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CORRECTING SOIL NUTRIENT DEFICIENCIES WITH ORGANIC MATERIALS IN THE ATOLL SOILS OF THE MARSHALL ISLANDS

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Abstract

The coralline soils of atolls suffer from multiple nutrient deficiencies that severely limit crop growth. This study was conducted to assess the nutrient status of the soils of the inhabited atolls within the Marshall Islands (MI), and to determine what local materials could be used to correct deficiencies limiting crop growth. Surface and subsoils from 25 atolls were collected and analyzed for their chemical properties, and soil test results were evaluated with a missing element pot study.

Soil tests revealed that the MI soils were severely deficient in K (0.12 $cmol_c\ kg^{-1}$) and marginally deficient in Cu (0.13 $ug\ g^{-1}$). The missing element study showed that the soil was deficient in K, S, N, P, and Cu. An incubation experiment and a series of greenhouse experiments were conducted to evaluate the ability of locally available organic materials to mineralize N and supply adequate nutrients to crops. *Vigna marina* and fish meal showed the highest N mineralization capacity, and the Gompertz equation provided the best fit. Chinese cabbage plants grew as well in soils amended with chicken manure, *Vigna marina*, and copra cake as they did in soil treated with chemical fertilizers. Plants grown in soil amended with fish meal did not grow as well due to inadequate K supply. Nitrogen recovery was highest in *V. marina* treatment at 92% followed by the chemical control (83%), chicken manure (34%), fish-meal (18%), and copra cake (9%). Added coconut leaves immobilized N and resulted in very poor cabbage growth. Comparisons between relative growth rate (RGR) and nutrient relative accumulation rate (RAR) showed that nutrients supplied from the *V. marina* amendment to the cabbage plant matched plant demand. In a rate

experiment in the greenhouse, adding 10.1 g kg^{-1} of *V. marina* leaves (dry weight) supplied 350 mg N kg^{-1} to 5 week-old corn plants representing 38% of the total amount of N added in the amendment. Splitting the application quantity improved corn growth at the highest addition rate. Copra cake showed less promise as a suitable organic amendment. Supplementing copra with chemical N and P, and *V. marina* leaves with and without Cu and B did not improve crop growth compared with copra alone. The soil exhibited low P adsorption capacity, and corn and lettuce growth responded to high Olsen P soil levels.

The results of the greenhouse experiments to showed that *V. marina* is a potential organic fertilizer material to correct soil nutrient deficiencies for good crop growth in the Marshall Islands.

Table of Contents

Acknowledgements.....iii

Abstract.....iv

List of Tables.....ix

List of Figures.....xii

Introduction.....1

Chapter 1. Literature Review.....5

- **Geography and Climate**.....5
- **Atoll Ecology and Traditional Agriculture**.....8
- ***Atoll Soils***.....10
- **Soil Organic Matter**.....13
- **Soil Fertility Research**.....16

Chapter 2. Evaluating the Soil Fertility Status of the Low-lying Coral Atolls of the Marshall Islands.....20

- **Introduction**.....20
- **Materials and Methods**.....22
  - **Soil Sampling**.....22
  - **Laboratory Analysis**.....23
  - **Missing Element Study**.....24
- **Results and Discussion**.....27
  - **Atoll-wide Soil Sampling**.....27
  - **Missing Element Study**.....48
  - **Soil Test Evaluation**.....55
  - **Atoll-wide Fertility Assessment**.....58
- **Conclusion**.....61

Chapter 3. Nitrogen Mineralization Dynamics in a Marshall Island Soil Amended with Locally Available Organic Materials.....64

Introduction.....64

Materials and Methods.....67

Soil and Organic Materials.....67
Laboratory Incubation.....69
Estimating Potentially Mineralizable N and Specific Mineralization Rate Constants.....72
Statistical Analysis.....76

Results and Discussion.....77

Nitrogen Mineralization Patterns.....77
Chemical Indices and N Availability.....86
Comparison of Kinetic Models for Net N Mineralization.....89
Cumulative Models.....89
Incremental Models.....96
The Segmented Model.....103

Conclusions.....108

Chapter 4. Correcting Soil Nutrient Deficiencies in the Atolls of the Marshall Islands with Local Organic Materials.....110

Introduction.....110

Materials and Methods.....113

Screening Organic Materials in a Greenhouse Experiment.....113
V. marina Rate Experiment.....118
Copra Cake Experiment.....118

Results and Discussion.....121

Screening Experiment.....121
Growth Response.....121
Nitrogen Mineralization.....126
Nitrogen Supply.....131
P, K, Mg, and S Supply.....137
Micronutrient Supply.....140
V. marina Experiment.....143
Growth Response.....143
N, P, and K Supply.....147
Ca, Mg, S, and Micronutrient Supply.....151

Management Implications.....154
Copra Cake Experiment.....156
Growth Response.....157
Macronutrient Supply.....160
Micronutrient Supply.....163
Management Implications.....165

Conclusion.....165

Chapter 5. Evaluating Phosphorus Availability in the Corraline Soils of the Atolls in the Marshall Islands.....170
Introduction.....170

Materials and Methods.....172

Results and Discussion.....176

Phosphorus Sorption.....176
Plant Available Phosphorus.....180
Chinese Cabbage Experiment.....180
Corn Experiment.....186
Lettuce Experiment.....189
Conclusion.....199

Chapter 6. Summary and Conclusions.....203

References.....210

List of Tables

Table		Page
1.1	Population by atoll	3
1.2	Soil organic matter content	15
1.3	Contrasting soil fertility with respect to vegetation cover	16
1.4	Micronutrient fertilizer application rates on atoll soils	18
2.1	Chemical properties of surface soil	25
2.2	Treatments and nutrient application rates for missing element study	26
2.3	Descriptive statistics for surface soils	28
2.4	Descriptive statistics for subsoils	28
2.5	The effect of latitude on precipitation	33
2.6	Results of regression analysis for soil properties and latitude	34
2.7	Correlation coefficients between pH, organic C, and exch. Ca	36
2.8	Effect of outliers on the relationship between EC and the soil nutrients	39
2.9	Results of Kruskal-Wallis test to determine location effect on soil nutrient concentrations	47
2.10	Nutrient tissue concentration for corn plants in the missing element study	50
2.11	Treatment effects on nutrient uptake by corn in the missing element study	52
2.12	Evaluating soil test suitability for nutrient deficiency diagnosis	55
2.13	Mean and median soil nutrient concentrations for each island and results of paired t-test	59
3.1	Chemical properties of Marshall Island soil, waste materials, and plant material	70
3.2	Quantity of organic materials added to soil in the N incubation experiment	71
3.3	Ionic composition of solution used to leach tubes	72
3.4	Kinetic models used to describe N mineralization	73
3.5	Quantities of N mineralized during each leaching interval	80
3.6	Percent of organic N mineralized from each material	81

3.7 Results of correlation analysis between N mineralized and selected chemical properties.....86

3.8 The relationship total N versus N mineralized.....87

3.9 Goodness of fit statistics for kinetic models fit to cumulative data.....91

3.10 Goodness of fit statistics for kinetic models fit to incremental data.....97

3.11 Parameters estimated from the segmented equation.....103

3.12 Correlation coefficients for parameters from the segmented equation.....108

4.1 Addition rates for organic materials used in the screening experiment.....114

4.2 Composition of blanket nutrient solution for the control treatment.....114

4.3 Quantities of *V. marina* leaves added to pots.....118

4.4 Treatment configuration for copra cake experiment.....120

4.5 Analysis of variance for copra experiment.....120

4.6 Selected orthogonal treatment comparisons for copra cake experiment.....120

4.7 Effect of removing blocks on ANOVA statistics.....124

4.8 Comparison of N mineralized from the organic materials in the greenhouse bioassay and the incubation study.....128

4.9 Combined N mineralization in the greenhouse after a second crop of corn.....131

4.10 N bioavailability measured by cabbage uptake.....133

4.11 ANOVA comparing RGR and RAR_N for cabbage.....137

4.12 ANOVA comparing RGR and RAR (N,P,K,Mg, and S).....139

4.13 Macronutrient cabbage tissue concentration in 4-week old cabbage plant.....140

4.14 ANOVA comparing RGR and RAR (B,Fe,Mn,Cu, and Zn).....142

4.15 Micronutrient cabbage tissue concentration in 4-week old cabbage plants.....142

4.16 Results of ANOVA on *V. marina* rate experiment.....144

4.17 Goodness of fit statistics for models fit to maize yields.....146

4.18 N, P, and K tissue concentrations in above ground biomass.....148

4.19 Nutrient recovery by maize plants.....149

4.20 Soil nutrient concentrations after maize harvest.....151

4.21 Ca, Mg, S, and micronutrient concentration in corn tissue.....152

4.22 Ca, Mg, and S uptake by maize plants.....152

4.23 Correlation coefficients for micronutrient uptake as a function of N, P, and S uptake 153

4.24 Micronutrient recovery by the maize plants.....153

4.25 Micronutrient supply from *V. marina* compared with fertilization rates.....154

4.26 Quantity of *V. marina* additions required to achieve desired yield goals.....155

4.27 Results of ANOVA on the effect of different copra treatments on cabbage yields.....158

4.28 Effect of copra treatment on micronutrient tissue concentration.....164

4.29 Macronutrient tissue content of five indigenous Marshall Island plants.....168

5.1 Selected physical and chemical properties of a Majuro surface soil.....173

5.2 Change in soil P fractions as a result of a cabbage crop.....186

5.3 Change in soil P fractions as a result of a corn crop.....189

5.4 Relative P efficiency values.....195

5.5 Effect of P addition rate on lettuce tissue concentrations.....198

List of Figures

Table		Page
1.1	Map of the Marshall Islands	6
2.1	Soil sampling scheme	23
2.2	Box-plots showing distribution of chemical measurements	29
2.3	Median organic C concentrations for each island	34
2.4	Relationship of exch. Ca and organic C	37
2.5	Relationship of exch. Ca and organic C without outliers	37
2.6	Relationship of total N and organic C	38
2.7	Relationship of total N and organic C without outliers	38
2.8	Relationship of EC and extractable Ca, Mg, and K	40
2.9	Relationship of EC and extractable Ca, Mg, and K without outliers	41
2.10	Box-plots comparing chemical properties for the entire dataset with data from Arno and Bikirin	43
2.11	Regression analysis on selected nutrients from Arno and Bikirin Island	45
2.12	Corn yields from missing element study	48
3.1	Schematic representation of segmented equation	76
3.2	Cumulative N mineralization curve for Marshall Island soil	78
3.3	Cumulative N mineralized in Marshall Island soil compared with continental soils	78
3.4	Cumulative N mineralization curves for the different organic amendment	81
3.5	Distribution of replicates for N mineralization form soil alone	83
3.6	Distribution of replicates for N mineralization form chicken manure	83
3.7	Distribution of replicates for N mineralization form fish meal	84
3.8	Distribution of replicates for N mineralization form V. marina	84
3.9	Box-plot showing outlier in *V. marina* dataset	85
3.10	Relationship of C:N ratio and N mineralized	88
3.11	Relationship of total N mineralized and N mineralized during the first week	89
3.12	Results of Gompertz equation fit to cumulative N mineralized	93

3.13 Plots of predicted values versus residuals for the Gompertz model fit to cumulative data.....95

3.14 Comparison of Gompertz model and the two simultaneous reaction models fit to incremental data.....99

3.15 Plots of predicted values versus residuals for the Gompertz model fit to incremental data.....102

3.16 Results of fitting the segmented model to the incremental data.....105

4.1 Relationship of ln cabbage yield to days after transplanting.....116

4.2 Dry matter yields for cabbage grown with different organic materials.....122

4.3 Treatment effect on cabbage growth.....122

4.4 Deficiency symptoms of cabbage plants.....123

4.5 Cabbage yield differences in blocks in the greenhouse.....124

4.6 Relative growth rates for cabbage grown with different organic materials.....125

4.7 N mineralization curves for the different materials.....126

4.8 N mineralized after 4 weeks of growth in the greenhouse.....127

4.9 Comparison of weekly soil and plant N levels.....133

4.10 Comparison of RGR and RAR_N for cabbage plants.....136

4.11 Comparison of RGR and RAR (N,P,K,Mg, and S).....139

4.12 Comparison of RGR and RAR (B,Cu,Fe,Mn, and Zn).....141

4.13 Effect of *V. marina* rate and application timing on corn yields.....145

4.14 Estimating quantity of *V. marina* to add to achieve 95% of maximum yield.....146

4.15 Non-linear regression analysis to estimate *V. marina* addition rate.....156

4.16 Effect of copra cake addition rate on cabbage yields.....158

4.17 Effect of different copra treatments on cabbage yields.....159

4.18 Effect of different copra treatments on macronutrient tissue concentrations.....161

4.19 Treatment effect on N uptake by cabbage plants.....162

4.20 Treatment effect on K uptake by cabbage plants.....162

5.1 Linear portion of P-sorption isotherm.....176

5.2 Freundlich equation fit to P sorption isotherm.....177

5.3 Relative proportion of Olsen extractable inorganic and organic P.....181
5.4 Initial concentrations for the three pools of Olsen extractable P.....182
5.5 Initail oxalate and 0.5 M NaOH extractable P.....183
5.6 Cabbage yield response as a function Olsen extractable P.....183
5.7 Phosphorus uptake by cabbage as a function of Olsen P.....184
5.8 Corn dry matter yields and P uptake as a function of Olsen P.....187
5.9 The relationship of tissue P concentration to Olsen P.....187
5.10 *Concentrations of three pools of Olsen extractable P with increasing* rates of added P in the lettuce experiment.....190
5.11 Lettuce response to increasing P rates.....191
5.12 Effect of removing block 1 from analysis.....192
5.13 Lettuce dry weight as a *function of* Olsen P_T and P_i.....193
5.14 P uptake by lettuce as a function of P added and extractable P.....194
5.15 The relationship of lettuce dry weight and tissue P.....197
5.16 The relationship between tissue P and extractable P.....197
5.17 The relationship between tissue P and tissue Zn.....198

Introduction

The Republic of the Marshall Islands is composed entirely of low-lying coral atolls. Coral atolls represent one of the youngest geologic features on the planet. They have a limited flora and fauna due primarily to their geographic isolation, limited land area, scarce water reserves, and infertile soils (Weins, 1962; Fosberg, 1990; Manner, 1987). Furthermore, the fragile atoll ecosystem is vulnerable to the destructive forces of hurricanes, tsunamis, drought, and human disturbances. Despite these formidable environmental barriers, human beings have populated the low-lying coral atolls of the Central Pacific (principally the Marshall Islands and Kiribati) for the last two to three thousand years during which time they developed distinct cultures. Their survival depended primarily on marine resources and subsistence agriculture based upon a limited number of food crops adapted to the harsh and fragile environment (Weins, 1962; Thaman, 1992a). Although there is evidence indicating that the first inhabitants of these atolls impacted the native atoll ecosystems as they adapted to their new home (Hatheway, 1953; Manner, 1993), a small and stable population (< 10,000) and an agricultural system that had minimal impact on the natural environment ensured their sustainability and survival (Thaman, 1992a; Spennemann, 1993; Merlin et al, 1994).

The 20th century has brought about dramatic political, economic, and social change in the Marshall Islands that is presently threatening the quality of life. Perhaps the most alarming change has been the rapid population growth. At the turn of the century the population was estimated to be somewhere around 10,000, a level that

had remained relatively stable over centuries (Merlin et al., 1994). After WWII, population growth rose dramatically to its present level of approximately 75,000. In fact, population growth rates of 4.3% yr^{-1} in the Marshall Islands are the highest in the Pacific (Spenneman, 1993). Today, more than 60% of the population is concentrated in the urban centers of Majuro and Ebeye on Kwajalein Atoll.

One of the more serious consequences of the population explosion and trend toward urbanization has been the rapid replacement of a traditional subsistence lifestyle with western oriented materialism and consumerism and a growing dependence on imported food (Sommers, 1987; Rapaport, 1990;). The population of Kili and Kwajalein, for example, are almost entirely dependent on food imports (Table 1.1). At present, 28% of the national debt is directly attributable to food imports (RMI Office of Planning and Statistics, 1995). Additionally, the large-scale substitution of traditional foods with imported canned food in the urban centers is linked to the rise in chronic diseases like diabetes and hypertension among adults and increasing incidents of malnutrition associated with vitamin deficiencies in children, especially vitamin A (Schoeffel, 1992; Finney & Laukon, 1993).

If the people of the Marshall Islands hope to reverse the trend towards increasing dependence on food imports, they must find ways to increase food production at the local level. Although foreign influence has changed social attitudes towards food production and consumption, a coherent agricultural research program can provide options that will help farmers increase their food production capacity. The government has placed special attention on increasing small-scale vegetable

production at the household level as a solution for the malnutrition problem. No formal research exists, however, to help guide such a program.

Table 1.1. Estimated population, land area, and available agricultural land by island/atoll. (Source: Asian Development Bank, 1997)

Atoll	Population	Land Area km^2	Population Density Persons/ha	% Households growing food for subsistence†	Agricultural Land Availability ha/household
South East					
Arno	2,093	13.0	1.6	95	3.4
Aur	554	5.6	1.0	80	4.5
Majuro	27,776	9.7	28.6	45	0.1
Mili	1,079	15.9	0.7	98	4.9
North East					
Ailuk	617	5.4	1.2	79	3.5
Likiep	609	10.3	0.6	99	7.4
Maloelap	1,006	9.7	1.0	85	4.3
Mejit	562	1.9	3.0	92	2.5
Utirik	517	2.4	2.1	81	2.4
Wotje	817	8.2	1.0	76	3.9
South West					
Ebon	937	5.8	1.6	76	3.7
Jaluit	2,160	11.3	1.9	69	2.2
Kili	761	0.9	8.2	0	0.8
Namdrik	1,029	2.8	3.7	92	1.9
North West					
Ailinglaplap	2,168	14.7	1.5	65	3.0
Bikini	13	6.0	0.02	-	-
Enewetak	904	5.9	1.5	42	2.8
Jabat	142	0.6	2.5	82	2.7
Kwajalein[a]	12,366	16.4	341	8	0.1
Lae	403	1.5	2.8	92	2.1
Lib	145	0.9	1.6	75	4.4
Namu	1,012	6.3	0.6	64	2.8
Ujae	566	1.9	3.0	89	2.1
Wotho	114	4.3	0.3	81	26.7
Total	**58,350**	**170.9**		**72**	**1.2**

[a] Computed for the land area of Ebeye only.

† Based on 1988 census, adapted from Bakker (1992)

The overall goal of the present research was to identify a range of soil amendment practices that give farmers in the Marshall Islands options for improving vegetable production at the household level. There were four primary objectives: (i) to identify the soil nutrient deficiencies limiting crop growth, (ii) to identify suitable organic fertilizer materials and characterize their nitrogen (N) mineralization potential, (iii) to evaluate and rank their capacity to supply nutrients to a vegetable crop, and (iv) to evaluate the P status of these soils.

Chapter One

Literature Review

The Atoll Environment

Geography and Climate

The Marshall Islands comprise 29 low-lying coral atolls and 5 islands sprawling over 2.1 million km^2 of the central Pacific Ocean (Fig. 1). Atolls are the calcareous remains of coral growth that have accumulated over millions of years on the peaks of submerged mid-oceanic volcanic islands (Wiens, 1962). The Marshall Islands are all low-lying with a mean elevation of 2 meters above sea level. The highest elevation, found on Likiep Atoll in the north, is only 6 m above sea level. The islands and islets are generally small and often very narrow. Most islets in the Marshall Islands are less than 1,000 m long and 500 m wide (Wiens, 1962). The ocean and regional weather patterns play a critical and ongoing role in atoll geomorphology. The constant action of waves and currents are continually eroding or building up islet coastlines and reefs resulting in a very dynamic geology. Storm generated waves and the occasional typhoons have had disastrous effects on the atoll ecosystem and human life.

Limited land area and the immense distances separating the atolls present significant constraints to agricultural development in general. Of the 181 km^2 of land area, less than half (approximately 8,200 ha) is considered arable (Asian Development Bank, 1997). According to the most recent data, the amount of available agricultural land in the atolls (excluding Majuro and Kwajalein) is estimated

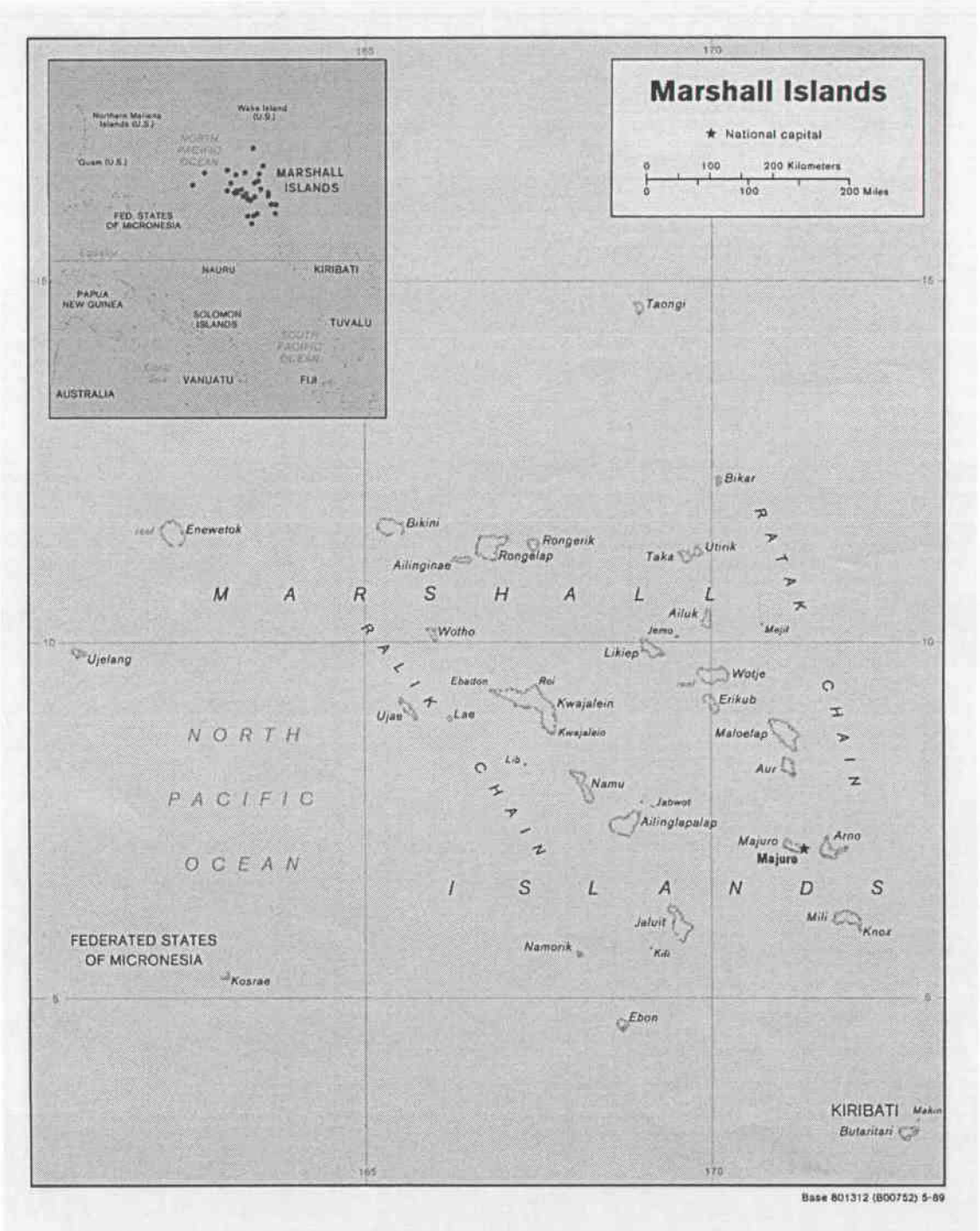


Fig. 1.1. Map of the Republic of the Marshall Islands and its location within the Pacific Basin.

at 2-5 ha per household (Table 1.1). Great distances of open-ocean separate the atolls from each other making transportation expensive by air and tedious by boat. Currently, Air Marshall Islands operates two aircraft between the atolls, but service is often interrupted due to mechanical problems. Inter-atoll shipping is complicated by a low cargo and passenger capacity, the great distances between atolls, and inadequate docking facilities in the outer atolls (Asian Development Bank, 1997).

Temperature variations and annual rainfall patterns play a critical role in shaping agricultural systems. The mean annual temperature in the Marshall Islands is 28°C with temperature differences between the warmest and coolest months averaging less than 0.3°C. This temperature regime coupled with abundant sunlight throughout the year generates favorable conditions for plant growth provided there is adequate water. Rainfall, on the other hand, is unevenly distributed across the archipelago with a distinct rainfall gradient running from north to south (Weins, 1962). Precipitation in the southern atolls averages threefold higher than in the northern atolls. On Enewetok atoll in the north-west, rainfall averages about 1350 mm annually increasing to 2700 mm on centrally located Kwajalein. The southern Marshalls are considerably wetter with annual precipitation on Majuro averaging 3500 mm (Wiens, 1962; Raynor, 1992a). Available data indicate that rainfall can total as high as 4100 mm annually on Jaluit and is even higher on Ebon, the most southerly atoll (Spoehr, 1949). The northern and centrally located atolls receive the bulk of their rainfall from June through November and are prone to drought conditions during the winter and spring months. The atolls in the south, on the other hand, enjoy moist conditions throughout the year under normal conditions. However, drought conditions can occur on even

the wettest atolls. Groundwater resources on most atolls are limited (Morrison, 1987) and the paucity of fresh water is considered perhaps the most critical obstacle to crop production (Asghar and Osbourn, 1987).

Atoll Ecology and Traditional Agriculture

Traditional atoll agriculture has depended largely on the unique atoll ecology (Thaman, 1992a; Merlin et al., 1994). Briefly, atolls can be divided into three broad ecological zones (Hatheway, 1953; Mueller-Dombois, 1998). The first zone consists of a mixed broadleaf forest composed of hardy, salt tolerant shrubs and trees forming a formidable windbreak along the windward coasts. Today, the windbreak zone is one of the few remaining examples of an intact native flora primarily because it is still recognized as an indispensable barrier to the damaging effect of the salt laden winds. In the interior section of most of the islands pure forest stands of *Pisonia grandis* and *Neisosperma oppositifolia* were dominant prior to anthropogenic alterations. Pure stands of these species are rare, however, and limited to uninhabited islands in the northern Marshall Islands (Manner, 1987; Fosberg, 1990). Abundant rainfall, litter accumulation, and guano deposition from nesting birds over many years combined to create relatively fertile soil conditions in these areas that the early settlers exploited by converting this land into the primary food producing land (Fosberg, 1992; Thaman, 1992b). Land along the lagoon was generally an open strand forest composed primarily of strand species including *Tournefortia argenta*, *Scaevola taccada*, and *Cocos nucifera*.

The atoll dwelling cultures of the central Pacific developed a multi-storied agroforestry system that incorporated a limited number of introduced food crops adapted to the harsh atoll conditions into the native vegetation patterns in order to overcome the effects of salt, drought, and poor soil fertility (Raynor, 1992a; Thaman, 1992b; Manner, 1993). In addition to providing protection from wind driven salt spray, the native forest played a vital role in supplying the early settlers with resources essential to their survival including food, building materials, fuel wood, medicine, and mulch for fertilizer. Prior to European contact the majority of the native forest in the Marshall Islands was probably intact. According to Hatheway (1953) land in agriculture at the time of European contact did not surpass 15% of the total area of Arno atoll. A small population (<10,000 for the entire archipelago) and an integrated approach to agroforestry combined to minimize adverse impacts on the native ecosystem (Thaman, 1992b; Raynor, 1992b). Large-scale urbanization and the copra industry have had the most devastating effect on the native vegetation (Sabath, 1977; Thaman, 1992b).

Traditional atoll agriculture was dominated by coconut palm (*Cocos nucifera*), pandanus (*Pandanus spp.*), breadfruit (*Artocarpus altilis*), two principal taro species (*Crytosperma chamissonis* and *Colocasia esculenta*), and to a lesser degree arrowroot (*Tacca leontopetaloides*), banana (*Musa spp.*), papaya, and a variety of lime species. Coconut, the dominant species even before foreign contact and the rise of the copra trade, was planted within the strand forest along the ocean and lagoon shores and dispersed throughout the interior of the islands. Coconut is adapted to the poor soils and salty environment of the atolls and required little management on the part of the

local farmers. Like coconut, pandanus is a salt tolerant species adapted to the poor soils. The nuts represented an important source of food, and the tree supplied a variety of raw materials for construction (Hiyane, 1971). Breadfruit, on the other hand, is less salt tolerant and was planted mainly near households along the lagoon and towards the interior of the islands where fresh groundwater is more common (Fosberg, 1990). Breadfruit tree productivity was maintained by regular mulching with green wastes (Raynor, 1992a). Traditional taro production throughout Micronesia consisted of excavating pits in the interior part of the islands until reaching the fresh groundwater, and filling them with a mixture of green leaves gathered from native trees and shrubs growing abundantly on the islands. Over time, the organic material decomposed forming an organic muck rich in nutrients and capable of supporting vigorous crop growth (Ali & Asghar, 1987; Thaman, 1992a & b).

Atoll Soils

The soils of the Marshall Islands reflect the relative geologic youth of atolls. They are formed predominantly from limestone parent material of organic origin composed of the dead skeletons of different types of marine algae, corals, foraminifera, and mollusks. Calcium and magnesium carbonates are the dominant minerals (Stone, 1951). Similar to the soils found on other low-lying atolls, soils in the Marshall Islands generally fall within the Entisol order according to the U.S. Soil Taxonomy system (Soil Survey Staff, 1998; Laird, 1989). These are recent soils with minimal profile development characterized by an abrupt transition from an organic

rich A horizon to a calcareous sand or limestone C horizon. The organic A horizon varies in thickness from just a few centimeters to as much as 1 m under undisturbed natural vegetation (Morrison, 1990). The presence of buried A horizons is a common feature resulting from debris deposited from large storm waves that periodically inundate islands. The presence of a large sea bird population in the historic past contributed to the formation of a unique soil with a phosphate hardpan underlying the organic surface layer (Fosberg, 1954).

The soils of the low-lying atolls of the Pacific are often referred to as infertile and not well suited to intensive agriculture (Stone, 1951; Fosberg, 1954; Finlay, 1987b; Caiger, 1987; Laird, 1989; Morrison, 1990; Fosberg, 1990; Fosberg, 1992; Finlay, 1992; Stone, 1951; Stone et al., 2000). The infertile conditions are directly related to the chemical, mineralogical and physical properties of these soils.

Soil mineralogy influences both the chemical and physical properties of a soil. Atoll soil mineralogy is dominated by Ca and Mg carbonates derived from coralline materials. Chemical analysis of soils collected on Tuvalu found that $CaCO_3$ contents in the surface layer (0-10 cm) ranged between 42 and 96% with a mean value of 84% (Caiger, 1987). Excessively high levels of Ca and Mg often result in serious K deficiencies in soils (Barber, 1997). The deficiencies arise primarily because of (1) the low K levels in the parent material, and (2) an exchange complex dominated by Ca^{2+} and Mg^{2+}. Existing data indicate that K deficiency is widespread in atoll soils (Caiger, 1987; Morrison, 1990; Gangaiya and Morrison, 1998). In addition to soil nutrient imbalances due to carbonate mineralogy, atoll soils contain no clay fraction (Hammond, 1969; Morrsion, 1990). In soils, the clay fraction plays several critical

roles in sustaining plant growth: (i) it is a source of minerals (Ca, Mg, K, Fe, Mn, Cu, Zn, B); (ii) it is a source of cation exchange capacity (CEC); and (iii) it increases the moisture retention capacity of the soil due to a preponderance of micropores.

Soil pH is a critical chemical factor controlling important reactions involving plant nutrients in the soil. Because atoll soils are dominated by $CaCO_3$, soil pH is generally high in both the surface and subsoil. Soil surveys performed on Tuvalu (Caiger, 1987) and Kiribati (Morrison, 1990) found surface soil pH ranging from 7.4 – 8.5 and subsoil values of 7.5 – 9.1. The alkaline nature of these soils has several important effects on plant nutrient availability. Soil N is sensitive to changes in pH. Under alkaline conditions NH_4^+ is rapidly volatilized to NH_3 and no longer available for plant uptake. This reaction shows that N would be lost from the soil if ammonium based fertilizers are used to amend the soils. In soils dominated by $CaCO_3$, P solubility is controlled by Ca^{2+}, and at pH above 7.0 phosphate is precipitated as $Ca_4H(PO_4)_3$ (octacalcium phosphate). Furthermore, pH determines the form in which P is present in the soil. Above pH 8.0 soil P is present as HPO_4^{2-}, a form not readily taken up by plants. The correlation between deficient levels of micronutrients (Fe, Zn, Mn, Cu,) and soils with high pH has been well-documented (Moraghan & Mascagni, 1991; Barber, 1995). The solubility of Fe^{3+} in soil solution decreases from 10^{-8} to 10^{-20} *M* as pH increases from 4 to 8. Iron solubility is lowest between pH 7.5 and 8.5 which corresponds to the pH range of most calcareous soils (Lindsay, 1991). At pH above 7.0, Mn precipitates as $MnCO_3$ and is no longer available for plant uptake. Zinc solubility decreases 100-fold with every unit increase in pH, above pH 7.7.

The observation of micronutrient deficiency symptoms in crops grown on calcareous atoll soils is widespread in the literature (Stone, 1951; Wiens, 1962; Morrison, 1992; Fosberg, 1990; Cable, 1992; Thaman, 1992a&b; Weeraratna, 1992; Widdowson and Trangmar, 1992). However, studies that quantify the nature and magnitude of the deficiency are more difficult to locate. Caiger (1987) characterized total (perchloric acid digestion) micronutrient content of soils from Tuvalu and found all micronutrient concentrations fell below the range deemed adequate according to standards set at the Tropical Soils Analysis Unit, Reading, UK. In terms of plant growth, however, total micronutrient levels are of little meaning because they do not represent what is available for plant uptake. Although micronutrient problems in the soils of the Marshall Islands have been discussed (Wiens, 1962; Liew, 1986a; Fosberg, 1990, Stone et al., 2000), existing data do not adequately substantiate or quantify these claims. Available micronutrient data for soils from Arno (Stone, 1951) and Rongelap, Enewetok, and Bikini (Gessel and Walker, 1992) are difficult to interpret because standard methods were not employed and meaningful comparisons are impossible (Gessel and Walker, 1992). A series of missing element studies on a coral soil from Niue found that of the micronutrients zinc was the most limiting with the results for iron availability less conclusive (Widdowson and Trangmar, 1992).

Soil Organic Matter

Soil organic matter plays an indispensable role in all soil processes – biological, chemical, and physical. It is essential for nutrient storage and recycling, and it serves as the principal source of energy for soil microorganisms. It has charge properties

that improve ion retention by increasing CEC. Soil organic matter has chemical and physical properties that facilitate aggregation of the mineral component improving both the physical properties of the soil and increasing moisture retention within the root zone (Swift and Woomer, 1993). In sandy atoll soils where clay is absent, the importance of organic matter is supreme. In these soils organic matter is the only source of nutrients, CEC and moisture retention. Without organic matter atoll soils would be essentially sterile and incapable of sustaining plant life.

A small number of studies illustrate the important role organic matter plays in sustaining plant life in the atoll environment. In terms of water retention, topsoil containing appreciable amounts of organic C (13%) exhibited a water holding capacity of 53% while subsoil with less than 1% organic C retained less than 4% of soil water at the permanent wilting point (Finlay, 1987b). Cation exchange measurements made on coralline soils from Tuvalu showed a twenty-fold decrease between the organic-rich surface layer and the subsoil (Caiger, 1987). Similar results were also obtained in soils from Kiribati (Morrison, 1990) and the Northern Marshall Islands (Gessel and Walker, 1992). Data from several sites on Arno Atoll illustrate the correlation of depth and soil organic matter content to the concentration of the macronutrients N, P, and K (Table 1.2). In general, soil macronutrient content is proportionate to organic matter content. Soil P levels, however, are also affected by existing or pre-existing bird populations. In areas where nesting birds are common, guano deposits can significantly increase soil P levels (Fosberg, 1954; Gessel and Walker, 1992).

Table 1.2. Soil organic matter content and total N, P, and K levels in soils on two islands from Arno Atoll. (Source: Stone, 1951).

	Depth cm	Organic Matter %	Total N %	P kg ha^{-1}	K kg ha^{-1}
Arno Island	0-15	16.7	0.88	89.6	123
	15-28	11.3	0.59	28.0	70.6
	28-48	0.28	0.04	28.0	20.2
Jabu Island	0-15	19.04	0.88	134	141
	30-46	0.20	0.04	56.0	15.7
	76-91	0.24	0.06	67.2	16.8

There is evidence in the literature that soil management has had some effect on soil organic mater and other soil chemical properties. The traditional method of growing taro (*Crytosperma chamissonis*) involved excavating a pit and filling it with organic materials. Over time this practice built up a rich organic soil (Thaman, 1992a & b). On the other hand, coconut plantations have depleted soil nutrient reserves. Typically, coconut lands received no nutrient inputs (Sideris, 1958; Wiens, 1962; Asian Development Bank, 1997). With the development of the copra industry over the last 100 years, nutrient losses through copra exports have been considerable. Stone (1951) estimated that each ton of copra removes the equivalent of 10.3 kg of superphosphate. If total copra production in the Marshall Islands was estimated at 77,300 short tons between 1983 and 1995 (RMI Office of Planning and Statistics, 1995), then net phosphorus (P_2O_5) losses are on the order of 193 tons of P over a twelve year period. These losses become alarming especially since phosphorus is not being returned to the soil. Furthermore, the traditional practice of burning coconut leaf residue for pest management purposes leads to losses of nitrogen and sulfur.

In addition to human induced changes in soil fertility, natural vegetation patterns and location within the individual islands influence soil nutrient concentrations.

Significant differences were observed in the chemical properties of surface soil samples taken from three locations on Rongelap Atoll each with different vegetation cover (Table 1.3) (Gessel & Walker, 1992). Organic matter content was highest (35%) under a native *Pisonia* forest covering the center of the Island compared to values of less than 5% for areas closer to the shoreline. Soil organic matter levels diminished to 16.7% in a coconut grove on Rongalap island while an eightfold decrease in organic matter levels was observed in an open strand area containing *Scaevola* and *Tournefortia* shrubs near the lagoon shoreline.

Table 1.3. Contrasting soil fertility with respect to vegetation cover and location on Rongelap Atoll.

Soil Property	Coconut grove and grassland (Center, Rongelap Island)	*Pisonia* and *Boerhaavia* (Center, Kabelle Island)	*Scaevola* and *Tournefortia* (Strand, Kabelle Island)
pH	8.1	7.8	8.6
% Organic Matter	16.7	35.6	4.5
% N	0.57	1.71	0.09
Olsen P (mg kg^{-1})	81.7	985	32.8
CEC[†]	22.2	37.7	3.7

[†]meq/100g (2 mm fraction)

Soil Fertility Research

Improving soil nutrient status to increase crop production and diversity in atoll soils remains problematic (Finlay, 1987a). The highly porous soil and its inherently low CEC complicate attempts to correct soil nitrogen and potassium deficiencies (Reddy and Chase, 1992; Caiger, 1987; Finlay, 1987a). Because added inorganic N

and K fertilizers move rapidly through the soil profile, they must be administered in small and frequent doses to insure adequate uptake by the crop (Reddy & Chase, 1992: Finlay, 1987a). Added as single large applications at the beginning of the cropping cycle not only reduces fertilizer efficiency, but also poses a very real contamination threat to limited groundwater resources (Morrison, 1987).

A number of fertilizer studies have found that micronutrient deficiencies are not easily corrected by simply applying inorganic fertilizers (Finlay, 1987b; Morrison, 1992; Weeraratna, 1992; Widdowson and Trangmar, 1992). Fertilizer experiments on coconut trees found that micronutrients applied as sulfate compounds were rapidly precipitated as hydroxides while micronutrients added in their more soluble chelated forms had a positive effect on coconut nutrition initially, but the effects were short-lived as the elements were rapidly leached out of the root zone. Examination of alternative application methods found that iron injected into coconut trunks and foliar applied iron improved tree growth and foliar nutrient concentrations (Trewren, 1985). Corn growth on a coralline soil from Niue was improved significantly by incorporating zinc (as ZnEDTA at a rate of 6 kg Zn ha^{-1}) into the root zone (Widdowson & Trangmar, 1992). Applied Zn had a residual effect on the second crop. The same study found that when Zn and Fe were added to the soil, *Crotolaria juncea* growth was reduced by inducing Mn deficiency due to Fe competition at the root surfaces. In addition, some studies show that excessive quantities of fertilizer are required to correct micronutrient disorders (Table 1.4). In a review of fertilizer use in atoll environments, Finlay (1987a) cautioned that fertilizer costs are often prohibitively expensive for the average Pacific Island farmer.

Table 1.4. Miconutrient fertilizer application rates for selected crops on atoll soils. (All data compiled from Iqbal (1992)).

Crop	Micronutrient	Application Rate kg ha^{-1}
Sweet Potato	$FeSO_4$	1000
	$MnSO_4$	150
	copper oxychloride	60
Cucumber & Onion	NPF	1067
	trace mix	1000
	chicken manure	12,000
Tomato	$FeSO_4$	1000
	$MnSO_4$	150
	$ZnSO_4$	30

The majority of the research conducted on the coral soils found in atoll environments consistently concludes that a successful crop production program is dependent upon sound soil organic matter management. The United Nations Development Program's Integrated Atoll Development Project declared that careful organic matter management was fundamental to the success of agricultural development in the Pacific (Liew, 1986b; Liew, 1987). Despite the importance attributed to organic matter in atoll agriculture, formal research on evaluating its benefits is scant. A few studies give qualitative descriptions of traditional organic matter management practices for swamp taro and breadfruit production on atolls (Ali & Asghar, 1992; Thaman, 1992a; Manuella and Cable, 1992; Sideris, 1958), but no data exist to determine the nutrient supplying capacity of traditional soil management strategies. Reynolds (1971) found that dry matter yields for a bean crop grown in a coral soil amended with a mixture of organic matter and NPK fertilizer increased fourfold over the control and twofold over the organic matter alone treatment. The results indicate a beneficial interaction between added fertilizers and organic matter,

but are inconclusive because the treatments were not replicated. Composted coconut palm leaves have been proposed as a suitable amendment to increase vegetable production (Chevillet, 1980), but if used alone this amendment probably would not provide sufficient nutrients for adequate vegetable growth. Another approach recommended filling the bottom of a shallow pit with fresh leaves, covering with soil and planting vegetable seeds in the overlying mound (Finney and Laukon, 1993; Stone et al., 2000). Neither paper, however, discussed the potential immobilization of soil N during the initial stages of decomposition, an important oversight, especially in a buried pit where anaerobic conditions predominate. A more recent experiment reported that coral soil amended with fresh green manure and mature compost increased tomato yields (Reddy and Chase, 1998). The study concluded that fresh green manure applied to the soil at a rate of 20-30 Mg ha^{-1} was the most efficient treatment. Application rates of this magnitude only make sense on small household vegetable plots. Such a practice is not sustainable on large areas due to the lack of available plant material.

Chapter Two

Evaluating the Soil Fertility Status of the low-Lying Coral Atolls of the Marshall Islands

Introduction

The Republic of the Marshall Islands comprises 29 low-lying coral atolls and 5 islands sprawling over 2.1 million km^2 of the central Pacific Ocean. The soils of the Marshall Islands reflect the relative geologic youth of atolls. They are formed predominantly from limestone parent material of organic origin composed of the dead skeletons of different types of marine algae, corals, foraminifera, and mollusks. Calcium and magnesium carbonates are the dominant minerals (Stone, 1951). Soils in the Marshall Islands generally fall within the Entisol order according to the U.S. Soil Taxonomy system. Two soil types are found on these islands: i) Udipsamments if the OC content of the surface horizon is less than 2.5%, and ii) Entic Haprendolls if the OC content in the surface horizon is above 2.5% (Soil Survey Staff, 1998). The coralline atoll soils are often referred to as infertile and not well suited to intensive agriculture (Stone, 1951; Fosberg, 1954; Finlay, 1987b; Caiger, 1987; Laird, 1989; Morrison, 1990; Fosberg, 1990; Fosberg, 1992; Finlay, 1992; Stone, 1951; Stone et al., 2000). The infertile conditions are directly related to the chemical, mineralogical and physical properties of these soils.

At present, interpreting the soil chemical properties of the low-lying atolls of the Pacific is problematic. The available literature concurs that these soils are relatively

young and undeveloped, and low in soil fertility and crop production potential (Morrison, 1992; Caiger, 1987). Existing soil data show that these soils are alkaline (Caiger, 1987), deficient in nitrogen (Reddy and Chase, 1992), exchangeable K (Reddy and Chase, 1992; Gangaiya and Morrison, 1998), and low in total micronutrient (Fe, Mn, Zn) content (Caiger, 1987; Widdowson and Trangmar, 1992). Interpreting these soil data in relation to plant nutrient requirements, however, is difficult because the chemical soil extraction procedures were not calibrated with crop nutrient requirements. For example, data for total P and Fe as reported in Caiger (1987) are not easily interpreted because this soil test does not estimate what proportion of P or Fe is in solution and available for plant uptake. One can only speculate that a small fraction of the total soil P is in solution because the high pH (~ 8.0) causes most of the P and Fe to precipitate as $CaHPO_4$ and $Fe(OH)_2$. In fact, most papers on atoll soil fertility assume soil P and micronutrient deficiencies based on soil chemical theory rather than soil analysis (Fosberg, 1990; Morrison, 1990; Stone et al., 2000).

Information on the chemical properties of the soils in the Marshall Islands is limited to the work of Stone (1951), Fosberg (1954) and Gessel and Walker (1992). While these studies provide valuable information describing the general properties of soils on Arno Atoll (Stone, 1951), the unique occurrence of subsoil phosphate rich hardpans on Jemu Island in the northern Marshalls (Fosberg, 1954), and how vegetation distribution and location affect soil OC, N, and P levels on Rongelap Atoll (Gessel and Walker, 1992), they cannot be used to evaluate the soil fertility status of soils in the Marshalls. The objectives of this study were to summarize the chemical analyses conducted on soils collected from 25 atolls in the Marshall Islands, identify any significant trends in soil

chemical properties, and evaluate soil test data for these soils in terms of nutrient supply capacity and crop production.

Materials and Methods

Soil Sampling

A soil sampling effort was conducted on 25 atolls to characterize the chemical properties of soils found in the Marshall Islands. Four soil sampling designs were employed during the collection process: i) soils were sampled at two depths and nine locations on 13 islands (Fig. 2.1); (ii) sampling locations 1, 2, 3 and 7, 8, 9 along each of the two long transects were composited into two separate samples, and samples 4, 5, 6 representing the middle of the 'W' shape were composited into one sample; (iii) soils were sampled at six locations along a transect running across undisturbed terrain of Arno Island, two surface soil cores were dug 25 and 50 m from the ocean shoreline, two more from the island interior, and a last set of 2 from 50 and 25 m from the lagoon shoreline; surface soil samples were collected from vegetable plots located at an experimental farm and selected households on Majuro (Laura). For schemes i and ii, samples from the organic rich surface layer and the coral sand subsoil were collected and stored in closed plastic containers. The samples were packaged carefully and shipped by air for chemical analysis at the Agricultural Diagnostic Service Center (ADSC) at the University of Hawaii in Honolulu.

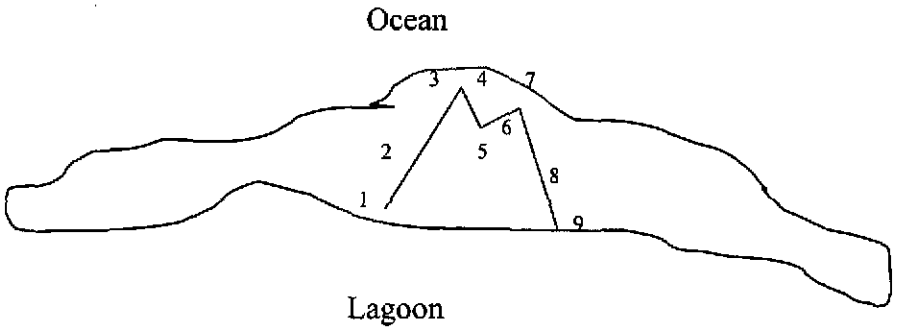


Figure 2.1. Soil sampling scheme (i) for atoll soil collection.

Laboratory Analyses

All samples were analyzed according to procedures developed by the ADSC (Hue et al., 2000). Soil pH was determined in a saturated paste equilibrated for one hour and measured with a pH meter. Electrical conductivity (EC) was determined in a 1:1 soil to water mixture with a conductivity bridge after shaking the slurry on a reciprocal shaker for 45 minutes and filtering. Exchangeable cations (K^+, Mg^{++}, Ca^{++}, Na^+) were extracted in a 1 *M* NH_4OAc at pH 7.0 solution with a soil-to-solution ratio of 1:20, shaken for ten minutes, and determined quantitatively by Inductive Coupled Plasma Emission (ICP). Sulfate (SO_4^{2-}-S) was extracted by shaking soil for 30 min in 1:5 soil:water mixture (Fox et al., 1964), filtered and S determined quantitatively with ICP. Micronutrient content was determined by the DTPA method as outlined by Lindsey & Norvell (1978). Ten g of soil was mixed with 20 ml of 0.005 *M* DTPA solution adjusted to pH 7.3 with TEA, shaken for two hours, filtered, and the micronutrients determined quantitatively by ICP. Soil P was determined by the Olsen P method (Olsen et al., 1954). Phosphorus in the

filtered extract was determined by ICP. Total N was determined by Kjedahl distillation (Bremner, 1996), and organic carbon (OC) by revised Walkley Black method (Heanes, 1984).

