K_{2.24}$	2.93 ± 0.50	2.46	0.105 ± 0.010
$N_{4.48}$ $P_{4.48}$ $K_{4.48}$	3.02 ± 0.14	3.42	0.083 ± 0.011

* Subscripts refer to hundreds of kilograms per hectare equivalent of N, P_2O_5, or K_2O respectively

Table 19. Methods Used for Plant Tissue Analyses.

Ca	Mostly EDTA titration; some by titration of oxalate precipitate with permanganate[a]
Mg	Mostly by EDTA titration; some by colorimetric estimation of $MgNH_4PO_4$ precipitate[a]
K, Na	By flame photometry with Beckman DU flame attachment[a]
N	By Kjeldahl digestion, distillation, and titration[a]
P	By the molybdivanadate colorimetric method[a]
Fe	By orthophenanthroline colorimetric method[b]
Mn	By the permanganate colorimetric method[a]
Zn	By the Zincon colorimetric method[b]
Cu	By ion exchange followed by the Zincon method[b]
B	By the curcumin colorimetric method[c]

[a] Methods adapted from Jackson (1958)
[b] Methods adapted from Sandell (1959)
[c] Procedure of Dible et al. (1954)

methods similar to those of Jenny et al. (1950), 6-quart portions of the soil were mixed on a plastic sheet with the appropriate fertilizer solution, placed in 7-quart wastebasket-type containers with drain holes, moistened with distilled water, then each planted with five seeds of a hybrid maize. The containers were placed in a random arrangement in a rain and wind shelter near the laboratory (Figure 12). The fertilizer materials were NH_4NO_3, H_3PO_4, and KC1, with iron added at 75 mg Fe per container using the EDTA complex. After about 30 days the shoots were harvested, divided into stem and upper and lower leaf fractions, oven dried at Enewetak, then ground to 40 mesh using a Wiley mill in Seattle, and analyzed by methods listed in Table 19. Radioactivity of principal isotopes was also assayed: ^{137}Cs by gamma ray spectroscopy using a 3-inch Th activated NaI crystal and ^{90}Sr by standard procedures.

The yields and analytical results for the various treatments are given in Table 20. There were strong responses in yield to additions of nitrogen and of potassium, but phosphorus added at the P_4 level had little influence. Phosphorus at the P_8 level depressed growth markedly, probably because it reduced the availability of iron or other micronutrients. The depression of calcium and magnesium by potassium addition is very obvious in the upper leaves as expected, and this is evident also for magnesium in the lower leaves and for both calcium and magnesium in the stems. The low supplying capacity of this soil for potassium is shown both by the low levels in the tissue when potassium was not added and by the mobility of potassium, with upper leaves being higher than lower leaves even in treatments which received potassium. The marked depression of ^{137}Cs uptake by potassium fertilization is consistent throughout the experiment, and depressions are great enough that even at the highest yields dilution could not explain the reductions. The ^{90}Sr activities were appreciably higher in the lower than in the upper leaves, a pattern which closely followed that of calcium. From the standpoint of general fertility, there was marked response to both nitrogen and phosphorus additions despite the high total amounts in the Japtan soil (Table 17). Magnesium contents of the tissue are high, approaching calcium on a percentage basis thus often exceeding calcium on a chemical equivalent basis. This is consistent with the substantial levels of exchangeable magnesium in Rongelap soils (Tables 2-6), which is likely the case for Bikini soils as well.

Plant Tissue Analyses

Many samples of plant tissues were collected on each of the eight expeditions during the period 1958 to 1964. The results of analyses of some food items were reported (Chakravarti & Held, 1961); most of the rest of the samples were of foliage, although some collections of wood and bark were made. Analyses were made for major cations, nitrogen, phosphorus, and micronutrients on a sizable number of these samples, mostly of coconut palm, *Tournefortia, Scaevola,* and *Guettarda.* The methods of analysis are given in Table 19. In most cases the elements were brought into solution by dry ashing at 450-500°C, then dissolving the ash in dilute HC1.

The analytical results are presented in Tables 21 through 24. A general evaluation of these follows, with respect to each element:

Figure 12 Maize in pot cultures in experimental shelter at Enewetak

Table 20. Yield, Chemical Compositon, and ^{90}Sr and ^{137}Cs Activities in Maize Grown in Pot Cultures at Enewetak Atoll

Treatment[a]		Mean Dry Weights (g)		Mean Chemical Composition (% Dry wt.)					Mean ^{137}Cs (Entire Shoot)	Mean ^{90}Sr
		Plant Parts	Total Shoot	Ca	Mg	K	N	P	becq/g	becq/g
	Upper lvs	1.25		1.15	0.91	0.42	1.44	0.11		6.68
Control	Lower lvs	0.27	2.12 ± 0.17	3.05	1.83	0.076	1.24	0.17	4.50	12.7
	Stems	0.59	(26%)[b]	0.81	0.75	0.47	1.03	0.23		5.50
	Upper lvs	0.93		0.95	0.81	0.55	—	0.15		4.55
Fe only	Lower Lvs	0.26	1.56 ± 0.34	2.16	1.20	0.093	—	0.28	3.83	8.67
	Stems	0.36	(19%)	0.88	0.79	0.79	—	0.30		4.97
	Upper lvs	5.52		0.64	0.34	2.81	1.86	0.25		2.23
$N_{2.24}P_{4.48}K_{2.24}Fe$	Lower lvs	0.43	8.20 ± 3.98	2.28	0.57	1.75	1.19	0.16	0.80	7.40
	Stems	2.45	(100%)	0.85	0.62	4.48	1.53	0.29		4.33
	Upper lvs	1.51		0.56	0.28	2.89	—	0.17		2.12
$N_{0}P_{4.48}K_{2.24}Fe$	Lower lvs	0.32	2.37 ± 0.54	1.86	0.60	2.41	—	0.12	0.60	6.65
	Stems	0.59	(29%)	0.66	0.40	6.07	—	0.44		2.57
	Upper lvs	4.42		0.63	0.34	2.60	—	0.16		2.28
$N_{2.24}P_{0}K_{2.24}Fe$	Lower lvs	0.46	7.28 ± 1.62	3.11	0.55	2.14	—	0.064	0.717	7.08
	Stems	2.40	(89%)	0.63	0.51	4.73	—	0.24		2.30
	Upper lvs	1.33		1.43	1.08	0.39	1.62	0.32		4.75
$N_{2.24}P_{4.48}K_{0}Fe$	Lower lvs	0.50	2.23 ± 0.72	2.60	1.21	0.13	1.72	0.49	4.83	7.37
	Stems	0.40	(27%)	1.29	1.16	0.67	1.46	0.72		5.75
	Upper lvs	5.05		0.56	0.26	3.33	—	0.24		4.52
$N_{2.24}P_{4.48}K_{4.48}Fe$	Lower lvs	0.41	8.19 ± 4.60	2.47	0.55	3.16	—	0.22	—	4.02
	Stems	2.28	(100%)	0.62	0.35	6.17	—	0.32		2.88
	Upper lvs	2.50		0.89	0.41	4.18		0.31		3.17
$N_{2.24}P_{8.96}K_{2.24}Fe$	Lower lvs	0.55	4.22 ± 1.69	2.83	0.66	3.74		0.30	—	6.20
	Stems	1.18	(51%)	0.82	0.49	6.02		0.38		2.57

[a] Subscripts of fertilizer treatments refer to hundreds of kilograms per hectare of N, P_2O5, or K_2O respectively.

[b] Percentages compare yields with $N_{2.24}P_{4.48}K_{2.24}Fe$ treatment.

Calcium - The contents in the dicotyledenous species were high, and in most cases higher in lower than in upper leaves, as would be expected for an immobile element. In palm the contents were lower, characteristic of a monocot, and in the few comparisons available lower leaves again had higher contents than upper leaves. This species collected on Bikini/Enewetak showed generally lower values than collections from Rongelap. The possibility of a systematic analytical error accounting for these lower values for Bikini samples cannot be ruled out, although even the lowest contents are substantial for this element.

Magnesium - The contents of this element are appreciable, and in almost all cases are higher in lower than in upper foliage, which in a mobile element indicates a more than adequate supply to the plant. In palm, magnesium sometimes equalled or even slightly exceeded calcium in percentage and more often on a chemical equivalent basis, which was surprising in view of the dominance of calcium in the substrate. However, this can reflect the appreciable exchangeable magnesium in the soils (Tables 2-6) and very likely also the high magnesium levels in ground waters (Table 27). The samples from Bikini/Enewetak (*Tournefortia*) were appreciably lower in magnesium than the Rongelap material, and the contents of lower leaves were usually not equal to those of the upper leaves.

Potassium - For all species the upper leaves seem to have fairly good levels of potassium, but the lower leaves are almost always lower and sometimes very low in this element, indicating from this mobility a limiting supply of potassium. Again, *Tournefortia* from Bikini/Enewetak was lower in potassium status than material from Rongelap.

Sodium - As might be expected near the sea, sodium contents were substantial in the dicotyledonous species, but this did not prove to be the case for the monocotyledon, coconut palm. In the dicots, the lower leaves commonly had higher levels than the upper leaves, and it was common for sodium to be higher than potassium. The collected foliage was not washed, so aerosol sodium chloride deposited on the leaves may have increased sodium values. However, *Scaevola, Tournefortia* and other species showed strong uptake of sodium in greenhouse experiments (Lésk6, 1968; Walker and Gessel, 1991), and palm (Table 24) shows low sodium in the field collections.

Nitrogen - Contents of this element are often low, especially on the beach fringes of the islands. Also this is very evident in recently planted coconut trees. In the centers of islands, where soil organic matter is higher and where bird roost is common, nitrogen levels can be much higher. Thus, nitrogen values vary appreciably among the collections, but in most cases nitrogen in the lower leaves is less than in the upper leaves, indicating a short supply of this mobile element. The plant condition rating of "good" in *Tournefortia* on Bikini and Enewetak (Table 22) is mostly associated with higher nitrogen levels.