Regression analysis using the PROC REG procedure in SAS (SAS Institute, 1991) was conducted to test the effect of latitude on soil chemical properties. Differences in chemical properties according to within island location for Arno and Bikirin islands were tested using PROC ANOVA in SAS. The Kruskall-Wallis test was used to test within island differences for all the islands by employing the proc NPAR1WAY. Pearson correlation coefficients to determine relationships between the different chemical properties were obtained using the proc CORR procedure in SAS. The proc UNIVARIATE procedure was used to obtain descriptive statistics on the data, and to test for normality by applying the Kolomogorov-Smirnov test using the D statistic. When appropriate, the data were transformed to achieve normality. On transformed data (P, Fe, and Mn) outliers were determined by identifying those points that were greater than 1.5 times the standard deviation (Moore and McCabe, 1989). For the remaining chemical determinations mathematical transformations did not normalize the data. In these cases, those points that were greater than 3 standard deviations from the mean were deemed outliers.

Missing Element Study

A missing element study was conducted in the greenhouse using a Marshall Island soil collected from Laura village on Majuro Atoll to help interpret results of the soil test, and validate whether established critical levels for the different soil tests are applicable to

the Marshall Island soils. A summary of the soil chemical properties and critical soil nutrient levels for corn are presented in Table 2.1. Treatments and nutrient rates are outlined in Table 2.2. Nitrogen and K were added in solution form at a rate of 25 mg kg^{-1} N and K at 8 evenly spaced intervals during the pot study for a total equivalent to 200 mg N and K kg^{-1}. The remaining elements were added separately in solution and mixed thoroughly with 2.5 kg air-dry soil. Deionized water was added to achieve approximate field capacity, and six corn (*Zea mays cv.* super sweet #9) seeds were planted in each pot. The pots were set up in the greenhouse in a randomized complete block design with 3 replicates per treatment. Pots were watered daily with deionized water to maintain moisture status, and corn was thinned to two uniform plants per pot 14 days after

Table 2.1. *Chemical properties for the surface layer (0-20 cm) of a soil collected on Arno.*

Determination	Units	*Laura* Soil
pH		7.8
EC	dS m^{-1}	0.33
Total N	%	0.52
Organic Carbon		6.99
P	mg kg^{-1}	50.0
K		0
SO_4-S	mg L^{-1}	6.67
Ca		9455
Mg		221
B		0.37
Mn	mg kg^{-1}	7.37
Fe		27.7
Cu		0.13
Zn		3.40

† *For Sandy soils (Tamimi et al., 1993)*

planting. The corn plants were harvested 4 weeks after planting, dried at 70°C for 72 hours, and weighed for biomass. Tissues were then ground in a Wiley mill to pass

through a 0.45 mm sieve, and analyzed for total N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn, and B. Soils were air-dried, and analyzed for pH, EC, total N, organic C, and extractable P, K, Ca, Mg, B, Fe, Mn, Cu, and Zn according to the procedures outlined above.

Differences between treatments for dry matter yield, tissue concentration and mineral uptake were determined by analysis of variance using proc ANOVA in SAS.

Table 2.2. Treatments, nutrient application rates, and chemical composition of nutrient additions used in the missing element study.

Treatment	Description	
Check	No nutrients applied	
Control A	All nutrients applied (N, P, K, Mg, S, B, Cu, Fe, Mn, Zn)	
Control B	Control A + Mo & Co	
-N	Control A without N	
-P	" P	
-K	" K	
-Mg	" Mg	
-S	" S	
-B	" B	
-Cu	" Cu	
-Fe	" Fe	
-Mn	" Mn	
-Zn	" Zn	
Nutrient	Form of Nutrient	Application Rate (mg nutrient kg^{-1})
N	NH_4NO_3	200
P	H_3PO_4	20
K	KCl	400
Mg	$MgCl_2$	50
S	H_2SO_4	50
B	$Na_2B_4O_7$	1
Cu	$CuCl_2$	5
Fe	Sodium ferric ethylenediamine di-(o-hydroxyphenylacetate) FeEDDHA	10
Mn	$MnCl_2$	10
Zn	$ZnCl_2$	10

Results and Discussion

Atoll-wide Soil Sampling

Soil samples from 25 atolls in the Marshall archipelago were collected and analyzed for their chemical properties in order to assess their fertility status. Table 2.3 and 2.4 present a summary of descriptive statistics for the surface and subsoil respectively when data from all 25 islands were pooled and analyzed together. The distributions of the surface soil chemical data are displayed in Figure 2.2. The box-plots show that considerable variability occurred for each of the soil measurements. With the exception of data for soil pH, the data are strongly skewed to the left with a significant number of data points showing extreme values.

The surface soil pH had a mean value of 7.84 that was slightly lower than the subsoil pH of 8.13, and variability in pH was generally low. There were two samples that showed pH levels of 6.2 and 6.8, considerably lower than the majority of the samples. Both samples were collected from traditional taro pits where the organic C concentrations were very high, 48.6 and 41.2% respectively. Other studies have found a similar trend of relatively lower pH levels in the surface layer compared to the subsoil (Stone 1951; Caiger, 1987; Reynolds, 1973). The skewed nature of the data for all the chemical determinations, except pH, suggest that the median is a more robust measure of central tendency. Median electrical conductivity (EC) level in the surface layer was 0.54 dS m^{-1} and in the subsoil 0.23 dS m^{-1}, both low levels. A small number of samples had EC values above 4 dS m^{-1}, a level that many plants cannot tolerate (El-Swaify, 2000). The median value showed that salinity was not a problem in these soils despite their proximity

Table 2.3. Descriptive statistics for surface soils for pooled data from all 25 islands.

Determination	Units	Mean	Std Dev	Min-Max	Median	Q1	Q3	Cv (%)
pH		7.84	0.24	6.2-8.3	7.85	7.70	8.02	3.06
EC	$dS\ m^{-1}$	0.86	1.40	0.18-15.0	0.54	0.43	0.77	163
OC	%	5.71	6.02	1.13-48.6	4.42	3.12	6.16	105
N		0.45	0.37	0.10-3.67	0.38	0.28	0.54	81.0
P		41.0	41.1	3.40-303	27.0	13.0	57.5	99.6
Na	$cmol_c\ kg^{-1}$	0.66	1.60	0.11-19.8	0.24	0.19	0.34	351
K		0.12	0.20	0-2.00	0.08	0.05	0.12	166
Ca		30.6	7.31	21.0-78.8	29.3	26.9	32.2	23.8
Mg		3.26	2.77	0.44-26.7	2.81	2.11	3.51	84.8
B	$\mu g\ g^{-1}$	0.67	0.65	0.11-7.22	0.55	0.43	0.73	96.6
Mn		2.69	2.00	0.19-14.3	2.30	1.20	3.55	73.60
Fe		11.4	18.0	0.14-149	5.69	2.62	13.3	157
Cu		1.32	5.31	0-56.0	0.13	0.07	0.53	401
Zn		19.3	53.6	0.02-411	2.18	0.22	10.1	275

Table 2.4. Descriptive statistics for the subsoils of pooled data from all 25 islands.

Determination	Units	Mean	Std Dev	Min-Max	Median	Q1	Q3	Cv (%)
pH		8.18	0.35	6.3-8.9	8.20	8.10	8.30	4.13
EC	$dS\ m^{-1}$	0.68	1.56	0.12-11.6	0.23	0.19	0.30	232
OC	%	3.10	7.73	0.21-51.5	0.76	0.51	1.40	252
N		0.26	0.49	0.03-3.44	0.11	0.08	0.17	194.0
P		19.3	34.1	1.5-246	8.40	4.70	18.0	176.0
Na	$cmol_c\ kg^{-1}$	0.47	1.62	0.06-19.8	0.23	0.17	0.30	340
K		0.05	0.12	0-0.69	0.01	0	0.04	235
Ca		28.1	9.77	20.2-87.5	26.0	24.2	27.5	33.9
Mg		2.76	2.63	0.54-17.1	2.18	1.54	2.95	95.1
B	$\mu g\ g^{-1}$	0.42	0.83	0.03-5.93	0.21	0.13	0.32	196
Mn		0.98	1.35	0.04-7.16	0.42	0.24	0.93	138.00
Fe		8.20	32.7	0.03-227	0.90	0.42	2.46	406
Cu		0.43	2.12	0-18.7	0.05	0.02	0.15	505
Zn		7.71	56.8	0-512	0.12	0.02	0.81	754

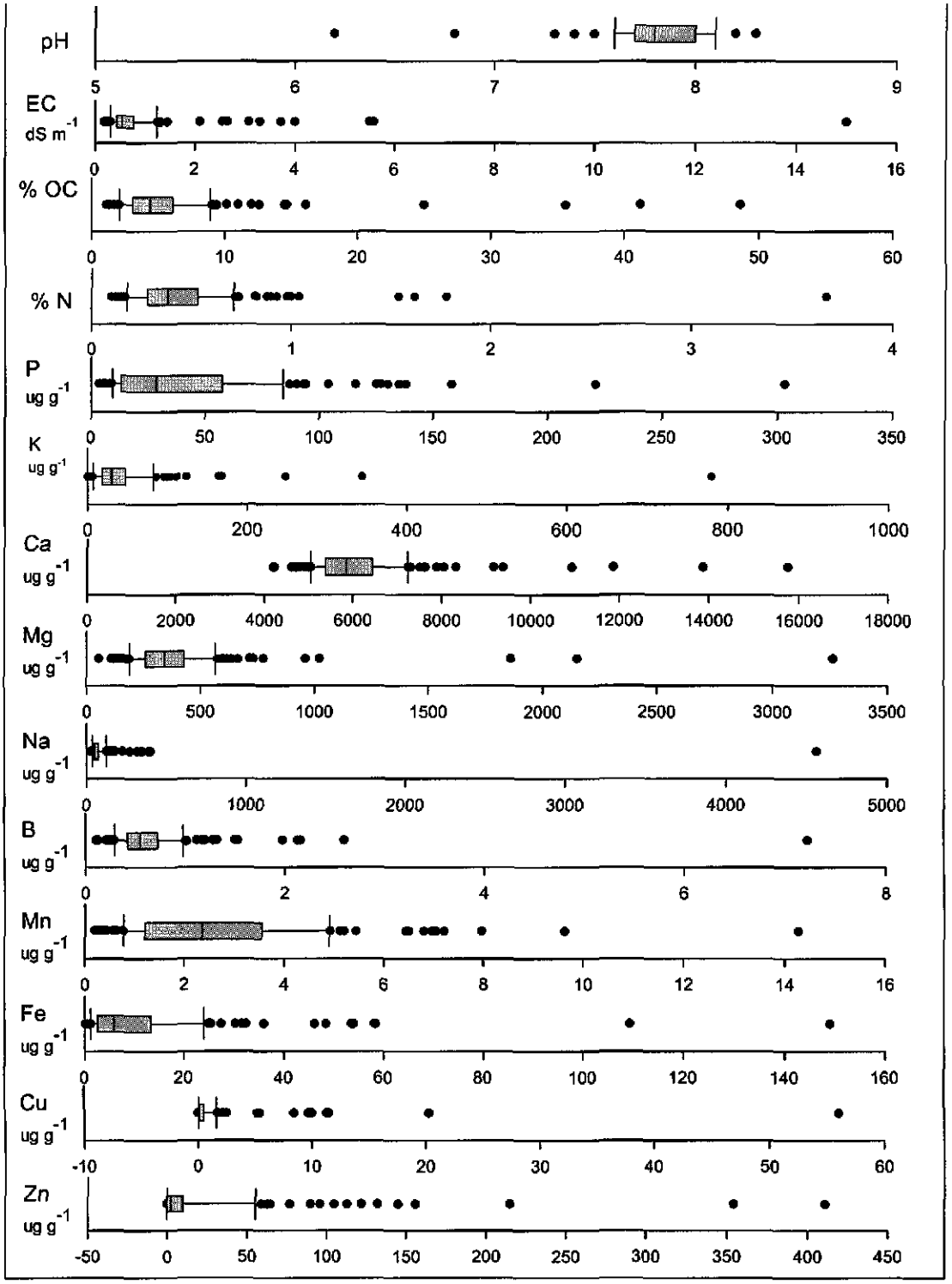


Figure 2.2. Box-plots showing distribution of data on chemical measurements of Marshall Island surface soils when data from all islands pooled together.

to the ocean. The coarsely textured soils promote rapid drainage thus reducing salt accumulation in the surface soil. These values are slightly higher than the levels found for the surface and subsoils of Tuvalu (Caiger, 1987).

Organic carbon (OC) levels in the Marshall Island soils were generally high in the surface layer with a median of 4.42%. The extremely high values (20 – 50%) of a small number of samples were probably because these samples came from the organic enriched muck soils found in traditional taro pits. Soil carbon levels dropped significantly in the subsoil to a median value of 0.76%. The Marshall Island soils showed a much wider range in OC levels compared with soil from Tuvalu (Caiger, 1987) and Christmas Island (Hammond, 1969). The mean OC value for the Marshall Islands was 5.71% compared with 3.59% in the soils from Tuvalu (Caiger, 1987). Total nitrogen (N) levels followed the same trend as OC with median surface levels of 0.37%, and a median subsoil level that decreased substantially to 0.11%. The range in total N levels in the Marshall Island soils is similar to values reported for other atoll soils (Stone, 1951; Morrison, 1990; Caiger, 1987). A small number of samples with high OC levels exhibited N levels greater than 1.00%. As mentioned above, these high levels are probably associated with traditional taro pits. The surface soil exhibited a median C:N ratio of 11.4, indicating that N should be readily mineralized.

Available P (Olsens) in both the surface soil and subsoil showed a wide range with a few values that were very high (> 100 mg kg^{-1}). The high soil P levels may be associated with phosphate rich subsoil layers derived from guano deposits, a unique feature of atoll soils (Fosberg, 1954). The median surface soil P concentration of 27.0 mg kg^{-1} was significantly higher than the subsoil concentration of 8.4 mg kg^{-1}. These

values were similar to mean Olsen P levels found in Tuvalu (Caiger, 1987). Previous research has established a critical soil P concentration of 10 mg kg^{-1} for calcareous soils. The median P concentration for Marshall Island surface soil was almost twice the concentration of the established critical level.

Exchangeable K in the surface soil was very low and negligible in the subsoil. A median surface exchangeable K value of 0.08 $cmol_c$ kg^{-1} was almost 5 times lower than the value of 0.38 cmol kg^{-1} determined as the optimum for plant growth (Barber, 1995). Caiger (1987) reported mean exchangeable K values of 0.12 $cmol_c$ kg^{-1} for soils from Tuvalu, and Gangaiya and Morrison (1998) found that deficient levels of exchangeable K were widespread on 6 Pacific Islands. On the other hand, Ca was the dominant exchangeable cation with a median value of 29.3 $cmol_c$ kg^{-1} for the surface soil and 26.0 cmol kg^{-1} in the subsoil. Calcium represents 88% of the exchangeable cations reflecting the carbonatic mineralogy of the soils. Exchangeable Ca values determined by NH_4OAc at pH 7.0 probably overestimates exchangeable Ca because lowering the pH from 7.9 to 7.0 will cause the dissolution of Ca from the $CaCO_3$ parent material. Median exchangeable Mg levels for the surface soil were 2.81 $cmol_c$ kg^{-1}, which falls within the established sufficiency range of 2.45 – 3.28 $cmol_c$ kg^{-1} for good crop growth. Magnesium levels decreased only slightly to 2.18 $cmol_c$ kg^{-1} in the subsoil. Median Mg levels were slightly lower than the mean of 3.21 $cmol_c$ kg^{-1} reported by Caiger (1987) for the soils of Tuvalu. The ratio of exchangeable Ca and Mg is an important factor affecting Ca and Mg nutrition in plants. A Ca:Mg ratio between 2 and 7 is ideal for optimum plant growth (Barber, 1995). The median Ca:Mg ratio for the Marshall Island soils was 10.4, a slightly wider ratio than the optimum, but probably not wide enough to significantly

inhibit Mg uptake. Exchangeable Na levels are generally low in the Marshall Island soils with a median value of 0.24 $cmol_c\ kg^{-1}$ in the surface and 0.23 $cmol_c\ kg^{-1}$ in the subsoil.

Micronutrient content of the Marshall Island soils showed considerable variability with a distribution skewed to the right due to the occurrence of a few unusually high values. Therefore, we used the median as a better value to represent the central tendency of the data. Boron content dropped from 0.55 $\mu g\ g^{-1}$ in the surface layer to 0.21 $\mu g\ g^{-1}$ in the subsoil. Caiger (1987) reported a mean soil B level of 0.75$\mu g\ g^{-1}$ for the soils of Tuvalu. A critical soil test value for hot-water soluble B has not been clearly defined, but a range in critical level has been estimated as 0.1-2.0 $\mu g\ g^{-1}$, the large range in critical values probably reflects the wide range in crop response to B (Sims and Johnson, 1991). Nevertheless, B levels for the Marshall Island soils fall within the reported critical range. Manganese concentration decreased tenfold from 2.30 $\mu g\ g^{-1}$ in the surface to 0.21 $\mu g\ g^{-1}$ in the subsoil. Surface soil Mn concentrations were within the reported critical range of 1.0-5.0 $\mu g\ g^{-1}$ for the DTPA soil test (Sims and Johnson, 1991). DTPA extractable Fe of 5.69 $\mu g\ g^{-1}$ in the surface layer and 0.90 $\mu g\ g^{-1}$ in the subsoil represented the two extremes of the established critical range of 1.0-5.0 $\mu g\ g^{-1}$. A median surface layer soil Cu concentration of 0.13 $\mu g\ g^{-1}$ represented the minimum soil concentration required for adequate crop growth for the DTPA soil test. Median surface soil Zn concentration of 2.18 $\mu g\ g^{-1}$ was slightly above the maximum critical value of 2.0 $\mu g\ g^{-1}$ while the subsoil Zn concentration of 0.12 $\mu g\ g^{-1}$ was just short of the minimum critical value of 0.2 $\mu g\ g^{-1}$. Based upon the critical ranges established for the DTPA soil test, the method best suited to calcareous soils, micronutrient soil test levels for the Marshall Island soils do

not appear to be uniformly low as reported in other studies (Caiger, 1987; Morrison, 1992). The critical ranges developed for the DTPA soil test should be applied cautiously to the Marshall Island soils because atoll soils are distinctly different from the soils on which these critical levels were developed. Specifically, the reported critical levels were developed on soils with a substantial clay fraction, and very low organic C levels.

There is a distinct rainfall gradient running from south to north across the Marshall Islands. Atolls located in the south experience significantly higher rainfall than the atolls in the north (Table 2.5). When other soil formation processes are held constant, soils in wetter climates tend to accumulate soil OC while soils in arid regions exhibit very low OC levels (Brady and Weil, 1999). In the Marshall Islands, topography and parent material do not vary across the gradient, but vegetation and soil organic matter

Table 2.5. The effect of latitude On precipitation levels in the Marshall Islands.

Atoll	Precipitation	Latitude
	mm yr^{-1}	
Enetwetok	1350	11.14
Kwajalein	2700	9.43
Majuro	3500	7.08
Jaluit	4100	5.55

content may respond to the distinct changes in moisture regime. We expect that vegetation would be denser on the wetter atolls, a factor that might lead to higher soil OC levels. Because OC is the principal reservoir of soil nutrients in coralline soils, regression analysis was used to test the hypothesis that the rainfall gradient affects soil

OC levels. Because rainfall data do not exist for each island, latitude was used as a proxy variable for rainfall. The results found in Table 2.6 indicate no clear relationship between

Table 2.6. Coefficient of determination values from linear regression analysis for different soil properties as dependent variables on latitude for the atolls in the Marshall Islands

Variable	Adjusted r^2
OC	0.01
N	-0.007
P	-0.007
K	0.03
Ca	0.01
Mg	0.03
B	0.07
Fe	0.11
Mn	0.01
Cu	0.09
Zn	0.18

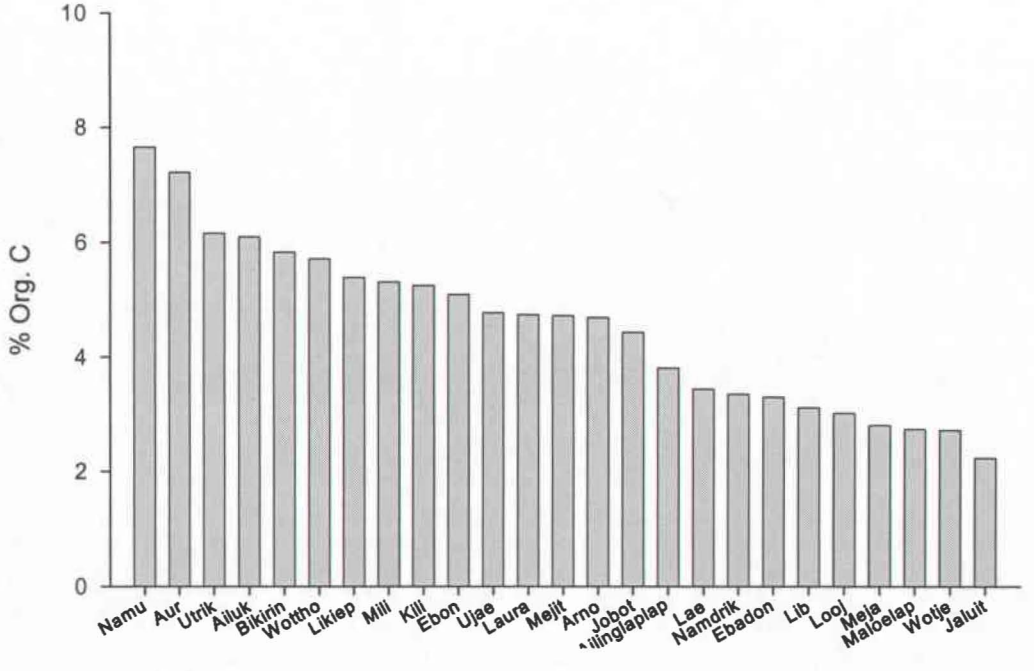


Fig. 2.3. Median organic C concentrations for soils from the 25 atolls sampled (atolls are not arranged according to latitude).

rainfall and soil OC levels. Median OC concentrations are highest on Namu and Aur (Fig. 2.3), both of which are centrally located atolls. The lowest concentrations were obtained for Jaluit Atoll located in the south, an atoll with relatively high rainfall.

Soil OC concentrations may also be affected by other factors such as island size or human activity. The larger islands within the atolls generally show deeper organic rich surface horizons over larger areas than the smaller islands suggesting higher OC concentrations in the soils of the larger islands. Humans can influence soil OC levels in several ways. Prolonged cultivation can deplete surface soil OC levels by the oxidation of soil organic matter. Humans can also enrich soil OC levels by continuous additions of plant residues to the soil. The traditional taro pit cultivation practiced by Micronesians is a good example of this (Ali and Asghar, 1992). Further correlation analysis was performed and found that OC levels for each island were not correlated to population, area, or population density. There were insufficient data to look at the effect of island size and human activity on soil OC levels. Based upon the available data, it appears that there are no clear geographical trends affecting the distribution of soil OC or other plant nutrients.

In atoll soils, the lack of any clay fraction means that plant nutrient reserves are essentially limited to the organic matter content of the soil. Earlier studies have emphasized the important role organic matter plays in atoll soil fertility (Morrison, 1990; Stone et al., 2000). Correlation analysis was conducted to determine whether soil nutrient concentrations were related to soil OC levels. The results displayed in Table 2.7

show that total N and Ca were highly correlated with soil OC levels with coefficients around 0.9, K, Mg, and B showed poorer correlation with coefficients between 0.5 and 0.6, and P and the micronutrients were not correlated to OC levels with coefficients less than 0.33. Graphical display of the data, however, shows that extreme values can

Table 2.7. Correlation coefficients and significance levels between soil nutrients and pH, EC, Organic C, and exchangeable Ca for pooled data from all islands.

Nutrient	pH		EC		Org. C		Exch. Ca	
	Corr. Coeff.	p-values	Corr. Coeff.	p-values	Corr. Coeff.	p-values	Corr. Coeff.	p-values
N	-0.6537	<0.0001	0.8695	<0.0001	0.8886	<0.0001	0.8338	<0.0001
P	-0.2643	0.001	0.2093	0.0099	0.3392	<0.0001	0.3378	<0.0001
K	-0.4486	<0.0001	0.5955	<0.0001	0.7524	<0.0001	0.6015	<0.0001
Ca	-0.6104	<0.0001	0.7116	<0.0001	0.9151	<0.0001	-	<0.0001
Mg	-0.381	<0.0001	0.8425	<0.0001	0.6536	<0.0001	0.5601	<0.0001
Na	-0.3997	<0.0001	0.8784	<0.0001	0.5571	<0.0001	0.4986	<0.0001
B	-0.474	<0.0001	0.8742	<0.0001	0.6144	<0.0001	0.5045	<0.0001
Mn	-0.173	0.0336	0.0153	0.852	0.1883	0.0206	0.1498	0.0664
Fe	0.0532	0.0935	0.2558	0.0015	0.1868	0.0217	0.2326	0.0041
Cu	0.0532	0.5162	-0.0045	0.9558	-0.0633	0.4402	-0.0598	0.466
Zn	0.041	0.6176	-0.0047	0.9548	-0.0387	0.6367	-0.0298	0.7165

disproportionately influence the strength of the relationship. For example, figure 2.4 and 2.5 show that the strength of the relationship of extractable Ca with OC may be exaggerated by a few extreme values. These extreme values correspond to those points that lie outside of the box plots found in Fig. 2.2. When these values were removed, the strength of the relationship decreased. For total N, on the other hand, removing the points deemed outliers did not change the relationship (Fig. 2.6 and 2.7). Results of regression analysis using both the complete data set and the data set where the extreme values were removed showed that including or excluding the extreme points changed the relationship between OC and soil nutrients.

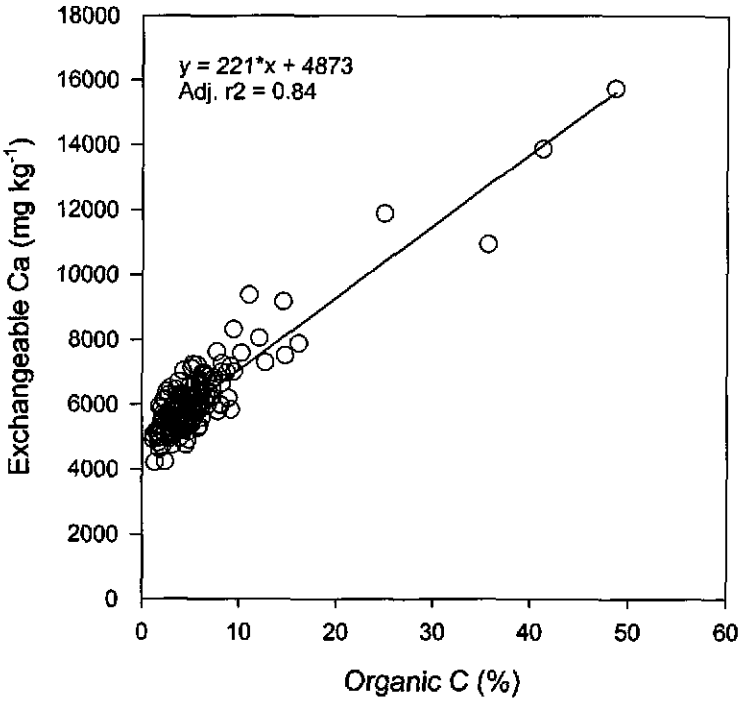


Fig. 2.4. Scatter plots showing the relationship of exchangeable Ca and organic C when all the data were included in the calculation.

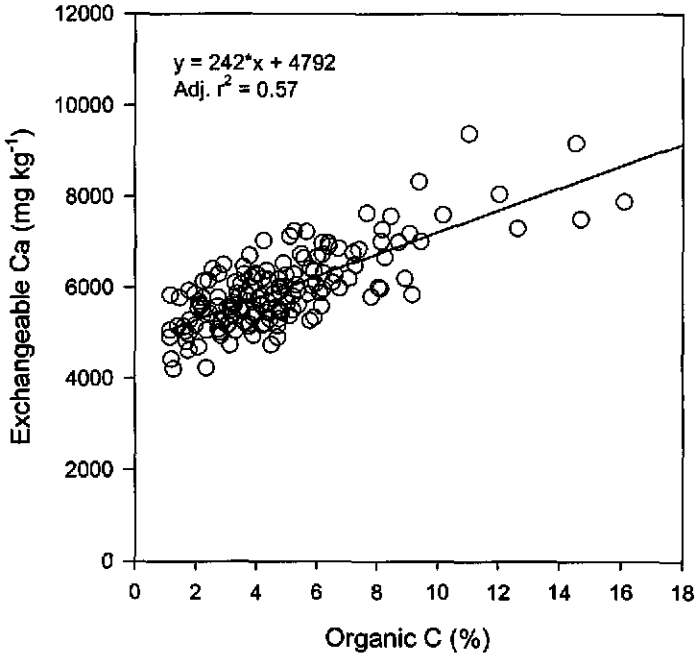


Fig. 2.5. Scatter showing the the relationship of exchangeable Ca and organic C when extreme values were excluded from the calculation.

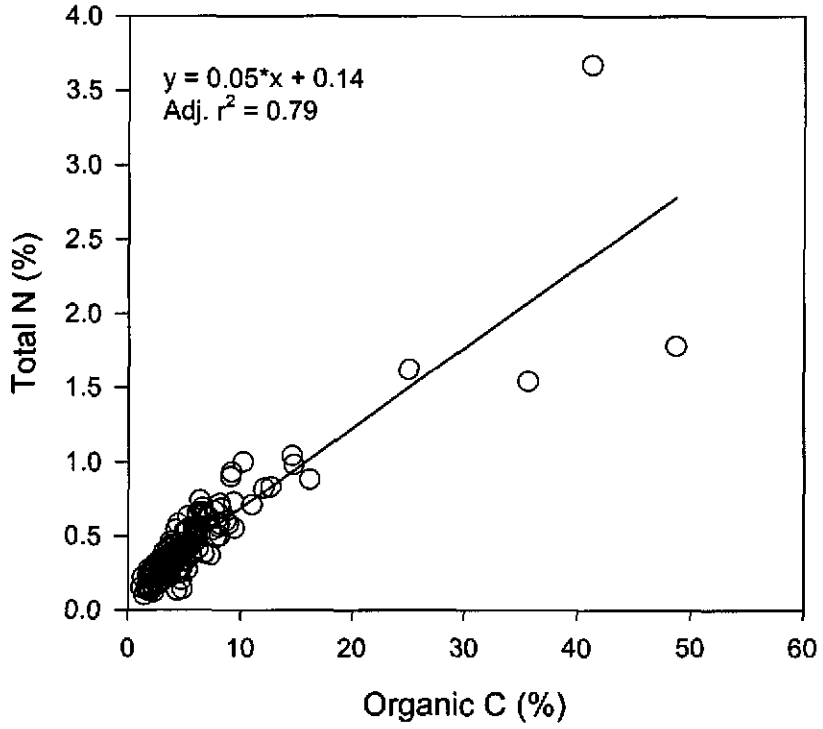


Fig. 2.6. Scatter plot showing the relationship between total N and organic C when all the data were included in the calculation.

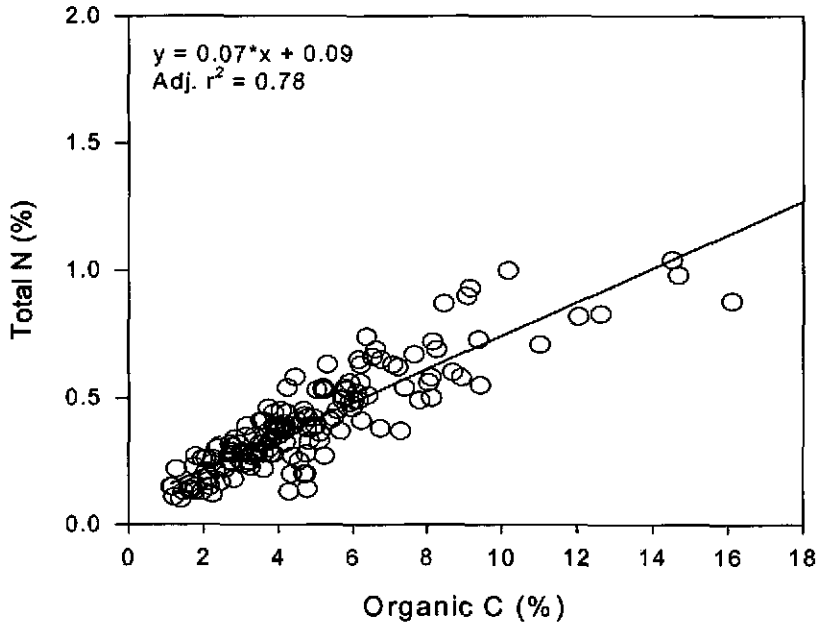


Fig. 2.7. Scatter plot showing the relationship between total N and organic C when extreme values were removed from the calculations.

Electrical conductivity is a relatively simple measurement that measures the total concentration of ionic species in solution. Because soil laboratories capable of conducting more sophisticated soil analyses are not available in the Marshall Islands, establishing whether meaningful relationships exist between EC and soil nutrient status would be an important step towards soil fertility diagnosis. Correlation analysis was performed to determine the relationship between EC and the concentration of the different nutrients in the surface soil (Table 2.8). Highly significant Pearson correlation coefficients showed that EC was correlated with the extractable cations and total soil N when all the data were included in the calculations. Regression analysis showed that the values at the higher end of the EC scale may have been over- influencing the relationship (Fig. 2.8). When the values that were larger than 3 standard deviations from the mean

Table 2.8. Results of regression analysis with EC as the independent variable when all the data were included and when outliers were removed.

Nutrient	Complete Data		Outliers Removed	
	Adj. r2	p-values	Adj. r2	p-values
N	0.87	<0.0001	0.46	<0.0001
P	0.21	0.0099	0.19	0.03
K	0.60	<0.0001	0.60	<0.0001
Ca	0.71	<0.0001	0.29	0.001
Mg	0.84	<0.0001	0.47	<0.0001
Na	0.88	<0.0001	0.34	<0.0001
B	0.87	<0.0001	0.38	<0.0001
Mn	0.02	0.0336	0.05	0.58
Fe	0.26	0.0935	0.51	<0.0001
Cu	0.00	0.5162	0.06	0.54
Zn	0.00	0.6176	0.01	0.92

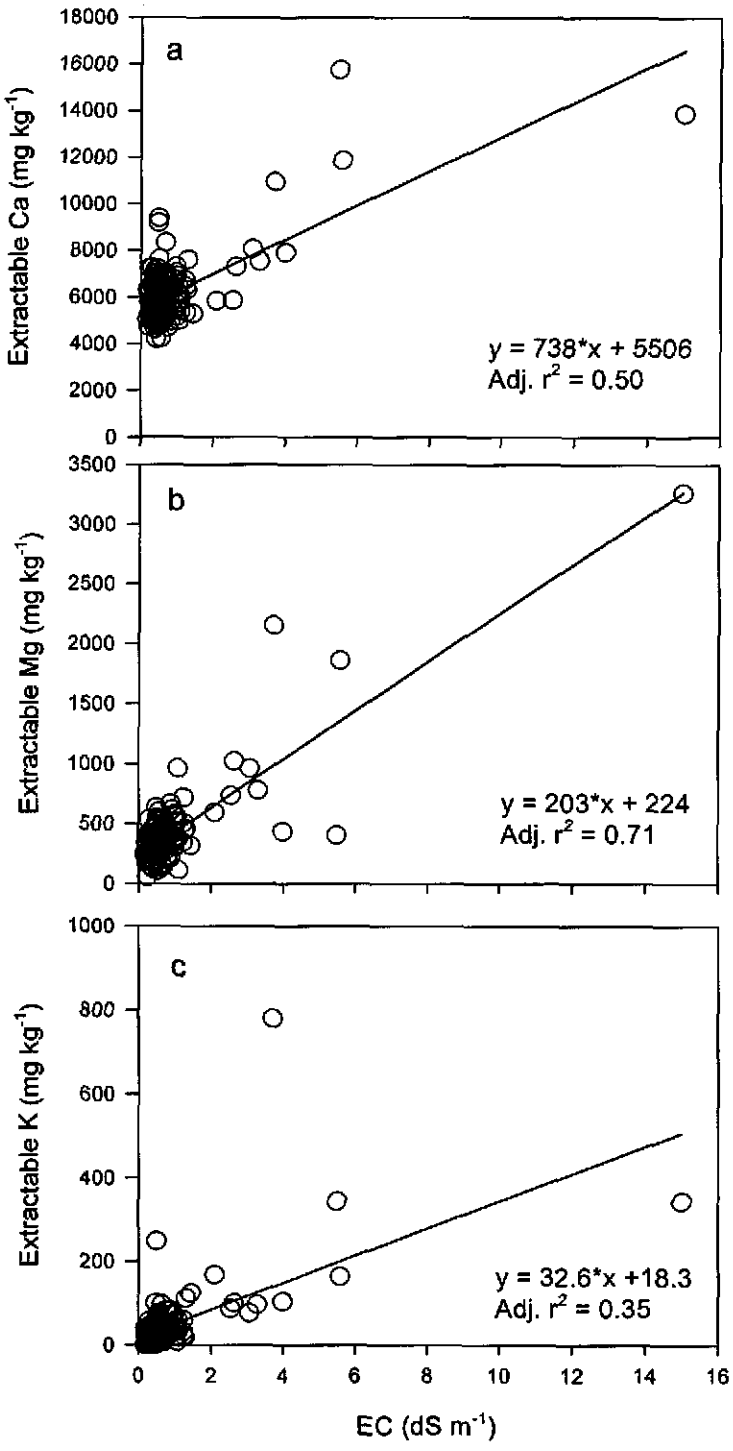


Fig. 2.8. Results of regression analysis between EC and extractable Ca (a), Mg (b), and K (c) when all data were included in the calculation.

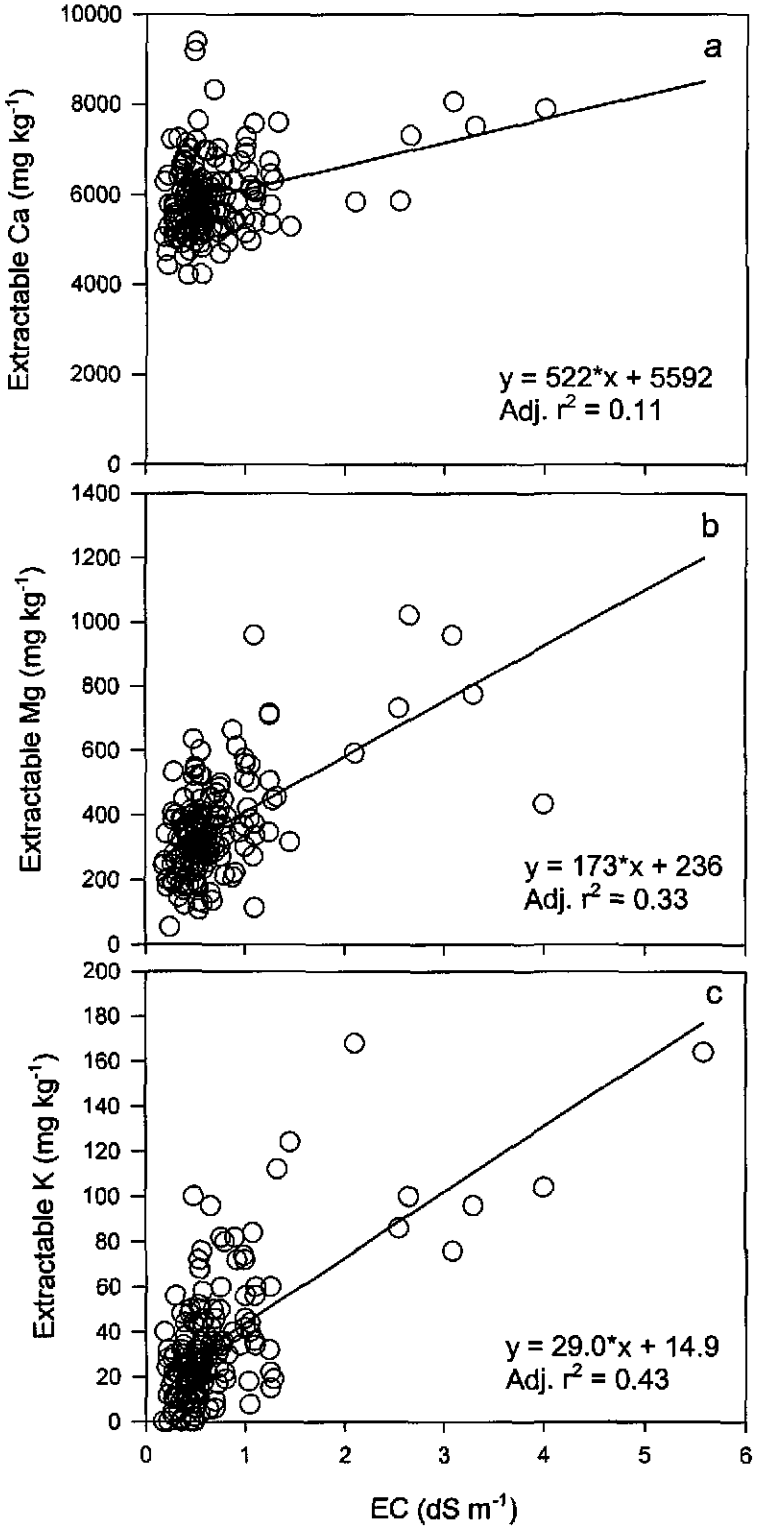


Fig. 2.9. . Results of regression analysis between EC and extractable Ca (a), Mg (b), and K (c) when outliers were removed from the calculations.

were removed, the Pearson correlation coefficients dropped noticeably for Ca and Mg, but remained constant for K. In Figure 2.9 it is clear that for the most common EC values ranging from 0.2 to around 1.5 dS m^{-1}, there was no clear relationship with extractable Ca, Mg, or K. As EC values increase to 4.0 dS m^{-1} a linear relationship was apparent. Based upon these results, EC cannot be used as a simple measurement to predict cation concentration in the Marshall Island soils.

Clearly, the presence of extreme values complicates interpretation of the data on an island-wide basis. The particular distribution of the data may have been influenced by the difficult circumstances under which the samples were collected and the inexperience of personnel dispatched to collect samples. In order to assess the native fertility of a soil, the sampling site should limited to areas that are representative of the native vegetation and free of human activity. These conditions cannot be confirmed for all the island sampling sites with the exception of Bikirin Island (Majuro Atoll) and Arno Island (Arno Atoll). Bikirin Island has been uninhabited for the last 50 years so all 9 sampling locations were representative of undisturbed native vegetation. On Arno, three transects located in undisturbed native forest running from the ocean side of the island to the lagoon were sampled. The transects consisted of two sampling locations on the ocean, center, and lagoon side of the island for a total of six locations per transect. A comparison of the data distribution between the data for Arno and Bikirin and the complete dataset from the island-wide sampling is displayed in Figure 2.10. The sampling design on Bikirin and Arno, confined to undisturbed native vegetation, reduced the number of extreme values. The box plots show clearly that the island-wide sampling procedure contained disproportionately more data points that fell outside of the whiskers

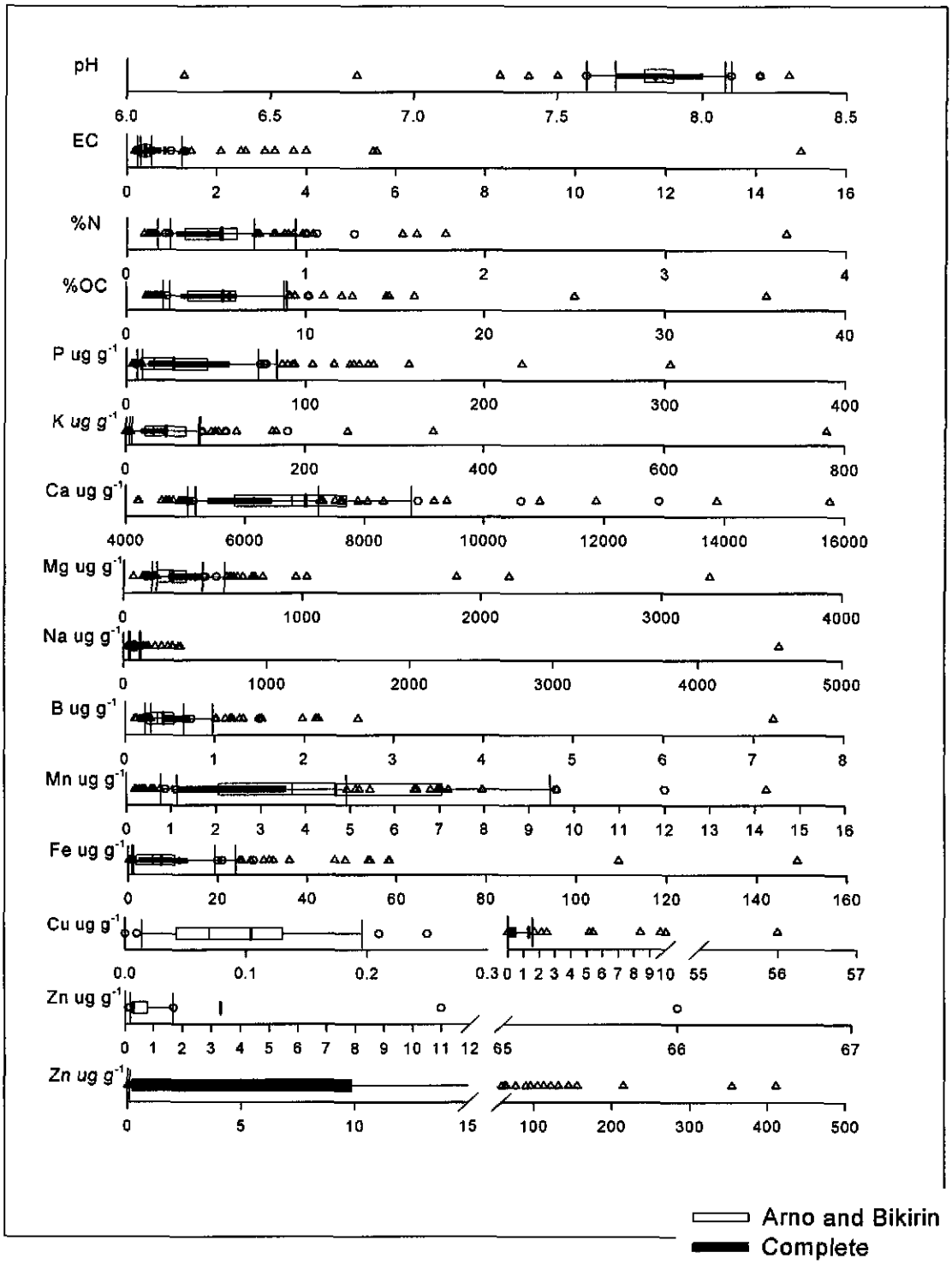


Figure 2.10. Box plots comparing data distribution between island-wide sampling scheme (△) and samples from undisturbed sites on Arno and Bikirin (○).

compared with the samples from Arno and Bikirin. This was especially apparent for the micronutrients. Sampling areas close to human habitation and activity can have important effects on soil chemical properties. In the Marshall Islands, it is common practice to dig trenches in the vicinity of households to dump household waste, including metal cans and containers. As the trenches fill up, others are dug on the property. This practice may explain the extremely high values found for Cu and Zn in the island-wide data set.

Organic C concentration of the surface soils from Arno and Bikirin showed a strong relationship with total N and extractable Ca, and K concentrations (Fig. 2.11). The strong correlation between OC and Ca and K probably reflects the important role organic matter plays in CEC for these soils. Organic C showed a weaker relationship with the other soil nutrients, limiting its use a means to predict soil nutrient levels. The more rigorous sampling design conducted on Arno and Bikirin improved the capacity of OC to predict total N and extractable Ca and K concentration in the soil, but showed no significant improvement for the remaining soil nutrients. Extending this type of sampling to several more atolls may be worth the time effort to see whether the use of one or two soil measurements can be used reliably to predict soil nutrient availability on an atoll-wide scale. Establishing clear relationships of this nature will help guide soil management decisions, and improve the diagnostic capabilities of extension workers with limited laboratory equipment. The use of calibrated soil test kits to guide farmers may be an appropriate alternative because they are simple to use, mobile, and relatively inexpensive.

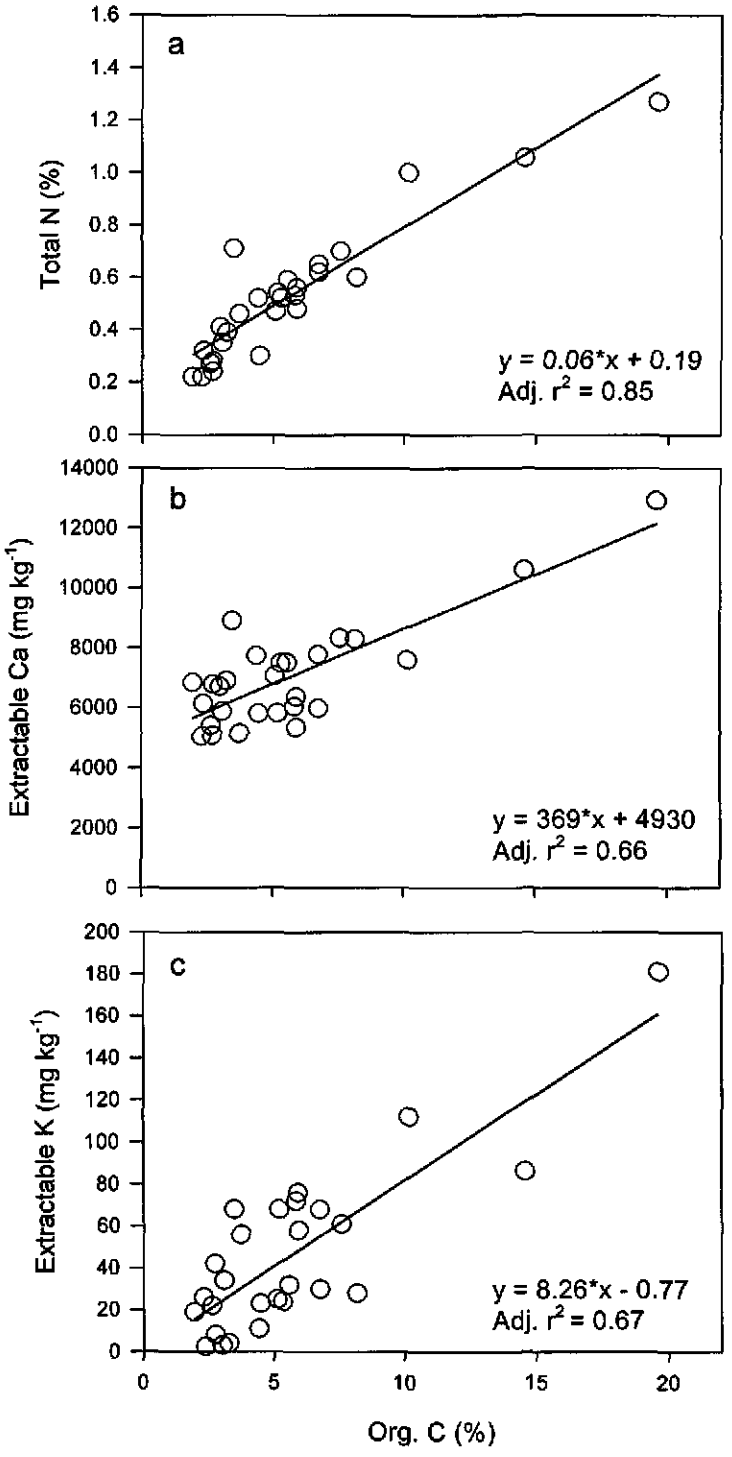


Fig. 2.11. The relation ship between org. C and total N (a) and extractable Ca (b) and K (c) for the surface soils collected from Arno and Bikirin islands.

The physical properties of soils in the Marshall Islands vary according to their location within the island environment. This variation is controlled by distance from the ocean shoreline. Soils close to the ocean shoreline contain a higher proportion of coarse fragments. Coarse fragment composition decreases toward the center of the island and transitions into a soil dominated by fine sand adjacent to the lagoon shoreline (Stone, 1951; Morrison, 1990). Using the samples collected on Bikirin and Arno Islands, the effect of location within island was tested using nonparametric analysis. The results are presented in Table 2.9. The Kruskal-Wallis test found a significant trend in nutrient availability based upon island location. Significantly lower ($p<0.05$) concentrations of soil N, P, and K were found in the coarser soils along the ocean shoreline compared with the central and lagoon locations. Organic C concentrations were highest at the lagoon location and lowest at the ocean sites. The macronutrients showed a similar trend. Soil pH showed an increasing trend moving from the lagoon to the ocean shoreline while soil Mg concentrations were lowest in the center of the island and highest at the lagoon locations. Variability in the concentration of the micronutrient was high, but for Mn, Fe, Cu, and Zn the highest levels were obtained at the ocean sites. Traditional agricultural practices that concentrated food crop production to the center and lagoon portion of the islands (Raynor, 1992; Thaman, 1992a; Manner, 1993) appear to have exploited the natural trends in soil chemical properties.

Table 2.9. Mean values, Wilcoxon scores (rank sum), and Kruskal-Wallis test results for soil chemical properties classified by within island location.

Determination	Location	N	$\bar{X}$	Mean Score	X^2	$Pr>X^2$
pH	Lagoon	8	7.84	12.5	4.935	0.085
	Center	11	7.82	11.5		
	Ocean	8	7.95	19.0		
EC	Lagoon	8	0.46	13.4	0.907	0.636
	Center	11	0.46	15.7		
	Ocean	8	0.35	12.3		
OC	Lagoon	2	7.68	6.50	4.329	0.115
	Center	5	5.63	5.80		
	Ocean	2	2.53	1.50		
N	Lagoon	8	0.69	17.3	6.499	0.039
	Center	11	0.53	16.0		
	Ocean	8	0.36	8.06		
P	Lagoon	8	38.3	19.1	10.10	0.006
	Center	11	28.2	15.5		
	Ocean	8	13.6	6.88		
K	Lagoon	8	71.7	17.9	8.189	0.017
	Center	11	47.7	16.0		
	Ocean	8	17.7	7.38		
Ca	Lagoon	8	7907	16.1	0.815	0.665
	Center	11	6618	13.1		
	Ocean	8	6668	13.1		
Mg	Lagoon	8	315	17.6	4.792	0.091
	Center	11	238	10.0		
	Ocean	8	287	15.9		
Na	Lagoon	2	98.0	7.50	3.333	0.189
	Center	5	78.8	5.00		
	Ocean	2	56.0	2.50		
B	Lagoon	8	0.46	17.1	3.200	0.202
	Center	11	0.49	14.5		
	Ocean	8	0.33	10.1		
Mn	Lagoon	8	5.66	16.3	4.200	0.123
	Center	11	5.14	15.8		
	Ocean	8	3.04	9.19		
Fe	Lagoon	8	5.81	12.6	0.373	0.830
	Center	11	6.63	14.6		
	Ocean	8	10.4	14.6		
Cu	Lagoon	8	0.10	13.0	0.187	0.911
	Center	11	0.08	14.3		
	Ocean	8	0.14	14.6		
Zn	Lagoon	8	0.77	16.3	1.265	0.531
	Center	11	0.35	12.2		
	Ocean	8	9.95	14.2		

Missing Element Study

Analysis of soil chemical properties on their own may elucidate important relationships and trends, but they do not necessarily determine the fertility and productive capacity of the soils, especially when the soil tests have never been calibrated to crop growth and yield. In order to get a preliminary evaluation of the native fertility of Marshall Island soils and the reliability of the soil tests, a missing element study was conducted. Corn yield data from the missing element study indicate that the *Laura* soil suffers from multiple nutrient deficiencies (Fig. 2.12). Corn in the unamended soil grew very poorly with dry matter yields 75% less than in the control treatments where the pots received a blanket nutrient solution. Corn dry matter yield was significantly ($P<0.05$) decreased in the treatments where K, S, N, P, and Cu were withheld. Potassium appears

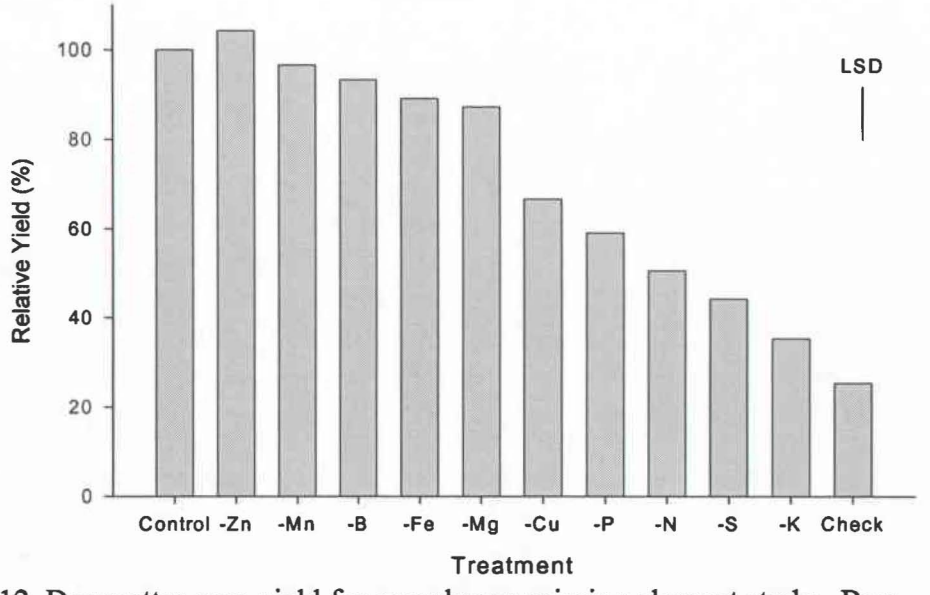


Figure 2.12. Dry matter corn yield for greenhouse missing element study. Bars represent means of three replications.

to be the most limiting soil nutrient. When K was not added to the pots, corn growth decreased by 65%. In the absence of N corn grew only 50% as well, and removing S decreased growth by 56%. Subtracting P reduced dry matter production by 40%, and in the absence of Cu dry matter yield decreased by 34%. When Mg, Fe, B, and Mn were not added to the pots, corn growth decreased only slightly, but not significantly from the control. Yields were not affected by subtracting Zn from the pots.

Tissue analysis of the corn biomass (Table 2.10) shows that N and P tissue concentrations for all treatments, including the two control treatments, fell below the critical range. In both cases, plants in the –N and –P treatments had the lowest N and P tissue concentrations. Phosphorus concentration in the tissue was low for all the treatments including the two controls receiving the full range of nutrients. The low P content of the plants may have been caused by an insufficient P addition rate or because the whole plant including the stalk were analyzed for P. Tissue K concentrations fell within the sufficiency range for the control treatments, but were approximately ten times lower in the –K and check treatments. Calcium concentrations were generally above the sufficiency level in all treatments and especially high in the check and –K treatments where the least amount of plant growth occurred. Similarly, leaf Mg concentrations were either within the critical range or above it. Sulfur tissue concentration was unusually high in the –S treatment. The high value may have been caused by the very low biomass recorded in this treatment, thus inflating the concentration value. The poor growth exhibited by the corn in the –S treatment suggested a an S deficiency in the soil, but the high S concentration in the tissue made it difficult to assign the poor growth to a S deficiency. Leaf B levels fell within the critical range and were lowest in the –B

Table 2.10. Treatment effects on nutrient concentrations in above ground biomass of corn plants grown in greenhouse for 42 days.

Treatment	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn
	%						$\mu g\ g^{-1}$				
Check	1.57de	0.23ab	0.38e	1.48a	0.76a	0.17efg	12.0abcd	65.7abc	30.7	2.67a	20.0bcd
Control A	2.30c	0.11cd	3.22cb	0.87b	0.35bc	0.20def	12.3abcd	75.3abc	8.33d	5.67a	18.0bcd
Control B	2.44c	0.12cd	3.19cb	0.80b	0.37b	0.22de	12.0abcd	70.3abc	9.67cd	3.33a	20.3bcd
-N	1.03e	0.15bc	2.80cd	0.73b	0.26bc	0.21de	12.7abc	45.7c	9.00d	2.00a	11.0cd
-P	2.60bc	0.10d	3.53b	0.88b	0.28bc	0.36c	13.3ab	74.3abc	12.7cd	3.67a	23.7bcd
-K	3.33a	0.23a	0.29e	1.31a	0.80a	0.57a	14.0a	106a	16.3bc	4.33a	17.3bcd
-Mg	2.40c	0.12cd	3.24bc	0.72b	0.27bc	0.39c	10.0bcd	75.7abc	12.0cd	1.67a	17.7bcd
-S	2.52bc	0.10cd	3.36bc	0.75b	0.23c	0.46b	12.7abc	77.0abc	15.0bcd	2.67a	32.7ab
-B	2.17cd	0.11cd	2.89cd	0.76b	0.33bc	0.39c	8.67d	59.0bc	9.67cd	6.00a	17.3bcd
-Cu	3.17ab	0.23a	4.34a	0.86b	0.33bc	0.22de	11.3abcd	88.7ab	22.0b	1.00a	43.0a
-Fe	1.92cd	0.10d	2.74cd	0.78b	0.34bc	0.23d	9.00cd	52.3bc	11.3cd	2.00a	15.7cd
-Mn	2.03cd	0.09d	2.77cd	0.77b	0.30bc	0.13g	12.0abcd	69.7abc	8.33d	2.33a	25.0bc
-Zn	2.12cd	0.10d	2.41d	0.74b	0.31bc	0.14fg	11.0abcd	66.0abc	9.33cd	3.33a	9.33d
Critical Range†	3.50-5.00	0.30-0.50	2.50-4.00	0.30-0.70	0.15-0.45	0.15-0.50	5-25	20-300	20-300	5-20	20-60
F-test	***	***	***	***	***	***	0.0005	0.003	***	ns	***
CV (%)	10.3	12.5	7.81	7.97	12.2	7.33	10.7	19.1	17.9	91.7	24.9

***Significant at the 0.0001 probability level.

ns = not significant. Within column means followed by a different letter differ significantly at the 5% probability level by Tukey's test.

† For whole plant <12" tall (Mills and Jones, 1997)

treatment, but the –B concentrations were not significantly different from the controls. Tissue Fe concentrations fell within the sufficiency range, but tended to be low across all treatments. Iron concentration in the –Fe treatment was not significantly different from the controls. Leaf Mn levels were below the critical limit with the exception of the check and –Cu treatments. Both the controls and the –Mn treatments exhibited very low Mn levels without seemingly affecting plant growth or showing any visual deficiency symptoms. Copper levels were generally below the critical level in all treatments with no significant differences between treatments due to high variability within treatments. Zinc concentration in the leaf was generally low across all treatments with the –Zn treatment having the lowest concentrations. Corn biomass in the –Zn treatment, however, was not significantly different from the controls.

The nutrient supply capacity of the *Laura* soil was evaluated by comparing differences in nutrient uptake by the corn plants (Table 2.11). Nitrogen uptake was four times less in the –N treatment and five times less in the check. When P,K and S were withheld from the nutrient solution reduction in plant growth caused significantly less N uptake than in the controls suggesting that there were probably significant interactions among these nutrients. Phosphorus supply to the corn plants was significantly lower in the –P treatment compared to the control. Poor growth in the check and the –S treatments resulted in the lowest levels of P uptake. Removing the other nutrients did not significantly impact P uptake. Potassium uptake in the –K treatment was more than 30 times less than in the controls, and in the absence of N, P,

Table 2.11. Treatment effects on nutrient uptake in above ground biomass of corn plants.

Treatment	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn
	----------mg pot^{-1}----------						----------µg pot^{-1}----------				
Check	46.8f	5.87d	11.5d	44.1e	22.6cde	4.99e	35.9g	196f	91.4bc	8.00a	59.7f
Control A	273ab	12.9b	380a	103a	41.5ab	23.6bc	146a	887a	98.1bc	68.1a	213bcd
Control B	285a	14.0ab	372a	93.5ab	43.5a	26.0b	140ab	819ab	112bc	37.7a	237abc
-N	61.6ef	9.18bcd	167c	43.5e	15.8e	12.3de	75.7efg	273ef	54.1c	12.1a	65.8ef
-P	184bcd	7.06cd	247bc	61.6cde	19.9de	25.3b	93.1def	521cd	88.8bc	25.5a	164cdef
-K	140cde	9.38bcd	11.8d	54.5de	33.5abcd	23.9bc	58.3fg	418de	66.2bc	17.7a	71.4ef
-Mg	246ab	12.4bc	333ab	73.3bcd	27.4bcde	40.0a	103bcde	776ab	123ab	17.0a	182bcde
-S	132def	5.44d	175c	39.4e	12.0e	23.9bc	66.5efg	404de	78.5bc	14.0a	169bcdef
-B	239ab	12.1bc	318ab	83.7abc	35.9abc	43.4a	95.3cdef	650bc	106bc	69.3a	191bcd
-Cu	248ab	18.6a	344ab	66.8bcde	26.1bcde	17.5bcd	87.7ef	696abc	173a	7.87a	337a
-Fe	201abcd	10.6bcd	287ab	82.3abcd	35.6abc	24.1bc	94.6cdef	547cd	118ab	21.4a	164cdef
-Mn	232abc	10.3bcd	316ab	88.2abc	33.7abcd	14.5cde	136abc	794ab	95.2bc	26.8a	286ab
-Zn	255ab	12.3bc	292ab	90.3ab	38.3ab	16.9bcd	135abcd	798ab	116ab	38.6a	113def
F-test	***	***	***	***	***	***	***	***	***	ns	***
CV (%)	15.8	17.6	14.3	13.2	17.6	14.6	14.4	11.5	19.8	117	22.7

and S, K uptake was significantly lower than in the controls. These results show the severity of the K deficiency problem in these soils. Calcium and Mg uptake were significantly lower in the check, -N, -P, -K, and –S treatments due to poor growth in these treatments. Sulfur uptake in the check and -N treatments was significantly lower than in the controls, but not different in the –S treatment despite significantly lower yields. This result suggests that withholding S may be inducing N deficiency rather than S deficiency. Boron uptake was lowest in the check, and significantly decreased in the absence of N, P, K, S, B, Cu, and Fe. Besides the check, the -K and -Cu treatments showed the lowest levels of B uptake. Iron uptake was lowest in the check, and significantly lower in the -Fe treatment and when the macronutrients were not included in the nutrient application. Manganese uptake was not significantly impacted by not adding Mn to the soil, but in the absence of N, Mn uptake was significantly reduced compared to the controls. No significant differences were detected in Cu uptake by the corn plants. However, the lowest values were obtained in the -Cu and check pots. Zinc uptake was highest in the -Cu, -Mn, and Control B (complete nutrients + Mo) treatments, and significantly depressed in thetreatments with the lowest growth (-N, -K, and check). In the -Zn treatment, uptake was significantly lower than in the Control B treatment, but not significantly different than in the Control A treatment. It appears that a high growth rate in the -Zn pots stimulated uptake of the native soil Zn.

The results of the missing element study confirmed the findings of previous studies showing that atoll soils were deficient in N and K (Finlay, 1987; Reddy and Chase, 1992; Gangaiya and Morrison, 1998). Depressed corn yields in the absence of

P additions confirmed the expectation of P deficiency in coralline atoll soils with high pH and soluble Ca levels (Morrison, 1992) based upon the tendency for P to form insolublke Ca compounds, but no previous experimental work exists quantifying the complex reactions controlling P in atoll soils. Contrary to earlier work where atoll soils were found to be deficient in Fe (Trewren, 1985) and Zn (Widdowson and Trangmar, 1992), the present study found that the *Laura* soil did not show significant deficiencies in either Fe, Mn, or Zn. In fact, corn growth showed the highest yields in the –Zn treatment. Slightly more chlorotic young leaves in the –Fe treatment was the only indication of an Fe deficiency. The visual symptoms, however, were not accompanied by tissue Fe levels below the critical level. Copper appears to be the only micronutrient significantly limiting growth in this soil. The B status of the soil is difficult to evaluate because the soil and plant uptake data for B indicate a probable deficiency, but corn growth was not significantly depressed in the –B treatment. Earlier experimental work (Finlay, 1987b; Widdowson and Trangmar, 1992) does not mention either a Cu or a B problem in atoll soils. Similarly, the apparent S deficiency in this soil was unexpected based upon the high organic matter content and the likelihood that sea spray was an important contributor of SO_4^{2-}. Interpreting the reduced yields in the –S treatment as solely due to a S deficiency in the soil may be misleading because corn plants in the –S treatment had unusually high S concentrations. The results of this experiment suggest that S may be a problem in these soils, but further work is required to fully characterize S dynamics in these soils. Several factors may contribute to a potential S deficiency in this soil: 1) loss by

leaching due to coarsely textured soil and high rainfall, 2) co-precipitation with $CaCO_3$, and 3) immobilization in the stable organic matter fraction.

Soil Test Evaluation

Assessing the fertility of atoll soils is difficult because no previous work exists calibrating standard soil tests to crop response in these particular soils. Results from the missing element experiment were used as a preliminary evaluation of specific soil tests and their suitability to diagnose nutrient deficiencies in atoll soils. Table 2.12 summarizes the performance of the soil test in diagnosing soil nutrient deficiencies based upon the greenhouse study. For K, B, Cu, Fe, Mn, and Zn expected response based on established soil critical levels and observed yield response determined by experiment were in agreement. Tissue concentrations and yield response, however, showed clear discrepancies for Zn and Mn. Yield response for the –Mn and –Zn

Table 2.12. Evaluating soil test suitability for nutrient deficiency diagnosis on an atoll soil based on missing element results.

Element	Soil Test	Critical Level	Laura Soil	Deficiency	
		mg kg^{-1}		Expected	Observed
P	Olsen ($NaHCO_3$)	10	50.0	No	Yes
K	NH_4OAc pH 7.0	200-400	21.3	Yes	Yes
Mg	"	600-800†	221	Yes	No
SO_4^{2-}-S	H_2O extractable	4.0-5.0‡	6.67	No	Yes
B	Hot H_2O Extractable	0.1-2.0§	0.73	No	No
Cu	DTPA Extractable	0.1-2.5§	0.13	No	Yes
Mn	"	1.0-5.0§	7.37	No	No
Fe	"	2.5-5.0§	27.7	No	No
Zn	"	0.2-2.0§	3.40	No	No

†For soils with low bulk density (Tamimi et al., 1993)
‡ Fox et al., 1964
§ Sims and Johnson, 1991

treatments were not significantly different from the complete control, but nutrient tissue concentrations were well below the critical concentrations. The low tissue concentrations suggest that Zn and Mn supply to the plants were not at an optimum level, but these low values were not accompanied by yield reduction or the appearance of visual deficiency symptoms. Iron concentration in the –Fe treatment was borderline sufficient. Further work is required to clarify micronutrient availability and yield response in these soils.

Expected response and observed response were not in agreement in the case of P. For calcareous soils, the Olsens procedure is recommended to estimate plant available soil P (Kuo, 1996). The critical level below which a P deficiency is expected has been established at 10 mg kg^{-1} (Thomas & Peaslee, 1973). Initial Olsen extractable soil P concentration in the *Laura* soil was determined to be 50 ug g^{-1}, fivefold higher than the established critical level. Poor growth and low leaf P concentration in the –P treatment, however, clearly indicated that native soil P levels were inadequate to maintain good corn growth. The established critical level was developed on clayey calcareous soils extremely low in organic carbon found in dry climates. The soils in the Marshall Islands represent the opposite end of the spectrum – no clay, high organic carbon, and a wet climate. The unique mineralogy and chemical nature of the Marshall Islands soils require that further work be carried out to determine a suitable critical level for the Olsen P extraction.

Interpreting the water extractable SO_4-S levels in the *Laura* soil are problematic. Fox et al. (1964) applied the same test to a range of soils and found that field grown corn plants were S deficient when water extractable SO_4-S was below 4.0

ppm (in solution). They reported slight deficiency between 4.0 to 6.0 ppm. The *Laura* soil showed extractable SO_4-S just above the slightly deficient range proposed by Fox et al. (1964). In soils with appreciable amounts of weathered clay, S supply can be maintained as the soil solution S is replaced with S adsorbed onto the clay fraction. In the *Laura* soil, on the other hand, there is no clay fraction capable of replenishing S taken up by the plant, and therefore, potential S deficiency becomes a problem. Like phosphorus, the low buffering capacity of these soils increases the likelihood of S deficiency. The organic matter fraction in these soils represents the most important source of S and procedures that can measure S in this fraction may be more appropriate. Heat soluble S may be a better measure of the S status in these soils because the organic matter plays such a critical role in nutrient dynamics (Fox et al., 1964).

Critical levels for exchangeable Mg have been set at 300-400 mg kg^{-1} for coarse soils developed from volcanic parent material with high organic matter content and low bulk densities (designated a'a land) in Hawaii (Tamimi et al., 1993), but corn yield was only slightly less in the –Mg treatment despite a relatively low concentration of exchangeable Mg concentration of 221 mg kg^{-1} in the *Laura* soil. The Marshall Island soil, despite its coarse texture, contains significant amounts of Mg in the parent material (Stone. 1951), and furthermore, is high in organic carbon, which imparts considerable CEC. The combination of these two factors may supply adequate amounts of Mg for the short term at least.

Boron deficient soils are rare and therefore critical soil test levels for B continue to be poorly defined. Critical levels for hot-water-soluble B range from 0.1

to 2.0 mg kg^{-1} (Sims and Johnson, 1991). Based upon this range, soil B levels in the *Laura* soil fall within the established critical level. Corn yield was not significantly decreased in the –B treatment confirming the validity of the critical soil test level. Tissue data show that B levels for all treatments fall within the critical concentrations for corn providing further evidence that the soil contains adequate levels of B.

Atoll-wide Fertility Assessment

Based upon the results of the missing element study and the evaluation of the soil test results, a preliminary fertility assessment of all 25 Atolls can be performed. Using soil nutrient concentrations of the Laura soil used in the missing element study as the benchmark, means for all the nutrients for each island were calculated excluding extreme values, and a two sample t-test was performed to compare soil test results for each soil nutrient with the soil test for the *Laura* soil (Table 2.13). The t-test was not performed on K because exchangeable K levels on all atolls fell well below the critical level. It is clear that K deficiency is a severe problem on all atolls in the Marshall Islands. Based upon the t-test, mean soil P levels on five islands were significantly lower than P concentration in the *Laura* soil, and P levels on the remaining islands were similar to the *Laura* soil. Using the results of the missing element study as a measure of P availability in the Marshall Islands soils, we would expect P deficiency to be highly likely on the soils with a significantly lower soil P level. Fifteen islands had P levels between 20 and 60 mg kg^{-1}, which is less than or equal to the *Laura* soil, and may also be P deficient based upon the missing element study. Five islands had P levels above 60 mg kg-1, and their status is difficult to

assess in terms of deficiency because no P critical range exists for these soils.on results from the missing element study. Magnesium levels fell below the critical level established for volcanic a'a soils of Hawaii, and were generally not different from the level found in the *Laura* soil. On Mejit and Utrik, two northerly atolls, Mg concentrations were significantly higher than the level found in the *Laura* soil. Rainfall on the northern atolls is significantly lower than on the southern atolls and the higher Mg levels in the northern atolls may be attributed to less exposure to leaching. Based upon the results of the missing element study, native exchangeable Mg levels appear to be sufficient throughout the atolls. These results suggest that the critical Mg level developed for the a'a soils of Hawaii by Tamimi et al. (1993) may be too high for sandy coralline atoll soils high in organic matter.

Table 2.13. Mean and median soil nutrient concentrations for each island and results of paired t-test between missing element soil and samples collected from each island.

Island	P	K	Mg	B	Mn		Fe		Cu		Zn	
					mg kg^{-1}							
	mean				mean	median	mean	median	mean	median	mean	median
Mili	20.0*	43.5	351	0.79*	2.68*	3.24	5.61*	4.10	0.45	0.24	5.23	4.56
Likiep	15.8*	30.8	332	0.73*	2.49*	2.68	10.6*	12.5	0.33	0.11	1.69	0.18
Jobot	26.3	37.9	334	0.50	3.25*	2.96	8.60*	4.62	0.12	0.11	1.26	0.33
Majuro (Bikirin)	17.4*	58.3	342	0.56	3.21*	3.52	4.72*	3.56	0.11	0.13	0.33	0.26
Arno	23.2	25.3	269	0.45	5.21*	5.43	12.5*	11.3	0.17	0.13	8.05	0.25
Ailuk	52.8	19.0	378	0.65*	3.70*	3.26	4.34*	3.90	0.13	0.07	0.34	0.14
Ailinglaplap	30.7	35.6	293	0.53	2.65*	2.12	3.23*	2.46	0.08	0.07	0.31	0.16
Jaluit	31.1	27.1	314	0.46	1.21*	1.07	16.8*	15.5	Outliers			
Majuro (Laura)	33.8	26.4	378	0.47	2.33*	2.12	7.20*	4.40	0.35	0.19	4.00	1.79
Namdrik	21.7	30.9	353	0.38	1.50*	1.26	12.7*	10.7	0.33	0.18	5.47	4.95
Kili	57.7*	56.7	360	0.71*	3.11*	2.61	5.43*	2.91	0.30	0.29	5.40	4.04
Mejit	21.9*	15.2	426*	0.62	0.85*	0.76	3.68*	2.88	0.22	0.08	2.98	0.23
Ebon	38.6	30.6	295	0.42	2.66*	2.68	13.6*	11.2	0.68*	0.5	13.3	11.9
Utrik	63.0	56.0	550*	0.71	1.91*	1.32	7.20*	2.50	0.43	0.45	5.74*	5.17
Kwajalein (Looj)	28.0	27.3	409	0.70	2.23*	2.20	4.47*	5.76	0.57	0.52	9.33	10.5
Kwajalein (Meja)	38.7	24.0	334	0.59	0.59*	0.29	0.64*	0.27	0.01	0.002	0.13	0.13
Kwajalein (Ebadon)	39.0	27.3	361	0.50	0.72*	0.59	1.35*	0.91	0.05	0.05	0.16	0.10
Namu	56.7	16.8	239	0.44	2.61*	2.77	11.9*	7.74	0.08	0.09	1.15	0.33
Lib	64.3	26.7	357	0.67	2.56*	2.56	4.43*	2.16	0.08	0.06	3.08	2.64
Lae	18.5	5.7	357	0.47	1.76*	1.16	7.46*	2.08	0.74*	0.47	3.67	3.67
Ujae	76.5	17.9	260	0.64	2.76*	2.80	5.96*	6.42	0.08	0.07	0.50	0.39
Wottho	60.7	14.3	296	0.64	1.80*	0.95	2.02*	1.30	0.05	0.06	1.24	0.09
Wotje	8.20*	49.0	359	0.73*	1.62*	1.57	3.56*	3.58	0.08	0.08	6.02	6.02
Maloelap	23.1	6.3	249	0.40	1.55*	1.32	10.8*	7.82	0.06	0.04	2.30	0.21
Aur	74.7	18.9	329	0.56	3.33*	3.70	10.1*	8.40	0.08	0.08	1.80	1.18
Missing Element Soil	50.0	0.0	221	0.37	7.37		27.7		0.13		3.40	

* Significantly different from the Laura soil at P=0.05.

The majority of the mean micronutrient concentrations for all the atolls fell within the established critical ranges with a few cases falling below and a smaller number above the critical levels established for B, Fe, Mn, Cu, and Zn. These critical levels must be applied with caution to the Marshall Island soils. The critical levels were developed on clayey soils with very low OC levels from relatively dry environments (Lindsay and Norvell, 1978). Mean B concentrations fell within the established critical range on all the atolls, and no significant differences were obtained when means from each atoll were compared with the *Laura* soil. These results suggest that B should not limit crop production throughout the atolls. Mean Mn and Fe levels were significantly lower for all the atoll soils than for the *Laura* soil. The difference was especially remarkable for Fe. Manganese levels were below the critical level in soils collected from Mejit and two islands from Kwajalein Atoll (Meja and Ebadon), and marginal on Jaluit, Namdrik, Utrik, Lae, Wottho, Wotje, and Maloelap. On these islands, Mn deficiency may limit crop production. For the remaining islands, Mn concentrations fell within the critical range, but were significantly lower than the *Laura* soil making a conclusion difficult to reach. Corn growth in the Laura soil may not have been limited by native soil Mn levels because that particular location in Laura may have been abnormally high. The range in Mn concentration for the 9 sampling locations in Laura was 0.94 to 4.74 mg kg^{-1}. Deficient levels of Fe were found on Meja, and marginal levels on Ebadon. Mean Fe concentrations for the remaining atolls fell within or above the critical range. As with Mn, because a significantly higher Fe concentration was obtained in the *Laura* soil, firm conclusions regarding adequate levels of Fe for good crop growth on these

islands cannot be made even though they may fall within the established critical range. Mean Cu levels were significantly greater than the *Laura* soil on two islands while 12 islands showed median Cu levels that were below the established critical level. Soils from four atolls exhibited marginal mean Cu concentrations similar to the *Laura* soil. These results indicate that Cu deficiency might be a problem on several atoll. This conclusion is more easily reached if median Cu values are considered rather than the mean. Median Cu are almost always less than the mean. When the mean is considered, nine locations had Cu levels at or below the critical level. When the median is used, sixteen locations showed deficient Cu levels. Mean Zn concentrations were above the critical level for all but two locations – Meja and Ebadon two islands from Kwajalein Atoll. Using mean values and assuming the established critical range for Zn is appropriate for these soils, Zn should not be a limiting factor in crop production for the Marshall Islands. When the median is considered, low soil Zn levels were found at six locations: Likiep, Ailuk, Ailinglaplap, Meja, Ebadon, and Wottho. Median Zn levels were borderline deficient on a further four atolls: Majuro (Bikirin), Arno, Mejit, and Maloelap.

Conclusion

Where comparisons are appropriate (pH, EC, Total N, and OC), the Marshall Island soils appear relatively similar in chemical nature to the soils of other low-lying atolls in the Pacific. Mean organic C levels in the Marshall Island soils, however, appear to be higher than those found in Tuvalu and Kiribati. The higher organic C levels in the Marshall Islands may be due to its wetter climate, especially in the

southern and central atolls, and denser vegetation. The rainfall gradient across the Marshall Islands does not significantly impact the chemical properties of the soil. Differences in soil physical properties within island locations appear to have a significant effect on the concentration of certain soil chemical parameters on at least some islands. These differences will necessarily influence management decisions regarding fertilization practices. Predicting nutrient availability with confidence using single soil tests like pH, EC, OC, and exchangeable Ca does not seem possible using the present data set. Because organic matter is such an important component of atoll soils, further work characterizing the organic fraction, its cation exchange capacity, and its role in nutrient availability will help provide a better understanding of these soils.

Preliminary interpretation of the soil test data based on the results of the missing element study found that the Marshall Island soils suffer from multiple nutrient deficiencies. Potassium deficiency is clearly the most severe constraint to agriculture in the Marshall Islands. The missing element study showed that P is limiting in these soils, but because no critical level has been established for P in these soils it is difficult to make conclusions regarding the extent and magnitude of the deficiency. Despite the high organic matter content of these soils, SO_4^{-2}-S availability was a limiting factor in the *Laura* soil and may be a limiting factor on other atolls as well. These soils appear to contain sufficient levels of exchangeable Mg for short-term crop production. One would expect rapid Mg depletion in intensive cropping systems. Using established critical levels for the DTPA micronutrient soil test and

the results of the missing element study, Cu appears to be the only micronutrient that poses a limitiation to crop production in the Marshall Islands.

The soils of the Marshall Islands are unique in their physical and chemical composition. The absence of a clay fraction and the relatively high organic matter content set these soils apart from most agricultural soils. Soil tests are often developed to measure nutrient reactions and interactions with the clay fraction. Soil test data interpretation and prediction also usually consider the clay fraction. This approach does not apply to the coralline soils of atolls. Instead, far more emphasis must be placed on the organic matter fraction and how it controls nutrient availability. The results presented here provide a preliminary evaluation of the fertility status of the soils in the Marshall Islands. These results can be used to guide more extensive field experiments in the Marshall Islands to i) assess crop response to N, P, K, Mg, S and the micronutrients for a variety of appropriate vegetable crops; ii) to evaluate established soil test procedures and adapt where necessary, and iii) evaluate the use of simple soil test kits to diagnose soil fertility problems.

Chapter Three

Nitrogen Mineralization Dynamics in a Marshall Island Soil Amended with Locally Available Organic Materials

Introduction

Organic matter is the principal reservoir of plant nutrients in the coralline soils of atolls. In the absence of a clay fraction, soil organic matter is the primary determinant of nutrient availability. The organic fraction controls nutrient availability through microbially mediated mineralization and immobilization reactions, chelation reactions increasing the solubility of the micronutrients, and nutrient retention in the root zone through CEC. Traditional atoll farming systems relied entirely on organic matter management to maintain soil fertility and ensure crop growth (Sideris, 1958; Ali and Asghar, 1992; Thaman, 1992; Manuella and Cable, 1992). Today efficient organic matter management is no less important as atoll farmers cannot afford imported chemical fertilizers, and the fragile atoll ecosystem cannot withstand the detrimental effects of poor fertilizer management.

Farmers in the Marshall Islands have relied on organic matter additions to maintain fertility in their traditional taro pits, and coconut, breadfruit, and pandanus groves (Stone, 1951). Most organic additions consisted of leaves and branches of native plant species including coconut all of which are generally low in nitrogen (N) content. Presumably, the combination of continuous replenishment of nutrients through the organic additions and the relatively low nutrient requirements of these

crops ensured a constant source of food. A rapidly rising population combined with a declining local agricultural sector have both contributed to increased reliance on imports of processed food with serious health consequences (Schoeffel, 1992). Recent government initiatives to increase local food production have failed largely because of poor crop growth due to infertile soils. Revitalizing food production in the Marshall Islands will depend largely on identifying suitable organic materials that correct soil nutrient deficiencies.

Organic materials have been used throughout history to improve crop growth (Brady and Weil, 1999). Animal waste including cow, pig, and chicken manures (Sims, 1995) and high N containing leguminous leaf residues (Jones et al., 1997) are common materials used to improve crop growth in the tropics. Fish waste, a sensible alternative in the Marshall Islands where fish is an important component of the diet and economy, has also been applied successfully as an organic fertilizer to improve crop growth (Gagnon, 1994; Jellum, 1995; Laos, 1998). Other agricultural wastes, such as coffee pulp and macadamia nut husk have also served well as organic soil amendments (Uribe-Henao, 1983; Wu, 1995; Bittenbender et al., 1998). The copra industry, the primary economic activity on Majuro produces large quantities of copra cake as a processing by-product. Like coffee pulp and macadamia husk it is a potential fertilizer material. While chickens and pigs are commonly raised in the Marshall Islands, they are not confined complicating the collection of their manure. Furthermore, cultural mores tend to regard the use of animal wastes on food crops as improper. Nevertheless, a large poultry operation on Majuro Atoll offers a readily

available source of chicken manure for local farms supplying the largest commercial food market.

On the less inhabited outer atolls where animal husbandry practices preclude the collection of large quantities of manure and transport costs may prohibit the distribution of copra cake for fertilizer, fish wastes and plant residues are the only sources of organic fertilizers. Leaf trimmings from leguminous trees are generally rich in N and are commonly recommended as fertilizer materials. There is one native leguminous tree species in the Marshall Islands (*Instia bijuga*), and rather than introducing alien species that may pose a threat to the native flora, the use of native species should take precedence. *Vigna marina* (beach pea), a native leguminous vine, grows abundantly throughout the atolls and is a potential organic source of N. The use of plant residues to improve crop growth has been proposed in the Marshall Islands, but no indication of the nutrient supplying capacity or the amount to add is mentioned (Finney and Laukon, 1993; Stone et al., 2000).

The N mineralization potential of organic waste materials and plant residues added to soil, is commonly estimated by first-order rate kinetics (Stanford and Smith, 1972; Chae and Tabatabai, 1986). Modifications of the first-order equation have been proposed to accommodate early N flushes (Jones, 1984; Beauchamp et al., 1986) and to separate the organic N fraction into a labile and recalcitrant pools (Deans et al., 1986). Further research has identified more complex kinetic models that accommodate observed mineralization lags (France and Thornley, 1985; Andren and Paustian, 1987; Diaz-Fierros et al., 1988). Some investigators have questioned the statistical validity of fitting kinetic equations to cumulative mineralization data, and

proposed that fitting the first derivative of the kinetic models to incremental mineralization data is a more statistically sound procedure producing more reliable parameter estimates (Ellert and Bettany, 1988). The objectives of this study were to (i) identify potential organic soil amendments and characterize their N mineralization rates and potentials, and (ii) to compare mineralization parameter estimates from kinetic equations fitted to cumulative N mineralization data, the same kinetic equations transformed to fit incremental data, and a segmented equation fit to the incremental data.

Materials and Methods

Soil and Organic Materials

A surface soil from Laura village, Majuro Atoll was collected, packaged into air tight plastic containers and shipped by air to Hawaii. In the laboratory at the University of Hawaii, a sub-sample was passed through a 2-mm sieve. A 100g sample was taken, dried at room temperature and analyzed for its chemical properties (Table 2.1).

Three organic waste materials and six indigenous plant materials were collected to assess their chemical properties. Three-month old chicken manure was collected from a poultry farm located in Laura on Majuro Island. It comprised a mixture of chicken manure, feathers and sawdust bedding. The fishmeal came from a tuna processing plant in Majuro and consisted primarily of a mixture of ground up fish bone and dried fish blood and entrails. The copra cake, a dried by-product of aged coconut meat used in the production of coconut oil, was collected from the

government run copra-processing plant in Majuro (TOBOLAR). The materials were collected and packaged in airtight containers in Majuro, shipped by air to the Agricultural Diagnostic and Service Center (ADSC) at the University of Hawaii, and analyzed for their chemical properties (Table 3.1). Fresh leaf samples of five indigenous plants commonly found in the Marshall Islands were collected from coastal sites on Majuro and Arno Atolls, dried for 72 hours at 70°C. packaged and sent to the ADSC for chemical analysis. Leaves of the same plant species were also sampled from coastal areas on Oahu, dried for 72 hours at 70°C and sent to the ADSC for chemical analysis. The results of the chemical analyses are summarized in Table 3.1.

Soil chemical properties were determined as follows: pH with glass electrode (1:1 soil/water ratio), organic carbon by the modified Walkley-Black method (Heanes, 1984), total N by micro-Kjeldahl (Bremner, 1996), extractable P with 0.5 M $NaHCO_3$ at pH 8.5 (Kuo, 1996), extractable cations (Ca, K, Mg, Na) with 1*M* NH_4OAc (Suarez, 1996), water soluble SO_4-S by water extraction for 30 minutes with soil solution ratio of 1:5 (Fox et al., 1964), extractable micronutrients Fe, Mn, Cu, and Zn by the DTPA method (Lindsay and Norvell, 1978), and B by hot H_2O extraction (Keren, 1996). Plant tissue samples were dried at 70°C for 72 hours and ground in a Wiley mill to pass a 40-mesh screen. Tissue samples weighing 0.30-g were dry-ashed at 500°C in porcelain crucibles for 6 hours in a muffle furnace, allowed to cool, and the residues were dissolved in 50 ml of 1*M* HCl. If the ashing was incomplete, 1*M* HNO_3 was added, evaporated to dryness on a hot plate, and the residue re-dissolved in 1*M* HCl. Analysis for P, K, Ca, Mg, S, Fe, Mn, Cu, and Zn were done

on the ash solution using ICP (Hue et al., 2000). For total N, approximately 2 g of Na_2SO_4 was mixed with a 0.25-g sample of prepared tissue material and digested in a 7 ml mixture of concentrated sulfuric acid, salicylic acid, and selenium. After 2 hours, 3-4 drops of sodium thiosulfate solution was added, let to stand for 45 minutes, then 4 ml of 30% hydrogen peroxide was added, and the mixture was digested at 410°C until a clear liquid was obtained (≈ 45 minutes). The liquid was cooled and brought to volume with deionized water in a 50 ml volumetric flask (Hue et al., 2000). Ammonium-N in the solution was determined colorimetrically by auto-analyzer.

Laboratory Incubation

The incubation experiment to characterize the N mineralization rates and potential of the different organic materials was conducted using the methodology outlined by Chae and Tabatabai (1986). The 3 waste materials, chicken manure, fish meal, and copra cake and 1 plant material, *V. marina*, were selected for the incubation. *V. marina* was selected because it had the highest N content and showed the greatest potential as good N source. The materials were added to achieve an N rate of 400 kg N ha^{-1} based upon the assumption that the waste materials would mineralize 40% of the total N (Sims and Wolf, 1994) and the *V. marina* 90% of the total N (Kang and Duguma, 1985) during the 27 week incubation period. The coconut leaves were added at the same rate as the *V. marina* leaves with the knowledge that considerably less N would mineralize during the incubation. Table 3.2 provides a summary of the amendment rates. The waste materials were passed through a 2-mm sieve and then

Table 3.1. Chemical properties of Marshall Island soil, waste materials, and plant material collected from the Marshall Islands and the island of Oahu, Hawaii.

Material	Org. C	Total N	C:N	NH_4-N	NO_3-N	P	K	Ca	Mg	S	Mn	Fe	Cu	Zn	B
	------%------			----µg g^{-1}----		----------%----------					----------µg g^{-1}----------				
Waste															
Copra Cake	42.9	3.07	12.3	149	4.67	0.55	1.73	0.24	0.31	0.27	23.3	157	14.0	43.7	9.7
Chicken Manure	37.4	4.35	8.21	1265	12.7	0.79	2.20	1.09	0.45	0.38	97.7	385	28.3	505	17.7
Fish meal	48.7	7.28	6.90	288	9.67	2.18	0.44	3.53	0.21	0.66	4.67	453	6.67	153	6.7
Plant: Marshall Islands															
Vigna marina	-	3.69	-	-	-	0.22	2.10	1.27	0.43	-	27.5	77	14.3	38.7	25.8
Ipomeoa pes-capre	-	2.66	-	-	-	0.38	1.47	0.7	0.37	-	33.3	78.3	10.7	21.3	23.8
Scaevola serica	-	1.55	-	-	-	0.22	1.74	2.44	0.49	-	17.8	37.3	15.3	18.0	31.0
Tournefortia argenta	-	1.29	-	-	-	0.20	1.39	1.97	0.52	-	21.0	37.2	13.8	17.5	34.5
Plant: Oahu, Hawaii															
Vigna marina	47.07	3.49	13.5	-	-	0.22	2.1	0.83	0.31		29.7	78.7	6.7	22.3	17.0
Ipomeoa pes-capre	-	2.03	-	-	-	0.18	1.71	2.10	0.63	-	25.2	410	11.3	20.2	36.5
Scaevola serica	-	1.78	-	-	-	0.22	1.6	2.00	0.56	-	66.1	100	13.6	35.4	33.6
Tournefortia argenta	-	1.98	-	-	-	0.19	1.48	2.33	0.63	-	32.5	435	14.0	26.4	37.5
Cocos nucifera	49.83	1.65	30.2	-	-	0.16	1.68	0.44	0.40	-	34.7	181	7.0	12.7	17.3

Table 3.2. The amount of each organic material added to achieve a rate of 400 kg N ha^{-1} for the incubation experiment. Materials were added assuming soil bulk density of 0.65 g cm^{-3} and 1.26 X 10^6 kg soil ha^{-1} for a Marshall Island soil.

Material	%N	*% of total N to mineralize*	Dry wt. per tube mg	Fresh wt. per tube mg
Chicken manure	4.35	40	1483	1676
Fish meal	7.28	40	886	931
Copra cake	3.07	40	2102	2291
V. marina	3.49	90	822	8217
C. nucifera	1.65	<10	822	8217

weighed while the leaves were cut into strips with approximately 5 mm widths, weighed on an OD basis and added fresh. The organic materials were thoroughly mixed with 100-g of field moist soil (81.3 g on an oven dry basis). The mixture of soil and organic materials was transferred to a leaching tube (d=10 cm, h=5 cm). A thin layer of glass wool was placed in the bottom of each leaching tube to prevent clogging of the porous bottom. The control consisted of the soil without any organic amendment. All treatments were prepared in triplicate. The tubes were placed on a suction flask, leached by applying vacuum suction with 160 ml of leaching solution in 3 increments to remove the initial mineral N, and weighed. The leaching solution was made to mimic the natural ionic composition of the Marshall Island soil minus the N component (Table 3.3). The leachate was collected and analyzed colorimetrically for NH_4^+ - N and NO_3^- – N using an autoanalyzer. The tubes were then covered with punctured plastic to prevent rapid moisture loss, but also provide adequate aeration.

During the incubation, the tubes were placed on a rack to maintain a vertical position and kept at a constant temperature of 29°C. The tubes were leached

according to the procedure outlined above after the first week and then at two or three week intervals thereafter for a total of 27 weeks. Moisture content was maintained by weighing every 4 days and adding the necessary water to bring the tube back to its initial mass. The volume of the leachate was recorded and analyzed colorimetrically for NH_4^+ - N and NO_3^- – N.

Table 3.3. Ionic composition of the leaching solution approximating the ionic composition of the Marshall Island soil solution (1:1 soil solution ratio). Iron, B, and Cuwere not included because their concentrations were too low.

P	K	Ca	Mg	Na	S	Zn
			mg L^{-1}			
0.08	2.95	104	5.89	5.65	6.18	0.09

Estimating Potentially Mineralizable N and Specific Mineralization Rate Constants

We tested three mathematical procedures to estimate potentially mineralizable N (N_0) and appropriate rate contants: (i) by fitting different kinetic equations to cumulative curves of mineralized N, (ii) by transforming the same equations into their incremental form and fitting them to incremental data, and (iii) by fitting a segmented equation to the incremental data.

The equations tested are presented in Table 3.4. The first-order rate decomposition model proposed by Stanford and Smith (1972) assumes that mineralization is proportional to N concentration and that the N is mineralized from only one general pool. The equation estimates the total mineralizable pool of N (N_0), and the rate at which it is released (k). The first-order equation was subsequently modified by adding a parameter N_e to accommodate observations that there is often an initial flush of mineral N during the initial stages of the incubation, (Jones, 1984;

Table 3.4. Kinetic models used to describe net N mineralization.