Table 21. Analyses of foliage of *Tournefortia* (*Messerschmidia*) plants from Rongelap Atoll

						Macroelements (% of dry tissue)						Micronutrients (mg/kg dry tissue=ppm)			
Sample	Date of Coll	Atoll	Island	Location on Island	Type of Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	B	^{137}Cs becq/dry g
Mess-106A,B	858	Rongelap	Rongelap	Over Pit 25	UL[a]	2.14	0.62	1.30	2.74	1.84	0.23				4.00±0.13
				at weather sta.	LL	3.48	0.86	0.26	4.73	0.88	0.21				2.50±0.12
Mess-200	959	Rongelap	Rongelap	(w. tip of island)	UL	2.40	0.65	1.97	1.99	-	0.32				
					LL	4.40	0.81	0.69	2.50	-	0.51				
Mess-6A,B	858	Rongelap	Kabelle	Near Pit 6	UL	3.96	0.52	2.13	1.99	2.50	0.23				7.17±0.084
					LL	6.78	0.64	0.60	3.45	1.13	0.17				4.75±0.22
Mess-128A,B	359	Rongelap	Kabelle		UL	3.61	0.43	1.80	2.23	-	0.26				5.83±0.10
					LL	7.07	0.62	1.04	2.23	-	0.21				8.67±0.17
Mess-129A,B	359	Rongelap	Kabelle		UL	2.95	0.46	1.95	1.65	-	0.29				8.33±0.12
					LL	3.15	0.55	1.22	2.92	-	0.16				11.2±0.13
Mess-130A,B	359	Rongelap	Kabelle		UL	3.38	0.47	1.44	2.43	-	0.16				3.67±0.083
					LL	8.74	1.01	0.13	2.13	-	0.075				1.83±0.067
Mess-209A,B	959	Rongelap	Kabelle	Wash Area	UL	3.85	0.70	1.00	1.96	2.04	0.22				
					LL	5.18	0.99	0.60	2.19	1.34	0.30				
Mess-210A,B	959	Rongelap	Kabelle	Wash Area	UL	4.43	0.94	0.83	1.66	1.45	0.24				
				12m E of 209	LL	5.07	0.92	0.27	2.20	0.91	0.28				
Mess-211A,B	959	Rongelap	Kabelle	E. end *Pisonia*	UL	2.79	0.54	2.70	1.59	2.78	0.31				
				fert. plots	LL	3.49	0.64	2.04	2.16	2.25	0.30				
Mess-120	363	Rongelap	Kabelle	Plot X	UL	3.28	0.63	1.24	5.60	-	0.21	48	23		
Mess-121				near cistern	LL	5.25	0.77	0.35	4.30	-	0.16	43	16	84	
Mess-128	363	Rongelap	Kabelle	Beach area	UL	3.70	0.85	1.53	1.95	-	0.24	28	25		
Mess-129				near cistern	LL	4.72	0.43	1.10	0.63	-	0.18	30	17		
Mess-207	959	Rongelap	Rochi	Along lagoon	UL	2.16	0.46	1.82	2.05	2.13	0.23				
				beach	LL	3.41	0.70	1.14	3.16	1.65	0.24				
Mess-214	959	Rongelap	Lomuilal	60m fr. lag.; 150m	UL	2.94	0.50	1.74	1.91	2.10	0.19				
				fr. SE tip of island	LL	4.63	0.57	0.75	2.72	1.90	0.18				
Mess-215	959	Rongelap	Naen	DUKW landing	UL	3.50	0.55	1.64	2.11	2.52	0.19				
					LL	4.63	0.57	0.90	3.12	1.90	0.15				
Mess-226	959	Rongelap	Naen	SE corner of island	UL	3.65	0.61	1.76	1.85	2.12	0.14				
				SW corner of island	LL	5.25	0.70	1.08	2.63	2.02	0.075				
Mess-228		Rongelap	Gogan	Open beach	UL	3.85	0.58	1.67	2.35	2.52	0.17				
				area-W. end	LL	5.04	0.68	0.65	3.24	1.33	0.098				

[a] UL = upper leaves; LL = lower leaves

Table 22. Analyses of foliage of *Tournefortia (Messerschmidia)* plants on Bikini and Enewetak Atolls collected in August 1964

						Macroelements (% of dry tissue)					Micronutrients (mg/kg dry tissue=ppm)				
Date of Coll	Atoll	Island	Location on Island	Plant Condition	Type of Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	Cu	Zn
864	Bikini	Aerokoj	Old airport area	Poor	UL[a]	2.46	0.95	0.99	1.48	1.40	0.27	26	21	10	26
			variable vigor;	Mottled	UL	1.19	0.40	0.83	2.60	2.40	1.40	27	11	13	21
			ferns present	Good	Bud	8.28	3.28	1.18	1.50	2.09	1.85	20	5.5	4,5	23
				Good	LL	0.94	0.37	0.81	2.78	0.90	0.41	9.5	18	16	104
				Mottled	LL	1.03	0.46	0.33	2.43	0.97	0.23	13	9.4	14	53
864	Bikini	Bikini	Near present	Poor	UL	1.47	0.33	1.14	1.75	0.93	0.80	19	8.5	6.5	13
			truck landing	Poor	LL	1.22	0.34	0.61	1.70	0.90	0.16	16	7.4	3.8	17
			along lagoon	Good	UL	1.50	0.41	1.80	1.65	1.97	1.00	19	3.0	9.3	11
			shore NW from	Poor	LL	2.30	0.34	0.29	2.50	0.50	0.40	12	11	1.5	68
			village area.												
			Vigor poor	Poor	LL	2.14	0.90	1.18	2.55	1,02	0.15	16	21	1.8	26
			on beach but	Good	LL	1.41	0.52	1.89	2.28	1.26	0.095	14	19	17	19
			good in interior	Good	LL	1.03	0.25	0.70	2.68	1.24	0.092	18	23	6.5	11
				Poor	LL	1.63	0.21	0.66	2.60	0.62	0.077	5.8	14	2.5	30
864	Bikini	Eneman	Disturbed site		L	3.69	0.76	1.36	0.80	1.47	0.24	17	9	29	57
			near crater												
864	Bikini	Eneu	Interior near old	Poor	LL	3.30	1.05	1.23	3.35	1.09	1.75	28	11	20	70
			recreational bldg.	Good	LL	2.73	0.53	0.35	3.95	1.14	0.65	43	8.5	34	21
			Varying dis-	Poor	UL	0.67	0.16	1.63	1.98	1.77	0.27	16	13	11	48
			turbance	Good	UL	0.81	0.23	1.43	1.78	2.77	0.12	25	19	6.8	21
864	Bikini	Nam	Disturbed	Poor	UL	2.12	0.50	1.51	1.55	1.23	0.13	15	12	5.8	16
				Poor	LL	2.06	0.38	0.78	2.78	0.69	0.10	12	17	14.5	19
864	Bikini	Lomilik	Very disturbed area;	Good	UL	0.98	0.41	1.23	1.98	2.11	0.18	145	19	4.8	18
			soil good and poor	Poor	LL	0.98	0.49	0.70	2.65	0.66	0.089	6.4	14	6.8	35
			mess present		LL	1.09	0.47	0.96	2.43	0.75	0.12	10	16	13	28
					L	2.84	0.67	1.85	0.70	1.27	0.30	16	3.5	12	25
864	Enewetak	Ikuren	Near Helipad	Poor	UL	2.01	0.62	0.35	1.88	1.05	1.00	1.5	9.0	5.5	15
864	Enewetak	Japtan	Disturbed on sur-	Good	UL	5.00	0.34	0.40	2.35	2.44	1.05	36	7.5	16	50
			face; good soil	Poor	LL	2.63	0.56	0.18	2.00	0.53	0.30	110	15	2.8	41
				Good	L	0.90	0.32	0.34	2.40	1.57	0.090	27	18	7.8	56
					L	2.06	0.36	0.88	1.83	1.85	0.26	36	20	12	52
864	Enewetak	Runit	Young, disturbed		L	2.24	0.96	1.08	0.90	1.14	0.31	40	32	48	100
			soil.												
864	Enewetak	Bokinwotme	Center was highly		L	2.91	0.71	2.08	0.60	2.20	0.28	25	13	38	22
			disturbed												

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[a] UL = upper leaves; LL = lower leaves; L = general leaf sample

Table 23. Analyses of foliage of *Scaevola* (Sca), *Guettarda* (Gue) and Squash (Squ) Plants collected on Rongelap Atoll