Model	Cumulative Form	Reference
First order	$N_i = N_0(1-e^{-kt})$	Stanford and Smith (1972)
First order E	$N_i = N_0(1-e^{-kt}) + N_e$	Jones (1984)
Two simultaneous reactions (TSR)	$N_i = N_0 S(1-e^{-ht}) + N_0(1-S)(1-e^{-kt})$	Molina et al. (1980)
Consecutive reactions	$N_i = N_0 - N_0(ke^{-ht} - he^{-kt})/(k-h)$	Noggle (1985)
Mixed order	$N_i = N_0(1-e^{-kt-0.05ht^2})$	Brunner and Focht (1984)
Gompertz (standard)	$N_i = N_0 e^{-he^{-kt}}$	Draper and Smith (1981)
Gompertz Fr	$N_i = N_0 e^{-he^{-kt}} - N_0^{-he}$	France and Thornley (1984)
Gompertz Fr E	$N_i = N_0 e^{-he^{-kt}} - N_0^{-he} + N_e$	Ellert and Bettany (1988)
Segmented	$y = a * \min(node,t) + b * \max(node,t) + c$	Shuai et al. (2003)

Where N_i is mineralized N, N_0 is potentially mineralizable N, N_e is the fraction of N released during the first week, S is a rapidly available pool of N, k is a mineralization constant associated with the slowly available pool, h is a mineralization constant associated with the rapidly available pool, a and b are slopes of the two linear segments the *node* is the point where the two segments are joined, and t is time in weeks..

Beauchamp et al.,1986). Further work proposed that N mineralization dynamics involved two pools of organic N, one rapidly mineralizable and another more stable fraction with a slower rate of mineralization. This process could be modeled with two first-order rate equations with four parameters estimating the rapidly mineralizing subfraction (F), the slower fraction (1-F) and rate constants (h and k) for each fraction (Molina et al., 1980; Deans et al., 1986). Using the hypothesis that microbially mediated N mineralization reactions in soil involve a series of intermediary components as reactants that are converted to products, a consecutive first-order equation with two rate constants was adapted from chemistry (Noggle, 1985) and

applied to describe N mineralization from barley straw (Andren and Paustian, 1987) and cattle slurry added to soil (Diaz-Firros et al., 1988). Further work sought to describe mineralization dynamics by applying mathematical equations that could fit lag periods. Bruner and Focht (1984) developed an equation that combined a first-order pathway with a second order process dependent on microbial biomass and substrate concentration. More recently, the Gompertz equation was applied to mineralization patterns with distinct lag periods (Ellert and Bettany, 1988; Agbenin et al., 1999).

Most research on N mineralization in soils fits kinetic equations to cumulative N mineralization data to estimate potentially mineralizable N and the relevant rate constants. Kinetic equations can also be fitted to N mineralization data from each leaching period plotted versus time on an incremental basis. Fitting kinetic models to incremental data offers the following advantages: (i) reduces interdependence among errors, (ii) removes need to transform data, (iii) permits deletion of missing observations, and (iv) offers an alternative picture of mineralization dynamics. Because of points one and two mentioned above, incremental models comply more closely to the assumptions of nonlinear least squares providing more validity to the parameter estimates than the cumulative models (Ellert and Bettany, 1988). The same equations presented in Table 3.4 were transformed into their incremental forms by a subtraction procedure (Appendix A) and fit to incremental data.

Segmented regression models have been commonly used to determine crop yield as a function of fertilizer application, and plant nutrient critical levels in soil fertility studies (Anderson and Nelson, 1975; Black, 1993). Linear-plateau models are

applicable to data that exhibit linear response up to a certain point at which a plateau is reached. Two linear segments are fitted to the data, one describing the increasing trend, and the other for the plateau. The point at which the switch between the two functions occurs is called the join-point or the node (Schabenberger and Pierce, 2002). This approach can be easily applied to data characterized by a linear increase to an apex followed by a linear decline; our mineralization data exhibited such behavior. We adapted a segmented equation (Shuai et al., 2003) to estimate N_0 and appropriate mineralization constants. The equation took the form

$$N_i = a^*\min(node, t) + b^*\max(node, t) + C$$

where N_i is the measured mineral N at time t, a is the slope of the first segment, b is the slope of the second segment, the node (join-point) is the point where the two segments join with x-coordinate denoting a specific time (t), and C is a constant. The segmented equation was fit to the incremental N mineralization data, and estimates for the slopes a and b, and the time interval associated with the node were calculated by least-squares regression using NLIN procedure of the SAS statistical analysis software (SAS Institute Inc., 1999). Potentially mineralizable N (N_0) was estimated by calculating the area under the curve formed by the two intersecting lines

$$N_0 = S_1 + S_2$$

where S_1 and S_2 are the areas of the polygon they represent (Fig. 3.1).

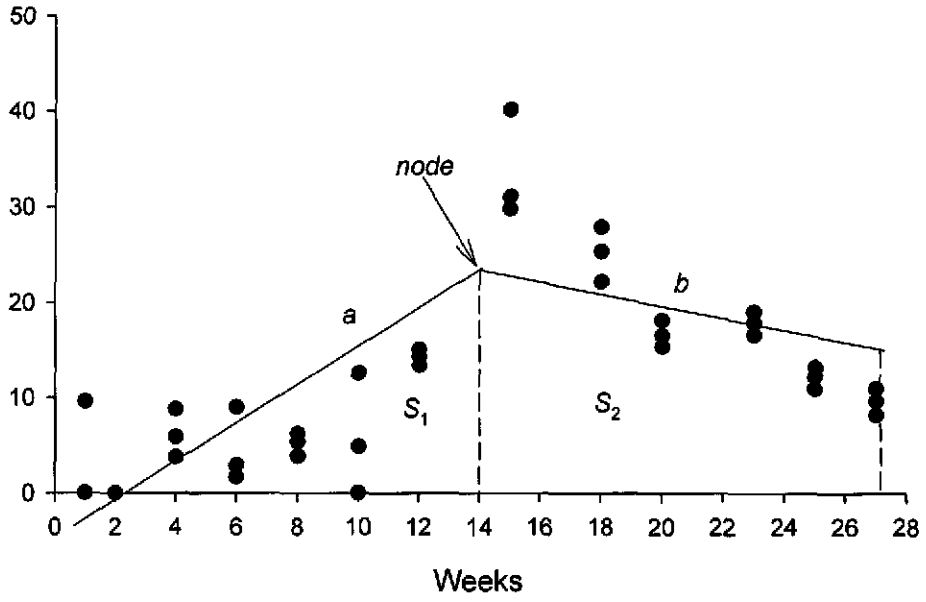


Fig. 3.1. Schematic representation of the segmented equation and parameter associations.

Statistical Analysis

Nonlinear regression was performed using Sigmaplot 2001 for Windows (Sigmaplot, 2001) for both the cumulative and incremental models. For the equations not available in the library, we used the built-in editor in Sigmaplot to write equations. The SAS program was used to verify Sigmaplot results on selected curves using proc NLIN (SAS, 1999). We evaluated the goodness-of-fit of the different models using the F_{lackfit} statistic. The F_{lackfit} was calculated in the following way (Draper and Smith, 1981):

$$F_{lackfit} = \frac{MS_{\text{Re sidual}}}{MS_{Pure}}$$

$MS_{Residual}$ is the residual mean square calculated from regression analysis fitting the equations to the data. The Pure error measures the inherent error in the data, and was determined using the proc GLM procedure in SAS for each material. The $F_{lackfit}$ test is superior to using the residual mean square to determine goodness-of-fit because it represents pure error (Draper and Smith, 1981). We used proc NLIN in SAS to fit the segmented equation, and used the root mean square error (RMSE) to compare the fitting procedure with cumulative and incremental kinetic equations.

Results and Discussion

Nitrogen Mineralization Patterns

The Marshall Island soil exhibited very low N mineralization potential throughout the 27-week incubation period. Following a small initial release during the first week of incubation, N mineralization remained constant with an increasing trend during the final four weeks (Fig. 3.2). The soil released a total of 24.9 mg N kg^{-1} of which almost 40% became available during the last four weeks of the incubation period. This increase near the end of the incubation contradicted the observations of other studies where N mineralization either remained constant or showed a gradual decrease with time (Stanford and Smith, 1972; Chae and Tabatabai, 1986). The Marshall Island soil had a relatively large reservoir of total organic N (0.55%), but the soil alone mineralized a meager 0.45 % of the total N during the 27-week incubation. The low mineralization potential exhibited by the Marshall Island soil differs markedly from the generally high mineralization potentials of continental soils (Fig. 3.3). Of the 39 soils analyzed by Stanford and Smith (1972), only one Psamment

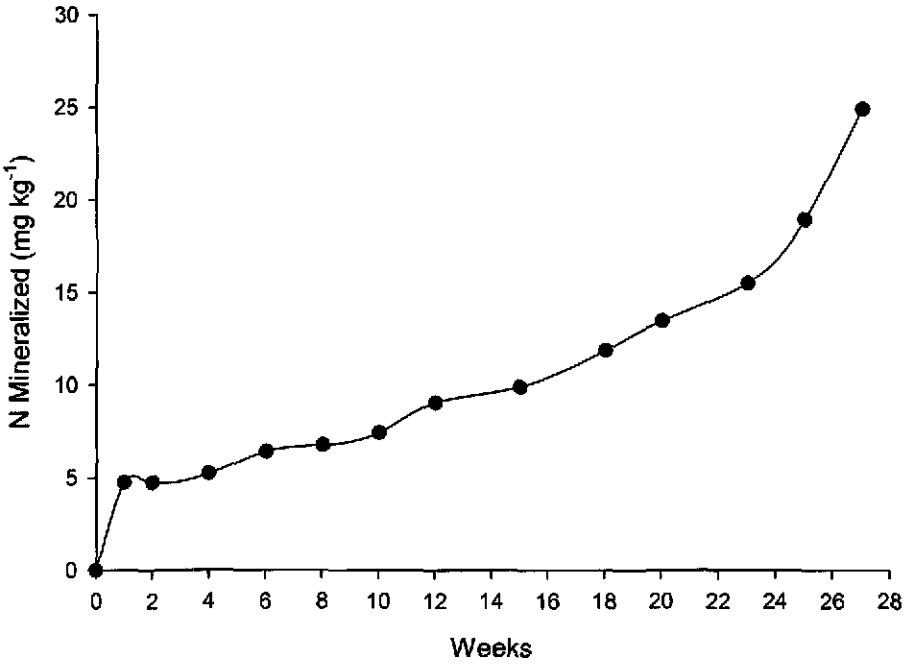
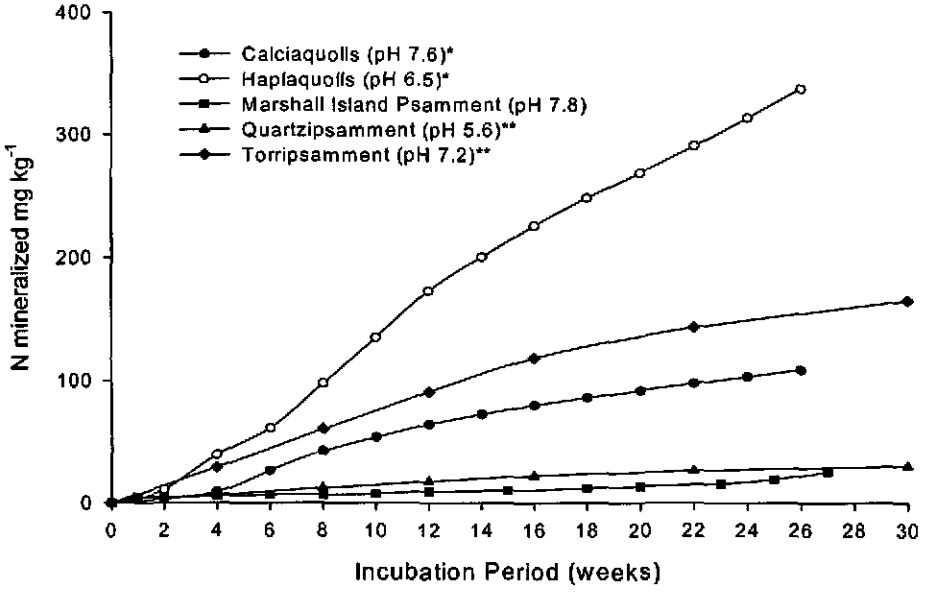


Fig. 3.2. Cumulative N mineralization curve for a Marshall Island soil during a 27 week incubation.



*Source: Chae and Tabatabai (1986), ** Stanford and Smith (1972)

Fig. 3.3. Cumulative amounts of N mineralized in a Marshall Island soil compared with soils from the continental United States.

from Lakeland Island SC showed a similar magnitude of N mineralized during a 30-week incubation. The acid reaction of the Lakeland Island soil and its very low organic C (0.26%) and total N (0.03%) may explain its low mineralization potential. An Oregon Psamment from the same study with near neutral pH, but low organic C (0.15%) and total N (0.03%) mineralized almost 30% of its total N fraction, and more than five times more N than the Marshall Island soil.

The slow mineralization rate of the Marshall Island soil may be related to its relatively high C:N ratio. The Marshall Island soil had a C:N ratio of 12.7, considerably higher than the C:N ratios of the Entisols included in Stanford and Smith (1972) which had C:N ratios ranging from 7.5 to 9.8 and total N mineralized from 156 to 246 mg kg^{-1} excluding the Lakeland Island soil. A high pH sandy soil from Spain with a C:N ratio of 13.9 immobilized N during a 14-week incubation, and another alkaline sandy soil from the same study with C:N ratio of 13.1 mineralized only 6.6% of the total N fraction (Serna and Pomares, 1992). The authors observed that soil C:N ratio was inversely proportional to N mineralization rate and soils with C:N ratio greater than 12 had the lowest cumulative N mineralization. Higher C:N ratios are indicative of an organic fraction that is more resistant to microbial decomposition (Alexander, 1977).

Amending the Marshall Island soil with organic materials increased the N mineralization potential dramatically (Fig. 3.4). All the organic materials except copra cake showed an initial flush in N mineralization during the first week (Table 3.5). All four treatments showed a lag in mineralization rate during the first eight to twelve weeks. The lag was most distinct in the copra cake, which did not begin to

mineralize significant quantities of N until week fifteen. The chicken manure treatment had a pronounced lag period where no mineral N was released after two weeks followed by a slow increase up until week twelve. The *V. marina* and fish meal treatments showed a lag period during the first eight to ten weeks, but continued to mineralize N at a higher rate than the other treatments. All four materials showed a significant increase in mineralization rate at 15 weeks followed by a slow decline through week 27. The soil amended with fresh *V. marina* leaves mineralized a mean of 303 mg N kg^{-1} from the added N in the material, the largest amount followed by fish meal (267 mg N kg^{-1}), chicken manure (207 mg N kg^{-1}), and copra cake (160 mg N kg^{-1}).

Table 3.5. Incremental amounts of N mineralized during distinct incubation intervals in the Marshall Island soil and soil amended with different organic materials.

	N mineralized within successive incubation periods (weeks) specified													
Treatment	0-1	1-2	2-4	4-6	6-8	8-10	10-12	12-15	15-18	18-20	20-23	23-25	25-27	Total
	mg kg^{-1}													
Soil	4.75	0	0.49	1.18	0.33	0.67	1.62	0.84	1.98	1.58	2.06	3.42	5.98	24.9
V. marina	95.5	9.53	16.3	9.05	10.4	12.8	18.8	38.5	30.7	18.1	19.5	13.3	10.9	303
Chicken manure	38.6	0	5.48	8.10	15.5	15.2	15.8	30.0	22.4	15.6	17.6	12.6	9.83	207
Fish meal	36.9	11.9	8.13	13.2	20.9	28.1	19.1	36.9	27.6	18.4	20.1	14.2	11.3	267
Copra cake	5.90	0	6.12	4.53	5.17	8.98	14.2	33.7	25.1	16.7	17.9	12.1	9.63	160

The *V. marina* treatment mineralized nearly 80 % of its total organic N (Table 3.6) more than twice the proportion mineralized by fish meal, three times that of chicken manure, and four times more than the percentage mineralized by the copra cake. The rapid release rate of *V. marina* observed in this study agrees with previous work showing that high quality leguminous leaves added to soil such as *Leuceana* and *Gliricidia* tend to mineralize 80-90% of their total N contents (Read et al., 1985).

Chae and Tabatabai (1986) reported that 86% of the added N in alfalfa leaves and 61% of the added N in chicken manure were mineralized in a calcareous Mollisol. Extensive research on Nrelease from chicken manure has shown that between 40 and 60% of the N is usually mineralized within three to four months (Sims, 1995). The higher C:N ratio of the Marshall Island soil and its relatively stable organic N fraction may have caused a certain proportion of the N released from the legume and chicken

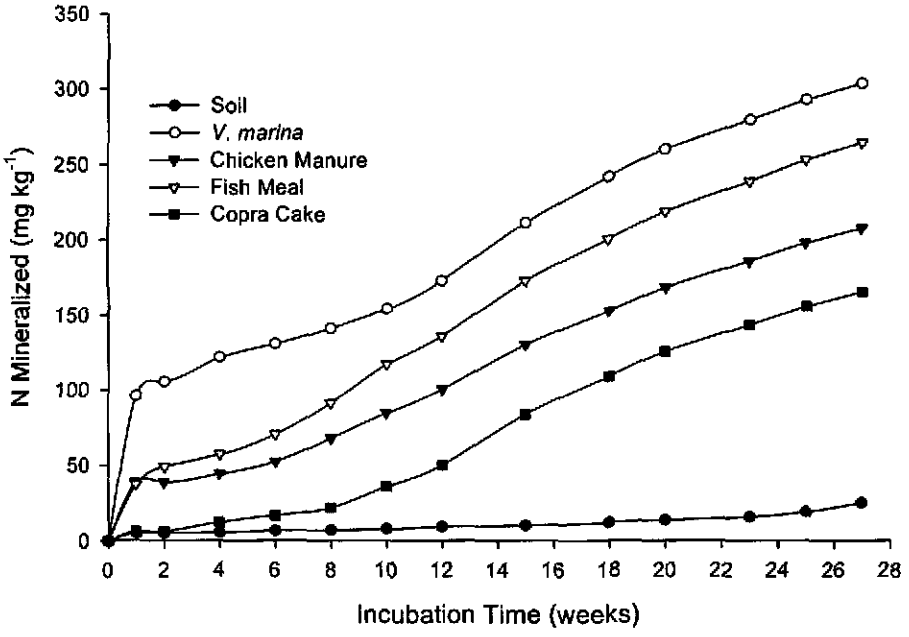


Fig. 3.4. Cumulative N mineralized in a Marshall Island soil amended with different organic materials. Points represent a mean of three replicates.

Table 3.6. Percentage of organic N mineralized from each organic material added to the soil from the Marshall Islands after a 27-week incubation period.

Material	% Total N *Mineralized*
V. marina	78.9
Chicken manure	22.9
Fish meal	30.5
Copra cake	17.0

manure to be immobilized thus lowering the total amount of N mineralized. The fish meal treatment mineralized 31% of its total N content during the incubation period, a similar range of 20 to 27% was obtained for fish waste mixed with sawdust in a 30-week incubation (Jellum et al., 1995). Only 17% of the N in the copra cake mineralized during the incubation period. The low proportion of N released from the copra cake was related to first, the lack of a significant flush of inorganic N during the first week compared with the other materials, and second, the more pronounced lag in mineralization during the first twelve weeks of the incubation. The low mineralization rate of the copra cake treatment compared with chicken manure and fish meal may have been caused by its higher C:N ratio and lower concentration of initially soluble N (Table 3.1).

Examining plots of the replicates for net N mineralized showed the presence of a distinct replicate effect for certain organic materials (Fig. 3.5). The soil alone treatment, for example, showed a distinct pattern in the distribution of the points for each replicate. Each replicate had the same general shape over time, but differed noticeably in the amount of N mineralized during the first interval. Replicate two mineralized twice as much N as replicate one and about ten times as much as replicate 3. During subsequent intervals, however, differences between replicates did not show this behavior. The chicken manure treatment followed the same behavior except the replicates did not follow the same order in net N mineralization (Fig. 3.6). In the fish meal treatment, replicates 1 and 2 behaved similarly, but replicate 3 mineralized considerably less N and the curve showed a more sinusoidal shape (Fig. 3.7). The *V. marina* treatment showed the most extreme anomaly; replicate 2,

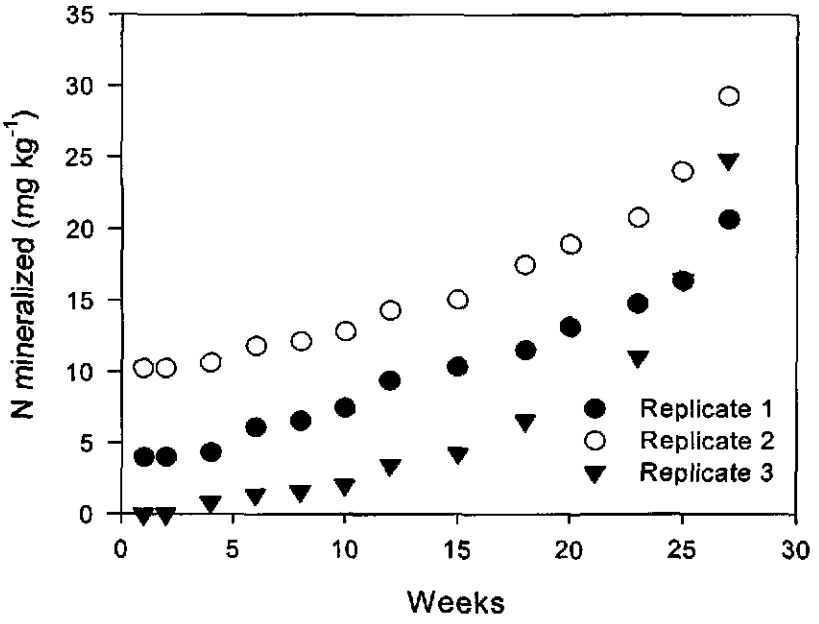


Fig. 3.5. Distribution of the three replicates for net N mineralization for the soil alone treatment.

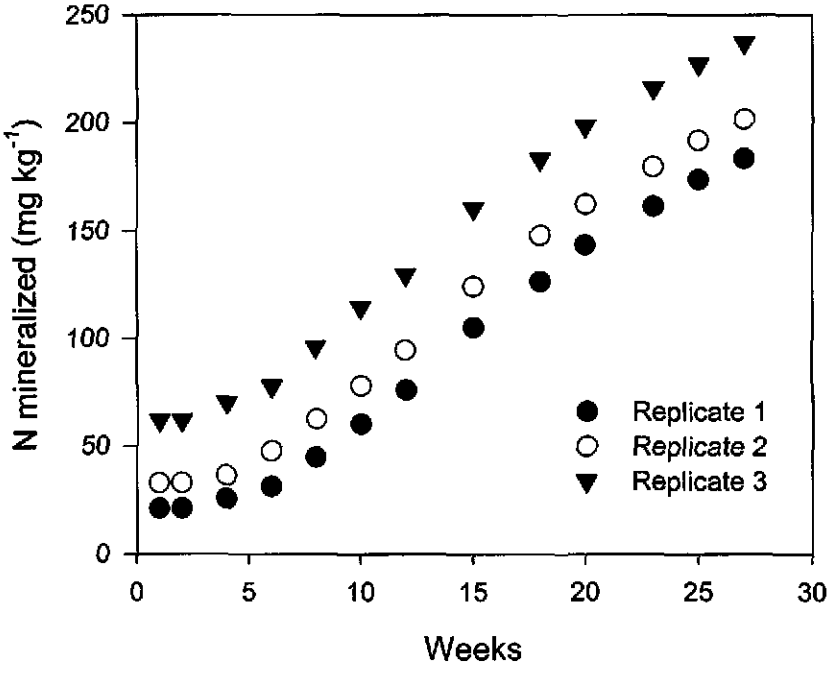


Fig. 3.6. Distribution of the three replicates for net N mineralization for the chicken manure treatment.

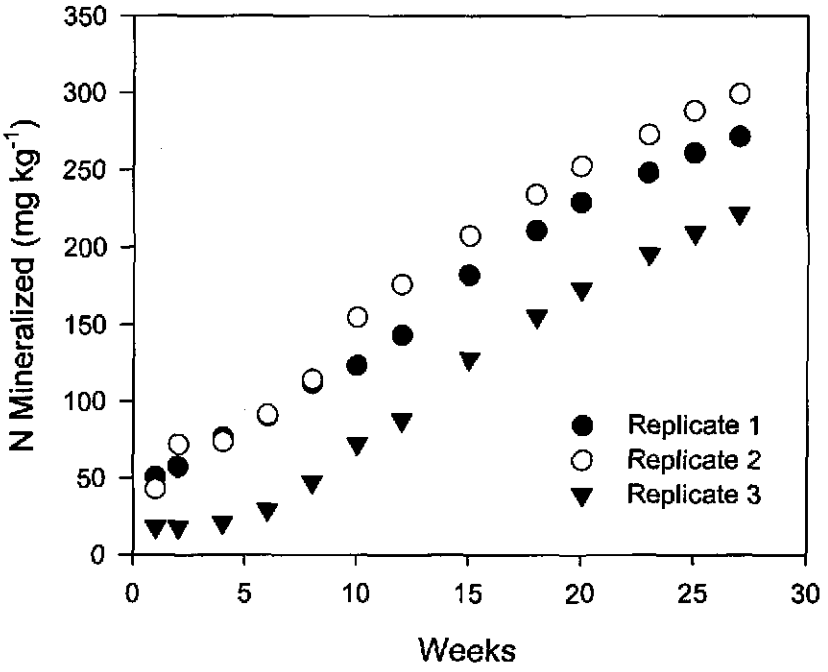


Fig. 3.7. Distribution of the three replicates for net N mineralization for the fish meal treatment.

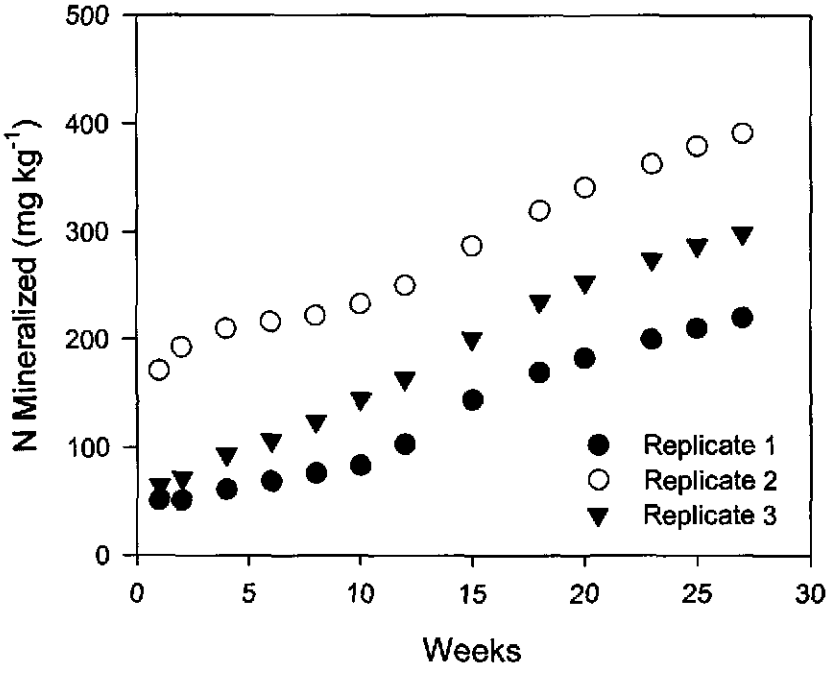


Fig. 3.8. Distribution of the three replicates for net N mineralization for the *V. marina* treatment.

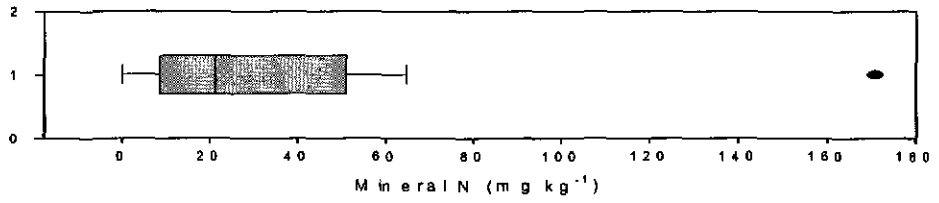


Fig. 3.9. Boxplot showing the quantity of mineral N extracted for all the treatments after the first week of the incubation. The outlying point represents replicate one from the *V. marina* treatment.

although similar in shape, mineralized almost twice as much N as replicate 1 (Fig. 3.8). The difference occurred during the first sampling interval. Figure 3.9 shows the quantity of mineral N extracted from replicate 2 after the first week compared with the replicates for the other treatments, and clearly its behavior did not conform to the other replicates. The funnel containing replicate 2 was accidentally knocked over on the second day of the incubation and the disturbance may have caused the abnormally high value of N. Because of this anomaly, replicate 2 was not included in the curve fitting exercise.

Nitrogen mineralization is controlled by environmental factors such as moisture, temperature, soil texture, soil reaction, and nutrient availability. We set up our incubation such that these environmental factors were uniform for each treatment and each replicate. All experimental units received the same amount of water initially, were, randomly placed in an incubator with uniform temperature, and leached with the same amount of extracting solution. Because we observed the replicate effect in the control treatment, we could attribute differences in replicates to the manner in which treatments were added to the soil. Particle size separation effects when we

transferred the soils to the leaching funnels may be a possible explanation for the differences in replicates. However, we have no clear explanation for the differences in replicates.

Chemical Indices and N Availability

Simple, reliable laboratory methods that provide an index of N availability from soils and organic materials added to soil are useful because they can be used to rank the N supplying capacity of the material. We tested the relationship between C:N ratio, total N (N_{tot}), soluble inorganic N expressed as the sum of NO_3^--N and NH_4^+-N (N_{sol}), an estimate of organic N expressed as the difference between N_{tot} and N_{sol} (N_{org}), the ratio of N_{org}:N_{sol}, and inorganic N released after incubating for 1 week (N_e) with the total amount of inorganic N mineralized during the 27-week incubation. Correlation analysis performed with all the treatments excluding replication 2 from the *V. marina* treatment (deemed an outlier) determined that the N_{org}:N_{sol} ratio had the strongest relationship with N mineralized followed by N_{org}, N_{tot}, and N_e (Table 3.7); N_{sol} showed a less robust, but nonetheless significant relationship while the C:N ratio was not significantly correlated to N mineralized.

Table 3.7. Results of correlation analysis with N mineralized as the dependent variable.

Independent Variable	n	Corr. Coef	p-values
C:N	14	-0.482	0.0807
N_{tot}	14	0.842	0.0002
N_{sol}	14	0.508	0.0637
N_e	14	0.794	0.0007
N_{org}	9	0.857	0.0031
N_{org}:N_{sol}	8	0.885	0.0035

N_{tot} = Total N concentration, N_{sol} = soluble NH_4+NO_3-N,
N_e = N mineralized during the first week,
N_{org} = N_{tot}-N_{sol}

Total N, a routine laboratory procedure, is often well correlated with the potentially mineralizable N fraction of organic materials (Molina et al, 1983; Frankenberger and Abdelmagid, 1985; Vigil and Kissel, 1991). When all the data were included in the calculation, there was a significant quadratic relationship between N_{tot} and the amount of N mineralized (Table 3.8). Removing the soil treatment and analyzing all the organic amendments together resulted in a weak linear relationship, but when only the waste materials (chicken manure, fish meal, and copra cake) were analyzed, excluding the soil or *V. marina* treatments, the linear relationship between N_{tot} and N_{min} became stronger. Net N mineralized decreased exponentially as C:N ratio of the waste materials increased (Fig. 3.10). The copra cake material had the highest C:N ratio and showed the lowest amount of N mineralized.

Table 3.8. Results of regression analysis using N_{tot} as the independent variable and N_{min} as the dependent variable.

Data	Equation	Adj. r^2	RMSE
All	$y=-17.3+83.0*X-6.10*X^2$	0.81	41.6
W/o Soil	$y=137+17.8*X$	0.27	45.9
W/o Soil & *V. marina*	$y=92.6+24.2*X$	0.70	28.6

N_{tot} = Total N concentration, N_{min} = N mineralized during 27-week incubation
RMSE = root mean square error

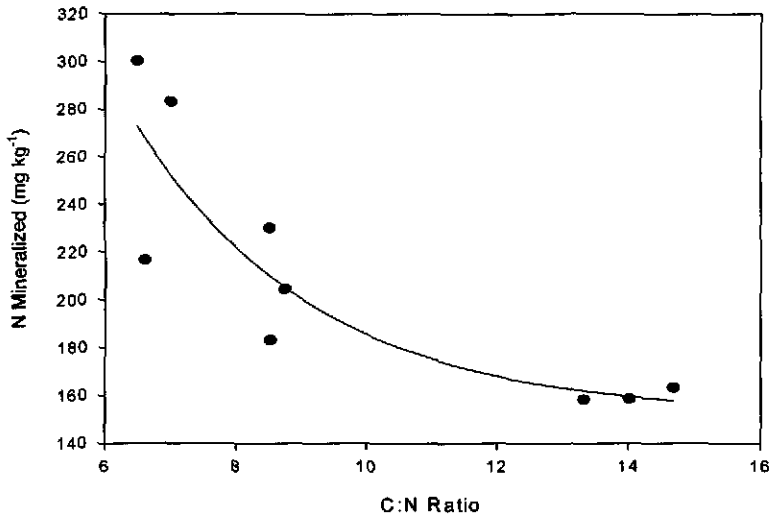


Fig. 3.10. Relationship between the C:N ratio andN mineralized for the three organic waste materials.

The presence of an initial flush in mineral N during the first seven days representing the rapidly available pool of N is normally accounted for by mathematical manipulation of different kinetic models (Jones, 1984; Beauchamp et al., 1986; Ellert and Bettany, 1988). The presence or absence of a large initial flush of mineral N during the first week can also be interpreted as an inherent property of the material that is directly proportional to its N mineralization potential. Achieving such a relationship with a one-week incubation could be a very powerful way to estimate the potentially mineralizable fraction of an organic material. Figure 3.11 shows a significant relationship between N_e and N_{min} for the four organic materials used in incubation. High within treatment variability for the initial quantity of N removed after the first week reduced the predictive power of the relationship.

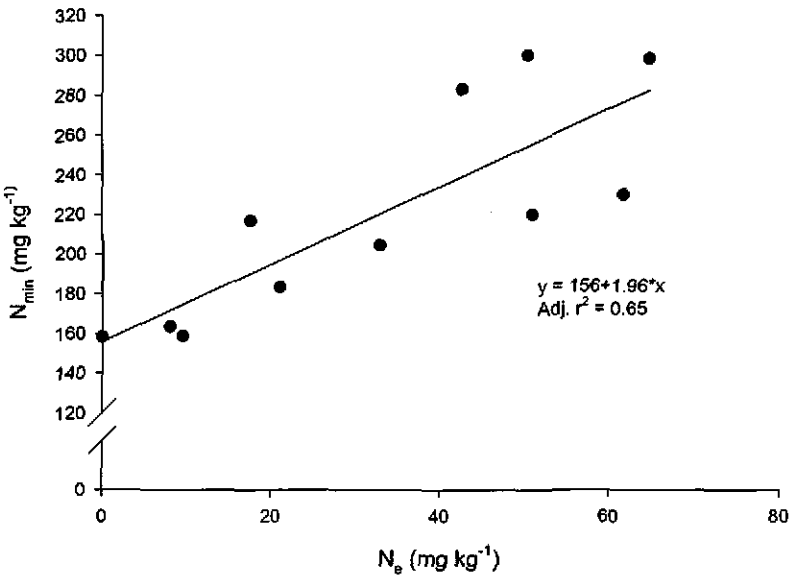


Fig. 3.11. Relationship between N mineralized in 27 days (N_{min}) and the quantity of N mineralized during the first week (N_e) of the incubation for all four organic materials added to a Marshall Island soil.

Comparison of Kinetic Models for Net N Mineralization

Cumulative Models

Applying kinetic models to cumulative N mineralization curves allows for the estimation of N_0 of the organic fraction and the rate at which mineralization proceeds. The cumulative N mineralization curve for the Marshall Island soil did not reach a plateau during the 27-week incubation. In fact, it showed a clear increase in mineralization during the last 4 weeks. We did not include the soil alone treatment in the fitting exercise. We fit the amended soil with the six different kinetic models, and used the $F_{lackfit}$ statistic to identify the best model for predicting N_0, k, and h where

applicable. The results of fitting the different kinetic models to the Marshall Island soil amended with the four organic materials are presented in Table 3.9.

For all four treatments the two and three parameter first order kinetic equations did not fit the data well (Table 3.9). The lack-of-fit was most likely caused by the presence of a lag in each of the four treatments. The two simultaneous reaction equation that divides N_0 into a rapidly mineralizable and a slowly mineralizable pool, generally improved the fit in the fish meal and *V. marina* treatment compared with the first order equation, but in the case of chicken manure and copra cake, where a more distinct lag occurred, the goodness-of-fit deteriorated compared with the first order equation. The consecutive reaction equation performed poorly on all treatments except for fish meal where it had a lower $F_{lackfit}$ than the first order equation, but caused an unreasonably high estimation of N_0. The mixed order equation did not fit the data better than the first order equation in all treatments except in the copra cake

Table 3.9. Results of fitting the 7 different kinetic models to cumulative N mineralization for the 4 organic materials added to the Marshall Island soil.

Material	Model[1]	Adj. r^2	RMSE	$F_{lackfit}$	N_0	N_e	k	h
Fish Meal	1st order	0.854	32.9	0.244	533 (199)		0.03 (0.01)[2]	
	1st order e	0.857	32.5	0.103	2952628	24.5	0	
	2 simultaneous rxns	0.845	33.9	0.110	415 (3303)	72.8 (>>)	0.06 (323)	0.06 (318)
	Consecutive rxns	0.858	32.5	0.103	814 (742)		0.01 (0.02)	1.04 (0.03)
	Mixed order	0.850	33.3	0.245	491 (>>)		0.03 (0.09)	0.0001 (0.005)
	Gompertz (standard)	0.863	31.9	0.028	345 (68.6)		0.08 (0.02)	2.50 (0.24)
	Gompertz E	0.860	32.2	0.011	280 (92.7)	36.5 (17.5)	0.11 (0.06)	3.63 (2.32)
V. marina	1st order	0.805	34.8	0.409	389 (109)		0.04 (0.02	
	1st order E	0.840	31.5	0.124	2588633	41.6 (16.7)	0	
	2 simultaneous rxns	0.775	37.4	0.097	287	-44.5	0.11 (81.3)	0.11 (80.7)
	Consecutive rxns	0.740	40.1	2.302	266 (26.9)		0.16 (0.03)	
	Mixed order	0.797	35.5	0.406	466 (16176)		0.03 (1.25)	-0.0003 (0.04)
	Gompertz (standard)	0.843	31.2	0.044	407 (164)		0.06 (0.03)	2.18 (0.29)
	Gompertz E	0.840	31.5	0.014	247 (96.3)	58.9 (19.1)	0.12 (0.07)	4.39 (3.45)
Chicken Manure	1st order	0.864	24.2	0.553	526 (267)		0.02 (0.01)	
	1st order E	0.876	23.1	0.453	3382965	18.9 (9.97)	0	
	2 simultaneous rxns	0.854	25.1	19.64	319 (3636)	157 (>>)	0.06 (845)	0.06 (802)
	Consecutive rxns (hk)	0.875	23.2	6.649	1380 (3881)		1.02 (0.05)	0.006 (0.018)
	Mixed order	0.859	24.6	0.558	387 (801)		0.02 (0.05)	0.0002 (0.004)
	Gompertz (standard)		22.5	0.090	319 (86.3)		0.07 (0.02)	2.54 (0.20)
	Gompertz E	0.883	22.5	0.008	207 (51.1)	35.9 (10.6)	0.12 (0.05)	4.82 (2.55)
Copra Cake	1st order	0.935	15.3	11.93	1672786 (>>)		0	
	1st order E	no fit						
	2 simultaneous rxns	0.981	8.24	30.03	313 (406)	7.61 (1731)	0.07 (1.40)	0.06 (1.26)
	Consecutive rxns	0.981	8.15	92.38	367 (45.9)		0.06 (0.006)	
	Mixed order	0.984	7.53	0.93	206 (15.3)		-0.002 (0.004)	0.005 (0.0009)
	Gompertz (standard)	0.986	7.07	0.538	212 (13.7)		0.11 (0.01)	5.37 (0.47)
	Gompertz E	0.987	6.71	0.179	187 (11.9)	7.04 (2.51)	0.14 (0.01)	7.53 (1.32)

[1]Refer to Table 3.5 for the equations for each model, [2]Standard errors in parentheses, RMSE =root mean square error.

where it obtained a much lower $F_{lackfit}$ than the first order, two reaction and consecutive reaction equations. Despite the low $F_{lackfit}$, parameter estimates appear problematic; the estimate for k was negative and the h value was 2 orders of magnitude lower than values obtained on other datasets (Ellert and Bettany, 1988; Agbenin, 1999).

The three and four parameter Gompertz equations provided the best fit to the data in all four treatments (Fig. 3.12). In all four cases, the Gompertz equation, with a fourth (N_e) parameter estimating the rapidly mineralizable fraction, resulted in the lowest $F_{lackfit}$ with a reasonable estimate of the N mineralized during the first seven days of the incubation. Including the fourth parameter improved the model's ability to account for the lag in mineralization during the first two to eight weeks. With the simpler three-parameter model, the predicted line did not reflect the mineralization lag early in the incubation. Estimates for N_0 ranged from 187 for copra cake to 407 mg kg^{-1} for *V. marina*, and were consistently lower than the estimates obtained with the other kinetic equations. The four-parameter equation always gave the lowest estimates of N_0. The three-parameter equation seemed to provide a more realistic estimate of N_0. Estimates for k ranged from 0.07 to 0.14 mg kg^{-1} $week^{-1}$ and for h from 2.18 to 7.53 mg $kg^{-1}week^{-1}$. Similar to estimates for N_0, values for the rate constants were always higher when estimated with the Gompertz equations compared with the other equations. The four-parameter model gave higher estimates for k and h in all four treatments. For *V. marina*, k and h values were twice as high with the four-parameter model compared with the three- parameter model. Applying the

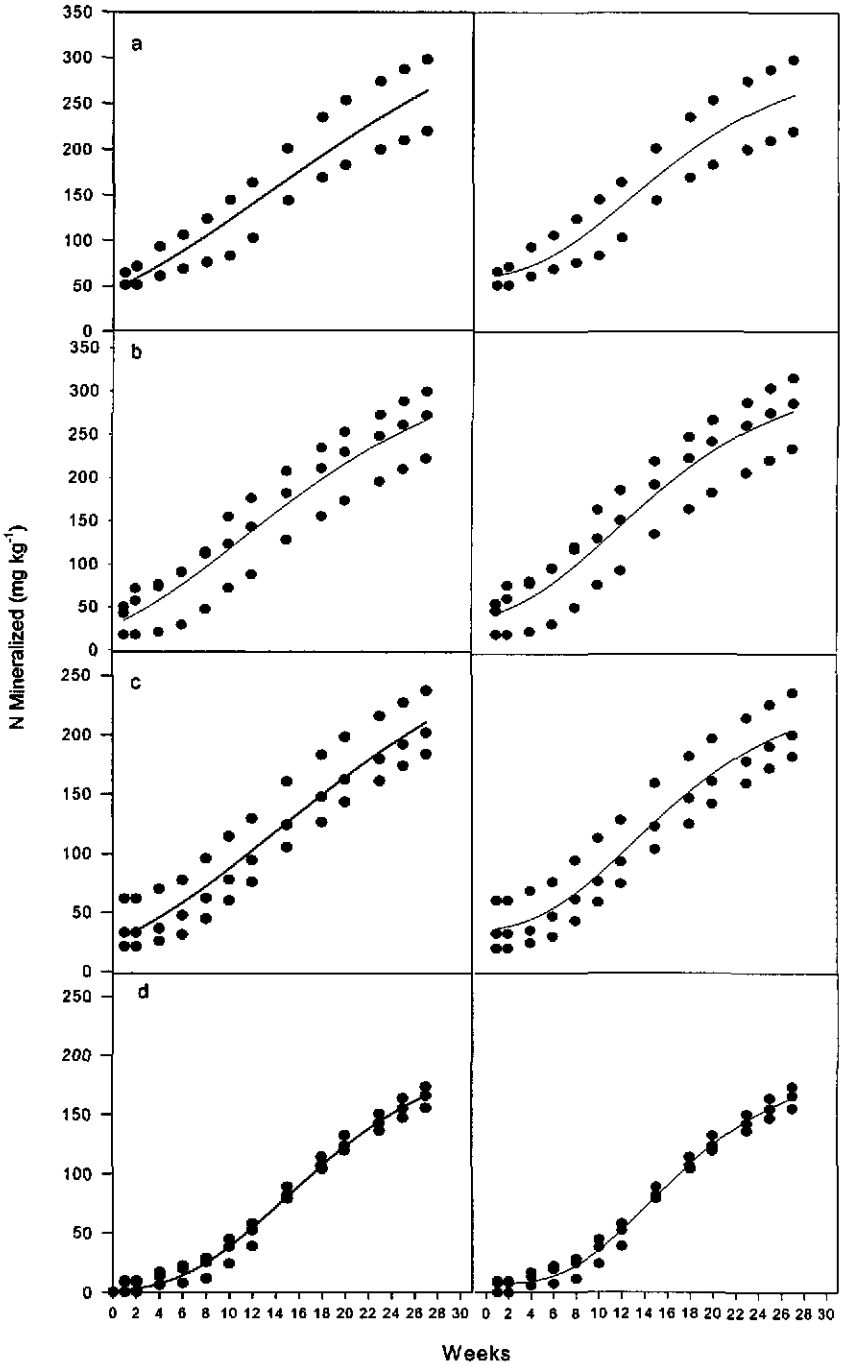


Fig. 3.12. Results of fitting the 3-parameter (left) and the 4-parameter (right) Gompertz models to N mineralization curves for soils amended with (a) *V. marina* (only 2replicates included), (b) fish meal, (c) chicken manure, and (d) copra cake.

"extra sums of squares" principle (Draper and Smith, 1981) showed that including the fourth parameter reduced the F-value compared with the three-parameter equation justifying its addition from a statistical perspective.

Previous work measuring N mineralization in soils has shown that the Gompertz model provides a good fit for data with mineralization lags (Ellert and Bettany, 1988; Agbenin, 1999). Ellert and Battany (1988) found that the Gompertz model obtained the lowest $F_{lackfit}$ for soils with N mineralization lags. They also found that estimates for N_0 were consistently lower with the Gompertz model compared with estimates from the other kinetic equations. The Gompertz and the consecutive reaction model provided the best fit to N mineralization data obtained from neem seed added to an acid soil (Agbenin, 1999). Estimates for N_0 were also lower using the Gompertz model than the first order rate equation and the consecutive reaction equation. Values for the rate constants k and h in both studies were similar in trend and value to those obtained in our study.

Comparing plots of the residuals versus predicted values showed that data points appear to separate according to replicate, and were not randomly distributed about zero (Fig. 3.13). The copra cake treatment was the only case where points showed a more random distribution about zero. Non-random residual plots are usually a sign that the basic assumptions of regression are being violated questioning the validity of the model.

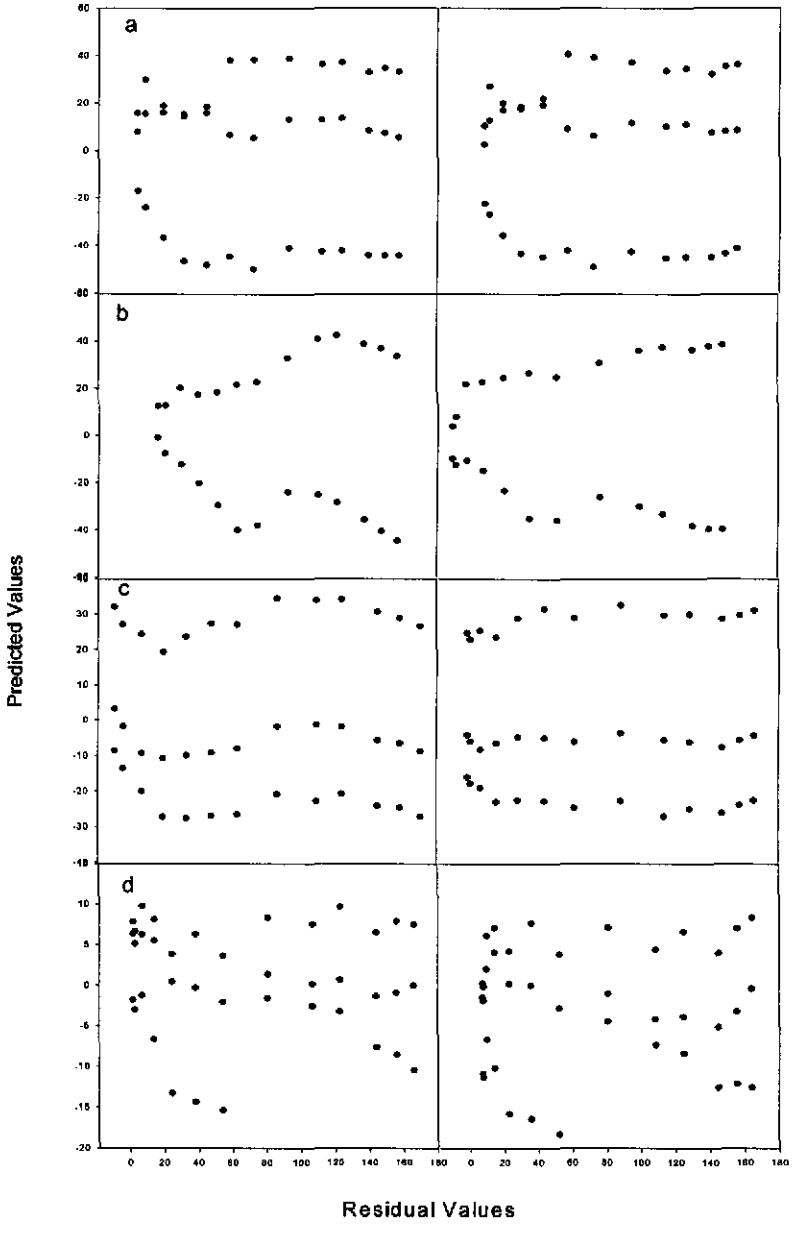


Fig. 3.13. Plots of Predicted values of N mineralization versus residuals for (a) fish meal. (b) *V. marina*, (c) chicken manure, and (d) copra cake data fit with the three-parameter (left) and four-parameter (right) Gompertz equations.