						Macroelements (% of dry tissue)						Micronutrients (mg/kg dry tissue=ppm)			
Sample	Date of Coll	Atoll	Island	Location on Island	Type of Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	B	^{137}Cs becq/dry g
Sca-120A	858	Rongelap	Rongelap	W. of Pit 23	UL[a]	1.78	0.42	2.97	0.95		0.16				0.98±0.083
Sca-120B					LL	2.79	0.60	0.89	1.73		0.23				2.33±0.13
Sca-103A	858	Rongelap	Rongelap	9m NE of Pit 24	UL	1.44	0.42	3.84	0.83		0.17				0.85±0.050
Sca-103B					LL	2.53	0.57	1.49	1.40		0.15				2.17±0.13
Sca-104A	858	Rongelap	Rongelap	9m NE of Pit 21	UL	1.79	0.52	3.28	0.68		0.16				1.27±0.085
Sca-104B					LL	2.52	0.82	1.15	1.76		0.21				3.33±0.13
Sca-105A	858	Rongelap	Rongelap	2-3m NE of Pit 25	UL	1.41	0.64	1.33	1.35		0.20				1.83±0.10
Sca-105B					LL	2.27	1.24	0.48	1.34		0.26				2.50±0.12
Sca-6A	858	Rongelap	Kabelle	Near Pit 6	UL	2.05	0.49	1.96	1.68	1.72	0.27				4.00±0.10
Sca-6B					LL	3.25	0.89	0.33	1.99	0.93	0.31				3.83±0.10
Sca-131A	359	Rongelap	Kabelle		UL	1.79	0.54	1.64	1.25		0.24				3.00±0.27
Sca-131B					LL	3.05	0.84	0.32	1.51		0.36				3.33±0.10
Sca-132A	359	Rongelap	Kabelle		UL	2.91	0.56	1.63	1.00		0.31				4.00±0.10
Sca-132B					LL	3.18	0.82	0.70	1.21		0.46				5.50±0.12
Sca-133A	359	Rongelap	Kabelle		UL	1.86	0.54	1.19	1.25		0.25				3.67±0.083
Sca-133B					LL	2.94	0.77	0.32	1.20		0.27				3.67±0.083
Sca-182	961	Rongelap	Anielap	w/ old btrys.	L	3.11	1.30	1.22	1.97	1.59	0.33	109	20	68	
Sca-183	961	Rongelap	Anielap	w/o old btrys.	L	2.19	0.68	2.28	1.12	1.41	0.39	200	15	51	
Sca-118	363	Rongelap	Kabelle	Plot X near Cistern	UL	2.69	0.62	1.90	1.37	2.01	0.29	48	37		
Sca-119					LL	2.99	0.75	1.25	1.89	1.45	0.32	33	28		
Sca-126	363	Rongelap	Kabelle	Beach area near	UL	1.89	0.57	1.92	1.74	1.21	0.21	29	27		
Sca-127				cistern	LL	2.82	0.76	1.09	1.94	0.46	0.24	35			
Gue-180	961	Rongelap	Anielap	w/ old btrys.	UL	0.92	0.41	0.92	0.92	0.97	0.14	21	3.8	50	
					LL	1.32	0.29	0.59	0.68	0.39	0.15	11	4.0		
Gue-181	961	Rongelap	Anielap	w/o old btrys.	UL	1.59	0.52	1.70	0.73	0.90	0.67	22	3.8	64	
					LL	2.05	0.57	1.05	0.60	0.51	0.13	18	4.8		
Gue-122	363	Rongelap	Kabelle	Plot X	UL	1.44	0.30	2.23	0.30	1.69	0.20	30	5.8	48	
Gue-123					LL	2.01	0.47	1.92	0.51	0.81	0.33	24	2.3		
Gue-130	363	Rongelap	Kabelle	Near cistern	UL	1.37	0.34	1.21	0.53	1.47	0.19	23	21		
Gue-131					LL	2.21	0.43	1.04	0.72	0.59	0.18	21	33		
						8.06	1.76	1.83	0.10	2.62	0.27				
Squ-110A	858	Rongelap	Eniaetok	House at ship	UL	16.8	3.16	0.94	0.11	1.15	0.23				
Squ-110B				landing	LL										

[a] UL = upper leaves; LL = lower leaves; L = mixed upper and lower leaves

Table 24. Analyses of coconut palm foliage collected on Rongelap Atoll

					Macroelements (% of dry tissue)						Micronutrients (mg/kg dry tissue=ppm)					
	Location on Island	Date of[a] Coll	Fertilizer[b] Treatment	Type of[c] Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	Cu	Zn	B	^{137}Cs becq/dry g
					Rongelap Island											
Row 1	Rows just south of village[d]		Ca nitrate		0.54	0.35	1.58	0.14	0.54	0.11	39				28	0.47
2			"		0.69	0.33	1.22	0.28	0.50	0.098	32					
3			Uramite		0.57	0.41	1.65	0.23	0.50	0.14	26				20	0.33
4			"		0.54	0.42	1.40	0.29	0.85	0.11	22				34	0.57
5		864	$(NH_4)_2SO_4$	c	0.57	0.51	1.31	0.14	0.51	0.11	42				26	0.43
6			"		0.61	0.52	1.30	0.29	0.75	0.31	30					
7			NH_4NO_3		0.71	0.21	1.42	0.28	0.68	0.11	34					
8			"		0.53	0.27	1.75	0.15	0.63	0.14	27					
9			"		0.54	0.17	1.50	0.22	0.57	0.16	25					
Row A	Additional rows south of village[d]		KCl		0.51	0.28		0.058	0.59	0.14	18				18	0.30
B			K_2SO_4		0.50	0.37		0.080	0.71	0.61	24				10	0.17
C			NH_4NO_3 + Fe spray		0.51	0.26		0.16	0.74	0.15	28				25	0.42
D		864	NH_4NO_3; KCl; Fe chel.	c	0.55	0.28		0.16	0.60	0.14	24				20	0.33
E			$MgNH_4PO_4$		0.47	0.22		0.28	0.64	0.18	15				29	0.48
1			No fertilizer		0.54	0.42		0.18	0.59	0.14	25				20	0.33
2			"		0.54	0.38		0.23	0.58	0.14	24				41	0.68
Row I	Rows in swale area[e]		Multitracin		0.65	0.62	0.21	0.31	0.97	0.11	65	17	9.4	16		
II			No fertilizer		0.57	0.33	0.36	0.51	1.02	0.14	38	8.4	9.0	14		
III			Fe-Tracin		0.73	0.42	0.49	0.44	0.91	0.11	15	3.2	7.6	13		
IV		864	Control	c	0.61	0.36	0.66	0.69	0.90	0.10	14	1.6	8.8	13		
V			Fe-Tracin + Mn, Zn, $CuNH_4PO_4$		0.47	0.43	0.24	0.66	1.01	0.098	50	12	8.0	15		
VI			Fe, Mn, Zn, $CuNH_4PO_4$		0.46	0.38	0.20	0.46	0.98	0.11	25	24	8.4	16		
VII					0.50	0.43	0.25	0.49	1.10		37	19	6.6	14		
Row I	Rows near soil pit no. 1[e]		No treatment		0.89	0.41	0.37	0.13	1.27	0.17	24	9.4	12	30		
I			"		0.72	0.74	1.00	0.32	1.27	0.18	20	13	12	15		
II			Unchelated Tracin		0.75	0.76	0.34	0.45	1.12	0.10	43	23	8.0	30		
II			Multi-Tracin	c	0.61	0.42	0.36	0.35	0.84	0.099	70	13	7.2	13		
III		864	No Treatment		0.91	0.49	0.35	0.43	0.95	0.12	12	9.4	8.2	13		
III			"		0.75	0.79	0.30	0.43	1.42	0.28	50	12	10	15		
IV			Fe-Tracin		0.82	0.71	0.31	0.39	1.18	0.17	21	5.6	9.4	15		
IV			"		0.81	0.44	0.55	0.37	0.94	0.18	27	5.2	14	6.6		
V			Fe-Tracin+Mn, Zn, Cu,NH_4PO_4		0.67	0.54	0.54	0.50	0.99	0.095	32	12	11	29		
V			"		0.55	0.40	0.60	0.41	0.69	0.11	18	24	16	25		
VI			Fe, Zn, NH_4PO_4		0.96	0.55	0.20	0.51	0.88	0.093	18	3.4	14	23		
VI			"		0.67	0.35	0.84	0.50	1.09	1.12	40	7.4	14	22		
VII			Fritted Trace Elements		0.61	0.32	0.55	0.55	0.88	0.12	43	23	14	14		
VII			"		0.82	0.75	0.29	0.35	1.12	0.12	18	12	12	18		

Table 24, continued

Location on Island	Date of Coll	Fertilizer Treatment	Type of Tissue[c]	Macroelements (% of dry tissue) Ca	Mg	K	Na	N	P	Micronutrients (mg/kg dry tissue=ppm) Fe	Mn	Cu	Zn
				Kabelle Island									
Near Cistern	961	Fe, Mn, Zn	L		0.31	1.14	0.62	0.82	0.088	32	2.4		
Near Cistern	961	Untreated	L		0.52	1.24	0.65	0.78	0.11	22	33		
Lagoon Beach	363	Fe Chel. spray	UL (green)	0.32	0.50	1.49	0.75	1.47	0.18	35	9.8		
		Tree 39 9/61	LL (green)	1.09	0.73	0.49	0.70	1.25	0.16	18	4.8		
Lagoon Beach	363	Fe, Mn, Zn	UL (yellow)	0.20	0.28	1.69	0.57	0.85	0.11	10.5	19		
		Tree 21 3/61	LL (yellow)	0.44	0.37	0.50	0.47	0.73	0.073	8.1	9.1		
Lagoon Beach	363	Fe Chel. 9/61	L (yellow)	0.47	0.42	1.28	0.72	0.92	0.17	10.7	55		
Lagoon Beach	363	Fe Chel 9/61	UL (green)	0.37	0.48	1.90		1.24	0.16	26	24		
		Tree 34	LL (green)	0.88	0.60	0.28		1.17	0.12	17	8.9		
Lagoon Beach	363	Fe Chel. 9/61	L (very yellow)	1.50	0.90	1.58	1.11	1.46	0.16	17	3.2		
Plot x	363	No Treatment	UL	0.15	0.10	1.80	0.32	0.91	0.17	31	11		
Plot y	363	No Treatment	UL		0.18	1.92	0.39	0.83	0.19	29	3.8		
			LL	0.76	0.60	0.50	0.29	1.13	0.17	21	3.5		
Lagoon Beach	864	No Treatment	L (poor)	0.84	0.59	0.40	0.33	0.73	0.099	33	11	14	7.3
Lagoon Beach	864	No Treatment	L (poor)	0.85	0.61	0.76	0.71	0.85	0.085	17	2.2	15	6.5
Soil Pit 7	864	No Treatment	L (good)						0.15	25	4.0	15	9.3
Lagoon Beach	864	No Treatment	L	1.50	1.20	0.58	0.15				2.4	10	11
Lagoon Beach	864	400 ml F.T.E. 8/63	L (good)	0.48	0.29	0.54	0.30	1.03	0.13	28	56	14	17
Lagoon Beach	864	200 ml FeEDTA 3/61	L (good)	0.64	0.44	0.50	0.46	0.84	0.16	22	6.4	14	17
Lagoon Beach	864	400 ml F.T.E. 3/61	L	1.02	0.27	0.58	0.29	1.05	0.17	28	78	17	75
Lagoon Beach	864	$FeNH_4PO_4$ 9/61	L (fair)			0.33	0.50	0.90	0.11	25	11	14	12
Lagoon Beach		Fe EDTA spray 9/61 + $FeNH_4PO_4$	L (good)	0.85	0.51	0.38	0.36	0.83	0.099	22	1.8	14	75
Lagoon Beach		200 ml Multitracin 8/63	L (good)	0.45	0.58	0.67	0.54	1.27			51	11	18

[a] Date of collection gives month followed by year (e.g. 864=Aug., 1964)

[b] Typically 450g of fertilizer salts were worked in around each of the some 15 young plants in the row trials. Micronutrient materials were similarly worked in, about 200 ml of dry material per seedling tree, or sprayed to dripping. "Tracin" is a Crown-Zellerbach patented name for lignin-based micronutrient complexing materials. F.T.E. = the sparingly soluble Fritted Trace Elements (Ferro-Enamel Corp.)