Incremental Models

The N mineralization data for each leaching interval were plotted as a function of time, the kinetic equations were transformed by subtraction into their incremental forms, and fitted to the data. The presence of a significant flush of mineral N after the first week of the incubation in all treatments except copra cake complicated the fitting process. Ellert and Bettany (1988) attempted to account for this initial flush by applying a segmented approach to the curve fitting procedure. We chose to remove the first interval from the analysis for three reasons: (i) the flush that occurred during the first week of incubation may be an artifact of preparing the soil in the laboratory, (ii) this flush is highly mobile and transient in nature, and (iii) fitting a separate linear segment between week 1 and 2 to account for the initial flush may not have much meaning since there are only two points in the fitting process.

The results of fitting the data to the incremental dataset are presented in Table 3.10. The two first-order rate equations and the mixed order equation did not fit the data in all four treatments. The first-order equation does appear to be flexible enough to fit the data. The consecutive reaction equation did not perform well; it consistently had low adjusted r^2 values, and the standard errors associated with the parameter estimates were inordinately high for all four treatments. The two simultaneous reaction equation performed better for all treatments except for *V. marina*. The Gompertz equations provided the best fit achieving the lowest $F_{lackfit}$ in all four treatments. Figure 3.14 shows how the Gompertz model increased the flexibility compared with the two simultaneous reaction model. In the cases of fish meal and *V.*

Table 3.10. Results of fitting the kinetic models to incremental N mineralization data for the 4 different organic material added to a Marshall Island soil.

Material	Model	Adj. r^2	RMSE	$F_{lackfit}$	N_0	N_e	k	h
Fish Meal	1st order	0.000	9.82	4.88	10.4		-0.0005 (0.01)	
	1st order e	-	-	-	-	-	-	-
	2 simultaneous rxns	0.384	7.63	1.83	29.6 (51.9)		0.11 (0.06)	-0.13 (0.12)
	Consecutive rxns	0.308	8.09	2.47	811 (442)		0.08 (43.3)	0.08 (43.2)
	Mixed order	No fit						
	Gompertz (standard)	0.449	7.22	1.52	80.8 (6.30)		0.13 (0.01)	3.37 (0.62)
	Gompertz E	0.460	7.15	1.34	60.6 (11.6)	8.79 (3.98)	0.19 (0.05)	7.93 (5.46)
V. marina	1st order	0.007	9.7	8.48	8.53 (1.72)		-0.01 (0.01)	
	1st order E	-	-	-	-	-	-	-
	2 simultaneous rxns	0.067	9.41	7.25	32.9 (31.3)		0.20 (0.18)	0.64 (2.25)
	Consecutive rxns	0.174	8.85	6.43	841 (273)		0.07 (72.8)	0.07 (72.9)
	Mixed order	No fit						
	Gompertz (standard)	0.339	7.92	4.71	73.6 (6.93)		0.12 (0.02)	3.98 (0.92)
	Gompertz E	0.264	8.35	5.25	180 (1192)	-39.7 (422)	0.06 (0.22)	1.43 (4.54)
Chicken Manure	1st order	0.101	7.65	16.9	5.70 (1.25)		-0.02 (0.01)	
	1st order E	-	-		-	-	-	-
	2 simultaneous rxns	0.653	4.75	4.76	96.6 (47.1)		0.04 (0.04)	-0.09 (0.03)
	Consecutive rxns (hk)	0.478	5.83	8.58	754 (663)		0.06 (452)	0.06 (452)
	Mixed order	0.000	8.16	18.9	8953 (>>)		0.002 (0.06)	-0.001 (0.004)
	Gompertz (standard)	0.681	4.55	4.39	64.1 (4.22)		0.14 (0.01)	5.08 (0.89)
	Gompertz E	0.673	4.62	4.37	60.8 (9.05)	1.50 (3.34)	0.15 (0.03)	6.05 (2.55)
Copra Cake	1st order	No fit						
	1st order E	-	-	-	-	-	-	-
	2 simultaneous rxns	0.577	6.31	10.4	345 (1658)		0.006 (0.04)	-0.09 (0.03)
	Consecutive rxns	0.367	7.72	17.2	963 (3013)		0.05 (534)	0.05 (534)
	Mixed order	0.000	9.73	28.6	1616 (>>)		0.007 (0.08)	-0.002 (0.005)
	Gompertz (standard)	0.765	4.7	5.01	80.5 (5.39)		0.21 (0.02)	18.8 (4.84)
	Gompertz E	0.824	4.07	3.06	74.8 (5.98)	4.81 (1.13)	0.30 (0.03)	67.1 (31.3)

marina where N release was relatively high at week two, the four-parameter Gompertz equation provided the best fit. For chicken manure where no N was released at week two, the three-parameter Gompertz model gave the best fit.

Parameter estimates obtained by the incremental and cumulative models were generally dramatically different. In the fish meal, *V. marina* and chicken manure treatments the incremental TSR and Gompertz models gave estimates for N_0 that were significantly lower compared with the estimates obtained with the cumulative models. A similar estimate of N_0 was obtained only when the TSR model was applied to the copra cake treatment. Based upon our analysis, N_0 estimates using the incremental approach do not appear reliable. Ellert and Bettany (1988) obtained consistently lower N_0 estimates with the incremental models, but the differences compared with the cumulative models were much less dramatic than in our case. The lower estimates of N_0 may have been a result of removing the N released during the first week from the calculations, but we would not expect the decrease to be so dramatic. When the first two leachings were removed from the curve fitting process in a previous study, differences in N_0 estimates were far less dramatic (Deans et al., 1986).

The estimates of the specific rate constants h and k with the incremental TSR equation ranged from 0.04 to 0.20 mg kg^{-1} $week^{-1}$ for k and from –0.13 to 0.64 mg kg^{-1} $week^{-1}$ for h. Our estimates of k fall within the range of values reported by Ellert and Bettany (1988) for the incremental version of the TSR model. The negative values obtained for h in three of the four treatments were surprising because previous research has always reported positive h values, and h describes a more labile pool

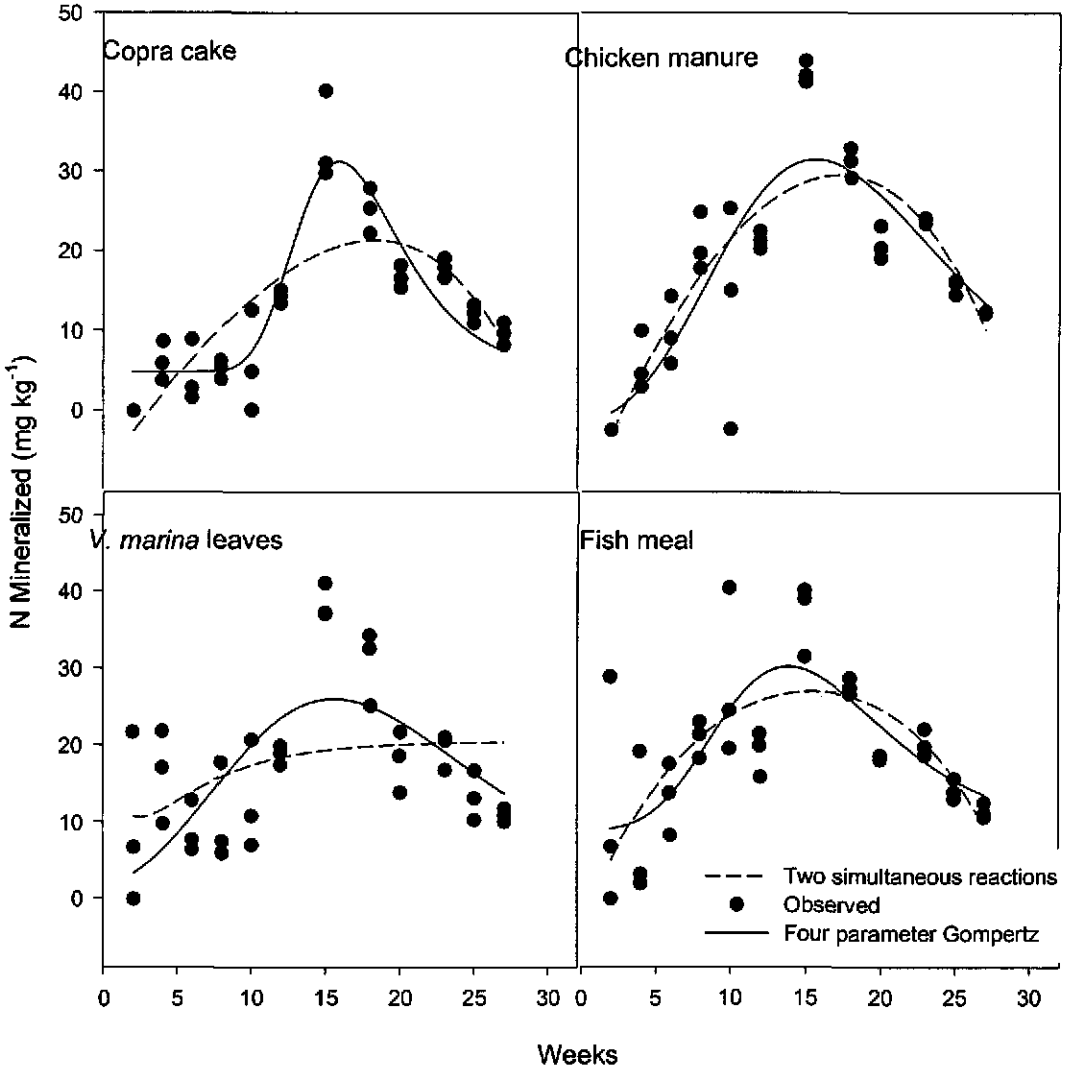


Figure 3.14. Comparing the fit of the two simultaneous reactions and Gompertz models for N mineralized from the four different organic soil amendments to incremental data.

of organic N. If positive *h* values represent N mineralization rates, negative values logically represent N immobilization. Nitrogen release curves for the fish meal, chicken manure, and copra cake treatments show mineralization lags early in the incubation indicating that immobilization reactions were dominant. Immobilization was most prominent in the copra cake treatment followed by chicken manure, and least in the fish meal treatment. If a negative *h* indicates immobilization we would

expect more negative values to be associated with materials that exhibited a larger degree of immobilization. However, our results showed just the opposite; estimates for *h* were most negative in the fish meal treatment, which showed less immobilization than the copra and chicken manure treatments. Negative *h* values may only be an artifact of the curve fitting process, and have no biological significance.

The three and four-parameter Gompertz equations gave estimates for *k* that ranged from 0.06 mg kg^{-1} wk^{-1} for the *V. marina* treatment to 0.30 mg kg^{-1} wk^{-1} for the copra cake treatment. Estimates for *h* ranged from 1.43 to 67.1 mg kg^{-1} wk^{-1}. Estimates for *h* and *k* obtained using the incremental models were usually higher than with the cumulative models, except for the *V. marina* treatment where the values for both methods were similar. In the case of copra cake, the incremental four-parameter Gompertz model gave an *h* value that was almost nine times greater than the cumulative model. In the case of copra cake, the high estimates for *h* may have some biological significance. The *h* parameter is a rate constant associated with the more slowly mineralizable pool of N. Copra cake showed a distinct lag period followed by a rise in mineralization. The increased rate of mineralization later during the incubation period may have been associated with the more slowly mineralizable pool of N, and correctly represented by a high *h* value. With the exception of the copra cake treatment, our estimates of *k* and *h* were within the ranges reported by Ellert and Bettany (1988). Unlike Ellert and Bettany (1988), we obtained large differences in estimates for N_o from the incremental and cumulative models. Most of the equations fitting the incremental data provided very low estimates for N_o.

The incremental fitting procedure consistently obtained much lower regression coefficients and higher values for $F_{lackfit}$ suggesting that the incremental dataset was not as good a predictor of N mineralation parameters as the cumulative data. On the other hand, plotting the residuals versus the predicted values (Fig. 3.15), we found that the incremental approach produced a more random distribution of the data compared with the cumulative approach (Fig. 3.13). In all, but the *V. marina* case, the distribution of the residuals was more random for the three-parameter Gompertz model than the TSR model. The more random distribution of the residuals suggests that fitting the incremental data did not violate the assumptions underlying regression. The results comparing the use of the cumulative models with the incremental models from the present study do not support the conclusions of Ellert and Bettany (1988) that the incremental models can replace the cumulative models to estimate N mineralization parameters. Goodness-of-fit statistics and unreasonable parameter estimates for the incremental models showed that the cumulative models were more suited to describing N mineralization dynamics in the present study.

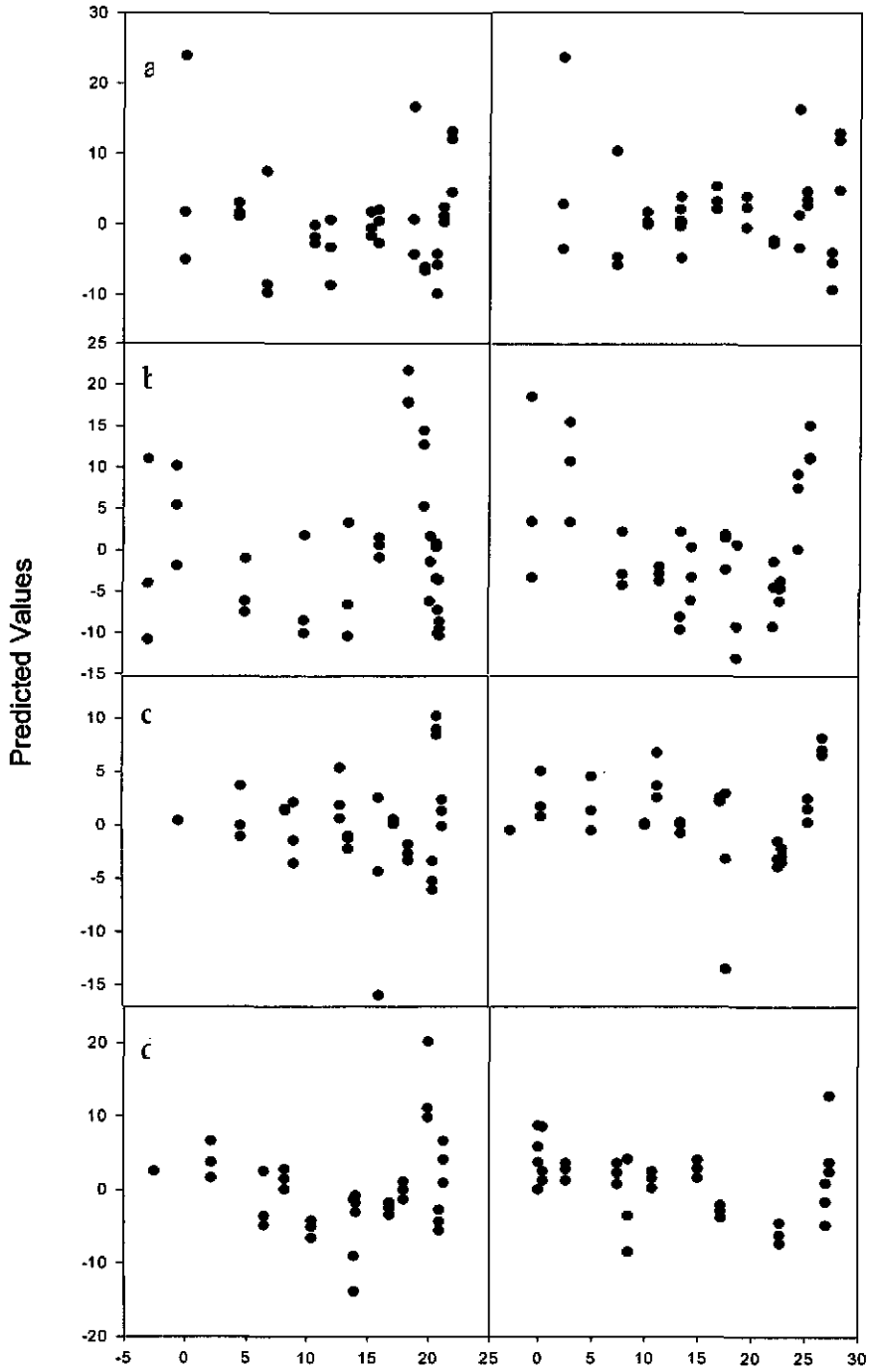


Figure 3.15. Plots of Predicted values of N mineralization versus residuals for (a) fish meal. (b) *V. marina*, (c) chicken manure, and (d) copra cake data fit with the incremental TSR (left) and three-parameter (right) Gompertz equations.

The Segmented Model

We fitted a segmented model to the incremental N mineralization data for all four treatments. Fitting this type of equation to the incremental data essentially breaks the mineralization process down into two distinct phases. The first phase, represented by the first line segment, marks the period of increasing mineralization rate. The second phase, characterized by the second line segment, marks a period of gradually decreasing mineralization rate. The segmented model provides estimates for: (i) the slopes of the two line segments, which are measures of an increasing mineralization rate (*a*) and a decreasing rate (*b*); and (ii) the time (*node*) at which the rate changes from positive to negative. Using these estimated values we can then calculate the area under the curve (an estimate of N_0) and the amount of N mineralized at the *node* (N_{max}). Parameter estimates derived from the segmented equation fitted to the four organic materials are presented in Table 3.11 with a graphical representation in Figure 3.16.

Table 3.11. Parameters estimated from segmented equations fitted to the incremental N mineralization data.

Materials	*a*	*b*	*Node*	N_0	N_{max}	RMSE
	mg N kg^{-1} wk^{-1}		wks	mg N kg^{-1}		
Fish Meal	3.59	-0.63	9.38	499	27.8	8.26
V. marina	2.62	-0.52	11.8	433	24.8	8.78
Chicken Manure	2.23	-0.55	13.2	363	22.2	5.17
Copra Cake	2.16	-0.64	15.0	341	22.8	6.15

The fish meal treatment exhibited the highest value for *a*, the rate constant associated with increasing N mineralization followed by *V. marina*, chicken manure

and copra cake. The estimated values for *a* of these materials were correlated with their total N concentration, fish meal having the highest concentration and copra having the lowest. Values for *b*, the rate constant reflecting decreasing rates of mineralization, did not differ significantly between the treatments. Estimates of the *node*, or the number of weeks before N mineralization rates changed from positive to negative, ranged from slightly less than 9.5 weeks for fish meal to 15 weeks for copra cake. The estimated value for the node was lower than the observed value in all treatments except for copra cake. Estimated value for N_0 was highest for the fish meal treatment at 499 mg kg^{-1} and decreased to a minimum of 341 mg kg^{-1} for copra cake. Like estimates for *a*, N_0 values were proportional to total N concentration of the materials. Estimates for N_{max}, or the maximum amount of N released at the node, were highest in the fish meal and *V. marina* treatments and lowest in the chicken manure and copra cake treatments. Calculated values for N_{max} were underestimated in all treatments with respect to experimentally derived values, especially for fish meal and *V. marina*.

From the graphs presented in Figure 3.16, it is evident that an equation with just two segments cannot adequately explain mineralization dynamics in all four materials. The best fit was achieved with the chicken manure treatment where mineralization dynamics were reasonably linear for both the increasing and decreasing phases of mineralization. The *node*, however, was underestimated causing an underestimation and questionable value for *b*. In the case of copra cake, two linear segments were insufficient to explain mineralization. The spread of data suggest that using three segments may be more appropriate; an initial segment from 2 to 10 weeks

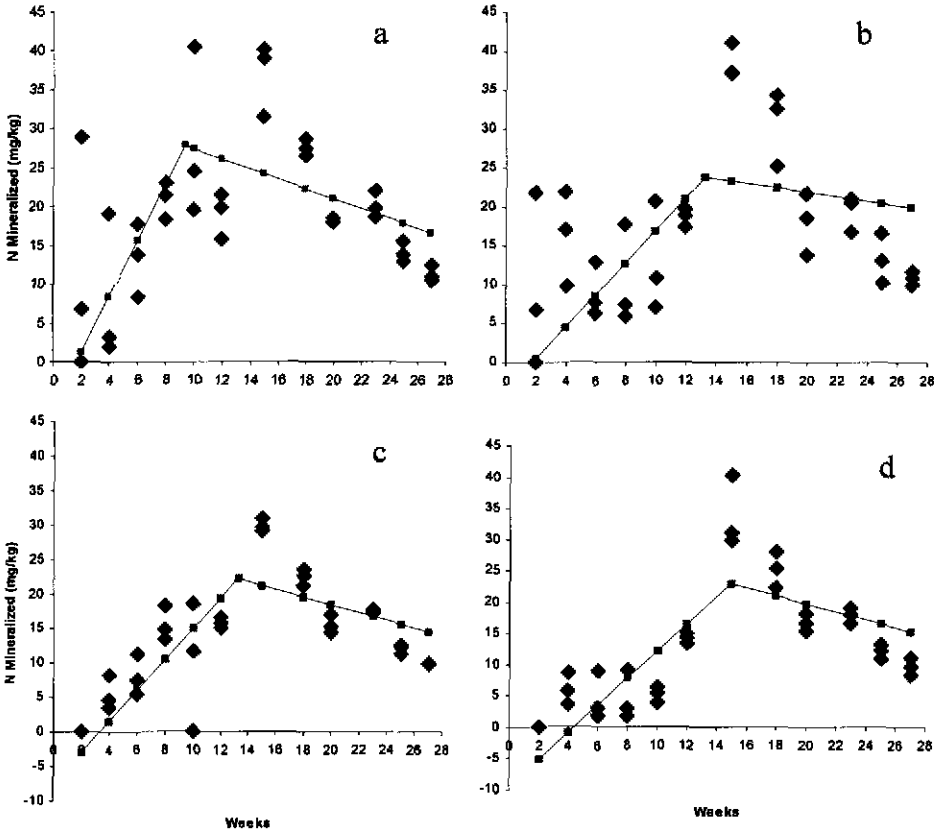


Figure 3.16. Results of fitting the segmented equation to (a) fish meal, (b) *V. marina*, (c) chicken manure, and (d) copra cake.

to account for a period of little mineralization, followed by a second segment with a steep slope up to 15 weeks, and ending with a third segment to describe the linear decrease in mineralization following week 15. The nonlinear nature of N mineralization during the first 15 weeks were inadequately fit by the first linear segment resulting in questionable estimates of *a*. The underestimation of N mineralized at the node also caused an underestimation of b, which describes the decreasing rate of mineralization. For fish meal and especially *V. marina*, variability in the data during the first ten weeks of the incubation caused a weaker fit. The data for *V. marina* indicate that a three-segment equation may be more appropriate to

explain what appear to be three phases in the mineralization process: an initial flush followed by a decline to week 8 with a steep rise to week 15, and ending with a linear decrease. In general, the segmented model was unable to account for the peak in mineralization at week 15 or 16. In all treatments except copra cake the model forced an early peak and therefore could not adequately describe mineralization dynamics for the last 10 to 12 weeks of the incubation. In fact, estimates for *b* were between 3 and five times lower than *a*, suggesting that the materials continued to mineralize N at a relatively high rate towards the end of the incubation period. The distribution of the data before and after the peak, however, showed that the slopes were similar. Estimates for *b* do not adequately describe the decreasing phase of mineralization and should be interpreted cautiously in describing the last phase of the mineralization process.

Based upon calculated $F_{lackfit}$ statistics for the four organic materials, the segmented equation did not provide as good a fit as the kinetic equations fit to the cumulative data, but showed similar goodness-of-fit as the Gompertz equation fit to the incremental data. Plots of the predicted versus residual values for the segmented equation showed a relatively random distribution of points for the fish meal and chicken manure treatments, but clear trends for the *V. marina* and copra cake treatments. Based upon $F_{lackfit}$ statistics and predicted versus residual values plots, the segmented model performed as well as the incremental kinetic models for the chicken manure and copra cake treatments. The inability of the segmented model to correctly estimate N_{max} and b raises questions regarding its suitability and demands that more work be done to improve the fitting procedure.

Despite its limitations, the segmented model offers a different way of looking at N mineralization dynamics in soils with practical implications for nutrient management in cropping systems. By plotting N mineralization data incrementally and fitting two linear segments we obtain the following information: (i) N release rate up to the maximum, (ii) the time associated with maximum release, (iii) the amount of N released up to the maximum, (iii) the rate of decline once the maximum has been achieved, and (iv) an estimate of the potentially mineralizable pool of N. Separating the mineralization process into two distinct phases, one increasing and the other decreasing, offers the opportunity to better match the N release with N uptake by crops. The ability to predict the time of maximum release, the *node*, is a powerful tool with the potential to improve synchrony between nutrient release from organic materials and crop uptake dynamics. Unlike the kinetic approach, which only provides estimates for mineralization rates and the mineralizable pool, the segmented model provides a direct and quantitative methodology for predicting the time associated with maximum N release. Preliminary correlation analysis using the fish meal, chicken manure, and copra cake treatments showed that the node was related to the total N and C:N ratio of the materials (Table 3.12); increasing N concentrations reduced the time to reach maximum N release, and conversely, increasing C:N ratios increased the time to attain maximum release. It appears worthwhile to collect more data from the literature and perform correlation and regression analysis to evaluate and perhaps quantify the relationship between the node and easily measured chemical properties. Using this approach, we may be able to provide rapid predictions for the

time of maximum release for different organic materials, and thus improve synchrony in organically managed farming systems.

Table 3.12. Correlation coefficients for node, total N, and C:N ratio for fish meal, chicken manure, and copra cake treatments.

	Node	*N*	*C:N*
Node	1		
N	-0.71	1	
C:N	0.71	-0.84	1

Conclusions

The Marshall Island soil showed an extremely low N mineralization potential compared with soils from the continental United States despite high concentrations of organic C and total N. Results from the incubation experiment indicated that the soil would not contribute significant quantities of mineral N during as many as four consecutive cropping sequences. The *V. marina*, fish meal, and chicken manure treatments exhibited an initial flush of mineral N after the first week with a lag and then increase in N mineralization. These three treatments appeared to have similar N mineralization potentials. The copra cake treatment, on the other hand, showed an initial lag lasting for the first 8 weeks of the incubation, and its release curves suggested that it was not as good a source of N as the other treatments. The total N content of the materials was the best predictor of N mineralization.

The mineralization rate and potential of the organic materials was best estimated by both the cumulative and incremental Gompertz equations. The incremental model achieved lower RMSE values, but did not provide reasonable estimates of N_0. The

biological significance of the two rate constants has yet to be established, but hypothetically they represent a labile and a more stable pool of organic N. The segmented equation achieved similar RMSE values to the incremental Gompertz model, and provided reasonable estimates of N_0. The two estimated mineralization constants were associated with an increasing and decreasing phase of mineralization, and estimates for the node showed the time at which a maximum in mineralization was achieved. These parameters have practical management implications that can be used to synchronize N release with plant N uptake. The segmented equation should be applied to other data sets to better evaluate its predictive capacities with mineralization data.

Our results indicate that *V. marina* is as good a source of N as fish meal and chicken manure. *V. marina* has the advantage that it is ubiquitous throughout the Marshall Islands, and it can be added to the soil as a fertilizer material without any processing. Because *V. marina* can withstand regular cuttings with rapid re-growth, it is a sustainable fertilizer material available to many Marshallese farmers. Furthermore, *V. marina* is commonly found throughout the Pacific basin, and could serve as a good fertilizer for rural island and atoll farmers. Future work must examine whether it can supply adequate quantities of N to support the high N requirements of vegetable crops.

Chapter Four

Correcting Soil Nutrient Deficiencies in the Atolls of the Marshall Islands with Local organic Materials

Introduction

Soil nutrient deficiencies are a major constraint to crop production on the low-lying atoll soils of the Marshall Islands (Caiger, 1987; Finlay, 1992; Morrison, 1992). The sandy, carbonatic, and alkaline conditions of these soils interact to limit nutrient availability to crop (Morrison, 1992). Cation exchange capacity is inherently low due to the coarse texture, and the carbonate mineralogy has lead to Ca^{2+} saturation of the exchange sites. These two factors have lead to serious K deficiencies (Gangaiya and Morrison, 1998). The high pH conditions and predominance of Ca^{2+} in the soil solution decrease the solubility of P (Lindsay and Norvell, 1979) and the micronutrients (Lindsay, 1991).

Correcting the nutrient deficiencies with chemical fertilizers has not been entirely successful (Finlay, 1987a). Correcting N and K deficiencies with soluble fertilizers has been problematic because the sandy texture and low CEC increase the leaching potential of these ions through the root zone. These fertilizers must be added in small doses frequently throughout the growing period to minimize losses to leaching (Caiger, 1987; Finlay, 1987b; Reddy and Chase, 1992). Several studies in atoll soils have shown that micronutrient deficiencies were not easily corrected with inorganic fertilizers due primarily to the low solubility of these elements in soils with pH values

near 8.0 (Finlay, 1987b; Morrison, 1992; Weereratna, 1992; Widdowson and Trangmar, 1992). Chelated forms of micronutrient fertilizers (Widdowson and Trangmar, 1992), and foliar applications (Trewren, 1985) have corrected micronutrient deficiencies, but they are expensive and not accessible to the average atoll farmer (Liew, 1987).

The traditional Micronesian cultures of the Pacific atolls relied primarily on the cultivation of coconut, breadfruit, pandanus, and a variety of root crops (Thaman, 1992a). Coconut and pandanus were well adapted to the poor soils of the atolls and they required little management (Hiyane, 1971; Thaman, 1992a; Thaman, 1992b). The regular use of mulches consisting of fresh and dead organic materials were common around breadfruit trees and in the pits excavated for taro production to maintain soil fertility levels (Hiyane, 1971; Raynor, 1992a; Thaman, 1992b). Based upon what was known of the traditional practice of using organic matter inputs to maintain fertility combined with the inaccessibility of chemical fertilizers to atoll farmers, researchers have consistently recommended the use of organic inputs to the soil as fundamental to a successful agricultural development program (Liew, 1986; Liew, 1987; Thaman, 1992b).

Despite the importance attributed to organic matter in atoll agriculture, formal research on evaluating its benefits is scant. A few studies give qualitative descriptions of traditional organic matter management practices for swamp taro and breadfruit production on atolls (Ali and Asghar, 1987; Manuella and Cable, 1992; Raynor, 1992a), but no data exist to determine the nutrient supplying capacity of

traditional soil management strategies. Reynolds (1971) found that dry matter yields for a bean crop grown in a coral soil amended with a mixture of organic matter and NPK fertilizer increased fourfold over the control and twofold over the organic matter alone treatment. The results indicated a beneficial interaction between added fertilizers and organic matter, but were inconclusive because the treatments were not replicated. Composted coconut palm leaves have been proposed as a suitable amendment to increase vegetable production (Chevillet, 1980), but if used alone this amendment probably would not provide sufficient nutrients for adequate vegetable growth. Another approach recommended filling the bottom of a shallow pit with fresh leaves, covering with soil and planting vegetable seeds in the overlying mound (Finney and Laukon, 1993; Stone et al., 2000). Neither paper, however, discussed the potential immobilization of soil N during the initial stages of decomposition, an important oversight, especially in a buried pit where anaerobic conditions predominate. A more recent experiment reported that coral soil amended with fresh green manure and mature compost increased tomato yields. The study concluded that fresh green manure applied to the soil at a rate of 20-30 Mg ha^{-1} was the most efficient treatment (Reddy and Chase, 1998).

The purpose of the present study was to evaluate the effectiveness of five locally available organic materials to adequately supply the nutrient requirements of a Chinese cabbage crop grown under controlled conditions in the greenhouse.

Materials and Methods

Screening Organic Materials in a Greenhouse Experiment

We conducted a bioassay in the greenhouse to evaluate the nutrient supply capacity of six organic materials consisting of chicken manure, fishmeal, copra cake, *Vigna marina*, and *Cocos nucifera* to a crop of Chinese cabbage (*Brassica rapa* var. *chinensis*). Field moist soil was passed through a 4-mm sieve, a 2-kg (1.52 kg oven dry basis) sub-sample was weighed onto brown paper, and the prescribed weight of amendment was thoroughly mixed with the soil. The organic amendments were added at the same rate as in the incubation experiment assuming that 40% of the N from the waste materials and 90% of the N in the *V. marina* leaves would mineralize during the five-week growing period (Table 4.1), and the chemical control treatment received a blanket nutrient solution summarized in Table 4.2. The mixture was placed in pots with a height of 18 cm and a diameter of 15.5 cm, and watered to approximately field capacity. The pots were allowed to stand for five days, after which 2-week old cabbage seedlings were transplanted, the pots were re-weighed and the correct amount of water was added to bring back up to field capacity. Each pot was fitted with a tray to collect any leachate, which was returned to the pot to prevent the loss of nutrients due to occasional over watering. The pots were set up in a randomized complete block design in the greenhouse fitted with 50 % shade-cloth. Blocks were arranged to account for a natural temperature and an artificial light gradient within the greenhouse. Temperature decreased from blocks 1 to 3, but block 3 tended to get direct sunlight after 2 PM because of the configuration of the shade-cloth.

The experiment consisted of a total of 105 pots to accommodate a weekly destructive sampling schedule. Soils and plants were harvested at 7, 14, 21, 35 and 42 days after transplanting. One pot for each treatment from each block was randomly selected on a weekly basis. At days 7 and 14 after transplanting, soil samples were collected and analyzed for $NH_4^+ - N$, $NO_3^- - N$, Olsens P, extractable

Table 4.1. Addition rate of organic materials for the greenhouse pot experiment. Each pot contained 1.52 kg soil (oven dry basis).

Material	%N	Material per Pot Dry Wt g	N per Pot g	kg Total N/ha
V. marina	3.49	14.1	0.49	551
Chicken manure	4.35	23.6	1.03	1145
Fish meal	7.28	14.1	1.03	1145
Copra cake	3.07	33.4	1.03	1145
C. nucifera	1.65	14.1	0.23	260

Table 4.2. Nutrient addition rate of the control treatment for the greenhouse experiment evaluating nutrient supply capacity of five organic materials added to a Marshall Island soil.

Element	Form	Rate	
		mg kg^{-1}	mg pot^{-1}
N	NH_4NO_3	200	358
P	KH_2PO_4	20	35.8
K	KCl	200	358
Mg	$MgCl_2$	96	172
S	K_2SO_4	50	89.5
Fe	Sequestrine (FeEDDHA)	10	17.9
Mn	$MnSO_4$	10	17.9
Zn	$ZnSO_4$	10	17.9
Cu	$CuSO_4$	2.5	4.48
B	$Na_2B_4O_7$	0.5	0.90

K, Ca, and Mg, $SO_4^{2-} - S$, hot H_2O soluble B, and DTPA extractable Fe, Mn, Cu, and Zn according to the analytical methods outlined in Chapter 3. Plants were not

sampled because growth was minimal across treatments. On days 21, 35, and 42 both soils and plant biomass were collected. Soils were analyzed in the same manner as described above, and plants were washed in deionized H_2O, dried at 70°C for 72 hours, weighed for dry weight determination, and analyzed for total nutrient concentration according the procedures outlined in the methods section of Chapter 2.

The nutrient supply capacity of the different amendments was evaluated by comparing the relative growth rate (RGR) to the relative accumulation rate (RAR) for each nutrient based upon the concepts laid out in Raper et al. (1977). Growth or nutrient accumulation can be described by the following regression equation with the form

$$\ln BM = a + b*t \quad (1)$$

where BM is the dry matter biomass of the cabbage plant, a is the intercept, b is the regression coefficient or slope of the line, and t is plant age in days after transplanting. Figure 4.1 illustrates the relationship between cabbage biomass and plant age for the *V. marina* treatment. Taking the natural log of the left hand side of equation 1 for times t_1 and t_2 we obtain

$$BM_1 = e^{a}*e^{bt_1} \quad (2)$$

$$BM_2 = e^{a}*e^{bt_2} \quad (3)$$

The regression coefficient b is equivalent to

$$BM_2/BM_1 = e^{bt_2}/ e^{bt_1} \quad (4)$$

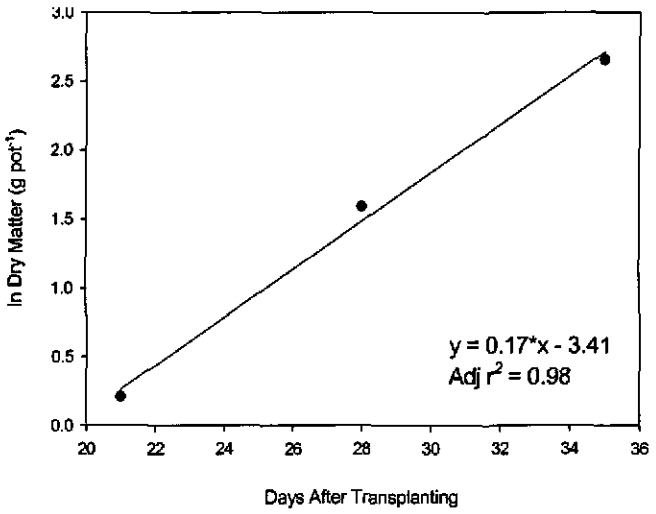


Fig. 4.1. Relationship of the natural log of cabbage dry matter biomass and plant age in days after transplanting where 0.17, the regression coefficient represents the relative growth rate.

Which is equivalent to the Relative Growth Rate (RGR), and is defined by the relationship

$$RGR = \ln[BM_2/BM_1]/(t_2-t_1) \quad (5)$$

where BM_2 is the cabbage dry matter at 28 DAP, BM_1 is the cabbage dry matter at 21 DAP, t_2 is 28 DAP and t_1 is 21 DAP. Relative Accumulation Rate (RAR) for the plant nutrients was calculated using the same approach with the equation

$$RAR = \ln[(BM_2*C_2)/(BM_1*C_1)]/(t_2-t_1) \quad (6)$$

where BM represents dry matter biomass and C is the concentration of the nutrient in the above ground plant material. Relative growth rate and RAR values for each nutrient were computed for each replicate. Differences RGR between treatments were determined by ANOVA using the proc ANOVA procedure in SAS. Values for RAR for each nutrient within a treatment were compared with RGR values for that treatment using ANOVA.

V. marina Rate Experiment

Cabbage plants grown with the *V. marina* leaves in the screening experiment showed slow growth rates during the first three weeks followed by a rapid rise in growth rate especially during the fifth week of the experiment. We hypothesized that the initial lag in growth was caused by the build up of possibly toxic intermediate organic substances as the *V. marina* leaves decomposed. To test this hypothesis, and to determine crop response to increasing rates of *V. marina*, we conducted a greenhouse experiment with *Zea mays* (L. supersweet #9). The *V. marina* amendment was added to supply 200 mg N kg^{-1} in two different ways: (i) in a split application with half prior to planting and the remaining half two weeks after corn emergence, and (ii) the whole quantity of leaves added prior to planting. Soils were prepared the same as in the screening bioassay described above and four rates of *V. marina* were applied to the pots (Table 4.3). Six seeds of *Z. mays* were planted in each pot, and thinned to two uniform seedlings 7 days after planting. Pots were weighed periodically to determine moisture loss and brought back to their original weight with deionized water. As the corn plants grew, moisture was replenished daily. The plants were harvested 5 weeks after planting by cutting the stalks at the soil surface. The stalks were rinsed in deionized water to remove any soil and dried for 72 hours at 70°C. The dried plant material was ground, dry ashed at 500°C for 3-3.5 hours, and nutrient concentration determined according to the method described in Chapter 2.

Table 4.3. Addition rates for *V. marina* leaves in a pot experiment evaluating nutrient supply capacity.

Rate (Dry wt.) Mg ha^{-1}	Dry wt.	Fresh wt.
	g pot^{-1}	
0	0	0
3.18	4.52	45.2
6.37	9.05	90.5
12.7	18.1	181

Copra Cake Experiment

The results of the screening experiment described above showed that copra cake improved growth compared with the untreated soil, but tissue analysis and final yields suggested that its N supplying capacity was insufficient. We hypothesized that supplementing the copra cake with either an inorganic or an organic source of N would improve N supply and increase crop growth. Furthermore, copra cake is a readily available waste material that could be a valuable fertilizer material for Marshall Island farmers. This experiment was conducted to assess its value. We conducted a greenhouse experiment with two rates of copra cake and evaluated the effects of supplementing with either a chemical or a *V. marina* addition with and without micronutrients (Table 4.4). The analysis of variance for the experiment is illustrated in Table 4.5, and Table 4.6 shows the different treatments and the null hypotheses being tested. A control treatment consisting of a blanket application of nutrients was included. Copra cake was mixed thoroughly with a 2 kg moist Marshall Island soil, and fresh *V. marina* leaves prepared as in Chapter 3 were mixed in with the soils. The chemical treatments were prepared in solution, added to the soils, and mixed thoroughly. For the blanket treatment solution 100 mg kg^{-1} N and K were added initially with the remaining 100 mg kg^{-1} added as solution 14 days after

transplanting. The control plots received an additional 50 mg kg^{-1} of Mg and K 25 days after transplanting to correct for possible Mg and K deficiencies. Treatments were prepared in triplicate. The prepared soils were carefully transferred into plastic pots, watered to achieve approximate field capacity, and weighed. Pots were allowed to equilibrate in the greenhouse for 1 week. After 1 week, soils were removed, remixed and two-week old Chinese cabbage plants (*Brassica chinensis* L. pekinensis) were transplanted into the pots. Treatments were arranged in a randomized complete block design. The greenhouse benches were equipped with a misting irrigation system using tap water and connected to an automated timing system. The timer was set to run the mist for 10 seconds every 16 minutes between 10:30 AM and 3:30 PM. The misting system was used to reduce the detrimental effects of high temperature during the middle of the day. Temperature ranged from a low of 23.9 to 39.3°C with daily averages ranging from 26.5 to 30.1°C.

Cabbage tops were harvested 35 days after transplanting. The tops were rinsed in deionized water, fresh weight determined, and dried at 70°C for 72 hours. Dry weight was determined and the dried plant material was ground, dry ashed at 500°C for 3-3.5 hours, and nutrient concentration determined according to the method described in Chapter 2. Soils were air-dried, roots removed and stored in the freezer at -3°C.

Table 4.4. Treatment configuration for copra cake greenhouse experiment.

Treatment	Application Rate
Control	Blanket application N, P, K, Mg, S, Fe, Mn, Cu, Zn, and B
Copra 1	10 Mg ha^{-1}
Copra 2	20 Mg ha^{-1}
Copra 1 + Chemical Copra 2 + Chemical	N at 200 mg kg^{-1}, P 160 mg kg^{-1}, and Mg 50 mg kg^{-1}
Copra 1 + *V. marina* Copra 2 + *V. marina*	*V. marina* at 6.37 Mg ha^{-1}
Copra 1 + *V. marina* + micronutrients Copra 2 + *V. marina* + micronutrients	B at 1 mg kg^{-1}, Cu at 5 mg kg^{-1}

Table 4.5. Analysis of variance table for the copra cake experiment.

Source		df
Block		2
Treatment		8
	Control	1
	Copra	1
	Vigna	2
	Chemical	1
	CopraXVigna	2
	CopraXChem	1
Error		16
Total		26

Table 4.6. Selected orthogonal treatment comparisons for the copra cake experiment and their respective H_0.

Treatment Comparison	H_0
Control vs rest	Amending the soil makes no difference
Copra 10 vs Copra 20	Increasing copra rate does not affect growth
Copra vs Copra+VM	*Supplementing the copra treatments with V. marina* does not increase growth
Copra vs Copra+VM(B+Cu)	Supplementing the copra with *V. marina* and B + Cu does not increase growth
Copra vs Copra+chemical	Supplementing the copra treatments with chemical nutrients does not increase growth

Results and Discussion

Screening Experiment

Growth Response

Dry matter yields for 35-day old cabbage plants grown with the 5 different organic soil amendments, the chemical control, and the soil alone are presented in Figure 4.2. Cabbage dry weights for the chicken manure, *V. marina*, and copra cake treatments were not significantly different from the chemical control at the 5% probability level. Yield for the fishmeal treatment was significantly lower than the chemical control, chicken manure and *V. marina* treatments, but no different from the copra cake treatment. The soil alone and coconut treatments produced significantly less dry matter than the control and other organic amendments. From a visual perspective, the chicken manure, *V. marina*, and copra cake treatments produced as healthy looking plants as the control treatment (Fig. 4.3). The fish meal treatment showed signs of K deficiency on the older leaves while the cabbage leaves in the

coconut treatment showed severe chlorosis indicating N deficiency compared with the control (Fig. 4.4).

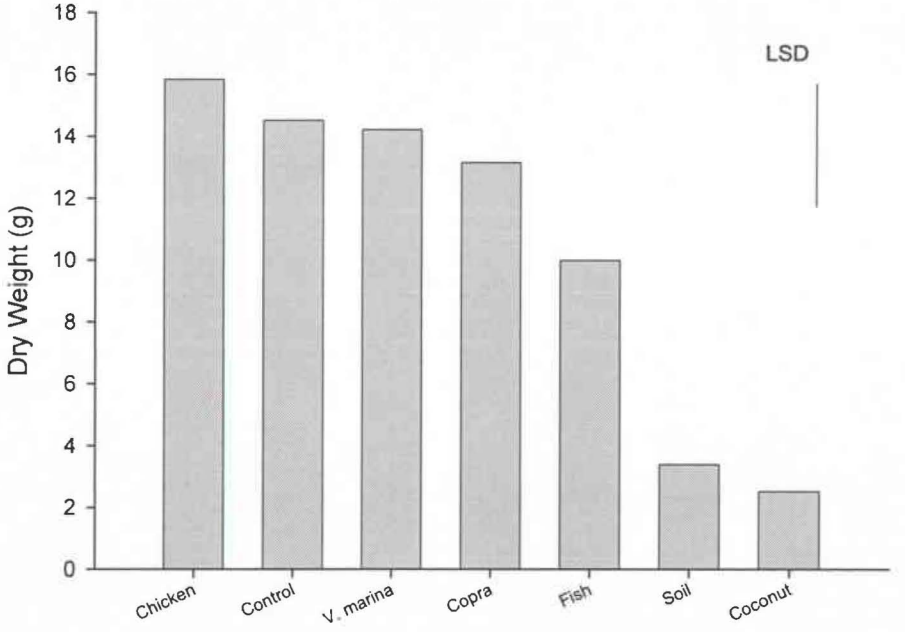


Fig. 4.2. Dry matter yield of Chinese cabbage plants grown with different organic materials from the Marshall Islands.

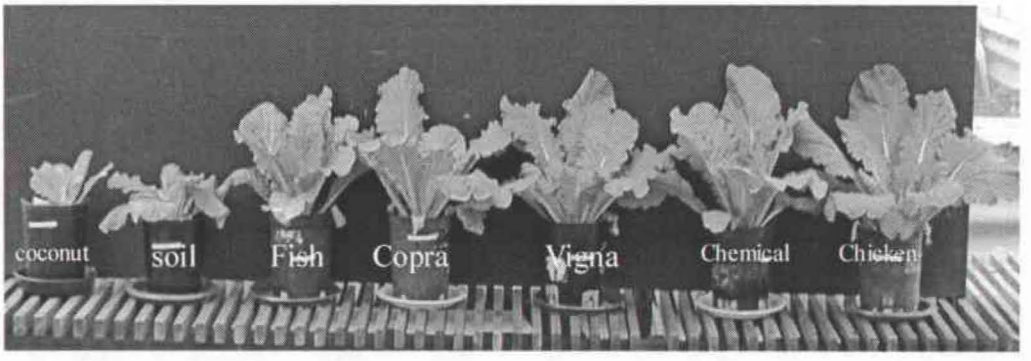


Fig. 4.3. Photograph of treatment effect on Chinese cabbage at harvesting showing the chlorotic leaves and stunted growth in the soil alone and coconut treatments.

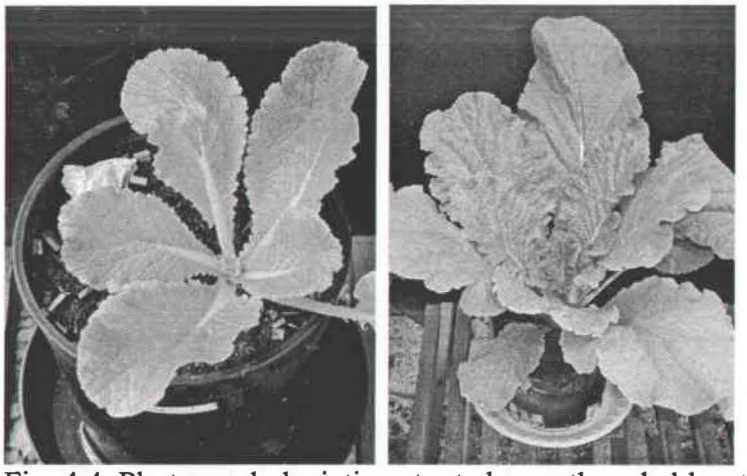


Fig. 4.4. Photograph depicting stunted growth and chlorotic leaves of the cabbage plant grown with coconut (left) compared with the chemical control (right).