[c] Most samples were from seedlings 1-2 m tall. Center pinnae were cut from 1 or 2 leaves of each of several plants in the Rows, or from single plants at Kabelle Island.

[d] These rows were fertilized 9/59 at establishment, and retreated 9/61 and 8/63.

[e] These trials near Pit 1 and in the swale area were established and fertilized 3/63.

Phosphorus - These values vary widely, probably reflecting the amount of soil organic matter as well as the spotty nature of bird roosting and droppings. The young coconut trees in the plantations were mostly rather low to very low in phosphorus. Among the dicot trees, sometimes concentrations in the lower leaves were less than in the upper leaves, indicating inadequate phosphorus supply; but in other cases the values for lower leaves were higher, indicating adequate or even excess supply.

Iron and Manganese - As to be expected in calcium carbonate dominated soils with pHs of 7 to 8, these elements proved to be low to very low. This is correlated with widespread chlorosis in young coconut trees, but chlorosis seems to be absent in older coconuts and in the native trees. Possibly this can be attributed to more extensive rooting.

Copper - Some copper values are low, especially in *Tournefortia from* Bikini (Table 22), but most copper levels seem to be in an adequate range.

Zinc - A few zinc values are low (10 ppm) in the coconut plantations, but mostly this element seems to be in sufficient supply.

Boron - The limited number of boron analyses showed generally adequate levels of this element.

A series of analyses were performed on wood and bark from six of the common tree species, for nitrogen only (Table 25). *Pisonia* and *Neisosperma (Ochrosia)*, which occur mostly in the central parts of the islands away from the beaches, show higher levels of nitrogen in both bark and wood than the other species. The presence of better developed soils in the centers of the islands as well as more droppings of roosting birds may account for these higher levels. *Pandanus* wood also is fairly high in nitrogen, probably because much of the stem is living parenchymatous tissue. At least in the case of *Pisonia*, high leaf nitrogen levels correlate well with the high values in the wood and bark.

On the atoll substrates, varying from fresh deposits of sand to well developed soils in the centers of larger islands, it is not surprising to find evidence in the chemical analyses of much variability in the supplying capacity for the essential elements. For potassium, nitrogen, phosphorus, iron, and manganese there appear to be numerous locations where the supply of one or more of these elements is inadequate. Consequently, to encourage best plant growth, mineral fertilization is usually necessary.

Growth Response of Coconut to Fertilization

The Rongelap people planted many coconut seedlings in 1959-60 with aid from the Trust Territory agricultural officer, who arranged for seed nuts from Yap Island. In 1959 and 1961, various fertilizer treatments were made in several of these plantations. In 1961 and 1964, height growth measurements were made on a series of these plants. The results are given in Table 26.

Table 25. Mean Nitrogen concentrations (% of dry weight) in wood, bark, and leaves of woody plants of Rongelap Atoll

	Plant Tissue		
Species	Wood	Bark	Leaves
Cordia	0.10	0.45	1.92
Guettarda	0.11	0.54	1.36
Neisosperma (= *Ochrosia*)	0.18	1.04	—
Pandanus	0.20	0.46	—
Pemphis	0.09	0.46	—
Pisonia	0.60	1.52	2.16
Scaevola	0.08	0.47	1.29
Suriana	0.16	0.58	—
Tournefortia	0.12	0.66	1.39

Table 26. Height growth[1] of seedling coconuts with fertilization on Rongelap Atoll

	Pit 1		Swale		Kabelle	
Treatment	cm	%[2]	cm	%[2]	cm	%[2]
Control						
1	5	5	36	24	0 all died	0
2	20	18	51	33		
Multi-tracin	99	85	91	75		
Fe-tracin	58	62	89	62		
Fe-tracin & Cu, Mn, Zn NH_4 Phosphates	66	54	74	58		
Fe, P, NH_4 Cu Phosphates	86	73	97	58		
Fritted Trace Elements	46	33	69	50		
Combined Micro-Nutrients					56	196

[1] Pit 1 and Swale results are the average of 10 plants for the period 3/63 to 8/64. Kabelle Island results are averages of 15 plants from 3/61 to 8/64.

[2] Growth during period as percent of initial height

Clearly all fertilizer treatments increased growth above that achieved by the control plants, although *Fritted Trace Elements* appeared to be less effective than the others. It seems likely that the principal response was to iron, not only from the greening which was very apparent, but also *Iron-Tracin* alone gave good results and the application of additional elements along with *Iron-Tracin* did not improve growth. However, *Multi-Tracin* stimulated somewhat better growth than *Iron-Tracin* at Pit 1 (Rongelap Island), and combined micronutrients resulted in good responses on Kabelle Island. In view of the low manganese concentrations in the palm foliage (see Table 24), one could expect that the manganese in the multielement materials would be beneficial. In retrospect, combination of nitrogen fertilization with the micronutrient treatments probably would have increased the responses.

WATER RELATIONS

General Aspects

In the northern atolls of the Marshall Islands, annual precipitation is about 125 cm, with a pronounced dry season in the months of January to May. The mean annual temperature is 27C, with afternoon highs reaching over 30C. With the very porous coral sands as the rooting substrate, and with high evapotranspiration especially during the dry season, water stress is a major influence in the survival and growth of vegetation. This is attested to by the relatively sparse vegetation in the northern Marshall atolls in comparison with the lusher plant growth in the southern atolls such as Majuro. Salinity in the atoll environment adds to the water stress through osmotic effects. This influence is always present, but becomes extreme during storms, with blowing of salty spray over the plants or with sea water even inundating lower lying areas. Thus all species which grow on these islands have some tolerance to salinity, and those which inhabit the beach and sand spit areas have to be very salt tolerant. An indirect indication of this tolerance is the accumulation of sodium in the leaves (see Tables 21 through 24). This ability to absorb sodium, then translocate it to the shoot system, allows these plants to build up higher osmotic concentrations in the leaves than can plants which do not translocate sodium readily.

Despite the considerable salt tolerance of *Scaevola*, its leaves often showed temporary wilting in the warmest part of the day, even though humidity seemed high. Perhaps rise in leaf temperature, which would increase transpiration, coupled with unfavorable osmotic relationships in the soil which would decrease water absorption, combine to induce water deficits. Mid-day temporary wilting was seen often in *Pisonia* as well.

As discussed earlier, one feature of atoll islands, especially larger ones, is the presence of a lens of fresh or brackish water in the coral sand matrix a meter or two below the surface and extending downward as much as several meters. There is good reason to believe that plants derive much of their water from such lenses, especially during the dry season (see below).

In the following sections, some data are presented on the ground waters and the growth of plants in strand sites and in salinized solutions in the greenhouse.

The Salinity and Ionic Composition of Ground Waters

Galvanized steel pipes (1.25 cm interior diameter) with wedge-shaped perforated points were driven into the soil at numerous locations on Bikini Atoll and on Rongelap, Eniaetok, Kabelle, and other islands of Rongelap Atoll. Depth of penetration commonly needed to be 1.5 to 4 m to reach ground water. A plastic tube was fed into the pipe down into the water, then a hand-operated suction pump used to obtain a sample of the water. The pHs of these samples commonly were 7.5 to 8.5. Electrical conductivity was read on the samples, some values for which are given in Table 27. Most of the pipes were driven at or near soil pits, most of which can be located on the maps of Rongelap and Kabelle Islands (Figures 5 and 6). With the electrical conductivity of sea water (about 50 mmhos/cm) as a reference, one can see that ground waters vary from the same concentration as sea water down to only slightly brackish waters characteristic of an ideal "fresh water lens." Even in the interiors of islands the ground water may be 1/4 to 1/2 as concentrated as sea water. Plants can nonetheless absorb water from solutions this strong (Léskó, 1968; Walker and Gessel, 1991).

For some of the ground water samples from Rongelap and Bikini atolls, analyses were made of the major cations. These data are given also in Table 27. Although sodium is the dominant cation, appreciable concentrations of calcium, magnesium, and potassium are present, similar in proportion to those in sea water.

Osmotic Relations of Strand Species

These aspects were studied by Walker and Gessel (1991). They determined osmotic potentials (Ψ_π) and sodium contents of leaf samples collected in the field on Rongelap Atoll, used ground water data such as those presented in Table 27, measured electrical conductivities also of soil solutions, and grew several woody atoll species in the greenhouse in culture solutions with varying levels of added salt. The mean Ψ_π of the field-collected leaves ranged from -1.9 to -3.1 M Pascals, compared with that of seawater at -2.7 M Pa. Sodium contents of the leaves were high, commonly being 1 to 3% of the dry weight. Ground water conductivities mostly ranged from 16 to 50 mmhos/cm (equal to about -0.86 to -2.7 M Pa Ψ_π), but saturation extracts of soils were only moderately saline [equivalent to Ψ_π values of about -0.05 to -0.07 M Pa]. In culture solutions, seedlings of four shrubby species (*Cordia subcordata, Guettarda speciosa, Scaevola sericea, and Tournefortia argentea*) and a local variety of squash (*Cucurbita pepo L.*) all grew well at solution Ψ_π of -0.28 MPa, but were depressed to about 50% yield at -0.42 M Pa. The woody species declined to about 10-20% yield at -1.4 M Pa, and grew only a little at -2.8 M Pa (a solution equal in Ψ_π to that of sea water).