We observed a high degree of variability between the three replicates, which was manifested in a high coefficient of variation of 22.2%. In all treatments, dry matter was highest in block three (Fig. 4.5). This effect was especially dramatic in the chicken manure, control, *V. marina*, and copra cake treatments. The dramatic growth differences observed in block 3 were presumably due to a proportionally longer daily exposure to full sunlight. Because pots in block three were situated on the western edge of the greenhouse, and were not covered by the shade cloth for most of the afternoon, they received considerably more radiant energy than the pots in blocks 1 and 2. Due to the configuration of the shade clothe, only the pots in block 1 were completely shaded from the sun throughout the day. The pots in block 2 were not shaded after 3:30 PM. Table 4.7 summarizes the effect on ANOVA statistics when different replicates were excluded in the analysis. Removing block 3, which received the most sunlight, from the analysis resulted in an insignificant block effect, the lowest MSE, but the highest CV and a less significant treatment effect. Excluding

block 1, which received the least amount of sunlight, did not remove the block effect and resulted in the highest MSE. Excluding block 3 from the analysis caused a significant reduction in mean cabbage yields, and tended to erase treatment differences. Removing block 1 caused the largest mean cabbage yields, and the highest amount of discrimination between treatments. The experimental design accounted for the block effect, but growth response in block 3 was as much as twice as large as growth in block 1. Such a large response difference may be too large to remove with a blocking design. Nevertheless, all three replicates were included in data analysis.

Table 4.7. Effect on ANOVA statistics when different blocks were removed from the calculations on data from a greenhouse pot experiment evaluating organic material amendments to a Marshall Island soil.

Blocks	CV (%)	MSE	Pr > F for Blocks	Pr > F for Treatment
1,2, & 3	22.2	5.48	0.001	<0.0001
1 & 2	24.8	4.71	0.25	0.009
2 & 3	22.8	7.22	0.02	0.006

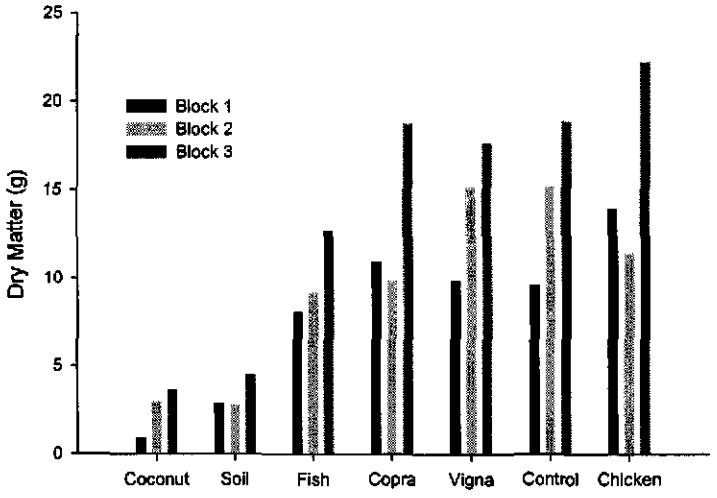


Fig. 4.5. Chinese cabbage dry matter yield differences between blocks across treatments in a Marshall Islands soil amended with different organic materials.

The Relative Growth Rate (g g^{-1} d^{-1}) (RGR) for the cabbage plants showed a significant response to the type of soil amendment (Fig. 4.6). The *V. marina* treatment exhibited the highest RGR, but was not significantly different from the RGRs for the chicken manure and control treatments, which behaved almost identically. The fishmeal and copra cake treatments showed similar growth rates that were significantly lower than the *V. marina* treatment, but not different from the control. The soil alone and *C. nucifera* treatments maintained growth rates that were significantly lower than those in the other treatments.

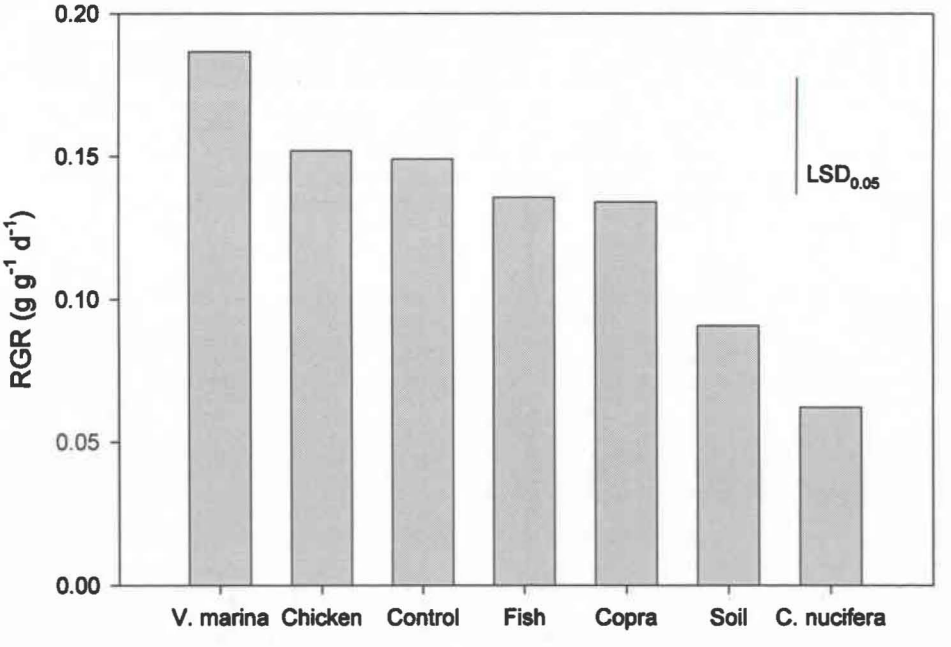


Fig. 4.6. Relative growth rate values between 3 to 5 weeks after transplanting for Chinese cabbage plants grown with different organic materials in a greenhouse experiment.

Nitrogen Mineralization

A destructive weekly sampling procedure was implemented to assess N mineralization and N supply capacity of the five organic materials. Cumulative N mineralization curves were calculated by summing soil $NH_4^+ - N$ and $NO_3^- - N$ with the N accumulated in the plant biomass (Fig. 4.7). The untreated soil supplied a minimal quantity of N to the plants. These results were similar to the results of the laboratory incubation experiment where the soil mineralized only a very small quantity of N. The soil amended with coconut leaves immobilized N during the five-

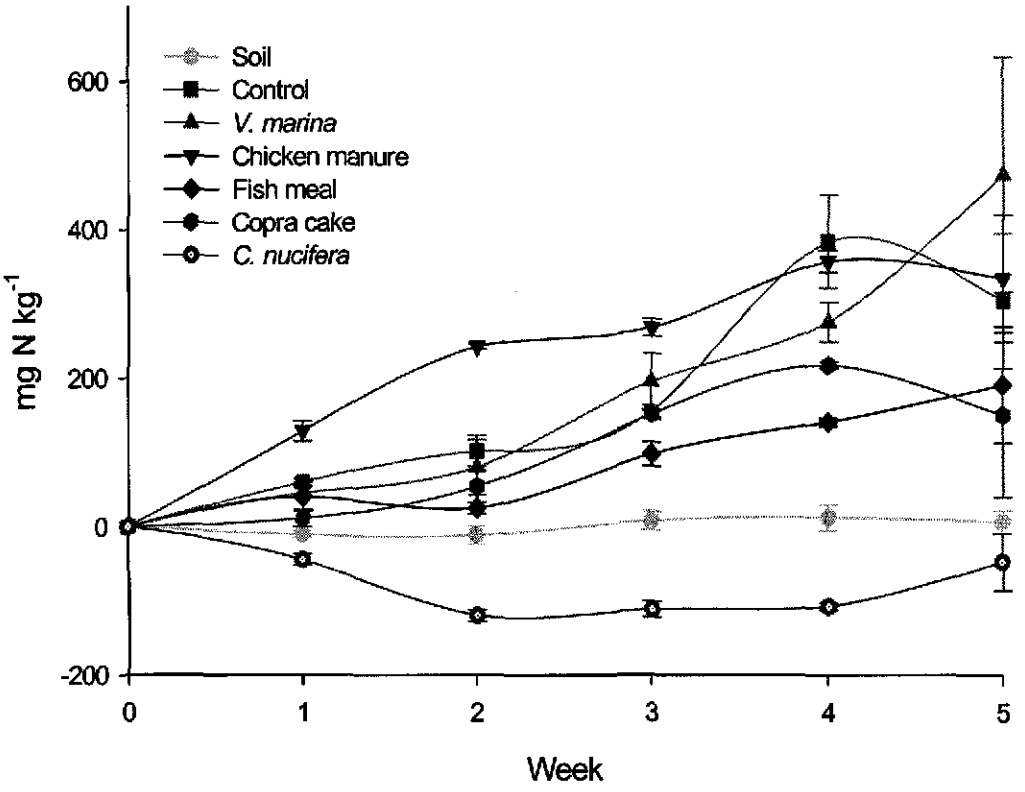


Figure 4.7. Cumulative N mineralization curves for the Marshall Island soil amended with five organic materials and a chemical control. Curves represent the sum of soil N and plant uptake N.

week pot experiment with a slight increasing trend during the fifth week, and was clearly not an appropriate soil amendment. The chicken manure treatment showed the highest N mineralization potential and supply capacity of all the materials through week 3 followed by the *V. marina*, copra cake and chemical control, and the fish meal treatments. At week 4, when growth rate was at a maximum, there were distinct differences in N supply capacity between the different treatments (Fig. 4.8). Nitrogen supply was highest and similar in magnitude in the chemical control and chicken manure treatments. The *V. marina* treatment supplied almost 30% less N than the chemical control, but significantly more than the copra cake and fishmeal treatments. Nitrogen supply from the copra cake was diminished by almost 50% and by more than 60% in the fishmeal treatment compared with the control.

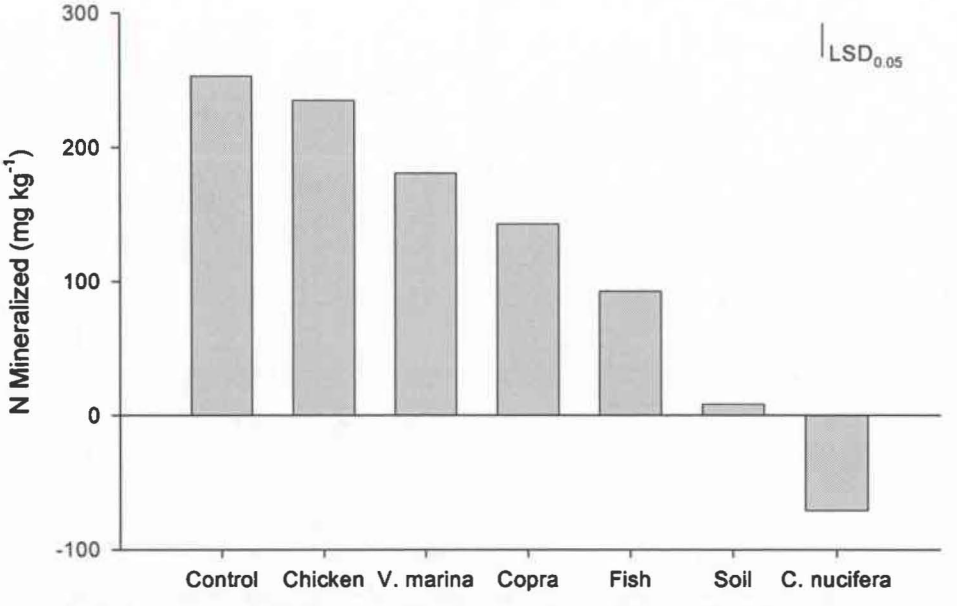


Figure 4.8. Treatment differences in combined soil and plant N after 4 weeks of cabbage growth. Negative values represent immobilization.

We observed a striking difference in the rate some of the organic materials mineralized N between the bioassay in the greenhouse and the laboratory incubation experiment despite similar addition rates (Table 4.8). Comparing values for N mineralized in the five-week bioassay with values for the sixth week of the incubation, the organic amendments in the greenhouse pots mineralized considerably more N than their incubation counterparts. The copra cake treatment mineralized five times more N and the *V. marina* and chicken manure treatments mineralized three times more in the greenhouse. A smaller difference occurred in the fishmeal treatment and the soil alone mineralized equally low amounts of N in both experiments. Similar differences were observed in the N mineralization rate for neem seed added to soil in a greenhouse experiment and a laboratory incubation (Agbenin et al., 1999). In soils that were not amended with organic materials, however, higher mineralization rates were not always associated with the presence of plants (Serna and Pomares,1991).

Table 4.8. Comparison of N mineralization results for the organic materials in the greenhouse bioassay with Chinese cabbage and the laboratory incubation experiment.

Treatment	N Mineralized			Fraction of Total N Added	
	Bioassay	Incubation		Bioassay	Incubation
		6 wks	27 wks		
	mg kg^{-1}			%	
Soil	3.94	6.42	24.9	-	-
V. marina	265	87.5	303	82.2	78.9
Chicken manure	187	52.2	206	27.7	22.9
Fish meal	107	70.2	267	15.9	30.5
Copra cake	84	16.5	160	12.5	17.0
C. nucifera	-26.4	-	-	-	-

Higher ambient temperatures in the greenhouse, rhizosphere effects, or a combination of the two might have caused the higher mineralization rates observed in the greenhouse bioassay. Temperatures in the greenhouse ranged from 15.4 to 36.5°C during the experimental period with a daytime average of 32.0°C and nightly average of 18.9°C. The incubation experiment was conducted at a constant temperature of 29.0°C. The three to seven degree increase in daily temperature could have had a substantial effect on mineralization rate if we apply the Q_{10} principle, which predicts that the rate of biological reactions will double with every 10°C increase in temperature. However, temperature differences alone cannot explain the three to fivefold observed increase in N mineralization. Root exudates are known to influence rhizosphere microbial activity and nutrient dynamics (Marschner, 1995). Specifically, the exudation of soluble C compounds from plant roots have been shown to stimulate microbial mineralization of organic N with a localized release of mineral N when microorganisms are grazed (Ritz, 1987; Clarholm, 1985a&b). Some researchers have reported estimates that 21 to 27% of plant N could be attributed to root-induced N mineralization (Hunt et al., 1987; Clarholm, 1989). Other work proposed that the observed increase in net N mineralization was not a result of microbial grazing, but that the roots successfully competed with the microorganisms for mineral N in the rhizosphere (Wang and Bakken, 1988). Subsequently, Bakken (1990) reported that N mineralization was1.8 to 7.9 times higher in amended soil in pots with plants compared with the amended soil alone. Still more research argues that root-induced N mineralization contributes only minimally to the plant's N requirements (Wheatley and Griffiths, 1990; Griffiths et al., 1991; Griffiths and

Robinson, 1992). The much larger N mineralization rates for the amended soils in the bioassay experiment compared with the incubation experiment suggest that the presence of the plants and the higher temperatures in the greenhouse had a stimulatory effect on the mineralization process. We cannot, however, separate and quantify the contribution of each factor in the stimulation of N mineralization.

Despite the more rapid mineralization rates observed in the greenhouse, less N was mineralized in the five-week bioassay with Chinese cabbage than in the 27-week laboratory incubation (Table 4.8). Following the harvest of the cabbage plants, corn was planted in the pots to quantify residual N (Table 4.9). Nitrogen recovery by the corn plants showed that the *V. marina* treatment had exhausted its N mineralization capacity during the cabbage experiment. The chicken manure treatment contained a relatively low residual N mineralization capacity while the copra cake treatment continued to mineralize N and *C. nucifera* treatment switched from immobilizing N during the first crop to mineralizing N during the second crop. When N mineralization values from the two bioassays are summed and compared with the total N mineralized in the incubation experiment we found that the two methods produced remarkably similar values for the soil alone and chicken manure treatments. The *V. marina* and copra cake treatments showed slightly lower, but not significantly different, values for N mineralized in the bioassay method compared with the incubation method. The fishmeal treatment mineralized significantly more N in the incubation method.

Table 4.9. Comparison of N mineralization results for the organic materials in the greenhouse bioassay with Chinese cabbage and a second corn crop with the laboratory incubation experiment.

Treatment	N Mineralized			
	Cabbage	Corn	$Bioassay_{Total}$	Incubation
			$mg\ kg^{-1}$	
Soil	3.94	28.2	32.1	24.9
Chemical control	200	18.0	218	NA
V. marina	265	6.57	272	303
Chicken manure	187	28.7	216	206
Fish meal	107	63.3	170	267*
Copra cake	143†	76.0	219	160
C. nucifera	-26.4	154	128	-

* Significant paired *t-test* $P_{0.05}$

†N data taken from week 4 of the bioassay experiment because week 5 results were problematic for the copra cake treatment

Nitrogen Supply

Matching plant nutrient requirements with sufficient fertilizer application rates is a fundamental, but difficult task. We evaluated this match in the following three ways: (i) visual examination of plots for plant N uptake versus soil N, (ii) the amount of N in the plant as a percentage of the total N added in the amendment, and (iii) comparing relative accumulation rate (RAR) for each nutrient with relative growth rate (RGR). Plots for N uptake versus N remaining in the soil are presented in Fig. 4.9. Because plants were not sampled until week three there are no uptake data for the first two weeks. Assuming that uptake during the first two weeks was less than the uptake at the third week, it is clear that N mineralization in all treatments, except the *C. nucifera* treatment, created a surplus of N in the soil. The N surplus was most dramatic in the chicken manure treatment where soil N reached a maximum of approximately 400 mg pot^{-1} by the second week. All treatments, except *V. marina* showed a decline in soil N at the third week presumably due to increasing plant

growth and N uptake. The *V. marina* treatment continued to show an increase in soil N possibly because plants had not begun rapid growth yet. The accumulation of soil N during the first three weeks when the organic materials were mineralizing N faster than plant N uptake is an example of asynchrony. Under field conditions in the Marshall Islands where the soils are sandy and rainfall plentiful, such a surplus of mineral N is vulnerable to leaching. After four weeks of growth soil N dropped significantly as plant N uptake increased dramatically in all treatments except in the *C. nucifera* treatment. Nitrogen uptake increased four-fold in the control and chicken manure treatments, three-fold in the *V. marina* treatment, and slightly more than two-fold in the fishmeal and copra cake treatments. At harvest soil N had decreased to low values while N uptake had reached a plateau or begun to decrease in all the treatments except in *V. marina*. The *V. marina* treatment continued to show a dramatic rise in N uptake between weeks four and five. The high N uptake during week five suggests that the *V. marina* leaves underwent a rapid increase in N mineralization rate during this period.

Another way of determining how well fertilizer application rates matched plant nutrient uptake is to calculate plant uptake as a proportion of the nutrient added in the fertilizer material. We present the results of N uptake as a percentage of N added in the amendment in Table 4.10. The cabbage plants captured the majority of applied N in the control treatment at harvest. This close match between plant N requirement and applied N was achieved by weekly applications of N in solution that was immediately available for plant uptake. Organic materials applied prior to planting

do not achieve the same level of synchrony because N release is microbially mediated and controlled by a variety of environmental factors.

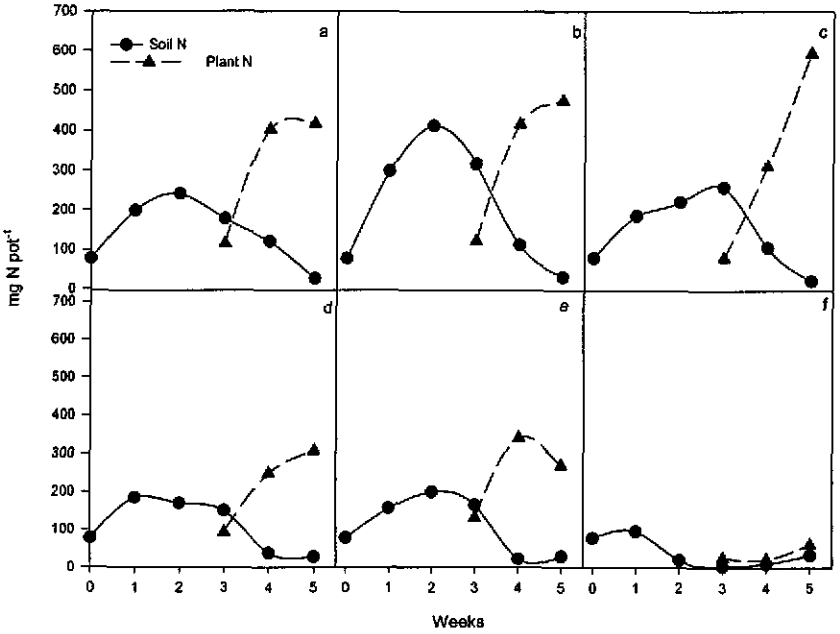


Figure 4.9. Soil and plant N levels for (a) control, (b) chicken manure, (c) *V. marina*, (d) fish meal, (e) copra cake, and (f) *C. nucifera* as a function of time.

Table 4.10. Nitrogen bioavailability to Chinese cabbage from organic materials.

Treatment	Bioavailable N	
	Week 4	Week 5
	%	
Chemical control	81.9a	82.5a
V. marina	39.1b	92.1a
Chicken manure	29.8bc	34.4b
Fish meal	13.4c	18.1b
Copra cake	22.4c	8.87b
C. nucifera	-36.4d	-25.3c

†Bioavailability = (N uptake$_{treatment}$-N uptake$_{Soil}$)/Added N)X100

Under the controlled conditions in the greenhouse, the *V. marina* treatment showed a remarkably efficient capacity to supply N to the cabbage plants. By harvest time, 92% of the applied N in the *V. marina* was accumulated in the cabbage plants. Field experiments assessing the N supply capacity of leaves from different green manure tree species report considerably lower N recovery percentages. Nitrogen uptake as a fraction of applied N by maize amended with *Gliricidia sepium* leaves ranged from a high of 63% (Zaharah et al., 1999) and 40% (Handayanto et al., 1997) to a low of 11.7% (Haggar et al., 1993). Field-work in Nigeria found that maize recovered up to 35% of the N applied in lablab (*Lablab purpureus*) residue (Ibewiro et al., 2000). Lower N uptake occurred when maize was grown with *Leucaena* leaves as the amendment with values ranging from 23.3% (Mafongoya and Dzowela, 1998) to a low of 3.5% of total applied N (Castellanos and Pratt, 1981; Rubaduka et al., 1993; Mafongoya and Dzowela, 1998). The high N recovery percentage by the cabbage plants in the *V. marina* treatment may have been due to the combination of the controlled conditions in the greenhouse, which minimized the possibility of N losses due to leaching, and enhanced the N release from the leaves.

Cabbage plants grown in the chicken manure, fishmeal, and copra cake treatments accumulated a considerably lower percentage of N applied in the amendments. The cabbage grown with chicken manure recovered 34% of the applied N a value that is lower than the 60% recovery rate from an earlier series of greenhouse experiments (Castellanos and Pratt, 1981). Sims (1987) found an average recovery rate of 41% for a three-year field study with maize amended with poultry manure. A review of research on poultry manure use in agriculture found that crops generally recovered

between 30-40% of the total added N during a cropping cycle (Sims, 1995). The cabbage plants recovered only 18% of the total N in the fishmeal treatment. The low recovery rate was probably a result of K deficiency limiting plant growth. In a recent field experiment, N recovery by maize plants grown with composted fish waste ranged from 6.62 –32.7% with the higher recovery rates associated with the intermediary application rate (Jellum et al., 1995). In the copra cake treatment, less than 10% of the total N became bioavailable after five-weeks of growth. At week four, the cabbage plants had recovered 22% of the total added N. There were no clear explanations for the discrepancy between weeks four and five, and may have been due solely to experimental error. The negative numbers associated with the calculations for N bioavailability for the coconut treatment represent N immobilization, and reinforce the observation that coconut leaves were clearly not a suitable source of N for a fast growing vegetable like Chinese cabbage.

Comparing nutrient accumulation rate with plant growth rate is another way to evaluate how well fertilizer applications satisfy plant nutrient requirements. In the following discussion we made comparisons of RGR and the RAR for each nutrient. We used the following approach to evaluate nutrient supply: (i) when RGR and RAR of a given nutrient are equal or not statistically different, nutrient supply is matching nutrient demand by the plant, and (ii) when RAR for a given nutrient is significantly lower than RGR, nutrient supply is not matching plant demand indicating a potential deficiency at the time of measurement or at some time in the future. In Figure 4.10 we compare RGR with the relative accumulation rate (RAR_N) for N between weeks three and four, the time interval where maximum growth rate occurred. Nitrogen

accumulation rate was highest in the *V. marina* treatment, but was not significantly higher (P=0.05) than the control, chicken manure, copra cake, and fish meal

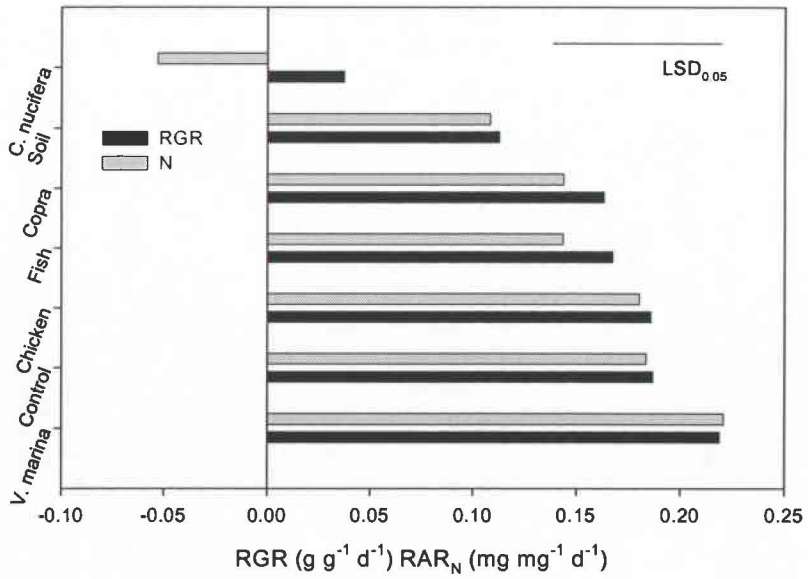


Fig. 4.10. Comparing RGR and RAR for N between the third and fourth week of growth.of Chinese cabbage plants grown with five different organic amendments.

treatments. The *V. marina* treatment showed significantly higher RAR_N than the soil alone and *C. nucifera* treatments, and the RAR_N in the *C. nucifera* treatment was significantly lower than the other treatments. The RAR_N for the *V. marina* treatment was slightly larger than the RGR indicating a good match between N supply and N demand. Nearly identical values for RAR_N and RGR values in the control and chicken manure treatments indicated apparent synchrony between N supply from the amendment and N requirement for the growing plant. For fishmeal and copra cake, there was a slight gap between RAR_N and RGR suggesting a lower supply capacity from these amendments. In the case of *C. nucifera*, we obtained a negative value for

RAR_N representing N immobilization and confirming the inappropriateness of this material as a soil amendment for a fast growing crop. Analysis of variance determined that there were no significant differences between RAR_N and RGR at the 5% probability level for all the treatments (Table 4.11). The fishmeal treatment showed a trend towards a gap between N supply and demand. Despite a negative value for RAR in the *C. nucifera* treatment, a very low RGR value and variability in the data resulted in means that were not significantly different from each other. Variability in the data, possibly associated with the block effect, weakened the precision of this approach. However, the simplicity of calculating two numbers that can be compared quantitatively remains an appealing method to determine the level of synchrony.

Table 4.11. Results of *f*-test for the comparisons of RAR_N and RGR for each treatment.

Treatment	RAR	RGR	Pr>*f*
	$g\ g^{-1}\ d^{-1}$		
Control	0.18	0.19	0.84
V. marina	0.22	0.22	0.98
Chicken manure	0.18	0.19	0.78
Fish meal	0.14	0.17	0.22
Copra cake	0.14	0.16	0.71
C. nucifera	-0.05	0.04	0.22

P, K, Mg, and S Supply

Plots of RAR for P, K, Mg, and S versus RGR (Fig. 4.11) help to identify cases where nutrient supply from the different treatments may not be satisfying nutrient demand. The low RGR in the *C. nucifera* treatment was connected to low N supply, and from Fig. 4.11 it appears that low K supply may also have contributed to poor

growth. The RAR_K value for the fishmeal treatment was significantly lower than its corresponding RGR indicating that fishmeal is a poor source of K (Table 4.12). Very low tissue K levels confirmed the poor K supplying capacity of fishmeal (Table 4.13). The inability of the fishmeal to supply adequate amounts of K is also reflected in its low initial K concentration. In the chemical control treatment, a significant difference between RAR_P and RGR at P=0.10 suggests that P supply from a chemical source did not satisfy plant requirements . Tissue P levels for the control treatment were also below the critical range further indicating a P supply problem. A significantly lower RAR_S (P=0.08) value compared with RGR was obtained in the chicken manure treatment. The copra cake, control, and *V. marina* treatments also showed lower probability levels indicating a trend towards inadequate S supply.

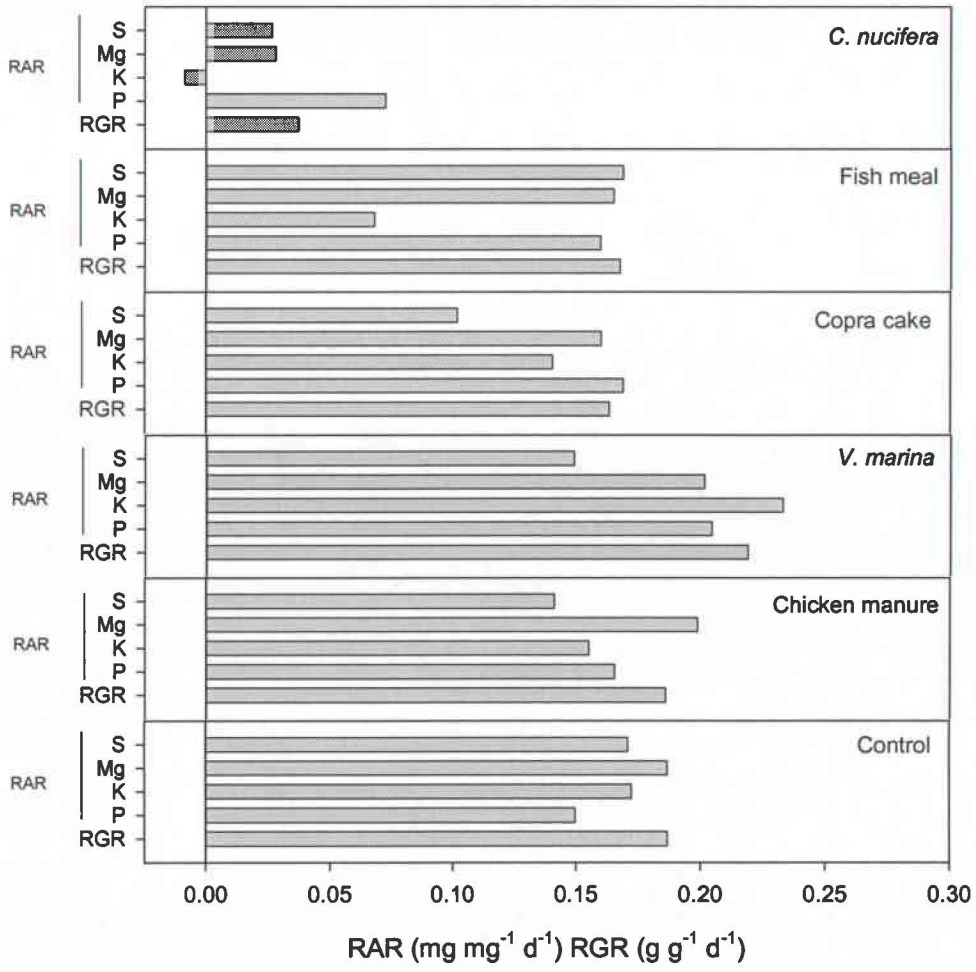


Fig. 4.11. Comparing RGR and RAR for P, K, Mg, and S between the third and fourth week of growth for Chinese cabbage plants amended with different organic materials.

Table 4.12. Results of *f*-test comparing RAR_P, RAR_K RAR_{Mg} and RAR_S with RGR within each treatment.

Element	Treatment					
	Control	*V. marina*	Chicken manure	Fish meal	Copra cake	*C. nucifera*
	Pr > *f*					
P	0.10	0.83	0.19	0.53	0.91	0.65
K	0.53	0.87	0.41	0.004	0.66	0.56
Mg	0.99	0.79	0.59	0.89	0.95	0.91
S	0.25	0.34	0.08	0.92	0.21	0.88

Table 4.13. Macronutrient tissue concentrations of 4 week old Chinese cabbage plants grown in the greenhouse with different organic amendments.

Treatment	N	P	K	Mg	S
			%		
Unamended soil	5.35b	0.35cd	0.87d	0.46a	0.68ab
Chemical control	6.23ab	0.34d	6.51b	0.33b	0.71a
V. marina	6.54a	0.36bcd	7.75a	0.28b	0.48c
Chicken manure	6.21ab	0.41bc	6.17b	0.31b	0.58bc
Fish meal	5.32b	0.38bcd	1.21d	0.43a	0.78a
Copra Cake	5.65ab	0.43b	6.74ab	0.28b	0.45c
C. nucifera	1.75c	0.63a	3.76c	0.27b	0.80a
$LSD_{0.05}$	0.97	0.07	1.19	0.06	0.14
CV (%)	11.0	9.88	15.4	10.9	12.3
Critical Ranges[†]	3.00-4.00	0.36-0.80	4.50-7.50	0.20-0.70	0.40-0.80

[†] Uchida (2000), treatments followed by the same letter are not significantly different at the 5% probability level.

Micronutrient Supply

Figure 4.12 shows that micronutrient supply from the different soil amendments versus growth rate was more variable than the relationship for the macronutrients. The most glaring differences occurred with Zn supply from the different materials. The negative values for RAR_{Zn} in the *V. marina* and copra cake treatments mean that these materials could not supply Zn rapidly enough to keep pace with the growth rate. Analysis of variance found that these discrepancies were highly significant in the case of *V. marina* and highly significant for copra cake (Table 4.14). The inability to supply Zn is a reflection of the materials: copra cake and *V. marina* materials had relatively low initial Zn contents. The low RAR_{Zn} in the copra cake treatment may have contributed to the poorer growth of the cabbage plants even though no clear deficiency symptoms were manifested. Zinc tissue concentration in the copra cake and *V. marina* treatments were relatively low, but not below the critical level (Table

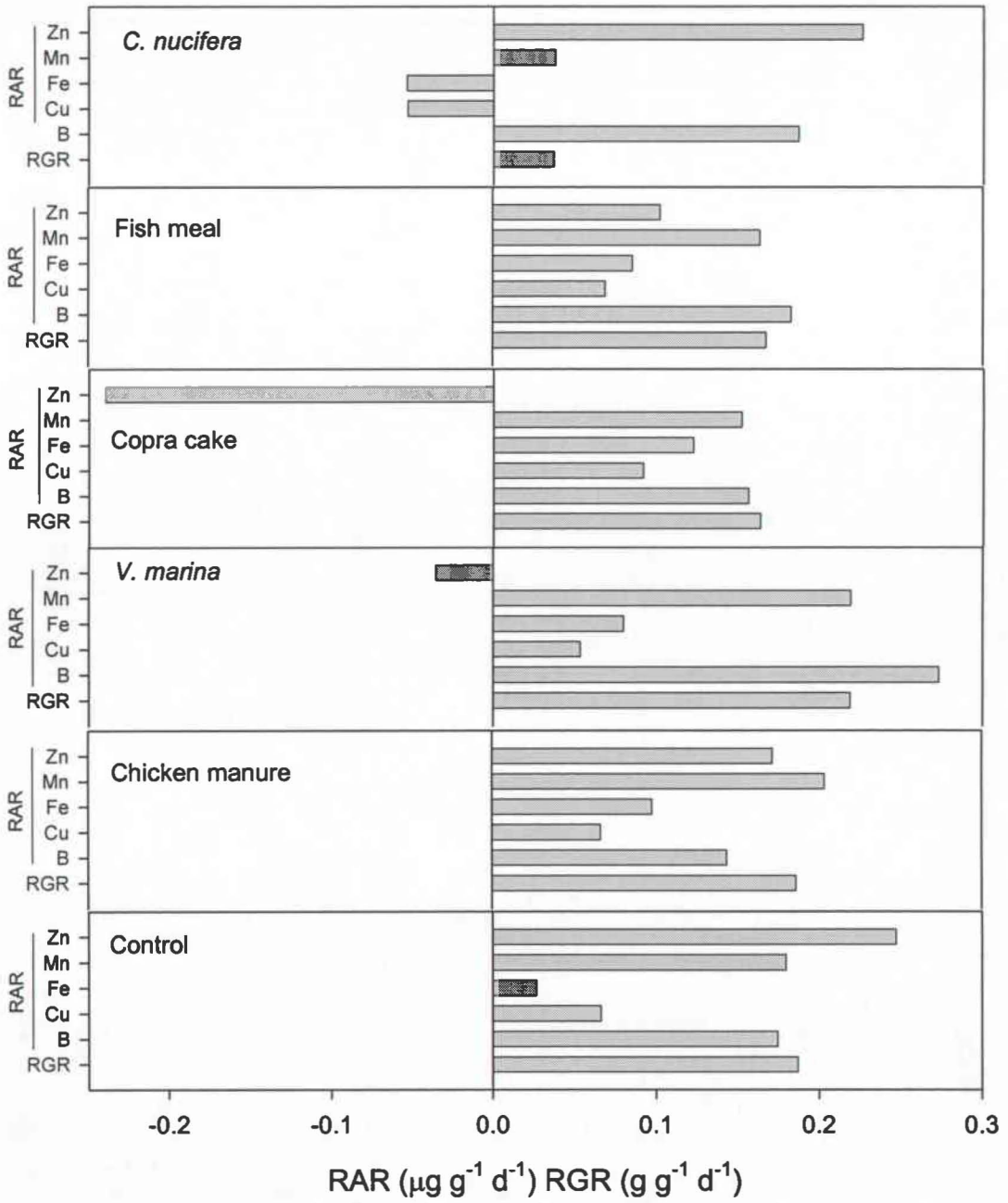


Fig. 4.12. Comparing RGR and RAR for B, Cu, Fe, Mn, and Zn between the third and fourth week of growth for Chinese cabbage plants grown with different organic amendments.

4.15). When Zn was added as $ZnSO_4$ as in the control treatment, RAR exceeded RGR, and RAR_{Zn} for the control was significantly greater than for the other organic materials except *C. nucifera*. These results indicate that the organic materials were

less effective at supplying Zn to the plant than the chemical source despite high initial Zn concentrations in the chicken manure and fishmeal materials.

Table 4.14. Results of *f*-test comparing RAR_B, RAR_{Fe} RAR_{Mn}, RAR_{Cu}, and RAR_{Zn} with RGR within each treatment for Chinese cabbage grown with different organic amendments in the greenhouse.

Element	Treatment					
	Control	*V. marina*	Chicken manure	Fish meal	Copra cake	*C. nucifera*
			Pr > *f*			
B	0.75	0.41	0.68	0.86	0.90	0.09
Fe	0.07	0.13	0.08	0.01	0.59	0.30
Mn	0.77	0.99	0.23	0.76	0.84	0.99
Cu	0.01	0.02	0.02	0.13	0.27	0.35
Zn	0.09	0.01	0.36	0.04	0.0004	0.04

Table 4.15. Micronutrient concentration in the tissue of 4-week old Chinese cabbage plants grown with different organic amendments in the greenhouse.

Treatment	B	Fe	Mn	Cu	Zn
	<----------ug g^{-1}---------->				
Soil	28.0bc	115a	57.0cd	2.3c	45.0abc
Control	45.7ab	107ab	20.3e	3.7a	46.0abc
V. marina	29.3bc	93.7ab	70.3b	2.7bc	39.7bc
Chicken manure	23.3bc	89.7ab	71.7b	3.0abc	44.3abc
Fish meal	24.0bc	103ab	83.3a	3.3ab	55.3ab
Copra Cake	16.3c	104ab	62.3bc	3.7a	35.3c
C. nucifera	65.0a	77.3b	51.0d	3.0abc	57.7a
$LSD_{0.05}$	27.9	32.5	9.5	0.9	16.3
CV (%)	43.6	15.3	9.7	14.4	17.4
Critical Ranges†	60-100	40-200	25-200	5-25	20-200

†Uchida (2000), treatments followed by the same letter are not significantly different at the 5% probability level

Iron and Cu supply from the different treatments tended to lag behind growth rates in all treatments. The decrease in RAR_{Fe} compared to RGR in the fish meal treatment was highly significant while in the control and chicken manure treatments differences were detected at the P=0.1 level. The low Fe supply from fishmeal was surprising given that this material had the highest initial Fe content compared with the

other organic materials. Significant differences between Cu supply and plant demand occurred in the control, *V. marina*, and chicken manure treatments. In the other treatments, Cu supply lagged behind plant demand. Copper tissue concentrations were below the minimum critical level in all treatments. The low initial Cu concentration of the organic materials may have led to low Cu supply, but the low RAR_{Cu} from the chemical source may indicate that other soil factors may have caused the low Cu supply.

Manganese and B supply from all the materials, with the exception of *C. nucifera*, showed a close match between RAR and RGR (Fig. 4.12). No significant differences were found between the supply of these nutrients and the plant demand.

V. marina Rate Experiment

Growth Response

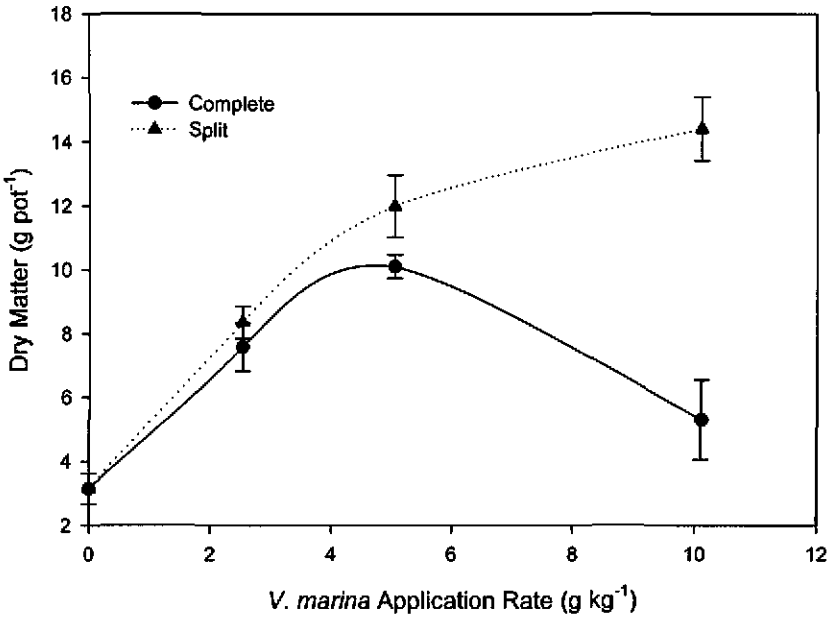
Maize growth showed a significant response to increasing rates of *V. marina* leaves and a significant interaction effect with the method of application (Table 4.16). Pots that received the entire quantity of the leaves prior to planting showed a significant yield reduction at the highest application rate (Fig. 4.13). When the *V. marina* amendments were split in two applications, half the quantity incorporated prior to planting, and the remaining half added as a surface application two weeks after planting, a significant yield increase was observed.

Table 4.16. Mean square values and significance levels from ANOVA of dry matter maize yields of soils amended with increasing rates of *V. marina*.

Source of Variation	*df*	Mean Square	F Value	Pr > F
Rate	3	72.0	118	<.0001
Timing	1	52.4	85.8	<.0001
Rate*Timing	3	26.4	43.2	<.0001

Crop residues incorporated into soils release intermediary organic substances during the initial phases (0-3 weeks) of the decomposition process that can create a toxic environment limiting plant growth (Putnam, 1994). The corn plants receiving the two higher rates of *V. marina* all prior to planting showed poor growth and chlorotic leaves during the first two weeks of the experiment. These symptoms were most severely manifested in the treatment receiving the highest rate of *V. marina* equivalent to 10.1g kg^{-1} soil. The treatment with 5.05 g *V. marina* kg^{-1} soil began to show vigorous growth and greening of its leaves during the third week. The treatment with the highest addition rate continued to show poor growth and general chlorosis through the third and into the fourth week. By the end of the fourth week, the plants began to show increased growth and vigor. Previous research has shown that the intermediary organic acids that are produced when plant residues are added to soil inhibit the growth of emerging seedlings and young plants that came into contact with decaying material (Lynch, 1978; Patrick, 1971). Earlier studies have shown that the phytotoxic effects of these intermediate substances were transient and crop growth recovered within two weeks after planting (Lynch, 1978; Chapman and Lynch, 1983). The large quantity of fresh plant leaves present in the pots at the highest rate most likely produced significant amounts of phytotoxic substances early

in the decomposition process causing the poor growth during the first two weeks of the experiment.



ig. 4.13. Dry matter yield of corn plants as a function of *V. marina* addition rate and timing of application. Yield based on two corn plants per pot, each point is a mean of three replicates.

Maize growth responded favorably to increasing rates of *V. marina* leaves applied as a split application. The asymptotic shape of the response curve indicates that the selection of addition rates covered the critical nutrient requirements for the crop. Using nonlinear regression techniques we fitted the data to estimate appropriate addition rates to achieve desired yields. We evaluated three common functions used to describe yield as a function of a nutrient addition (Black, 1993): the quadratic equation, the square-root equation and the Mitscherlich equation. We evaluated the goodness-of-fit for each model by calculating an $F_{lackfit}$ statistic, and found that the data were best fit by a quadratic function (Table 4.17). By converting dry matter into

relative yield and plotting as a function of *V. marina* additions, we estimated the rate of *V. marina* required to achieve 95% of maximum yield to be 7.06 g kg^{-1} on a dry matter basis (Fig. 4.14).

Table 4.17. Goodness-of-fit statistics for three models fit to dry matter maize yields of soils amended with increasing rates of *V. marina*.

Model	Adj. r^2	RMSE	$F_{lackfit}$
Quadratic	0.97	0.73	0.00
Square-root	0.96	0.89	0.11
Mitscherlich	0.97	0.76	0.02

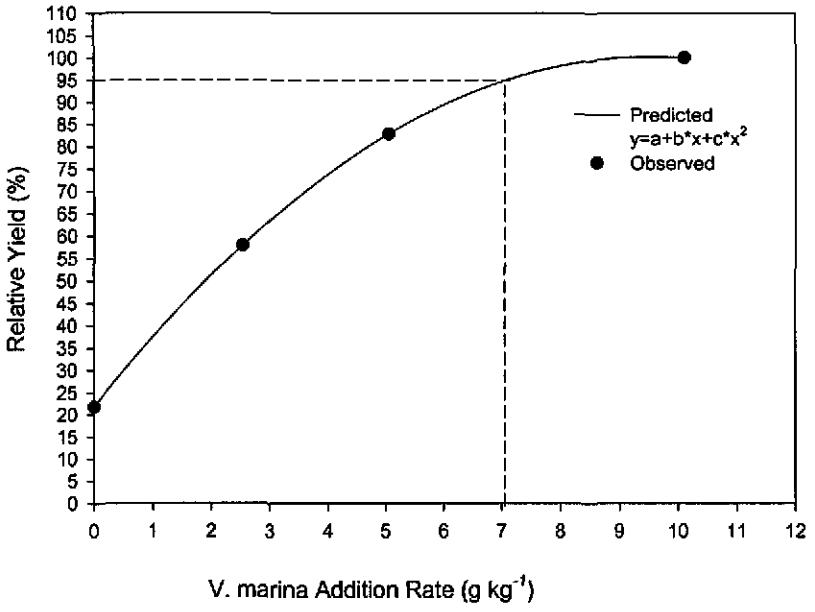


Fig. 4.14. Quadratic equation fitted to relative yield as a function of *V. marina* addition rate to estimate the quantity of *V. marina* required to achieve 95% of maximum yield

N, P, and K Supply

Results of final N, P, and K concentrations in the above ground corn biomass are presented in Table 4.18. Nitrogen and P concentrations in the tissue were below established critical levels for whole plants at all the *V. marina* addition rates. Clear N deficiency symptoms were apparent on the plants grown at the two lowest rates while slight yellowing of the oldest leaves occurred at the second highest rate, and no symptoms occurred at the highest rate. The low tissue concentrations in the plants grown at the highest rate may have been due to the fact that the plants were about 60 cm high, which is two times higher than the height of the plants for which the critical levels were developed. The inclusion of the stems in the tissue analysis may have had a significant dilution effect. Tissue P concentrations were two times lower than the established critical level across all treatments. The low tissue levels, however, were not accompanied by any noticeable P deficiency symptoms. *V. marina* leaves contain 0.22% P, a high enough concentration to expect P mineralization rather than immobilization in the soil biomass (Anderson, 1980). Several studies, however, have reported that green manures in the tropics do not supply enough P to maintain adequate crop growth (Tian et al., 1993; Sanchez and Palm, 1996; Lupwayi and Haque, 1998; Mafongoya and Dzowela, 2000). Potassium tissue levels showed a response to increasing rates of *V. marina* with the highest level of *V. marina* supplying enough K to bring tissue K levels above the minimum critical level. Previous mineralization studies with green manures found that K was released rapidly from decomposing leaves becoming available for plant uptake (Tian et al., 1992a; Hartemink and O'Sullivan, 2001).

Table 4.18. N, P, and K tissue concentrations in the above ground maize biomass from plants grown with increasing rates of *V. marina*.

Addition Rate	N	P	K
g kg^{-1}		%	
0	2.43	0.09	0.51
2.53	2.12	0.12	1.33
5.51	2.07	0.12	1.80
10.1	2.19	0.15	2.67
Critical Range†	3.5-4.50	0.30-0.50	2.80-3.80

†Fifth mature leaf in 5-6 week-old plant (Uchida, 2000)

Increasing the rate of *V. marina* additions resulted in a significant rise in macronutrient accumulation in the maize plants (Table 4.19). Nitrogen supply ranged from 42.8 in the soil alone to 176 mg kg^{-1} at the highest rate, and K from 8.93 to 215 mg kg^{-1}. Phosphorus supply was considerably lower, ranging from 1.6 mg kg^{-1} in the soil alone to 11.8 mg kg^{-1} at the highest rate. Macronutrient recovery rates decreased with increasing rates of *V. marina* for N and P, but remained constant for K. The percentage of N recovery at the low and intermediates rates was considerably higher than the 20% or less recovery rate reported for most green manure inputs (Giller and Cadisch, 1995). At the highest rate of *V. marina* addition, the recovery rate dropped to around 38%, a value that compares well with several field studies evaluating the N contribution of *Gliricidia sepium* leaves to maize (Handayantoet al., 1997; Zaharah et al., 1999). When *V. marina* was added at 5.05 g kg^{-1}, or the equivalent of 6.4 Mg ha^{-1}, the total amount of P added to the soil was slightly lower than P contributions from *Tithonia diversifolia* leaves added at a comparable rate in a field study in Kenya (Gachengo et al., 1999). However, the P recovery rate of 55% was two times higher in the Marshall Island soil. At the highest *V. marina* rate, P recovery declined significantly to 42% in the Marshall Island soil. The higher recovery rate in the present study may have been due to the controlled nature of the pot study or the lower

P sorption capacity of the atoll soil compared with the weathered Ultisol in the Kenyan study. Potassium contributions from the *V. marina* were significant, and the recovery rate was remarkably high. We might expect a high K recovery rate under the controlled greenhouse environment where leaching losses were minimized. Under field conditions in the Marshall Islands, however, where leaching conditions are exacerbated by low soil CEC, coarsely textured soils, and high rainfall such a high recovery rate of K would be unlikely. One experiment on an atoll soil with low CEC showed the high leaching potential of added K, and the necessity of adding fertilizer K frequently in small controlled doses (Reddy and Chase, 1992).

Table 4.19. Nutrients added, total above ground nutrient uptake, and nutrient recovery by the maize plants grown with increasing rates of *V. marina* in the split application treatment.

V. marina Rate	Nutrients Added			Nutrient Uptake			Nutrient Recovery		
	N	P	K	N	P	K	N	P	K
g kg^{-1}	mg kg^{-1}						%		
0	0	0	0	42.8	1.6	8.93	NA	NA	NA
2.53	88.3	6.07	80.0	99.4	5.64	62.3	64.1	66.6	77.9
5.05	177	12.1	133	138	8.27	120	53.8	55.1	90.2
10.1	353	24.3	240	176	11.8	215	37.7	42.0	89.6
$LSD_{0.05}$				24.1	2.91	9.34	19.4	24.2	9.22

Soil inorganic N levels at the time of harvest generally reflected the treatment induced growth patterns. Inorganic N levels in the soil in all treatments at harvest were very low in the pots that received the split application of *V. marina* (Table 4.20). The pots that did not receive the amendment showed higher levels of soil NO_3-N. With increasing rates of *V. marina* additions, N recovery rate decreased significantly. The remaining amounts of added N were not accounted for in the soil at harvest. The discrepancy could be explained by (i) the N had yet to be mineralized, (ii) N was lost

to denitrification reactions in the rhizosphere, or (iii) N was lost by volatilization from the surface applied *V. marina*. Ammonia volatilization from surface applied manures is significant and well documented (Sommer and Hutchings, 2001; Søgaard et al., 2002). Ammonia losses from green manures applied to soils has not been as well documented, but some field work has found that NH_3 losses were substantial during the first five days after incorporation, and increased with temperature increase (Rana and Mastrorilli, 1998). Laboratory work showed that significant NH_3 losses occurred from surface applied green manures during the first 14 days, but that losses to volatilization were decreased dramatically when the green manure was incorporated into the soil (Janzen and McGinn, 1991). Furthermore, atoll soils with pH near 8.0 favor the volatilization of NH_3. Ammonia loss to volatilization in the split application treatments was likely the cause of the lower N recovery rates at the higher application rates. The treatments that received the full application of leaves prior to planting showed similar N recovery rates. At the highest rate, however, soil NO_3-N levels were significantly higher than in any of the other treatments. The excess N in the soil was probably due to the poor growth these plants exhibited early in the experiment, and the subsequent inability to recover rapidly enough to keep up with the eventual rise in N mineralization.

Table 4.20. Soil nutrient concentrations after harvesting the maize plants grown with increasing rates of *V. marina*.

V. marina Rate	NO_3-N	
	Split Application	Full Application
g kg^{-1}	mg kg^{-1}	
0	5.07	5.07
2.53	0.86	2.87
5.05	0.63	1.39
10.1	0.92	25.5
$LSD_{0.05}$	0.81	2.48

Ca, Mg, S, and Micronutrient Supply

Calcium and Mg levels in the harvested maize tissue were within or above the established critical ranges (Table 4.21). Sulfur concentrations were below the established minimum critical level for the fifth leaf taken from 6 week old corn. Because the entire corn plant was ground up and submitted for tissue analysis, we can expect that lower S levels in the stalk may have caused the S concentration for these samples to be below the critical level. This, however, does not necessarily mean that there was an S deficiency. Green manure prunings generally release Ca and Mg rapidly significantly increasing soil levels within two weeks of incorporation, and remain constant thereafter (Tian et al., 1992b; Lupwayi and Haque, 1998). Calcium and Mg uptake by the maize plants increased significantly with the first rate of *V. marina* addition, but showed no significant change as *V. marina* rates were increased (Table 4.22). Sulfur uptake showed a significant response to *V. marina* rates, but because we had no S analysis on the *V. marina* tissue we could not determine an S recovery rate.

Table 4.21. Calcium, Mg, S, and micronutrient levels in the above ground tissue of maize plants grown with increasing rates of *V. marina*.

Addition Rate	Ca	Mg	S	B	Fe	Mn	Cu	Zn
g kg^{-1}	----------%----------			----------ug g^{-1}----------				
0	1.84	0.92	0.20	14.3	69.7	16.3	4.33	33.0
2.53	1.20	0.50	0.15	10.3	59.0	19.3	4.00	21.0
5.51	0.89	0.36	0.15	9.67	52.3	17.7	4.00	17.3
10.1	0.79	0.33	0.16	10.3	50.3	20.0	3.67	21.3
Critical Range	0.30-0.80	0.15-0.45	0.21-0.70	5-25	50-250	20-300	5-20	20-60

Source: Uchida (2000)

Table 4.22. Calcium, Mg, and S uptake by maize plants grown with increasing rates of *V. marina*.

Addition Rate	Ca	Mg	S
g kg^{-1}	----------mg kg^{-1}----------		
0	32.5	16.3	3.52
2.53	55.9	23.2	6.87
5.51	59.2	24.2	9.78
10.1	62.6	26.5	12.6
$LSD_{0.05}$	19.2	4.91	0.84

The micronutrient content of the maize plants at harvest was generally low with the exception of B. Boron concentrations were within the critical range while Fe tissue levels were clustered close to the minimum critical level for all treatments. Zinc concentration was generally close to the minimum critical level, and dropped below the critical level at the second highest addition rate. Manganese concentrations were below the critical level in all treatments except at the highest addition rate where its concentration was equal to the minimum level. Copper levels were below the minimum critical level for all treatments. Despite the generally low micronutrient content of the maize tissue, none of the plants across treatments showed any symptoms typical of micronutrient deficiency. Micronutrient uptake by the maize plants increased significantly for each of the elements as *V. marina* rates increased (Table 4.24), and showed strong correlations with N, P, and S uptake (Table 4.23).

Micronutrient recovery rates were relatively high at the lowest addition rate of *V. marina*, but were dramatically lower at the highest addition rate. Interpreting the drop in recovery rate as organic amendment rate increased is difficult. The micronutrients contained in the V. marina leaves may have been unavailable for plant uptake because they remained bound in complex organic molecules that did not breakdown during the decomposition process. Total micronutrient contribution from the added *V. marina* at all three rates was significantly below the general micronutrient fertilization recommendations for calcareous soils with high pH (Martens and Westermann, 1991) (Table 4.25). Only in the case of B did the contribution from *V. marina* begin to approach the recommended fertilization rate. In the cases of Fe and Mn, supply from *V. marina* was ten times lower, and for Cu 100 times lower. These data suggest that *V. marina* is not a good material to correct micronutrient deficiencies.

Table 4.23. Pearson correlation coefficients for micronutrient uptake as a function of N, P, and S uptake by maize plants. correlations are significant at P<0.0001.

	N	P	S
Mn	0.9305	0.9394	0.9274
Fe	0.9662	0.9132	0.9463
Cu	0.8699	0.8658	0.863
Zn	0.8033	0.7342	0.7569
B	0.8708	0.8329	0.833

Table 4.24. Micronutrients added, total above ground micronutrient uptake, and micronutrient recovery by the maize plants grown with increasing rates of *V. marina*.

V. marina Rate	Nutrients Added					Nutrient Uptake					Nutrient Recovery				
	B	Fe	Mn	Cu	Zn	B	Fe	Mn	Cu	Zn	B	Fe	Mn	Cu	Zn
g kg^{-1}	----------μg kg^{-1}----------										----------%----------				
0	0	0	0	0	0	25.3	122	28.7	7.54	58.1	NA	NA	NA	NA	NA
2.53	72	183	52	17.7	81	48.2	275	90.5	18.9	97.8	31.9	83.6	118	64.1	49
5.05	143	365	104	35.4	162	63.7	347	118	26.6	115	10.8	19.7	26.3	21.8	11
10.1	286	731	209	70.7	323	83.2	406	161	29.6	169	6.81	8.08	20.6	4.24	17

Table 4.25. Micronutrient contributions associated with the *V. marina* addition rates and the optimum fertilization rates for sweet corn.

V. marina Rate	Nutrients Added					Recommended Fertilization Rate†				
	B	Fe	Mn	Cu	Zn	B	Fe	Mn	Cu	Zn
g kg^{-1}	mg kg^{-1}									
0										
2.53	0.07	0.18	0.05	0.02	0.08	1.11	7.9	3.97	3.93	11.1
5.05	0.14	0.37	0.10	0.04	0.16					
10.1	0.29	0.73	0.21	0.07	0.32					

† Source: Martens and Westerman (1991)

Management Implications

A survey of different field trials in the tropics shows positive crop responses to green manure addition rates that generally ranged from 1.7 to 5 Mg ha^{-1} on a dry weight basis (Xu et al., 1992; Xu et al., 1993; Handayanto et al. 1997; Lupwayi and Haque, 1998; Vanlauwe et al., 1998; Gachengo et al., 1999). The *V. marina* rates applied in the greenhouse pot study span these ranges beginning at 2.2 Mg ha^{-1} at the lowest rate and ending at 8.9 Mg ha^{-1} dry matter at the high end. In an attempt to assess the feasibility and sustainability of proposing *V. marina* as a soil amendment, we looked at a range of scenarios. The scenarios are presented in Table 4.26, and outline a range of plot sizes and the quantities of *V. marina* required on a dry weight and fresh weight basis to satisfy a range of maize biomass yield targets based on biomass yields obtained in the pot study. Plot sizes range from a small kitchen garden plot to more substantial plots (25, 100, and 400 m^2) that a farmer interested in commercial vegetable production might put under cultivation; hectare plots are included as a reference only as they are probably impractical in the atoll setting.

Table 4.26. Evaluating how the quantity of *V. marina* amendment varies with plot area and target yields.

Plot Area	*V. marina* Dry Weight			*V. marina* Fresh Weight†		
	95% Yield	67% Yield	50% Yield	95% Yield	67% Yield	50% Yield
m^2		kg			kg	
9	8.01	3.80	2.14	44.5	21.1	11.9
25	22.2	10.6	5.95	124	58.6	33.1
100	89.0	42.2	23.8	494	235	132
400	356	169	95.3	1977	938	529
10,000	8,900	422	238	49,444	2,345	1,323

† Calculation based on V. marina H_2O content equivalent to 82%.

The quantities of *V. marina* required to meet 95%, 67%, and 50% biomass production were estimated by fitting a quadratic equation to the biomass data and calculating *V. marina* quantity for the desired yield target (Fig. 4.15). The fresh weight quantity of *V. marina* required to meet 95% biomass production for a 3 m^2 plot was 44.5 kg and for a 5 m^2 plot 124 kg. Based upon visits to Majuro and Arno atoll where we observed *V. marina* growth and distribution, these quantities of *V. marina* are readily available, and we believe periodic harvesting for green manuring is sustainable. On the atolls with similar or higher rainfall distribution, we expect that *V. marina* distribution will be equal to or greater than that observed on Majuro and Arno, and thus a practical and sustainable fertilizer option for small-scale vegetable gardening. On the drier northern atolls such as Likiep where we observed a lower distribution of *V. marina*, availability may be limited to the wet months of the year, and the option may not be sustainable. When the plot size is increased to 100 m^2, *V. marina* requirements to satisfy a 95% yield target probably surpass the availability and sustainability of the resource. If the yield target is reduced to 67%, *V. marina* requirements drop by half, and on a 100 m^2 plot 235 kg of fresh material is not

unreasonable, especially on the wetter atolls where *V. marina* is found in great abundance. For 400 $m^2$and hectare plots the quantities of *V. marina* required to achieve 95% yield probably exceed the sustainability of the *V. marina* resource base.

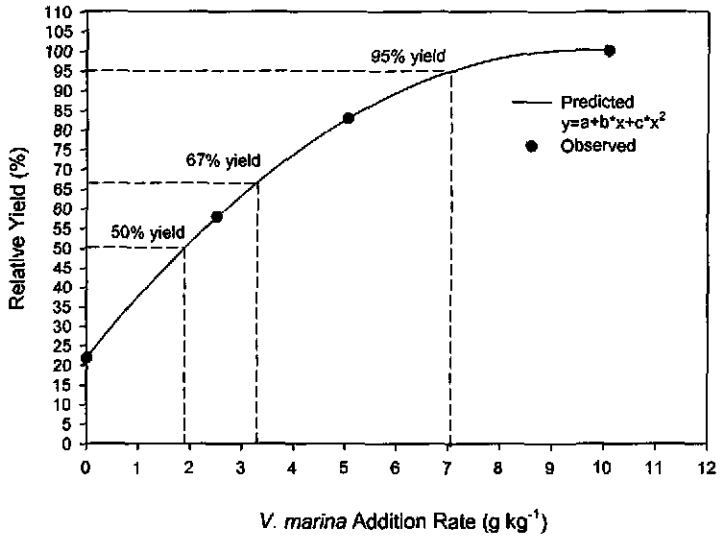


Fig. 4.15. Non-linear regression analysis to estimate *V. marina* addition Rate to satisfy a range of target maize biomass yields.

Copra Cake Experiment

Results from the N mineralization incubation study and Chinese cabbage bioassay in the greenhouse indicated that the copra cake material had a lower N supplying capacity than the other materials. Furthermore, based upon cabbage tissue analysis from the greenhouse bioassay, none of the organic materials supplied adequate amounts of B and Cu to maintain minimum critical levels in the tissue at harvest. Based upon these findings we established a pot experiment to test the following hypotheses: (i) increasing the rate of copra cake addition will improve crop growth and crop nutrient status, (ii) supplementing the copra cake with *V. marina* will improve N nutrition and crop growth, (iii) fortifying the *V. marina* with supplements

of B and Cu will improve micronutrient status of the plant and improve growth (see Tables 4.4, 4.5, & 4.6 for treatment configuration and H_0 being tested).

Growth Response

Results of ANOVA on cabbage dry weight response to the treatments are presented in Table 4.27. Increasing the rate of the copra cake amendment was the only factor that showed a significant effect on growth response. Increasing the copra cake addition incrementally from 10 to 20 Mg ha^{-1} showed a significant increase in cabbage yield compared with the chemical control (Fig. 4.16). Supplementing the copra cake treatment with *V. marina*, *V. marina* + B and Cu, or chemical N, P, and Mg did not have a significant effect on cabbage growth. The highest yields were achieved when the copra cake at both levels was mixed with the *V. marina* leaves receiving the B and Cu supplement (Fig. 4.17). The dry matter increase, however, was not statistically significant compared with the other mixtures. Mixing the copra cake with *V. marina* alone with copra cake at 20 Mg ha^{-1} showed almost identical yields to the copra cake alone treatment at the same rate. The chemical N, P, and Mg supplements at both copra rates showed near identical yields, and there was no detectable difference between the copra cake at 10 Mg ha^{-1} with and without *V. marina*.

Table 4.27. Results of ANOVA for Chinese cabbage yield grown with two levels of copra cake supplemented with *V. marina* and chemical treatments

Source		*df*	Sums of Squares	Mean Squares	F Value	Pr > F
Model		10	55.7	5.57	2.72	0.0391
	Block	2	1.22	0.61	0.30	0.75
	Copra	2	42.2	21.1	10.31	0.0015
	Vigna	1	1.89	1.89	0.93	0.3511
	Chemical	2	6.85	3.43	1.68	0.2204
	Copra*Vigna	1	0.04	0.04	0.02	0.8855
	Copra*Chemical	2	3.51	1.75	0.86	0.444
Error		16	30.7	2.04		
Total		26	86.3			

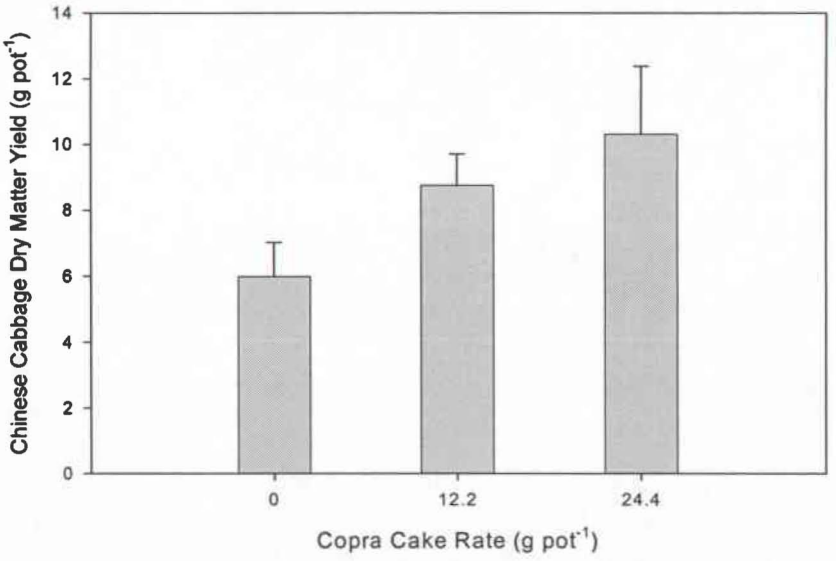


Fig. 4.16. Above ground Chinese cabbage dry matter biomass as a function of increasing copra cake additions. Error bars represent the standard deviation.

The cabbage plants showed unusual leaf pigmentation and leaf growth patterns throughout the five-week experiment. By the second week after transplanting all the cabbage plants lacked a good green pigmentation. The chemical control and the copra cake treatments at 10 Mg ha^{-1} showed the least degree of greenness. By the third week many of the plants were showing blotches of pale green tissue throughout the mature leaves, but the signs did not correspond to any one classical nutrient

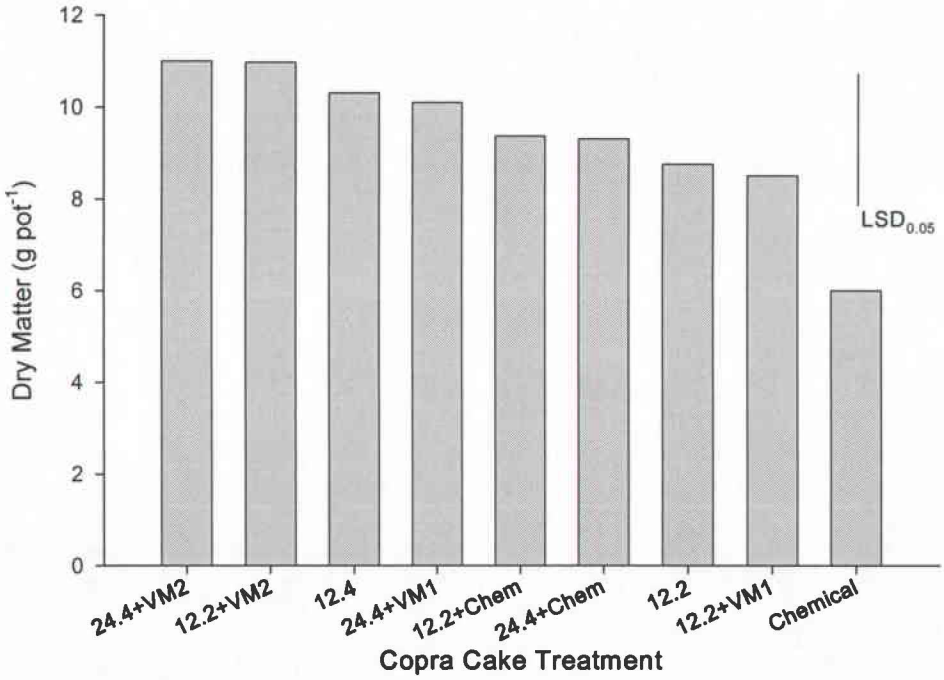


Fig. 4.17. Above ground Chinese cabbage dry matter production as a function of copra cake treatment. Numbers on the x-axis represent Copra cake addition rate (g pot^{-1}). VM 1= *V. marina* added at 5.05 g pot^{-1}, VM 2= *V. marina* at the same rate with B (1.52 mg pot^{-1}) + Cu (7.59 mg pot^{-1}), chem.= N (152 mg pot^{-1}), P (121 mg pot^{-1}), and Mg (75.9 mg pot^{-1}).

deficiency symptom. The greenest plants were found growing in the pots that were supplemented with *V. marina* leaves. The control plants showed the most glaring

symptoms and were not growing well, despite weekly additions of N and K fertilizers. In order to prevent the possibility of Mg or K deficiency, an additional 50 mg of Mg and K were added to the control pots at the end of week three. Five small leaf disks, obtained by using a paper hole puncher, from the most recently matured leaf from each pot were taken and sampled for total N to ascertain plant N status. Tissue N concentration ranged from a high of 6.23% to a low of 5.30%, values that were well within or above the critical range for Chinese cabbage (3.5-5.0%) ruling out N deficiency as a cause for the leaf discoloration.

In addition to the pale green pigmentation, several plants showed distorted leaf growth. The new leaves did not expand uniformly, but rather, they twisted as they expanded. This characteristic did not correspond to any particular treatments, but was distributed randomly among the pots. This peculiar growth pattern could not be attributed to any specific plant, soil, or environmental factor. The temperature in the greenhouse was high with daily temperatures ranging from 32.5 to 39.3°C. But we cannot explain the peculiar growth to high temperatures alone.

Macronutrient Supply

Macronutrient concentration in the above ground cabbage biomass at harvest showed high levels in the control treatment due to poor growth. Supplementing the copra at both rates with *V. marina* leaves significantly increased plant N concentration compared with copra alone treatments (Fig. 4.18). Nitrogen uptake from the two *V. marina* treatments was higher at both levels of copra than the copra alone or copra + chemical treatments, but the differences were not significant at P=0.05 (Fig. 4.19).

Potassium tissue levels showed the greatest degree of response to the different treatments. Analysis of variance showed that there was a highly

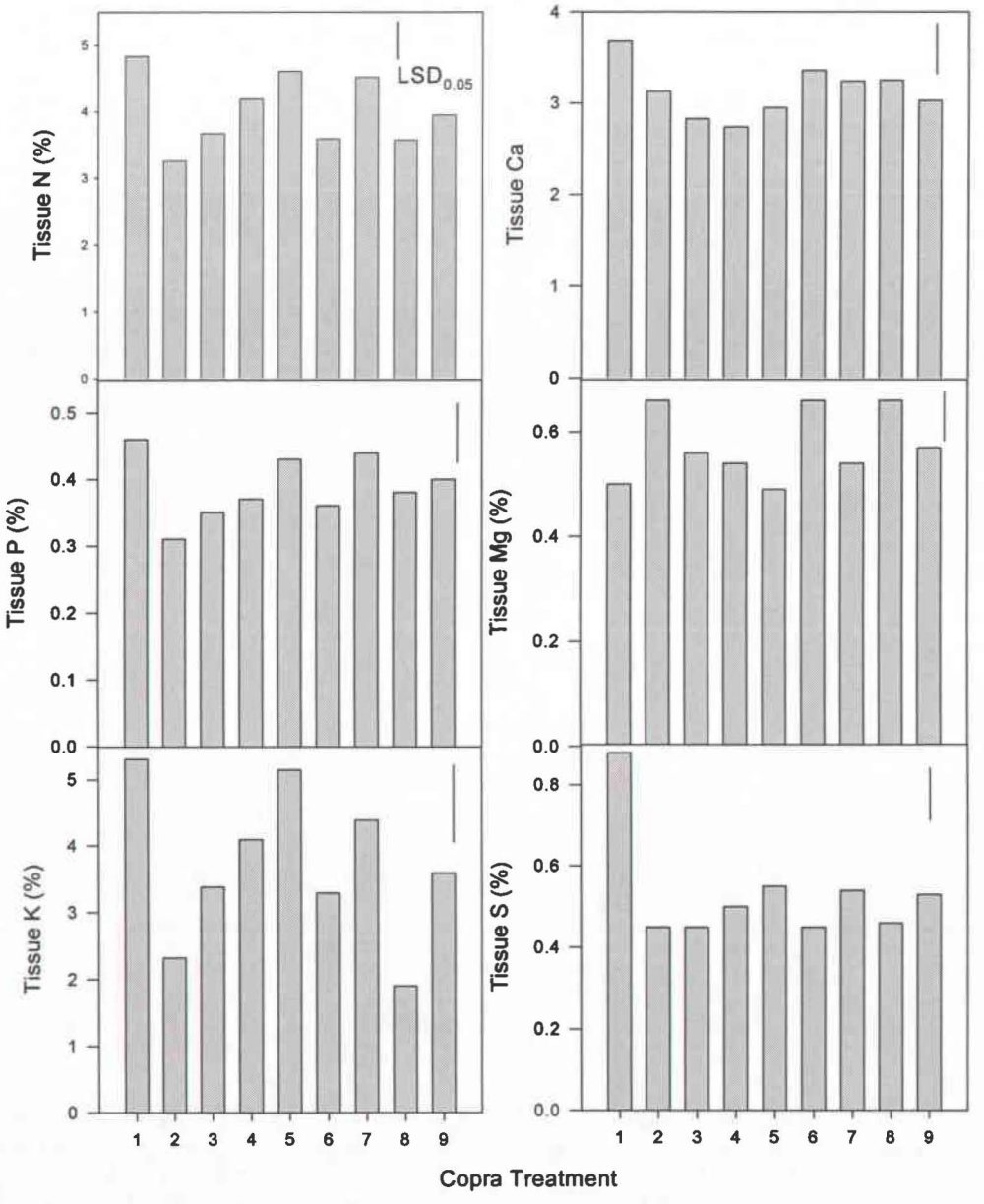


Fig. 4.18. Macronutrient tissue concentration in the above ground biomass of Chinese cabbage grown with different copra treatments: 1 = control, 2 = copra 10 Mg ha^{-1}, 3= copra 20 Mg ha^{-1}, 4 = copra 10+*V. marina*, 5 = copra 20+*V.marina*, 6 = copra 10+*V. marina* (B+Cu), 7= copra 20+*V. marina* (B+Cu), 8 = copra 10+ chem, and 9 = copra 20+chem..

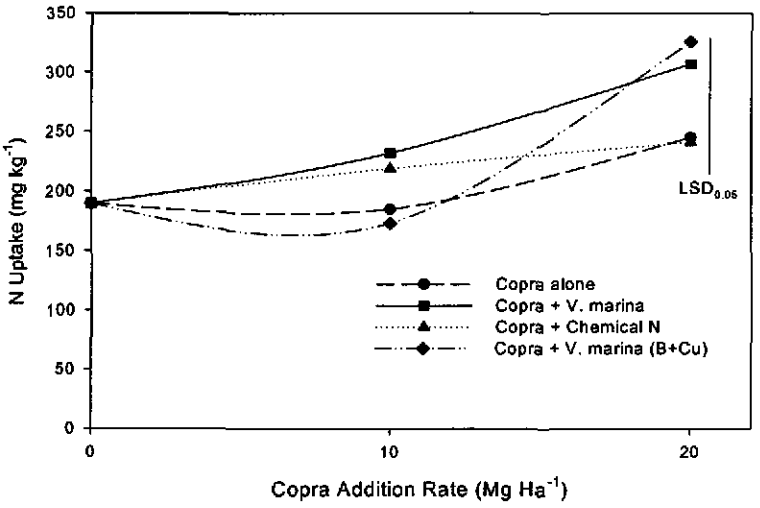


Fig. 4.19. Comparison of N uptake by Chinese cabbage plants grown with copra alone, copra augmented with *V. marina* with and without B+Cu, and copra augmented with a chemical source of N, P, and Mg.

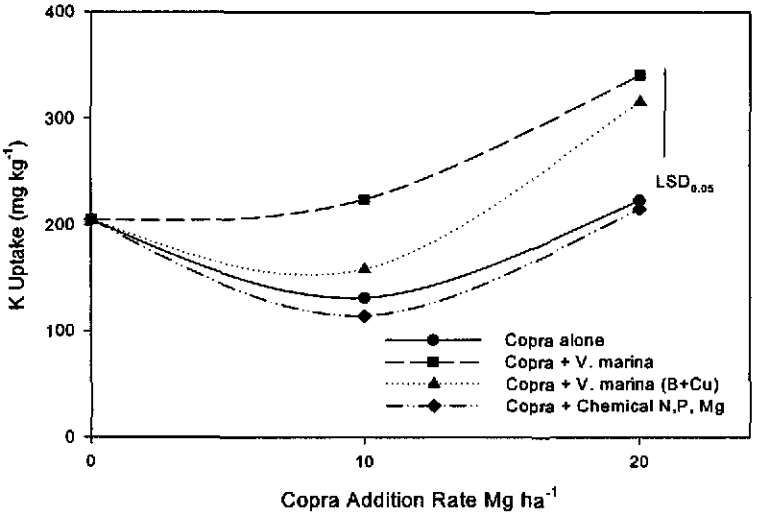


Fig. 4.20. Comparison of K uptake by Chinese cabbage plants grown with copra alone, copra augmented with V. marina with without B+Cu, and copra augmented with a chemical source of N, P, and Mg.

significant effect of copra addition rate and supplementing with *V. marina*. At 10 Mg the copra treatment significantly reduced K uptake compared with chemical control (Fig. 4.20). Increasing the copra addition to 20 Mg ha^{-1} raised K uptake back to the same level as the control. Supplementing the copra at the highest level with *V. marina* with and without B and Cu significantly increased K uptake over the control and the copra supplemented with chemical N, P, and Mg treatments. These results agree with results from the previous two greenhouse experiments described above where it was demonstrated that *V. marina* was an excellent source of K.

Tissue P concentrations showed some response to the different treatments. The most important being that copra at 10 Mg $ha^{-1}$and supplemented with *V. marina* or a chemical source of P did not improve plant P status compared with the copra alone at the same rate. Significant differences in P tissue concentration were obtained at the highest copra level. Phosphorus uptake by the cabbage plants showed no significant response to the copra treatments. Supplementing the copra with a chemical source of P did not increase tissue P concentrations or P uptake compared with the copra alone treatments. Calcium, Mg, and S tissue levels and uptake did not vary significantly between treatments.

Micronutrient Supply

Tissue analysis revealed that the very poor growth associated with the control treatment was due to deficient levels of Mn (Table 4.28). Despite adding Mn at a rate of 10 mg kg^{-1}, and no previous indication that the Marshall Island soil was deficient in Mn, the Mn was unavailable for plant uptake. This was surprising because the

same Mn rate had been employed in the three previous pot experiments without any sign of Mn deficiency. There are no immediate explanations for the extremely low Mn content of the control plants. The plants grown in the copra alone treatments showed Mn concentrations above the critical level. The highest levels of tissue Mn were obtained in the copra supplemented with *V. marina* with and without B + Cu. Besides the extremely low Mn uptake in the control treatment, no significant differences in Mn uptake were obtained between the different copra treatments.

Table 4.28. Micronutrient tissue concentrations of above ground Chinese cabbage plants grown with different copra cake treatments. Copra 10&20 correspond to copra added at 10 and 20 Mg ha^{-1}, VM1= V. marina supplement, VM2 = V. marina supplemented with B + Cu, and Chem = chemical supplement of N, P, and Mg.

Treatment	B	Fe	Mn	Cu	Zn
			ug g^{-1}		
Control	32.3b	57.7a	6.33e	6.0b	45.0bc
Copra 10	16.3c	45.3a	53.3d	2.3c	40.3bc
Copra 20	15.0c	43.0a	61.0c	2.7c	57.7ab
Copra 10 + VM1	16.7c	42.3a	65.0bc	3.0c	46.7bc
Copra 20 + VM1	15.0c	44.7a	75.7a	3.3c	47.7abc
Copra 10 + VM2	43.5a	45.0a	68.5ab	7.5ab	68.5a
Copra 20 + VM2	34.0b	97.3a	68.3abc	8.7a	43.7bc
Copra 10 + Chem	36.3ab	35.0a	50.0d	6.3b	31.3c
Copra 20 + Chem	35.3b	35.7a	50.3d	6.3b	41.7bc
$LSD_{0.05}$	7.63	79.0	7.41	1.6	21.1

Means followed by the same letter are not significantly different at the 5% probability level

Supplementing the *V. marina* treatment with B and Cu significantly increased B and Cu tissue concentration compared with the copra alone treatments. Boron uptake by the plants, however, showed no significant response to treatments. Copper uptake in the copra at the highest level supplemented with the *V. marina* and B+Cu showed a significant increase compared with the copra alone treatments. The higher B and Cu tissue concentrations, however, did not correspond with significantly higher cabbage

yields suggesting that other factors were controlling growth. No clear trends were observed for Fe or Zn.

Management Implications

The results of the pot study showed that increasing copra cake additions improves crop growth compared to soil with no copra cake. Supplementing the copra cake with *V. marina, V. marina* with B+Cu or chemical fertilizers showed potential to improve growth, but significant differences could not be determined because of high within-treatment variability. However, tissue levels and uptake results indicated that mixing copra with *V. marina* improved N and K supply, two limiting nutrients in atoll soils. These results indicate that if copra is available to the farmer, it will improve crop growth when used alone at a rate of 20 Mg ha^{-1}. For a small plot of say 9 m^2, a farmer would have to add 18 kg of copra cake; a 25 m^2 plot would require 50 kg. Clearly on a small scale, copra cake is not needed in large quantities. If there are high costs associated with shipping the copra cake back to the outer atolls, then this may not be a practical solution for farmers. If shipping is cheap and reliable, then copra cake may be a suitable fertilizer material. The extra cost and labor of mixing other materials to try achieve higher yields are probably not worthwhile given that the likelihood of improving yields is marginal based upon the results of the pot study.

Conclusion

Fertilizing a Marshall Island soil with locally available organic materials shows great potential to improve crop growth. The material should be selected based upon its chemical composition and potential to supply N, P, K, S, and Cu especially.

Results from the screening experiment showed that chicken manure improved crop growth and plant nutrition. The chicken manure supplied a balanced plate of plant nutrients with good biomass production. In the Marshall Islands, chicken manure may not be a practical fertilizer material due to animal husbandry practices and cultural views on manure use. Although many Marshallese families raise chickens for local consumption, they do not keep their chickens enclosed, and therefore, have no way of collecting the manure. Additionally, from a cultural perspective, animal manure is regarded as unsuitable for use on food crops. On-farm demonstration plots using chicken manure to improve crop growth combined with extension education activities may help to show farmers that using chicken manure is a viable alternative to improve food production.

The use of high quality leguminous plants as green manures to build soil fertility and improve crop yields on small farms in the tropics has been studied extensively (Giller and Cadisch, 1997; Palm et al., 1997a). Introducing alien legumes as a source of green manure does not make sense in the fragile ecosystem of the Marshall Islands. This study, however, has identified an indigenous legume, *V. marina*, as a suitable soil amendment to improve crop growth. The leaves of this common vine are rich in N and K, two nutrients that are highly deficient in atoll soils. The N mineralization studies in the laboratory and the greenhouse showed that N mineralized rapidly from these leaves, and can meet the N demand of vegetable crops. The relatively high K content of these leaves provide an adequate source of K to correct the serious K deficiency of the Marshall Island soil. The vine is abundant along the lagoon shorelines of many of the atolls in the Marshall Islands, and easily accessible to local

farmers. Based upon rates used in the pot experiments, preliminary calculations showed that using fresh *V. marina* leaves as a fertilizer material would be sustainable for small-scale vegetable production.

According to its chemical analysis, fish waste is an excellent fertilizer material except for its low K content. This is a serious limitation in atoll soils where K is often the most limiting plant nutrient. Our results clearly show that fish waste cannot be used alone to improve crop production; it must be augmented with a material high in K. Based upon our results, *V. marina* could be mixed with the fish waste to supply K. Other plant materials could also be used to supply K, but care must be taken not to add plant materials with a high C:N ratio (> 20-25), which could immobilize the N in the fish waste and induce N deficiency. A good composting program mixing fish waste and locally available plant materials would be a good source of plant nutrients for the rural farmers on the outer atolls.

Results from the screening experiment and copra mixing experiment suggest that copra cake is not the best fertilizer material available to Marshall Island farmers. In the absence of animal manures, fish waste, and high N containing plants, copra cake can increase crop growth compared with the untreated soil, but it is not a reliable source of N and K for vegetable production. Mixing copra with N and K rich materials, such as *V. marina*, did not clearly show an improvement in crop growth. Although the copra cake does improve crop growth compared to the unamended soil, copra would have to be transported back to the outer atolls, and the costs associated with the transport may not be worth the small improvements in crop growth. This is

an important consideration if other fertilizer materials like *V. marina* and fish waste are available on the outer atolls.

Previous efforts in promoting a composting program in the Marshall Islands focused on using coconut leaves as a mulching material to enhance vegetable growth (Finney and Laukon, 1993). The very low N content of coconut leaves makes it especially unsuitable as a fertilizer material, and the greenhouse screening experiment clearly showed the negative impacts of using coconut as a green manure. The ability of a green manure to supply adequate quantities of nutrients to a crop depends on its initial chemical composition (Palm and Rowland, 1997b). Initial leaf N content often serves as the best single criterion to predict N availability, and a critical examination of N mineralization data from eleven laboratory incubation studies found that plant materials with an initial N concentration above 2.5% tended to undergo net mineralization while plants with initial N below 2.5% showed net N immobilization (Palm et al., 2001). Chemical analysis of the leaves of some common indigenous plants in the atolls found that of the five plants tested only two had an initial N concentration above 2.5% (Table 4.29). Based upon these chemical analyses, *Ipomea pes-capre*, a common vine along the lagoon shores, should also be tested as a fertilizer material.

Table 4.29. Macronutrient content of five indigenous strand plants common throughout the Marshall Islands

Plant Species	N	P	K
		%	
Vigna marina	3.69	0.29	1.19
Ipomea pes-capre	2.66	0.38	1.47
Scaevola serica	1.55	0.22	1.74
Tournefortia argenta	1.29	0.20	1.39
Cocos nucifera	1.65	0.16	1.68

The findings from the present research provide valuable information on the nutrient supply capacity of some organic materials found in the Marshall Islands. This information, however, cannot be used directly to provide recommendations for farmers in the Marshall Islands. Rather, they serve as the foundation from which a coherent research program can be established to test these materials in field trials in the Marshall Islands.

Chapter Five

Evaluating Phosphorus Availability in the Coralline Soils of the Atolls in the Marshall Islands

Introduction

Phosphorus deficiency has been widely reported in the acid weathered soils of the humid tropics (Sanchez and Uehara, 1980) and the calcareous soils of many regions of the world (Sharpley, 1984; Afif, 1993; Mahmood-ul-Hassan et al., 1993). The deficiency is caused primarily by P adsorption reactions with the solid phase. In the acid soils of the tropics, P is adsorbed on the crystalline and amorphous Al-Fe oxide surfaces while in the calcareous soils P adsorption at low P concentrations depends largely on the mineralogy of the soil. Phosphorus adsorption at low P concentrations can occur on the $CaCO_3$ surfaces (Sharpley, 1984; Sharpley et al., 1989), but in the presence of Al-Fe oxide minerals P is preferentially sorbed on these minerals rather than $CaCO_3$ (Ryan et al., 1985; Pena and Torrent, 1990;.Zhou and Li, 2001). At high P concentrations, precipitation reactions involving P and solution Ca^{2++} (Tunesi et al., 1999) and Ca-phosphate minerals (Delgado et al., 2001) make P unavailable for plant uptake.

In addition to adsorption reactions, soil texture plays a fundamental role in controlling P availability for plant uptake. Phosphorus moves to the plant roots by diffusion, and as plants remove P from the soil solution P adsorbed on the solid phase is desorbed replenishing soil solution P. The ability of a soil to supply P as it is

removed from solution has been termed P buffering capacity (Fox and Kamprath, 1970). Because sorption reactions occur on the surfaces of soil minerals, adsorption reactions and buffering capacity are related to clay content; as clay content increases, P sorption increases and the soil has a greater buffering capacity (Kamprath and Watson, 1980) . In soils with high buffering capacity, phosphorus fertilizer applications have a significant residual effect as initially adsorbed P is desorbed to replenish solution P taken up by plants (Barrow, 1980; Guo et al., 2000). Sandy soils with lower surface area have relatively low P buffering capacities, and cannot supply P to the soil solution (Fox and Kamprath, 1970; Zhou and Li, 2001). Soils with low buffering capacity require frequent P fertilization to maintain adequate soil solution P concentrations.

The P status of the atoll soils of the Marshall Islands has not been studied in any detail. Early work uncovered the existence of phosphatic hardpans caused by the accumulation of precipitated P from guano deposits in the subsoil of the uninhabited islands of the northern Marshalls (Fosberg, 1954). Based upon the carbonate mineralogy and high pH of atoll soil, theory predicts that P solubility is limited by the tendency of P to precipitate with Ca (Lindsay, 1979; Morrison, 1990). Little data exist, however, quantifying P availability. The existing soil test data for P in atoll soils is difficult to interpret because they have not been correlated to plant growth response (Stone, 1951; Caiger, 1987; Gessel and Walker 1992).

A soil test measuring the plant available pool of P is an important first step in determining the P status of a soil and its P fertilizer requirement (Kamprath and Watson, 1980). The Olsen extraction procedure using 0.5 *M* $NaHCO_3$ at pH 8.5 is

commonly used to measure available P in calcareous soil (Kuo, 1996). The critical limit according to this procedure has been established at 10 mg P kg^{-1} below which P deficiency is expected. The median value for Olsen extractable P for the surface soils from the 25 atolls sampled in the Marshall Islands was 27 mg kg^{-1}. Despite this relatively high median concentration, P deficiency was obtained for corn grown in a Marshall Island soil with Olsen P of 50 mg kg^{-1}. A soil test can only be of value if it has been correlated to plant response.

The objectives of the present study were to (i) characterize P adsorption in a Marshall Island soil, (ii) measure plant response to P in a Marshall Island soil, and (iii) provide a preliminary evaluation of the Olsen extraction method to predict plant P requirements.

Materials and Methods

An atoll soil from Majuro atoll in the Marshall Islands was collected and used to evaluate plant available P. Some relevant chemical properties of the soil are found in Table 5.1. The first step involved a P sorption study under controlled conditions in the laboratory. The sorption study was conducted according to the method outlined by Fox and Kamprath (1970). The soil was air-dried and sieved to < 2mm. Three g of soil was placed in a 50 ml centrifuge tube, and 30 ml of phosphate solution added. The phosphate solution was made by adding increasing quantities of KH_2PO_4 to a 0.01 M $CaCl_2$ solution to obtain a P concentration range of 0, 2, 4, 16, 32, and 64 μg ml^{-1}. The treatments were replicated three times and two drops of toluene were added to each tube to arrest microbial activity. The tubes were placed on a longitudinal

shaker and shaken for 30-minutes twice daily for the 6-day equilibration period. Temperature was kept constant at 26°C while the tubes equilibrated. Following the equilibration, acid-washed charcoal was added to clarify the solution and filtered through #40 whatman filter paper. Inorganic P in the solution was determined by the method of Murphy and Riley (1962). The P that disappeared from the solution was presumed sorbed. Sorbed P was plotted against P remaining in the solution.

Table 5.1. Selected physical and chemical properties of the Laura surface soil

Soil Texture			Chemical Properties				
Sand	Silt	Clay	pH	Organic C	$CaCO_3$	Olsen P	Ca
----------%----------				----------%----------		$mg\ kg^{-1}$	$cmol_c\ kg^{-1}$
95.2	3.02	1.81	7.84	4.95	92.6	42.8	1.45

Plant available P was assessed with a series of greenhouse pot experiments with Chinese cabbage (*Brassica chinensis*), corn (*Zea mays* cv supersweet #9), and lettuce (*Lactuca sativa*) using the Laura soil (Table 5.1). Phosphorus, as KH_2PO_4, was added at the following rates: 0, 10, 20, 40, 60, 80, 100, and 160 mg kg^{-1}. The P addition rates corresponded to soil solution P concentrations ranging from 0.2 to 5.0 μg ml^{-1}. The P treatments were added to 1.52 kg soil (oven dry basis) in solution form, mixed thoroughly, brought up to approximate field capacity with deionized water, and left to equilibrate for 48 hours. The treatments were replicated twice. After equilibration, soils were remixed, and each pot received a blanket nutrient solution similar to the control treatment of the organic materials screening experiment (Table 4.2). Two-week old Chinese cabbage plants were transplanted into the pots, and the pots were arranged in a randomized complete block design, blocked to account for the natural temperature gradient in the greenhouse. Moisture content of the pots was maintained

by weighing the pots every 2 to 3 days and adding water to bring the pot back to the original weight. After the third week of growth, the pots were watered twice daily to maintain adequate moisture supply to the rapidly growing plants. Mature cabbage plants were harvested at 35 days after transplanting by cutting the stem at the soil surface. The plants were washed carefully in deinonzed water, dried at 70°C for 72 hours, and weighed for dry matter determination. The dried tissue was ground, dry-ashed at 500°C in a muffle furnace, and digested in 0.1 *M* HCl solution. Phosphorus in solution was determined by the method of Murphy and Riley (1962). Following no response to P by the Chinese cabbage, corn was planted in the same pots as the cabbage. No additional P was added, but the pots received N and K at 25 mg kg^{-1} on a weekly basis for four weeks, and an initial supplement of S and Mg at 50 mg kg^{-1}. Six corn seeds were planted initially, which were then thinned to two uniform plants per pot one week after planting. The corn was grown for 35 days, harvested and prepared for P analysis in the same manner described for the cabbage plants.

A third greenhouse experiment with lettuce was conducted using a wider range of P treatments. Phosphorus treatments consisted of the following rates: 0, 20, 40, 80, 160, 320, and 640 mg kg^{-1}. These rates corresponded to a soil solution P concentration ranging from 0.2 to 28 μg ml^{-1}. The treatments were replicated three times and arranged in an RCB. Two-week old lettuce seedlings of uniform size were transplanted into the pots. An automated misting system was used to keep the plants cool during the heat of the day. The plants were harvested after 35 days of growth, and prepared for analysis in the same way described above.

Initial soil P was determined using three different extraction methods: (i) 0.5 *M* $NaHCO_3$ at pH 8.5, (ii) 0.1 M NaOH, and (iii) acid ammonium oxalate (Guo and Yost, 1999). The inorganic and organic fractions of the $NaHCO_3$ extraction was determined by splitting the extraction solution in two after filtration – 25 ml underwent analysis for inorganic P (P_i) by the Murphy and Riley method, and the other 25 ml was placed in a heat resistant centrifuge tube, treated with 0.5g of $K_2S_2O_8$, 3.0 ml of 2.5 *M* H_2SO_4, autoclaved at 200°C for one hour to convert organic P (P_o) into inorganic P; this solution represented total P (P_T) in the extract (Thien and Myers, 1992). The solution was allowed to cool to room temperature and analyzed for inorganic P by the Murphy Riley method. The organic P fraction was obtained by difference: $P_o = P_T - P_i$. Following the harvests of the cabbage plants, inorganic and organic P were determined using the 0.5 *M* $NaHCO_3$ extraction.

Sorption parameters for purposes of comparison were calculated using linear and Freundlich isotherms as follows:

Linear isotherm:

$$S = K*C - S_o$$

where S is the amount of P sorbed by the solid phase ($\mu g\ g^{-1}$), K is the slope or the P-buffering capacity (PBC), C is the P concentration in solution after 6-days equilibration, and S_o is a constant estimating the amount of originally sorbed P.

Freundlich isotherm:

$$S = K_f*C^n$$

Where K_f and n are empirical constants, with $n<1$.

Curve fitting procedures for the P response data generated in the greenhouse experiments were done using Sigmaplot for Windows Version 7, and parameter estimates were validated with proc NLIN in the SAS (1999).

Results and Discussion

Phosphorus Sorption

At the low end of the concentration gradient (equilibrium concentration 0.2 -1.6 μg ml^{-1}) P-sorption was linear, and fitted with the linear isotherm (Fig. 5.1). The slope of the line, equivalent to the PBC of the soil, was estimated at 26.9, and the x-intercept, which represents the equilibrium point where no net sorption or desorption occurs, was estimated to be 0.09 μg ml^{-1}, significantly underestimating the measured equilibrium P concentration of 0.2 μg ml^{-1}. At higher equilibrium concentrations, P-sorption followed a curvilinear trend, and was fitted well with the Freundlich isotherm (Fig. 5.2). The estimate for K_f was 36.4 and for n it was 0.76.