Walker and Gessel found in their greenhouse study that seedlings of several species which occur on or near atoll beaches can endure exposures of the roots to osmotic

Table 27. Ionic composition of Rongelap and Bikini Ground Waters (including a comparison with sea water)

Sample	pH		Conduct.	Ionic Concentrations (mEq/L)							Na^+ – %
	Field	Lab	(mmho/cm)	Ca^{++}	Mg^{++}	K^+	Na^+	Cl^-	$SO_4^=$	HCO_3^-	of sea H_2O*
				Sea Water							
Rongelap	8.0		50.0	-	-	-		-	-	-	-
Friday Harbor, WA			66.2	18.6	90.6	9.2		612	49.1	2.47	-
Standard*				20.6	108	10.0	473	551	56.8	2.36	100
				Rongelap Atoll							
Pit 1	7.7	7.72	34.8	14.3	59.5	5.65	348	298	30.2	4.80	74
1a			43.3	14.1	59.6	5.62	-	370	30.4	4.83	-
1b			34.6	14.2	60.1	5.83	-	289	31.0	4.75	-
4	7.5	7.92	27.9	16.6	46.6	4.44	-	232	22.3	7.02	-
4x		7.90	25.2	15.7	42.4	4.23	-	204	-	6.90	-
5	7.5				45.6	4.13	268	210	21.4	7.51	57
7		8.0	26.9	19.6	45.2	3.52	-	220	21.4	12.2	-
7x		7.82	24.0	16.1	40.5	4.05	-	208	-	8.90	-
12		7.88	37.7	18.3	59.8	6.59	-	315	31.5	6.21	-
22	7.9		12.7	-	-	-	-	-	-	-	-
23	7.9	8.20	25.6	13.9	41.8	4.05	-	218	-	5.76	-
27		7.40	14.2	7.54	22.5	2.49	-	123	-	4.33	-
				Bikini Atoll							
Aerokoj (Airukiiji)			3.14	3.25	6.58	0.54	20.9	-	-	-	4.4
Nam (Pit 17)			7.25	6.00	13.4	1.59	52.2	-	-	-	11
New Tower 1 }Bikini			10.4	8.70	22.4	1.84	104	-	-	-	22
New Tower 2			11.1	8.15	24.0	1.76	104	-	-	-	22
Bwikor (Yurochi) (surface pond)			23.4	8.95	42.4	4.09	276	-	-	-	58
Eneu (Camp Blandy)			27.8	13.5	56.2	3.53	284	-	-	-	60

* From *Handbook of Biological Data*, William S. Spector, Ed., W. B. Saunders Co., N.Y. 1956

concentrations equivalent 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 extensive root systems penetrating to appreciable depths. These strand 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 summarized the nature of the Pacific atoll vegetation (Fosberg, 1953) and recently he wrote a description of the vegetation of Bikini Atoll for the Bikini Atoll Rehabilitation Committee (Fosberg, 1988).

The following sections are based on observations made at Rongelap and Bikini Atolls during the period 1958-64, made by Ralph Palumbo, Edward Held, Stanley Gessel and Richard Walker. Our observations were generally in good agreement with those of Fosberg (1953, 1988).

PLANT COMMUNITIES

Kimmel (1960) described seven plant communities occurring in the northern half of Rongelap Island (Figure 13). His terminology will be followed here with minor exceptions. The communities are named for the most conspicuous or abundantly occurring genus. The community names are: I *Suriana* Society, II *Scaevola-Guettarda* Community, III Coconut Grove Community, IV *Pisonia-Tournefortia* (*Messerschmidia*) Community, V *Ochrosia* Community, VIII Mixed Forest, and IX Coconut Plantation Community, and we have added the *Cordia* Community and the *Pemphis* Community here. Increased coconut planting has decreased the areas of these plant communities somewhat, but all could be recognized as of February 1986. Since the island has been mainly uninhabited since that time, there has probably been substantial regrowth of native woody species.

Scaevola-Guettarda Community. *Scaevola sericea* generally constitutes about 80 percent of the vegetation in the *Scaevola-Guettarda* community, but commonly occurs in dense, pure stands. This is the most prevalent community along the beaches where, typically, it is wedge-shaped, since the shrubs grow taller with increasing distance from the shoreline. Fingers of bare sand characteristically penetrate the community from its shoreward margin inland for as much as a few meters. In such openings herbaceous species are common: esp. a grass, *Lepturus repens*, a sedge, *Fimbristylis* sp. and a vine, *Triumfetta procumbens*. In some leeward areas, typified at Kabelle Island, the *Scaevola* community is open. The surface of the soil, almost pure sand in these areas, is covered with black algal crust and wherever one digs, the shrub roots are evident, apparently

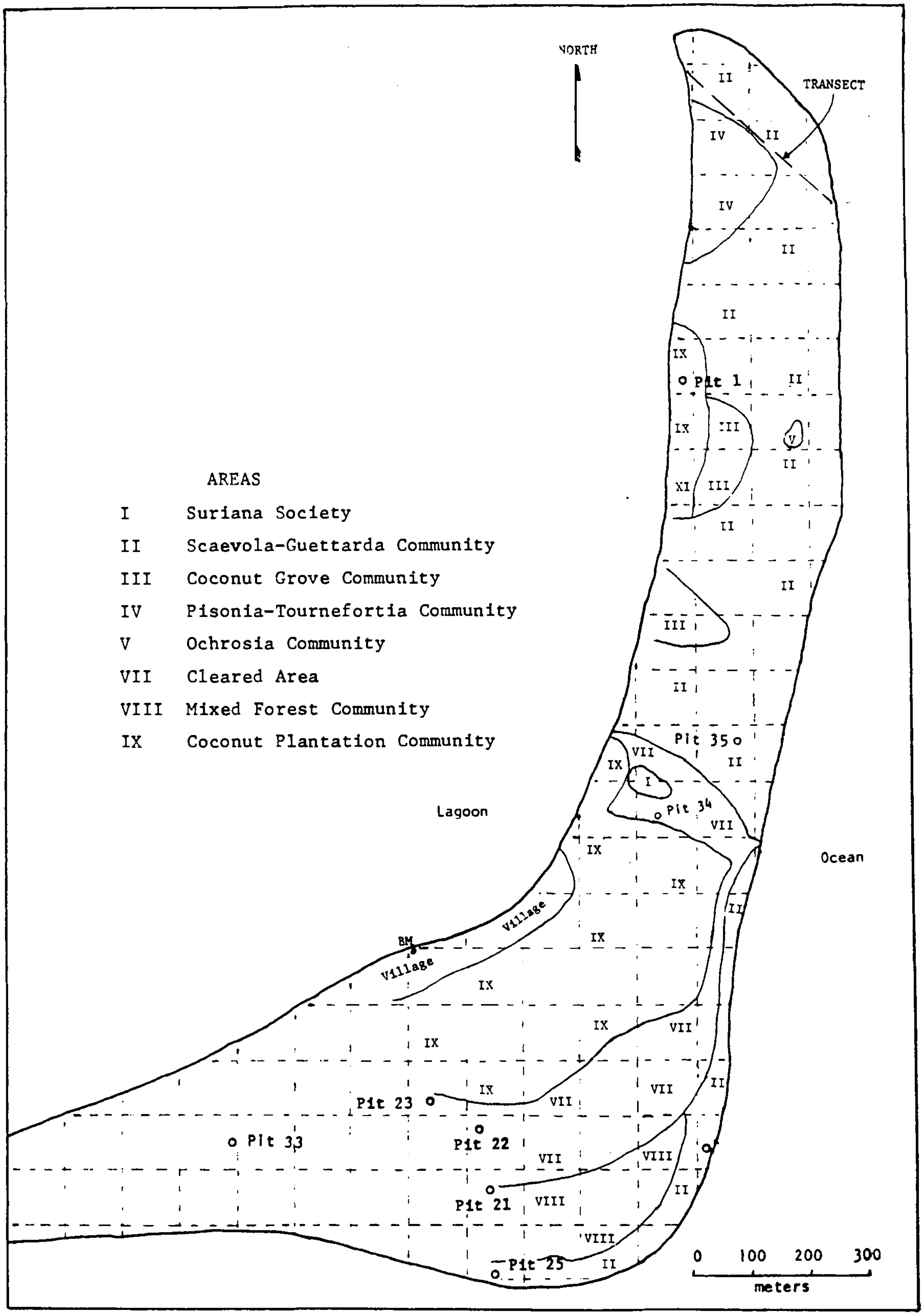

Figure 13. Vegetation Map of the Northeastern Part of Rongelap Island. [As charted in 1959 (after Kimmel, 1960); much altered by 1986]

utilizing the resources of the entire soil area. Occasionally, the shrubs have a yellow or pale orange cast when seen from a distance. Closer inspection shows the presence of *Cassytha filiformis* parasitizing the plants. The principal co-dominant, *Guettarda speciosa,* is found primarily on the leeward shores or in protected areas. Other associated species include *Tournefortia argentea, Pandanus* spp, the coconut, *Cocos nucifera, Terminalia samoensis* and *Morinda citrifolia.*

Suriana Society. Pure stands of *Suriana martima* form small communities along the windward shores of some islets. *Suriana* also occurs in the interiors of Rongelap, Lomuilal and Naen Islands, but only where there is evidence of overwashing with sea water. Severe dieback nearly always occurs in *Suriana* communities but its cause is not apparent, for while windblown sand is deposited along the bases of shrubs on the beaches, there is also dieback in the interior areas where there is no such accumulation and where, presumably, the effects of salt spray and wind are less severe than on the beach.

Pisonia-Tournefortia Community. *Pisonia grandis* is indeed well named; by atoll standards it is a tremendous tree rising upwards to as much as 20m and forming a dense closed canopy during the wet season. However, during the dry season, many leaves are shed so that the crowns become very thin. Although not as tall and often recumbent, scattered old specimens of *Tournefortia* are usually present also.

How this community starts is not known. It is generally associated with more fertile soils but scattered individuals of *Pisonia* do occasionally occur anywhere and the species readily reproduces by sprouting. The sticky fruits of *Pisonia* are sometimes seen attached to birds, and this is probably an important means of dispersal of the seeds.

A substantial part of our work on Rongelap Atoll was centered on Kabelle Island, the vegetation of which has been little disturbed by humans, since it is remote in the atoll, is visited only occasionally, and has only a few coconut trees. A depiction of the approximate distribution of vegetation on this island is given in Figure 14. A feature of special interest is the presence of very large and obviously quite old *Tournefortia* trees in the central part of island . Trunk diameters of such trees, which are often partially or completely recumbent, may be up to almost one meter. One might hypothesize that *Tournefortia* seedlings established on such an island when it was small and persisted as the island accreted and enlarged. *Tournefortia* seeds float in sea water and their germination is stimulated by this soaking (Léskó and Walker, 1969). Eventually *Pisonia* would establish in the central part of the larger island, but the old *Tournefortia* would still be present. Such a scenario seems to fit with the presence of those old trees among the *Pisonia* on Kabelle Island. Age of trees in a tropical environment, where annual rings are lacking or undependable, is difficult to ascertain. However, we know that medium-sized *Tournefortia* trees on Kabelle Island changed only slowly over the 28 year span from 1958 to 1986 (Table 29).

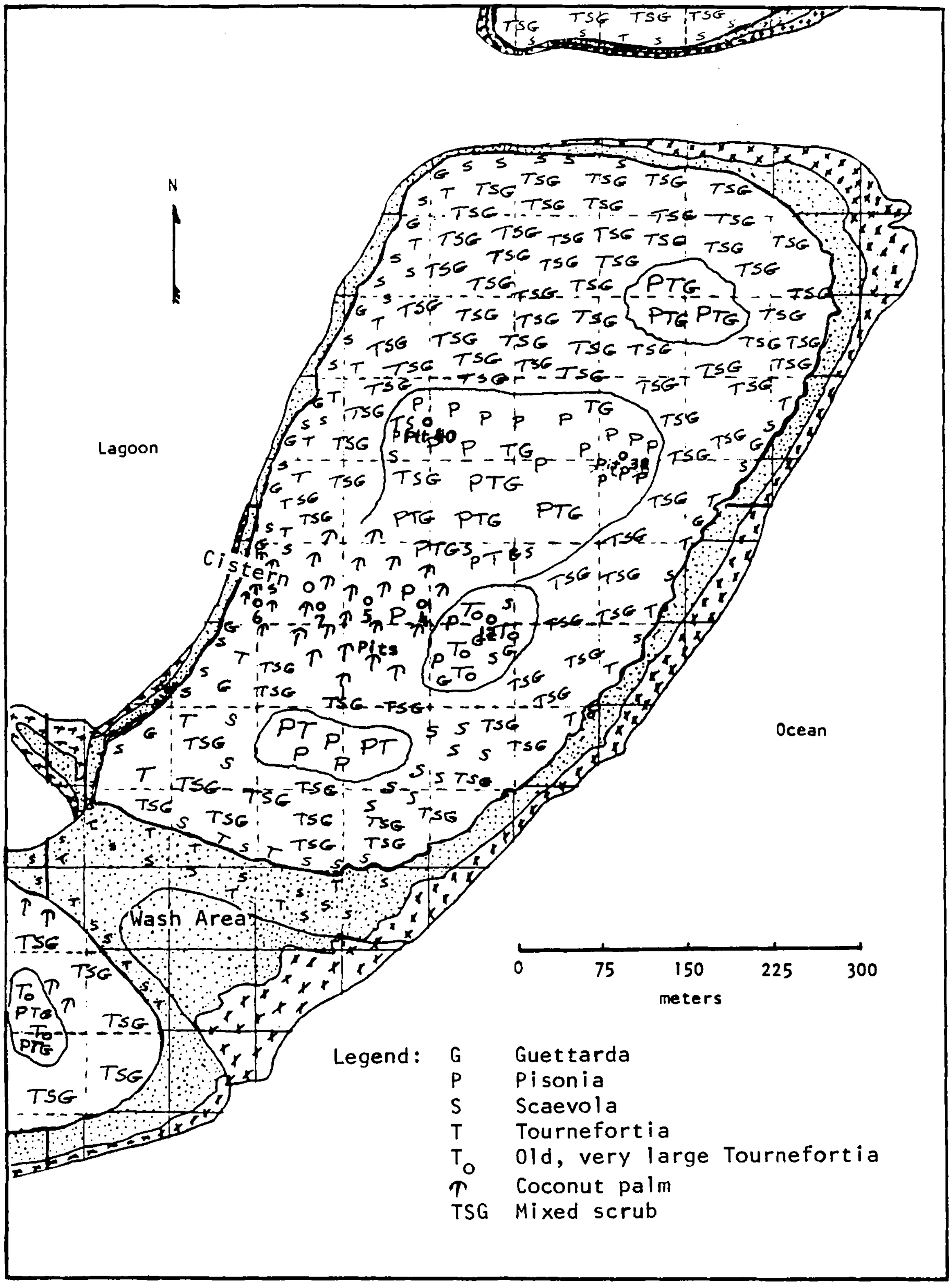

Figure 14. Map of Kabelle Island, Rongelap Atoll, showing distribution of vegetation (Note: Charted in 1959, but little changed in 1986).

The wood of *Pisonia* is soft and porous and, presumably, solitary trees are easily blown down during storms. Such a fallen trunk initiates roots and puts up shoots which eventually dominate the area, forming dense stands with a ground cover of *Boerhaavia tetranda* and *Boerhaavia diffusa*.

The best soils at Rongelap are found in the *Pisonia* communities. Litter deposition is heavy and a thick humus layer often develops. The stands are favorite nesting areas for fairy and noddy terns. It was conservatively estimated (by the late Dr. Frank Richardson) that some 1,400 terns, frequenting and nesting in a *Pisonia* community of about 0.25 hectare in area on Kabelle Island, consumed about 48 tons of fish per year. The birds thus bring nitrogen, phosphorus, and other nutrients from the sea to the islands. The better coconut groves (on the larger islands) appear to be in areas which were once *Pisonia* groves, but with the fertility of the soil diminished by the agricultural practices used.

Ochrosia Community. *Ochrosia* (now named *Neisosperma oppositifolia*) forms a community of a few trees at Naen Island and there were several small communities at Rongelap Island in 1959. The latter have meanwhile succumbed to clearing for the planting of coconut. In 1959, these small communities consisted of young trees 6 to 9 m tall, with large leaves forming a dense canopy. *Ochrosia* seedlings were abundant and, together with scattered *Scaevola* shrubs, formed a second layer 1.5 to 2 m high. The dominance of *Ochrosia* was complete and on Rongelap Island it was encroaching on an adjacent *Scaevola* community. *Ochrosia* forests composed of large trees growing in pure stands in areas other than Rongelap have been reported by Fosberg (1953).

Cordia Community. *Cordia subcordata* communities characteristically occur in boulder areas and are best developed on Rongelap Atoll at Mellu Island and Anielap Islet , where the canopy rises to obvious height. The bases of the *Cordia* trees may be up to almost a meter in diameter, and the trunks and branches grow at all angles, often close to the ground where boulders are found piled against their seaward side at Mellu Island. The appearance of the community is tangled and rugged. Occasionally, there is a *Pisonia* tree, but *Cordia* is clearly dominant and there is no ground cover.

Coconut Plantation Community. The trees are usually spaced 3 to 6 m apart in reasonably straight rows. As previously mentioned, beginning in the late 1950s, Trust Territory agriculturalists provided coconuts from superior trees of Yap Island. These coconuts were sprouted in nurseries at Rongelap; the seedlings were then transplanted to holes almost a meter deep, partially filled with coconut husks and other humus-producing material. In this method, as the trees grow, soil is gradually filled in around their bases, resulting in better root structure, greater productivity of the trees, and greater resistance to wind throw than is the case if nuts are planted more shallowly.

Coconut Grove Community. This consists of three layers: first, a canopy of coconut palm fronds, 10-13 m high, which is either continuous or broken, depending on the age and condition of the plantation; next, there is a layer from 1/2 to 4 m high, consisting of coconut seedlings, a few *Pandanus* seedlings, and occasional *Pseuderanthemum atropurpurem* and *Clerodendron enerma* shrubs, *Tacca*, and occasionally, small *Morinda* trees. The third layer is the ground cover, which is varied and may be composed of grasses, *(Lepturus, Digitaria pruriens, Eleusine indica)*, the sedge, *Fimbrystilis*, and scattered individuals of other herbaceous plants. Of the associated species in this community, *Pandanus* and *Tacca* are food plants and the fruit of a third, *Morinda*, is eaten by the pigs and allowed to grow to a limited extent throughout the plantation area.

There are at least three distinct types of *Pandanus* at Rongelap. One has edible fruit, a second has leaves which are especially prized for weaving fine quality mats, and a third, called wild *Pandanus* or erwan, has fruits which are edible but not desirable and leaves which are not particularly sought after for weaving. However, the leaves of all three types are used for making coarse mats and baskets. *Tacca*, or arrowroot, is conspicuous in the second layer of the community during the wet season and lends a noticeable seasonal aspect to the community since the leaves die down completely during the dry season. The shoots arise from corms forming a dense, luxuriant growth which completely shades the soil surface. Arrowroot corms provide the only source of locally-produced starch.

In general, the coconut plantation is an open, shaded community, both easy and pleasant to walk through. But these qualities remain only so long as the plantation remains under cultivation. If neglected for two or three years, the coconut plantation community becomes a coconut grove community, in which volunteer coconut seedlings along with *Pandanus* trees and a variety of native shrubs have invaded. In some areas, especially those cleared and burned, the grass *Lepturus* may form extensive stands.

Mixed Forest Community. The mixed forest community is composed of a variety of species, none of which is dominant. The canopy, rising up to 7 to 9 m, usually consists of *Pisonia*, coconut, *Terminalia* or *Cordia*, with *Morinda, Guettarda, Tournefortia*, and *Scaevola* forming the somewhat lower layers. The trees usually are clumps of a few coconut trees, or clones of *Pisonia, Scaevola*, or *Cordia*. The general aspect is one of a dense heterogeneous mixture of a number of species, with the canopy being the only distinct layer and with essentially no ground cover other than seedlings of the coconut and sprouts of the *Pisonia*. It is perhaps noteworthy that *Neisosperma (Ochrosia)* does not occur in the mixed forest communities.

Pemphis Community. Finally, there is a *Pemphis* community which was not described by Kimmel (1960) because it does not occur in the northern half of Rongelap Island. It is best developed on the leeward, lagoon shore of Mellu Island where *Pemphis acidula* grows among the boulders and beach rock high in the intertidal zone, occupying a position similar to that of *Suriana*, but growing to a height of 4 to 6 m. Both at Mellu and elsewhere, *Pemphis* trees can be seen standing in sea water at high tide. Rarely, small *Pemphis* groves occur inland, as does one in the narrow neck between Rongelap village and Jabwan on Rongelap Island, where there was very likely occasional inundation in the past.

In addition to those plants mentioned in discussing the plant communities, in the village area there is the breadfruit, *Artocarpus altilis,* and *Papaya carica,* the fruits of which are utilized as food. There are also ornamentals, which include the spider lily, *Crinum* sp., *Croton* sp., and *Achryanthes canescens.* Squash or pumpkin, as it is called locally, is planted in a few areas behind the houses.

A QUANTITATIVE DESCRIPTION OF THE *SCAEVOLA-GUETTARDA* COMMUNITY ON RONGELAP ISLAND

(A study carried out by Dr. Mark Behan in 1959)

The purpose was to describe quantitatively the *Scaevola-Guettarda* (Sca, Gu) community with respect to the relative abundance of the species, the area occupied by each, and the total number of individuals per unit area. Also the homogeneity of the stand with respect to the distribution of the different species, and obtaining an index to predict future changes which may occur in the composition of the stand by focusing some attention upon the seedling population, were given some attention. (for methods see Phillips, 1959)

1) Location

This transect started in vegetation at the lagoon fringe about 100 m south of the northern tip of the island, then ran southeast for about 250 m to the seaward beach ridge (see Figure 13).

2) General Description of the Vegetation

The vegetation seemed typical of the *Sca-Gu* community, in which *Sca* predominates numerically, and the vegetation as a whole was dense and of an average height of about 3 to 4 m. The *Sca* appeared to be approaching maturity as judged by its height, stem size, bark thickness, and the number of sprouting old prostrate stems. Field notes describing the transect are as follows: "The transect covers what appears to be a mature *Sca-Gu* association in which the *Sca* is mostly shrublike, with several spreading branches at the base, about 4 m tall. The *Gu* is more arborescent and of about the same height. The canopy is continuous and composed predominantly of *Sca. Gu* occurs frequently as seedlings. In places a small pure stand of mature *Gu* may be seen, and in contrast to the *Sca,* the seedlings of *Gu* occur at several stages of maturity. *Sca* seedlings, although frequently seen, are conspicuous by the lack of seedlings taller than 10 cm. *Pisonia* (Pi) occurs as a mature tree at the beginning of the transect. *Pandanus,* Coconut, and *Tournefortia* were observed infrequently near the transect, but did not occur on it. *Gu* appeared to be spread farther apart from their neighbors than did *Sca,* and the ground beneath the crown of the more mature *Gu* was generally barren of plant life. This was not the case with *Sca,* as many seedlings of both *Sca* and *Gu* were often observed under the crown of *Sca.* Herbaceous cover was scant and consisted mostly of *Ipomoea, Triumfetta, Boerhaavia,* and *Tacca.*"

3) Quantitative Data

Methods: At 6 m intervals along the transect a station was established and a line was drawn at right angles to the direction of the transect. The species and distance to the nearest plant was recorded in each of the four quarters formed by these two lines according to the principles of the Quarter method. At each station a note was made of the cover directly over that point, the species and distance to the nearest seedling in any direction from that point, and the presence and species of the herbs in the vicinity of the station.

4) Results

Cover: At 14 stations the plant crown which covered the station was noted. At 11 stations (79%) *Sca* covered the station; at 2 stations (14%) *Gu* covered the station and in one instance (7%) *Pi* covered the station.

Calculated Values	Mature Plants				Seedlings			
	All	Sca	Gu	Pi	Sca	Gu	Pi	
Mean Distance: from the station to the nearest plant in each quarter								
Sum of distances	604	443.5	125.0	34.5	27.6	47.5	11.7	feet
Number of distances	105	83	15	6	10	14	2	
Mean distance	5.81	5.34	8.40	5.75	2.8	3.0	5.9	feet
Mean Area occupied by an individual	33.8	28.5	70.5	33.1	7.6	8.7	34.8	feet^2
Relative Density $\frac{\text{No. of points of occurrence of species "x"}}{\text{No. of points of occurrence of all species}} \times 100$	100%	79.8%	12.8%	5.1%	38.5%	54.0%	7.5%	
Density or number of individuals per acre $\frac{43560}{d^2}$	1289*	1030*	165*	64*				
Relative Frequency $\frac{\text{number of stations of occurrence of species "x"}}{\text{number of stations}} \times 100$		100%	46%	15%				

* = relative density X total number of individuals per acre

5) Analysis of Quantitative Data

The mean area calculations clearly show that the *Sca* forms a much more dense community than does *Gu,* which substantiates the field observations. Adequate data were not obtained to draw a conclusion of similar nature about *Pi,* since only six points included this species. The average mean area for all species indicates a very dense community, confirming the field observation. The mean area showed that each individual occupied a plot about 1.7 X 1.7 m.

The relative density data is interesting because it also quantitatively confirms the field observation that even though *Sca* may form the principle cover and number abundance of the community, *Gu* will probably become a more dominant species in time. This conclusion is reached by comparing the relative density of the mature plants with that of the seedlings. The data show that in the case of *Sca,* the mature plants comprise by far the majority of the mature vegetation. The seedling population, however, is dominated by *Gu.* In addition, very few *Sca* seedlings exceeded 10 cm in height, indicating a great deal of *Sca* seedling mortality. This was not the case with *Gu,* in which a continuous distribution of ages was noted. This is consistent with the known shade tolerance of *Gu* and shade intolerance of *Sca,* and the frequently encountered situation of *Gu* growing up through a crown of *Sca.*

The number of individuals per acre forms an index of the productivity of the land. It would be a much more valuable number if some idea of the average volume or weight or both of the species occupying this site were known.

The relative frequency is an expression of the dispersal of the various species throughout the area. As may be seen from the data, because of the abundance, *Sca* is thoroughly dispersed throughout the community, and *Gu* is more evenly dispersed than the general field impressions would lead one to think. A field impression indicated that *Gu* may occur often as a pure stand, or may be distributed in clumps or clusters; this impression is undoubtedly valid, but *Gu* also is fairly evenly distributed throughout the area as an individual as well. As one approaches the seaward beach area in this transect *Gu* is no longer encountered in the abundance found farther from the beach. If one were to recalculate the relative frequency of *Gu,* excluding the last 20 m of the transect, the relative frequency of *Gu* rises to 52%. *Gu* did not appear among the samples for the last 20 m of the transect, but was infrequently observed.

6) Summary

Measurements were made along a transect by use of the quarter method of a typical undisturbed *Sca-Gu.* The data gathered indicated:

1. The aerial cover and relative density of the population coincide, and the mature vegetation is composed predominantly of *Sca* (80%) and secondarily by *Gu* (13%). The condition in the seedling population is reversed, with *Gu* representing 54% of the see-

dling population and *Sca* comprising 38% of the seedling population. This observation, combined with the apparent high seedling mortality of *Sca* and the shade tolerance of *Gu* confirmed that this community will probably become more and more dominated by *Gu* in the future.

2. The average mean area indicated that the vegetation as a whole is quite dense. It also indicated that *Gu* occupied about twice the area per individual as did *Sca.* This confirms that *Gu* is more widely spaced than *Sca,* as may be observed in the field by shrub-like appearance and high density of *Sca,* and the more arborescent and widely spaced appearance of *Gu.*

3. The relative frequency of the species within the population indicated that *Gu* was fairly evenly dispersed throughout the community while *Pi* was clumped or clustered about a comparatively small area. This was substantiated by the field observation, as *Pi* was encountered only at the beginning of the transect.

4. Insufficient data was obtained to characterize the *Pi* community.

5. It was suggested that future work include some measure of the average weight or volume of the various species in the community. If this were known these measurements could be incorporated into a reasonably accurate estimate of the total production of the area.

WEIGHT OF VEGETATION (BIOMASS)

Total biomass production data are now commonly used to compare productivity of different ecosystems. Unfortunately, we were not able to secure much information of this kind on the various expeditions to the Marshall Islands. However, when vegetation clearing was taking place on Bikini Island in 1967 to prepare for the coconut plantation, records were taken as a *Scaevola* brush area was being cleared. Vegetation consisted mostly of *Scaevola,* but with some admixture of *Dodonaea.* A circular area was cleared and records of vegetation weight kept by different size circles from 29.2 m^2 to 262.7m^2 (Table 28). Litter on the soil surface was also collected and weighed separately. In this case, total above-ground biomass was about 9000 g/m^2 and litter about 1400 g/m^2. Litter weights under different species from various Rongelap Atoll islands are given in Table 9.

VEGETATION GROWTH RATES

The periodic visitor to this island environment gets the impression of relatively rapid establishment of plant cover even on severely disturbed areas. Great variation in the size of plants from one local environment to another is apparent, but with little information on reference ages it is difficult to establish rates of growth. Although our data are limited, we established several plant measurement areas for both radial and height extension on different species, and made periodic measurements.

Radial Growth. Because *Pisonia* trees attain a greater size than any other vegetation and in places form a respectable forest cover we established measurement sequences in two different areas, both on Kabelle island. In both instances trees were identified by numbered tags placed at 1.4 m above the ground surface (breast height) and initial diameter taken at that point. One series near Soil Pit 12 was established in 1958 while the other at Pit 38 was set up in 1961. The trees were remeasured each time a visit was made to the area, with the last measurement in 1964. We found the localities on a return in 1986, but either identifying tags had been removed by other visitors or had been incorporated into the trees, so we were not able to identify the numbered trees. Results are presented in Table 30. These show considerable variation in individual tree growth. The Pit 38 area is a more uniform *Pisonia* forest area and with greater influence of nesting sea birds. Pit 12 is near the water cistern and more subject to human disturbance. Trees at Pit 12 averaged 0.39 cm diameter growth a year while those at Pit 38 averaged 1.32 cm/year.

We set up a similar study of *Tournefortia* trees on Kabelle Island during the period 1959 to 1961. Final measurements were taken in 1964 on most trees, but two of these were found in 1986 and remeasured. Up to 1964, diameter growth rates varied from 0.1 to 1.5 cm/yr with better growth on better soil (Table 29). The tree on the better soil (Pit 12) grew an average of 1.6 cm/yr through 1986, while on the young coral sand soil (Tree #25) growth though 1986 was only 0.7 cm/yr, even though it was a young healthy tree of only 2.5 cm diameter in 1959.

Height Growth. In order to evaluate height growth, a series of *Scaevola*, *Guettarda*, and *Tournefortia* plants were identified by numbered tags and initial heights taken from 1958 to 1961. These were remeasured at each visit to the island through 1964. We could only identify one plant for remeasurement in 1986. Results are given in Table 31. As with diameter, there is considerable variation in height growth within a species. This is probably related to the soil quality in which the plants are growing and exposure to wind. *Scaevola* plants averaged 21.4 cm/yr height growth, *Guettarda* 27.2 cm/yr and *Tournefortia* 16.4 cm/yr. *Tournefortia* #25 grew quite rapidly through 1964, while a younger plant, but slowed down as it grew older and much broader and averaged 15.8 cm/yr over a 28-year period. Many of the plants used in this study were growing on quite poor soils and exposed sites. The growth rates therefore probably represent the low end of the scale for annual height growth of these species, especially since Rongelap is one of the northern and thus drier atolls.

NATURAL AND MAN-MADE CHANGES IN THE VEGETATION

The buried horizons which are present in many of the soil profiles, especially those nearer windward beaches (see Figures 9 and 10), are convincing evidence of dramatic changes which have occurred in the vegetation in the past, presumably from wind and

Table 28. Air Dry Weight of Vegetation Components and Litter for Bikini Island Clearing Area (1967)

Area of Sample m^2	*Scaevola* g/m^2	*Dodonaea* g/m^2	Total Vegetation g/m^2	Litter g/m^2
29.2	9,233	48.6	9,282	919
87.6	8,890	58.6	8,949	1,883
145.9	9,037	19.6	9,057	1,202
262.7	9,037	39.1	9,076	1,397

Table 29. Diameters (cm) and Diameter Growth Rate (cm/yr) of *Tournefortia* Trees on Kabelle Island, Rongelap Atoll

		Measurement Dates							Total Growth		Rate	
Tree No.	Location	3/59	3/61	9/61	3/63	8/63	8/64	3/86	to ‘64	to ‘86	to ‘64	to ‘86
					Diameter (cm)							
11	Pit 12	18.8	20.8	21.6	22.6	23.1	24.4	62.9	5.6	44.1	1.1	1.6
73	Wash area		20.8		20.8	20.8	21.0		0.3		0.1	
	Wash area		24.1		24.6	24.6	24.6		0.6		0.1	
41	Pit 38			17.0	18.5	18.8	20.3		3.3		1.1	
42	Pit 38			16.5	17.3	17.5	18.5		2.0		0.7	
43	Pit 38			18.8	20.8	21.3	23.4		4.6		1.5	
44	Pit 38			13.7	14.0	14.2	14.5		0.8		0.3	
45	Pit 38			16.8	16.8	17.3	17.8		1.0		0.3	
25	Wash area	2.5						22.6		20.1		0.7

Table 30. Diameter (cm) and Diameter Growth Rate (cm/yr) of Pisonia Trees on Kabelle Island, Rongelap Atoll

Location	Dates							Growth	
Tree No.	8/58	3/59	3/61	9/61	3/63	8/63	8/64	58-64	Rate
Pits 7-12				Diameter (cm)					
1	26.9	26.7	26.7	26.9	26.9	27.2	28.4	1.52	.25
2	25.4	25.4	26.2	26.4	26.9	26.9	27.4	2.03	.34
3	27.2	27.7	29.5	29.9	31.5	32.0	33.0	5.80	.97
4	40.1	40.1	40.1	40.1	40.1	40.1	40.6	0.51	.08
5	29.2	29.2	30.2	30.2	30.7	30.7	31.2	2.03	.55
6	34.8	34.8	34.8	34.8	35.0	35.0	35.3	0.51	.08
7	42.7	42.7	43.2	43.2	43.2	43.4	43.9	1.30	.21
8	47.0	47.0	48.3	48.3	48.8	49.3	50.5	3.80	.63
								Mean:	0.39
								Growth	
Pit 38								61-64	Rate
13				22.1	22.9	23.0	24.1	2.0	.67
14				31.0	32.5	33.0	35.6	4.6	1.53
15				15.7	18.3	18.7	21.8	6.1	2.03
16				19.6	20.8	21.3	22.6	3.1	1.02
17				24.4	25.2	26.2	27.9	3.6	1.20
18				22.1	25.0	25.9	28.2	6.1	2.03
19				32.2	33.5	33.8	35.6	3.3	1.10
20				33.3	34.5	34.8	36.3	3.1	1.02
								Mean:	1.32

Table 31. Height (cm) and Height Growth Rate (cm/yr) of Native Shrubs in the Wash Area on Kabelle Island, Rongelap Atoll

Tag No.	Measurement Dates								Total Growth	Rate
	8/58	3/59	9/59	3/61	9/61	3/63	8/63	8/64		
Scaevola					Height (cm)					
301	12.7	19.0	50.1	60.1	60.1	111.8	147.3	167.6	129.5	21.6
323	43.1		88.9	121.9	121.9	132.1	139.7	152.4	109.2	18.2
354	38.1		86.4	127.0	152.4	172.7	190.5	200.0	165.1	27.5
356	27.9	50.8	78.7	88.9	99.1	106.7	121.9	137.2	109.2	18.2
361	81.3		127.0	142.2	157.5	172.7	177.8	190.5	109.2	18.2
362	25.4		63.5	55.9	76.2	96.5	116.9	124.5	99.1	16.5
267	91.4	101.6	114.3	114.3	114.3	121.9	121.9	134.6	43.2	7.2
1				43.1	73.7	127.0	147.3	170.2	96.5	32.1
4				40.1	53.3	127.0	137.2	152.4	99.1	33.0
24					213.3	251.5	256.5		43.2	21.6
									Mean:	21.4
Guettarda										
21					289.6	312.4	340.4		50.8	25.4
23					190.5	221.0	248.9		58.4	29.2
									Mean:	27.3
Tournefortia										
345	25.4	27.9	43.2	50.8	61.0	71.1	91.4	124.5	99.1	16.5
372	55.9	55.9	66.0	91.4	101.6	121.9	129.6	157.5	101.6	16.9
319			76.2	88.9	94.0	101.6	111.8	114.3	38.1	9.5
328	17.8		43.2	55.9	63.5	86.9	76.2	76.2	58.4	11.7
341	83.8		86.4	104.1	111.8	124.5	132.1	142.2	58.4	9.7
368	142.2		149.9	162.5	165.1	182.9	182.9	195.6	53.3	8.9
370	91.4		101.6	111.8	121.9	129.5	139.7	144.5	53.3	8.9
2				50.8	73.7	106.7	130.0	130.0	56.3	18.8
3				76.2	104.1	152.4	170.2	185.4	81.3	27.1
25[1]	76.2				248.9	279.4	315.0	330.2	254.0	43.3
26					43.2		60.1	73.7	30.5	10.2
22										
									Mean:	16.5

[1] This plant was identified and measured on 2/86 with height of 518.2 cm and growth rate of 15.8 cm/yr for 28 yrs.

water of typhoons. Before man inhabited these atolls, and before copra production was an economic enterprise, the reasonably well developed soils in the centers of the larger islands are believed to have supported good stands of *Pisonia grandis* with some older *Tournefortia*, with a band of *Scaevola-Tournefortia-Guettarda* scrub along the beaches (Fosberg, 1949). With the development of copra production during the last 100 years, much of the *Pisonia* as well as a good deal of the scrub which is not too near the beaches has been replaced with coconut palms. This replacement involved considerable burning of the native vegetation.

The atomic weapons testing program on Enewetak and Bikini Atolls destroyed most of the palms and native vegetation on affected islands. Recovery of plants following a nuclear detonation on Enewetak Atoll was described by Palumbo (1962). Likewise rather rapid regrowth of native species after clearing for testing operations or from detonations on Bikini Atoll was documented by Gessel and Walker (1987).

As mentioned earlier, in the late 1950s and early 1960s, the Rongelap people aided by agricultural officers of the Trust Territories of the Pacific Islands, cleared scrub and planted many coconut seedlings of a strain from Yap Island. Likewise they replaced quite a few old coconut trees with seedlings of this strain, which is known to be quite productive. On Enewetak and Bikini Atolls, rehabilitation programs sponsored by the Trust Territories and the U.S. government in the late 1960s and early 1970s involved removal of testing debris, clearing of much of the centers of the larger islands, and the planting of coconuts. However, the lack of people living on Bikini and caring for the coconut groves has allowed native scrub and volunteer coconut seedlings to encroach on the groves. The move of the Rongelap people to Kwajalein Atoll in 1985 has permitted similar overgrowing to begin on Rongelap. Some photographs depicting these changes are included in Gessel and Walker (1987).

CONCLUDING REMARKS

In this bulletin, we have presented a substantial amount of data on the soils, plants, and ecology of atolls located in the Northern Marshall Island group--Rongelap, Bikini and Enewetak. Almost all of this information came from unpublished field records and laboratory analyses, graduate student theses, or other unpublished materials in our files. Reference has been made to published works by other workers and by our own group, some of which are reports which received limited distribution. We would appreciate readers informing us of relevant published or unpublished studies which we have overlooked. Also, we welcome correspondence with anyone interested in more detail concerning methods or observations.

Obviously, many of the results contained in this publication are fragmentary or incomplete. However, this will perhaps indicate the paucity of information on atoll soils and vegetation, and we hope stimulate other studies in this fascinating environment.

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