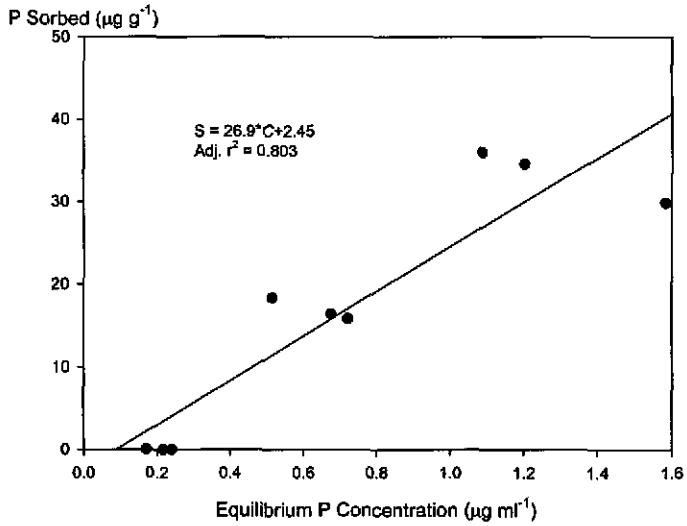


Fig. 5.1. Linear P-sorption isotherm of a Majuro soil at low equilibrium P levels.

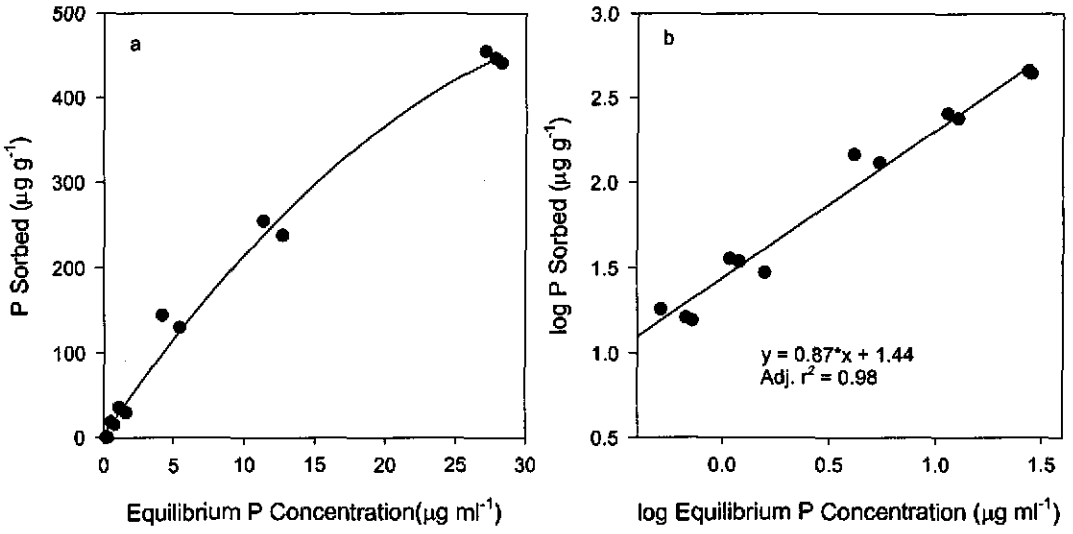


Fig. 5.2. Freundlich P-sorption isotherm (a) for the Majuro soil and its linear form (b) for the full range of equilibrium P levels.

The Marshall Island soil exhibited very low P sorption capacity. This finding was expected based on the carbonate mineralogy of the soil and the lack of a clay fraction (Table 5.1). Phosphorus sorption is correlated with the occurrence of well-crystallized and amorphous sesquioxides and soil clay content. High P-fixing Oxisols and Andisols with high sesquioxide content common in the Hawaiian Islands have high P fixing capacities ranging from 900 to 2800 µg g^{-1} at an equilibrium P concentration of 0.2 µg ml^{-1} (Sanchez and Uehara, 1980). The Marshall Island soil represents the opposite end of the P sorption spectrum. The calcareous soils of south Florida showed similar chemical and physical properties, and P sorption capacities to the Marshall Island soil (Zhou and Li, 2001). Phosphorus sorption studies on these Florida soils under vegetable production with pH values near 8.0, high $CaCO_3$ content and organic C ranging from 1.5-3.0% showed similar P sorption characteristics with

the Marshall Island soil. Their phosphorus buffering capacities derived from the linear isotherm at P equilibrium concentrations between 0.2 and 1.0 μg ml^{-1} ranged from 17 to 69. These PBC values were related to the quantities of carbonate and noncarbonate clay. Soils with low concentrations of noncarbonate clay exhibited the lowest PBC with values of 22.5 and 16.8, similar to the PBC measured in the Marshall Island soil. While we did not distinguish between carbonate and noncarbonate clay, it is reasonable to assume that the small clay fraction of the atoll soil in this study was predominately carbonatic in nature. Mineralogical analysis of an atoll soil from Christmas Island found no presence of Fe or Al oxides in the clay fraction (Hammond, 1969). The important role of noncarbonate clay in P sorption was elucidated in the high P-sorption observed in the Rockdale and Biscayne series under pine forest and wetlands (Zhou and Li, 2001). These soils contained three to four times more noncarbonate clays than the soils under vegetable production and they sorbed 99% of the added P at the low P equilibrium concentrations.

Values of the derived estimates for the empirical constants K_f and n from the Freundlich isotherm for the Marshall Island soil showed similarities with the Florida soils under vegetable production. Values for K_f in the Florida soils ranged from 12 to 58 and the changes in K_f were highly correlated to noncarbonate clay content. The estimate of n in the Marshall Island soil was higher than all n values for the Florida soils. Examination of the P-sorption characteristics of a range of calcareous soils in North Africa and West Asia found similar effects of $CaCO_3$ and Fe oxide content on K_f values (Afif, 1993). Values for K_f were much higher for most of these soils except in two cases where they fell within the range of the Marshall Island soil and Florida

soils. In both cases, total clay content was relatively low, $CaCO_3$ high, and extractable Fe (citrate-bicarbonate-dithionite) low.

Despite chemical properties such as high $CaCO_3$ content, high pH, and high levels of solution Ca^{2+} (Tunesi et al., 1999), which tend to promote P-sorption, results from the P-sorption study showed that the Marshall Island soil had a very low capacity to sorb added P. The low sorption capacity was related primarily to two properties of the Marshall Island soil: (i) sandy texture with a clay fraction < 2% leading to low surface area, a critical parameter influencing P-sorption; and (ii) the absence of Fe and Al oxides with a high P sorption capacity. Fox and Kamprath (1970) found that a sandy soil (< 1% clay) from North Carolina showed a similarly low capacity to sorb added phosphorus. The low P-sorption was attributed to low surface area. In a follow up study, the same authors found that P sorption was also minimal in a sandy soil high in organic matter (Fox and Kamprath, 1971). In addition, to the lack of P-sorbing minerals and sandy texture, the Marshall Island soils are high in organic matter content further reducing their capacity to sorb P.

Phosphorus sorption by soils plays an important role in the supply of P to growing plants. In high P-fixing soils, P deficiency is common because P is removed from solution as it reacts with the solid phase requiring high addition rates to achieve adequate solution levels. In this type of system, P associated with solid phase acts as a reservoir of P as soil solution P is depleted due to plant P uptake (Barrow, 1980). In other words, solution P levels are buffered against drastic declines as P is desorbed from clay surfaces. In coarsely textured soils with low surface area and low PBC, soil solution P concentrations must be kept high with P additions to compensate for

the inability of P to desorb from the solid phase (Fox and Kamprath, 1970; Fox and Kamprath, 1971; Woodruff and Kamprath, 1965). The surface soils in the Marshall Islands generally show relatively high values of Olsen extractable P, with a median value of 27 mg kg^{-1}, compared to the minimum critical level of 10 mg kg^{-1} established for calcareous soils. The observance of P deficiency in corn in the Marshall Island soil with Olsen extractable P of 50.0 mg kg^{-1} is in agreement with earlier findings that sandy soils require high soil P concentrations to maintain adequate growth.

Plant Available Phosphorus

Chinese Cabbage Experiment

Chinese cabbage was grown in the Marshall Island soil supplied with eight rates of P in a greenhouse pot experiment. The relative proportion of P_o to P_i in the Marshall Island soil with increasing levels of added P is presented in Figure 5.3. The proportion of P_o did not vary significantly with increasing rates of added P except at the highest P rate where the organic pool decreased significantly compared with the 0 and 20 mg kg^{-1} P addition rate. The P_o pool represented 31% of the total bicarbonate pool in the 0 P soil. This was a relatively low value compared with some Argiudolls from Kansas that showed a high proportion of P_o ranging from 70 to 96% (Thien and Myers, 1992). A sandy Entisol from the same dataset had a P_o value of 36%, which compared well with the Marshall Island soil, but the Entisol had an extremely low organic matter content (0.06%).

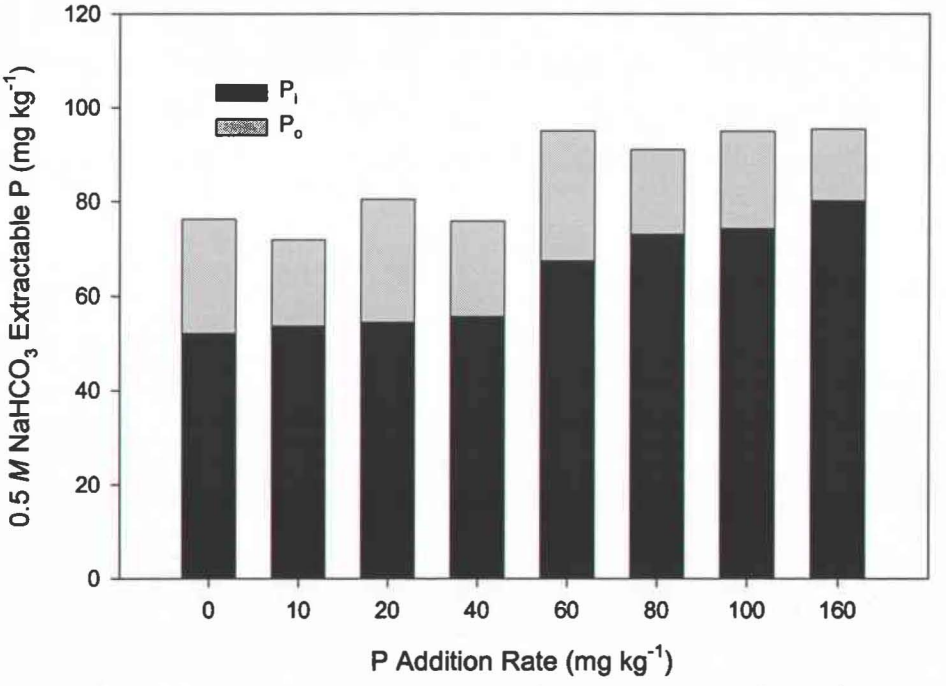


Fig. 5.3. Relative proportion of Olsen extractable Po to Pi two days after P was added to a Marshall Island soil used in a pot study testing Chinese cabbage response to P.

The effect of P addition rate on the distribution of the three bicarbonate pools is presented in Figure 5.4. Extractable P_T and P_i increased linearly with P addition rate, but extractable P_i showed a stronger relationship with added P. The slope of the line is a measure of P availability, and the value of 0.20 obtained for the inorganic fraction of the Marshall Island soil is lower than the values obtained for some calcareous soils from the continental U.S. with values ranging from 0.31-0.81 (Sharpley et al., 1989). The bicarbonate extraction did not account for all of the added P. In fact, only 60% of the added P at the 160 mg P kg^{-1} rate was recovered by the bicarbonate extraction. The oxalate and NaOH extractable P were also assessed in relation to added P (Fig. 5.5). In both cases, extractable P did not change significantly with increasing rates of added P. The oxalate extraction selectively removes P associated with Al and Fe

oxides (Wang et al., 1991) while the NaOH extraction gives an estimate of P adsorbed on active surfaces including $CaCO_3$ (Delgado et al., 2001) . The lower concentrations of P extracted with oxalate was probably a result of precipitation reactions between the P and dissolved Ca^{2+}. Guo and Yost (2000) found that the oxalate extraction method was an unreliable method for measuring available P in two calcareous soils in Hawaii. Precipitation of P in the NaOH extraction in calcareous soils also results in low extractable P concentrations (Delgado et al., 2001) consistent with the results of this study.

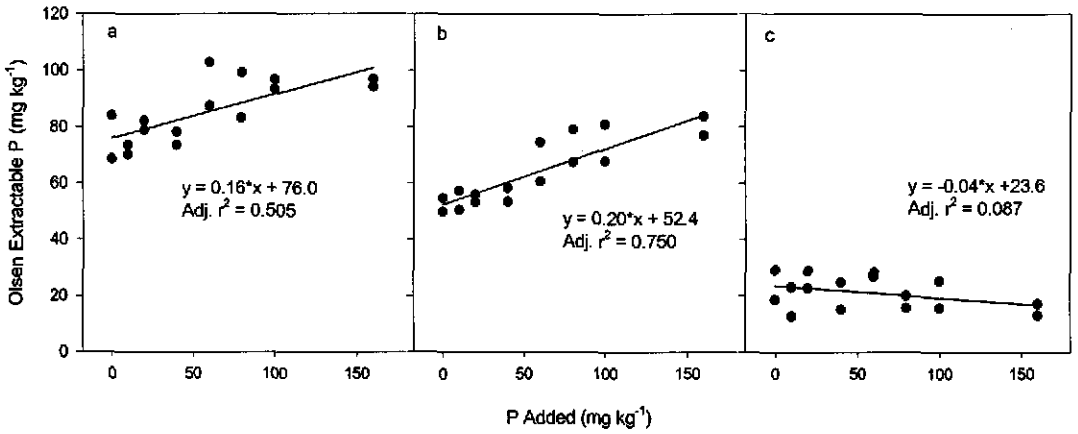


Fig. 5.4. Initial values for three pools of Olsen extractable P (a) total, (b) inorganic, and (c) organic as a function of added P in a the Marshall Island soil used for the Chinese cabbage experiment

The increase in extractable P did not cause a response in Chinese cabbage growth or any significant changes in the concentration of P in the tissue (Fig. 5.6). Despite the lack of either a growth or tissue P concentration response to increasing rates of added P, the P concentration of the cabbage tissue never attained the established *minimum critical level of* 0.40%. Tissue P concentrations and P uptake by the cabbage plants showed responses to increasing levels of extractable P_i (Fig. 5.7).

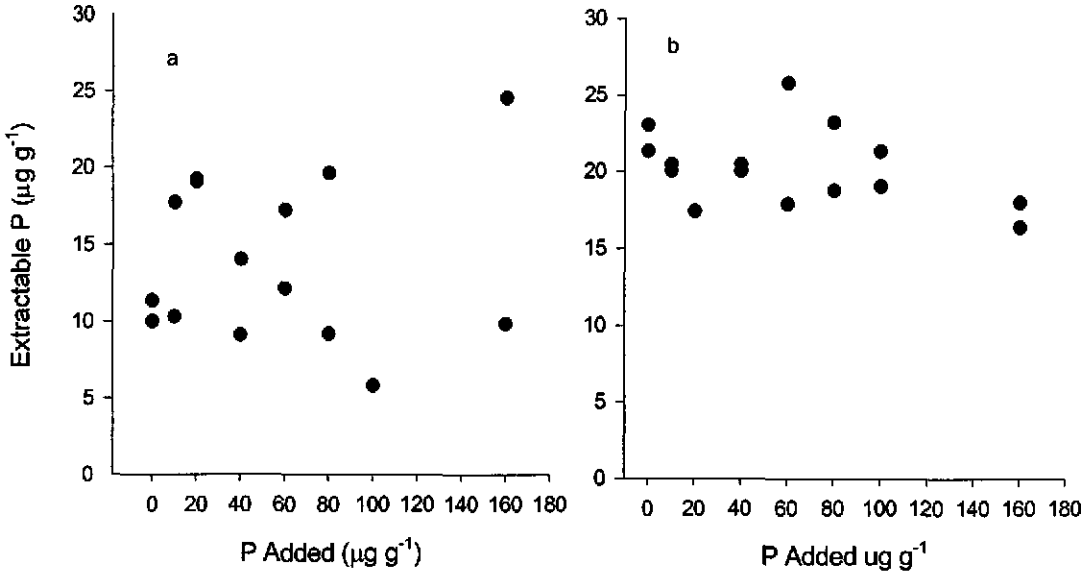


Fig. 5.5. Initial oxalate (a) and 0.5 M NaOH(b) extractable P as a function of added P to a Marshall Island soil planted with Chinese cabbage (*Brassica chinensis*).

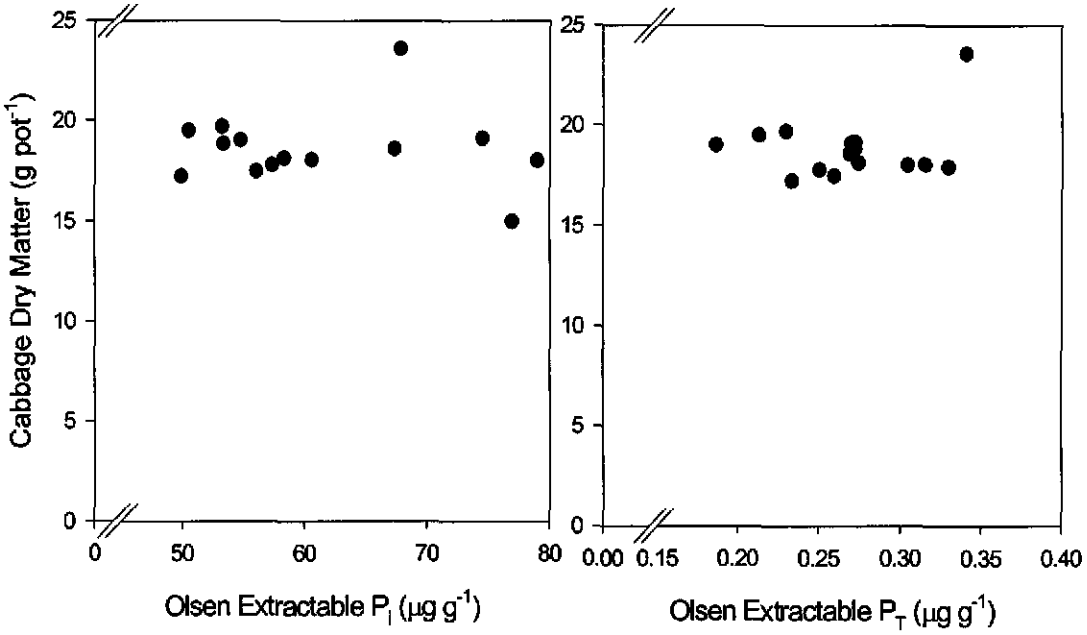


Fig. 5.6. Chinese cabbage (*Brassica chinensis*) dry matter yields as a function of increasing concentrations of extractable soil P.

Phosphorus uptake showed a weak linear relationship with extractable P_i while tissue P appeared to have reached a plateau, and the relationship was better described with Mitscherlich function. In both cases the relationship was weakened by a high degree of variability. The absence of a growth response to added P, and the good growth obtained across all treatments suggests that native soil P levels are adequate for Chinese cabbage growth. In a previous experiment, Chinese cabbage plants grown with chemical fertilizers at optimum levels and P added at 20 mg kg^{-1}showed similar growth with tissue P levels of 0.34%.

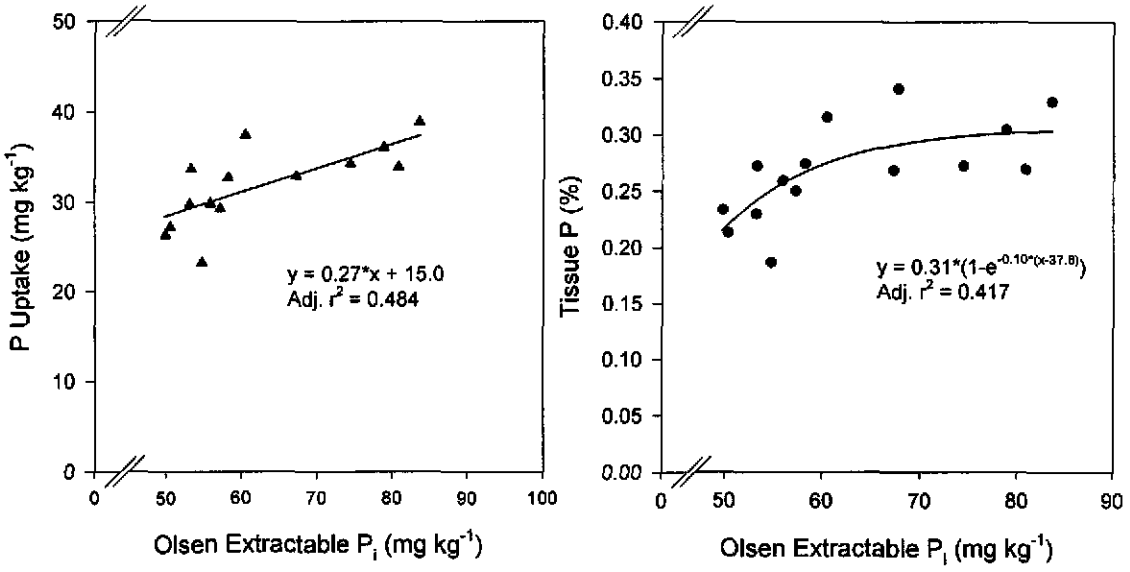


Fig. 5.7. Phosphorus uptake by Chinese cabbage plants and tissue P concentrations in relation to increasing concentrations of Olsen extractable P.

Comparisons between the different pools of initial soil extractable P and extractable P following the harvest of the cabbage plants showed some significant changes (Table 5.2). Total extractable P and Pi decreased after harvest with a greater degree of change in the Pi fraction. No significant change in all three P pools was observed in the 0 P treatment. The organic P pool showed no significant changes

except in the 60 mg kg^{-1} P treatment. We observed a considerable gap between the difference in extractable P after harvest and the amount of P accumulated by the cabbage plants. In all P treatments except the 60 mg kg^{-1} treatment, P uptake exceeded the change in soil P_T from initial to post harvest. The discrepancy can be explained by two possible mechanisms. First, P availability in soils depends on the dynamics of sorption and desorption reactions. As P concentration in the solution decreases due to plant P uptake, P associated with solid phase will dissolve increasing soil solution P until equilibrium is reached (Bohn et al., 1985). In this way, the soluble P pool can be replenished by P sorbed to the solid phase. Second, the contribution of organic P to plant uptake is important especially in tropical soils (Anderson, 1980; Sharpley, 1995). In the Majuro soil, with its high organic matter content, mineralization of organic P during the growing cycle can be an important source of plant available P. The P_o pool in this study showed no significant changes after the cabbage harvest suggesting a dynamic equilibrium between mineralization and replenishment from a moderately labile P pool. Research has found that the moderately labile organic P pool can replenish the available P pool as inorganic soil solution P concentration decreases (Sharpley, 1985; Tate et al., 1991). The work of Thien and Meyers (1992) showed that under laboratory conditions soils enriched with C and N to stimulate microbial activity and thus mimic rhizosphere conditions showed significant increases in P_o measured by the Olsen's procedure. They called this P_o fraction bioavailable P and postulated that it represented a plant available pool of P not measured by conventional extraction procedures. This bioavailable pool of P

from the organic fraction may have also contributed to the available P pool in the Marshall Island soil.

Table 5.2. Comparisons between initial extractable P for the three pools, post harvest extractable P, the change in soil P, and P uptake by the cabbage plants. Tests for significance for change in P were done by ANOVA comparing means for initial and post harvest P.

Rate	Olsens Extractable P									P Uptake
	Initial			Post Cabbage Harvest			Change in P			
	P_T	P_i	P_o	P_T	P_i	P_o	P_T	P_i	P_o	
	mg kg^{-1}									
0	76.2	52.3	23.9	57.7	34.1	23.6	-18.5ns	-18.2ns	-0.28ns	24.8
10	71.8	53.9	18.0	57.2	34.7	22.5	-14.6ns	-19.2*	+4.56ns	28.3
20	80.5	54.6	25.8	54.3	37.2	17.1	-26.2**	-17.4**	-8.77ns	29.7
40	75.8	55.8	20.0	61.0	40.4	20.6	-14.8ns	-15.5*	+0.64ns	33.2
60	95.0	67.5	27.5	60.9	43.3	17.6	-34.1*	-24.2ns	-9.95*	35.8
80	91.1	73.1	17.9	61.0	43.6	17.4	-30.0ns	-29.5*	+0.51ns	34.4
100	94.9	74.4	20.6	68.4	44.0	24.4	-26.5*	-30.4*	+3.81ns	43.4
160	95.5	80.3	15.2	73.4	55.7	17.6	-22.1*	-24.6*	+2.48ns	38.8

*significant at *0.05*, ** significant at *0.01* levels, ns not significant at *0.05*

Corn Experiment

Following the cabbage harvest, corn was planted in the pots without adding additional P. The pots were supplemented with weekly additions of N and K to achieve a total of 200 mg kg^{-1}. Corn above ground biomass production after five weeks showed a response to increasing levels of extractable P (Fig. 5.8). Biomass showed a weak linear relationship with soil P_T, but only 59% of the variation in dry weight production could be explained by inorganic + organic bicarbonate P. Corn growth did not reach a plateau at the higher concentrations of extractable P suggesting that either additional levels of P are necessary to obtain optimal growth or corn growth was limited by some other factor. Phosphorus uptake showed a linear increase with increasing levels of extractable P ($r^2 = 0.623$). Tissue P concentrations were generally low even at the highest P treatment, and never attained the minimum

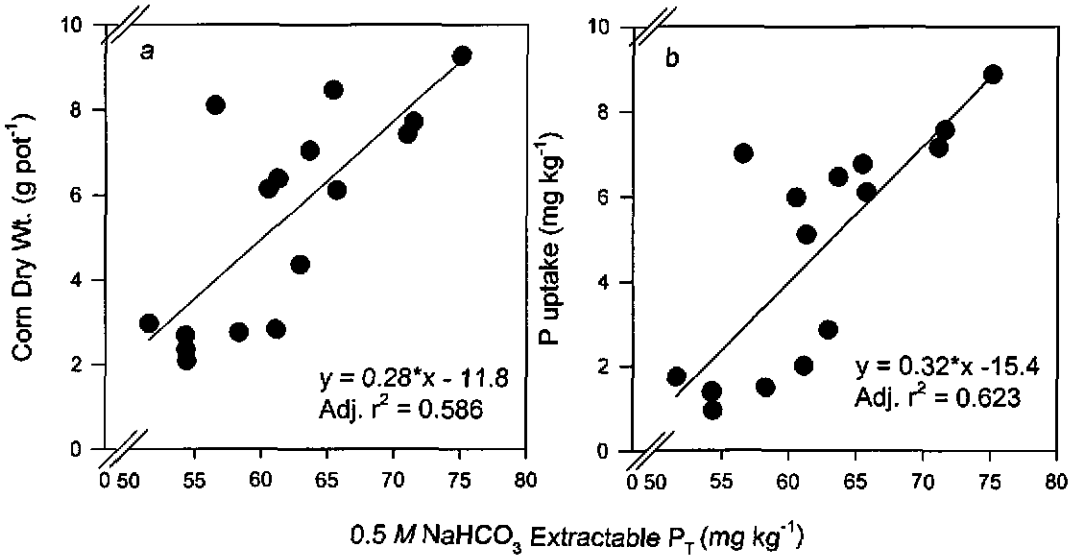


Fig. 5.8. Above ground corn dry matter production (a) and P uptake (b) in relation to Olsen extractable P in five-week old corn plants.

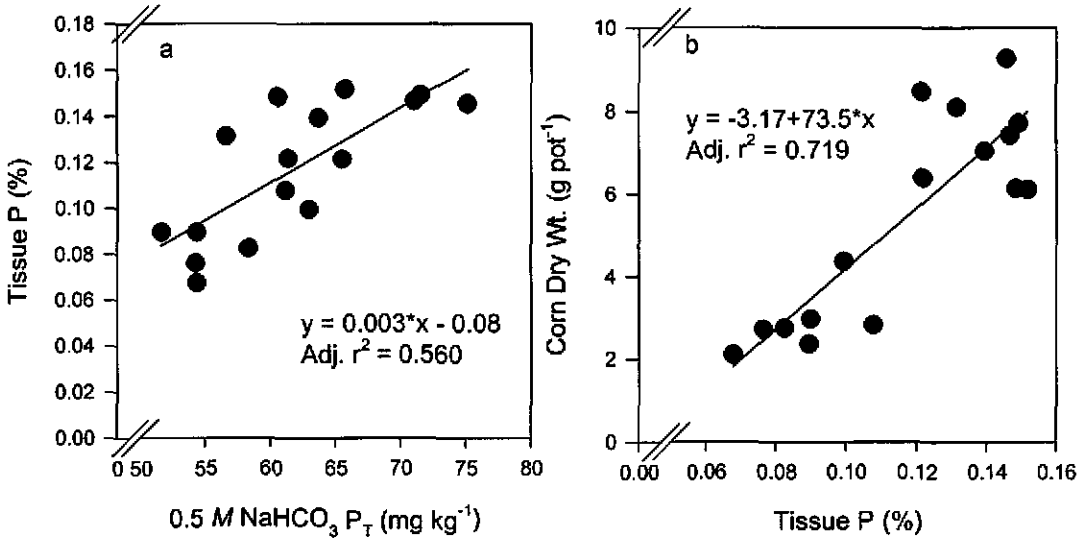


Fig. 5.9. The relationship of tissue P concentration and extractable P (a) and corn dry matter production and tissue P (b) for five-week old corn plants.

critical level of 0.30%. They showed a linear tendency with increasing concentrations of extractable P (Fig. 5.9), but the correlation was weak ($r^2 = 0.560$). A stronger linear relationship was obtained comparing tissue P with corn dry matter production. In both cases, the lack of a plateau effect in tissue P and dry matter production at the higher P levels suggested that the internal P requirement for optimal growth was not met by the range of P added to the soil.

Unlike the results obtained in the cabbage experiment, no significant changes in the extractable P pools were obtained between the pre-corn soil and the post-corn soil (Table 5.3). In two cases, added P at 20 and 80 mg kg-1, extractable P_T increased following the corn crop. At these two rates P uptake did not match with a measured decline in the P_T pool. For the remaining rates, P uptake showed a better match with measured decline in P_T than was obtained in the cabbage experiment (Table 5.2). The P_i pool showed very little change after the corn crop suggesting that (i) P in this pool was not available to the growing plants or (ii) that P concentration remained constant because it was being continually replenished from another pool as crop uptake removed P. Guo and Yost (2000) found that the available P pool in a variety of soils continued to be replenished with P from more resistant pools under exhaustive cropping conditions. The bicarbonate extraction did not account for a substantial quantity of added P prior to planting, this unaccounted for P may have been sequestered in an unmeasured pool, and provided a source of P as the crop P uptake removed P from the inorganic pool of P. Initially added P may have also become sorbed to the solid phase. Phosphorus availability in a calcareous system tends to decline with incubation time due to the increasing importance of sorption

processes (Sharpley et al., 1989). The P_o pool showed a tendency to decline suggesting that the corn may have been accumulating P from this pool. As P sorption reactions reached equilibrium making inorganic P less available to plant roots, the P mineralization from the organic fraction could have been available for plant uptake (Anderson, 1980; Thien and Myers, 1992). The lack of any significant differences, however, makes any conclusions difficult to substantiate.

Table 5.3. Comparisons between initial extractable P for the three pools, post harvest extractable P, the change in soil P, and P uptake by the corn plants. Tests for significance for change in P were done by ANOVA comparing means for initial and post harvest P.

Rate	Olsens Extractable P									P Uptake
	Pre-corn			Post Corn Harvest			Change in P			
	P_T	P_i	P_o	P_T	P_i	P_o	P_T	P_i	P_o	
	mg kg^{-1}									
0	57.7	34.1	23.6	48.3	34.8	13.5	-9.46ns	+0.72	-10.2ns	1.47
10	57.2	34.7	22.5	54.8	35.0	19.8	-2.46ns	+0.25ns	-2.71ns	2.30
20	54.3	37.2	17.1	55.7	38.7	17.0	+1.39ns	+1.46ns	-0.08ns	1.37
40	61.0	40.4	20.6	54.9	40.6	14.3	-6.14ns	+0.22ns	-6.36ns	3.97
60	60.9	43.3	17.6	57.0	41.9	15.1	-3.95ns	-1.48ns	-2.47ns	5.54
80	61.0	43.6	17.4	65.6	48.2	17.4	+4.55ns	+4.55ns	0.00ns	6.87
100	68.4	44.0	24.4	62.1	44.1	18.0	-6.29ns	+0.07ns	-6.36ns	6.63
160	73.4	55.7	17.6	63.4	45.1	18.4	-9.92ns	-10.6ns	+0.72ns	8.22

Lettuce Experiment

Adding P at 0, 40, 80, 160, 320, and 640 mg kg^{-1} increased extractable P_T and P_i in the Majuro soil prior to planting lettuce seedlings (Fig. 5.10). The P_T pool showed a curvilinear tendency with increasing P addition rates, and was fitted with a first order exponential equation. The inorganic pool showed slightly lower extractable P values at all P levels except the highest, and showed a linear relationship with added

P. The organic P pool showed no clear response to adding P, except at the highest P rate where values for P_o were two to four times lower than at the lower rates.

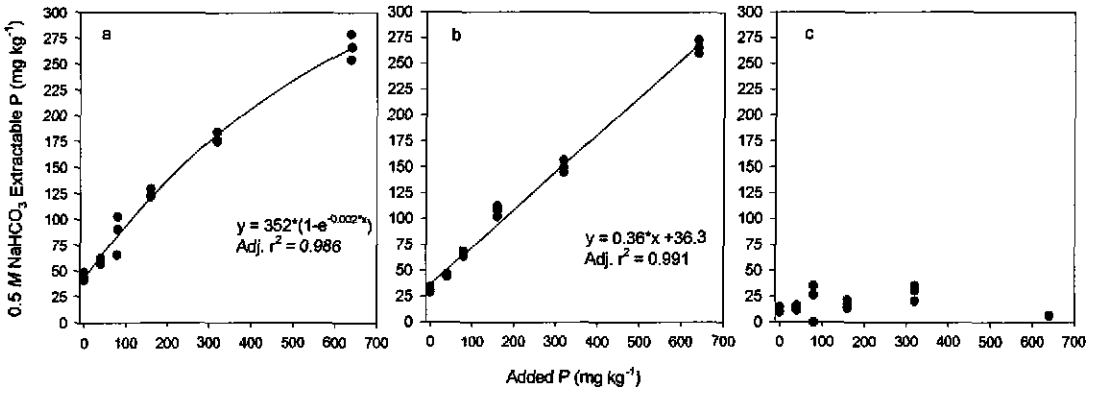


Fig. 5.10. The relationship of Olsen extractable P_T (a), P_i (b), and P_o (c) with increasing amounts of added P in pots prior to lettuce transplanting.

There was a significant lettuce yield response ($P<0.001$) to applied P in the Majuro soil (Fig. 5.11). The response was curvilinear and best described by the Mitscherlich equation, but the highly variable distribution of the data weakened the predictive capability of the fit ($r^2 = 0.567$). The high variability within treatments could not be readily explained by the experimental conditions in the greenhouse. Moisture content of all the pots was controlled twice a week by weighing pots to maintain moisture at approximately field capacity. Pots within blocks were randomized weekly to account for any uneven distribution of water from the overhead mist system. Temperature and light conditions were generally uniform throughout the greenhouse. The only uncontrolled factor was a strong draft running parallel to the blocks when the door was opened. The door was kept closed during the experiment, but since other people used the facility it was opened for exit and entrance purposes. The draft would have affected block 1 more than the others. Removing block 1 from the analysis appeared to have a slight reduction

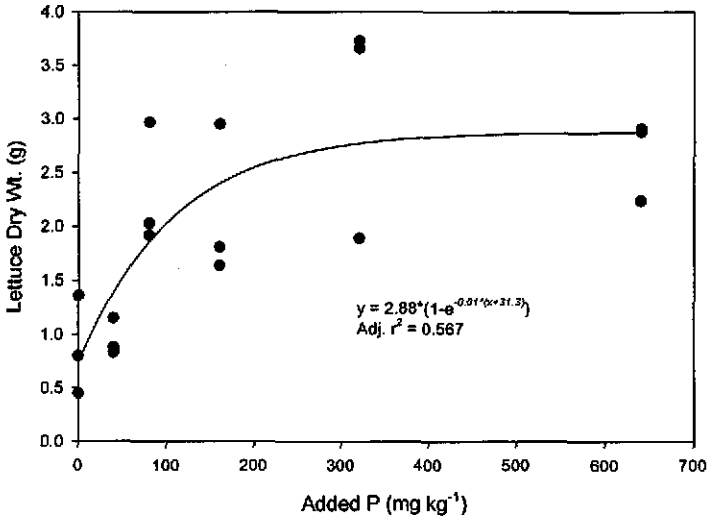


Fig. 5.11. *Lettuce response to increasing P rates in the Majuro soil.*

in the variability increasing the coefficient of determination to 0.623 (Fig. 5.12), and deletes the two low yields at the two highest rates, but a two-fold yield difference was still obtained at the 160 mg P kg^{-1} treatment. The slight improvement in coefficient of determination did not appear to warrant the removal of the block from the analysis.

A plateau in lettuce yield appeared to coincide with a P addition rate of approximately 320 mg kg^{-1}. Field grown lettuce in a near neutral Australian sandy soil achieved a yield plateau at approximately 290 kg P ha^{-1} (McPharlin and Robertson, 1997). Converted to the same unit of measurement, the lettuce grown in the Marshall Island soil reached its yield plateau at about 400 kg P ha^{-1}. The higher rate may be due to the small volume of soil in the pot, which tends to increase the P requirement. A pot experiment with a sandy soil with a pH of 7.3 achieved a lettuce yield plateau at 120 mg P kg^{-1} (Smith and Scaife, 1973). Lettuce was also grown in a peat soil with a pH of 6.9 where low yields were obtained and the yield plateau was

not reached at the highest rate consisting of 240 mg P kg^{-1}. The authors attributed the low yield to low concentrations of P in solution due to P sorption by the organic matter. In the Marshall Island soil, the combination of sandy texture and high organic matter may be contributing to the high P rate required to achieve maximum yields. In a near neutral South Florida Histosol, maximum lettuce yields were achieved at P rates between 200 and 400 kg ha^{-1} (Nagata et al., 1992), close to the rates associated with maximum yields in the Marshall Island soil.

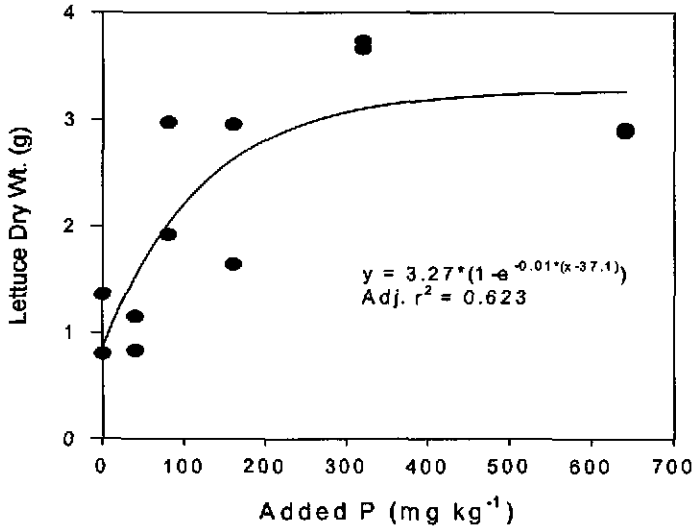


Fig. 5.12. Relationship of lettuce dry weight production as a function of added P when data from block 1 were removed from the calculation.

Maximum lettuce growth was also associated with high extractable P levels (Fig. 5.13). The Mitscherlich equation provided the best fit, and P_T explained slightly more of the variability in lettuce yield ($r^2 = 0.583$) than P_i ($r^2 = 0.548$). Based upon the estimates from the Mitscherlich equation, the yield plateau was reached at an

extractable P level equivalent to 207 mg kg^{-1}; a concentration that appears unreasonably high. Optimal lettuce yields were achieved with an Olsen P concentration of 80 to 115 mg kg^{-1} in an Australian sandy soil (McPharlin and Robertson, 1997), and 150 mg kg^{-1} in a sandy soil from the United Kingdom (Cleaver and Greenwood, 1975). In an early study on soils with different textures, Fox and Kamprath (1970) showed that the combination of a low P sorption capacity and sandy texture requires a higher P concentration in solution to maintain good plant growth.

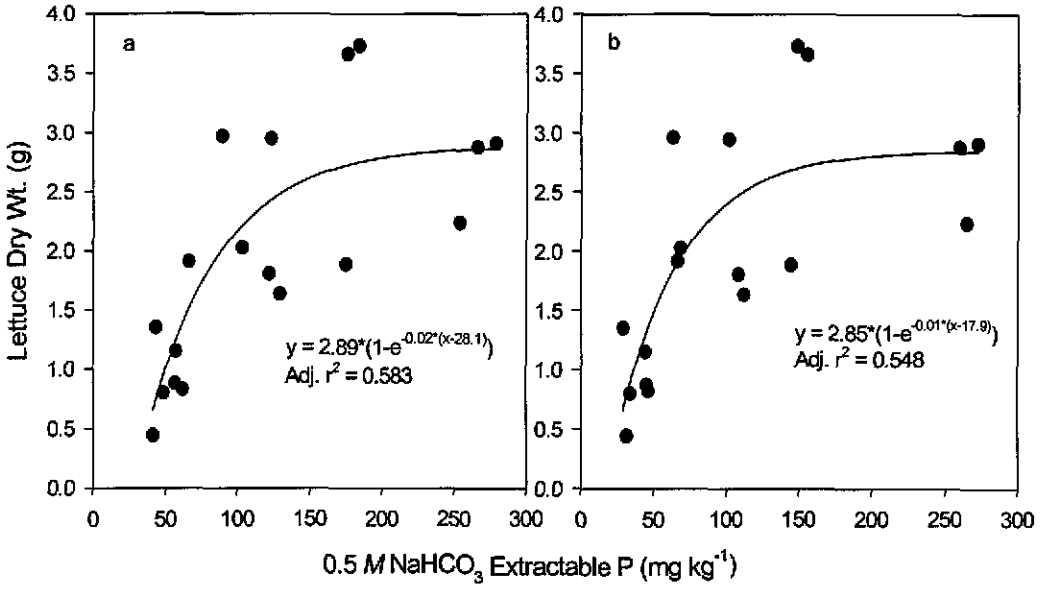


Fig. 5.13.Lettuce dry weight as a function extractable P_T (a) and P_i (b) for five-week old plants grown in a Majuro soil with increasing levels of added P.

A higher P concentration in solution is achieved by adding higher rates of P fertilizers. The high P demand of lettuce may also explain the high extractable P levels obtained in our study. The limited volume of soil in the pots and the tendency for roots to accumulate at the sides and bottom of the pots reduces P uptake and further increases the P requirement (Baker and Woodruff, 1961).

Phosphorus uptake by the lettuce plants showed a significant response to added P and extractable P ($P<0.001$; Fig. 5.14). The relationship was best explained by the Mitscherlich equation. Lettuce removal of P from the soil ranged from 1.58 mg kg^{-1} in the 0 P treatment to 11.2 mg kg^{-1} in the 320 mg P kg^{-1} treatment. Converted to a hectare basis for comparative purposes these uptake values correspond to 2.0 and

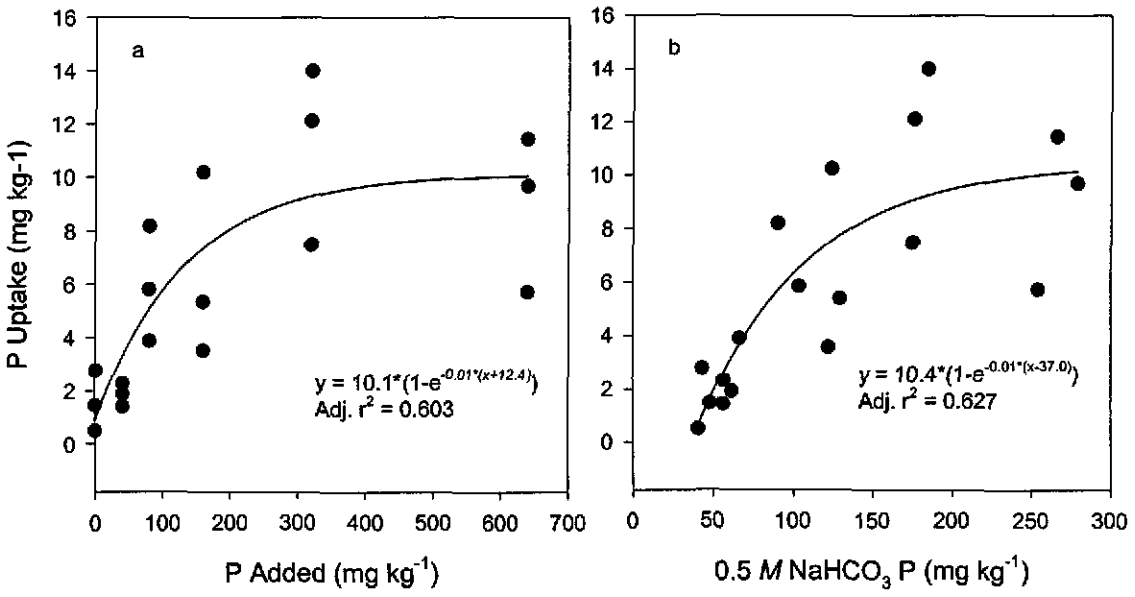


Fig. 5.14. Mitscherlich equation fitted to P uptake by lettuce plants and P added (a) and Olsen extractable P_T (b).

14.1 kg P ha^{-1} respectively for the Marshall Island soil. The P uptake in the Marshall Island soil was higher at the 0 P level compared with P uptake of 0.39 kg ha^{-1} by lettuce in an Australian sandy soil, but the lettuce plants supplied with P at 400 and 600 kg ha^{-1} took up twice as much P at 30 and 28 kg ha^{-1} respectively (Mcpharlin and Robertson, 1997). A plateau in P uptake was reached at a P addition rate of 320 mg kg^{-1} and an extractable P concentration of 172 mg kg^{-1} based on estimates from the

Mitscherlich equation. Phosphorus uptake reached a plateau in the Australian sand at similar P addition rates. In a Florida muck soil, P uptake by lettuce varied with variety, but showed similar ranges of P uptake to those observed in the present experiment (Nagata et al., 1992). Calculated values for the relative efficiency (RE) of P in this experiment are presented in Table 5.4. Based upon P applied, RE values ranged from 0.01 at the highest rate to 0.07 at 80 mg P kg^{-1}. These values are considerably lower than those obtained in the Australian sandy soil (McPharlin and Robertson, 1997) suggesting that added P was less available in the Marshall Island soil. Calculating RE based on P_T and P_i did not cause large changes.

Table 5.4. Calculated relative efficiency (RE) values for P based on P addition rate, extractable P_T, and P_i for lettuce plants grown in a Marshall Island soil.

Rate	Olsen Extractable P		P Uptake	Relative Efficiency (RE)		
	P_T	P_i		Rate†	P_T	P_i
	----------mg kg^{-1}----------					
0	44.4	31.4	1.57	NA	0.04	0.05
40	58.7	45.2	1.89	0.05	0.03	0.04
80	86.8	66.4	5.98	0.07	0.07	0.09
160	125	108	6.38	0.04	0.05	0.06
320	179	150	11.2	0.03	0.06	0.07
640	267	266	8.95	0.01	0.03	0.03

†RE = P Uptake/Rate, P Uptake/P_T, or P Uptake/P_i

Phosphorus concentration in the lettuce tissue showed a significant ($P<0.001$) linear relationship with dry matter production (Fig. 5.15). Tissue concentrations reached a maximum of about 0.4%, a concentration that fell within the lower end of critical range for lettuce grown in Australia (0.35-0.60%) (Piggott, 1986), or at the critical limit according to Jones et al. (1991). McPharlin et al. (1996) observed a lettuce yield plateau at tissue P concentrations of 0.6% while Smith and Scaife (1973)

showed a plateau in yield with tissue P levels at 0.5%. There was no indication of a plateau in lettuce yield as P concentration increased in the tissue in the Marshall Island soil. Examining the relationship of tissue P to extractable P (Fig. 5.16) showed that predicted tissue P concentration increased to 0.32% as extractable P increased to approximately 150 mg kg^{-1}, then showed little change as extractable P increased to near 300 mg kg^{-1}. The lack of a tissue P response at the higher soil P levels suggests that P accumulation was limited by some other factor. Response to P fertilizers depends on the nutrient status of the other plant nutrients in the soil. The response will be limited if any of the other nutrients are deficient (Black, 1993). In order to avoid nutrient limitations, the Marshall Island soil received a blanket solution of micronutrients, Mg, and S, and N and K were supplied on a weekly basis. The concentration of plant nutrients in the lettuce tops was generally within the critical range for adequate growth (Table 5.5). Calcium, Mn, and Cu levels appeared to be slightly below or at the low end of the minimum concentration, but plants did not exhibit any deficiency symptoms associated with these nutrients. Increasing tissue P concentration showed a tendency to reduce Zn levels in the lettuce tissue (Fig. 5.17), but this effect

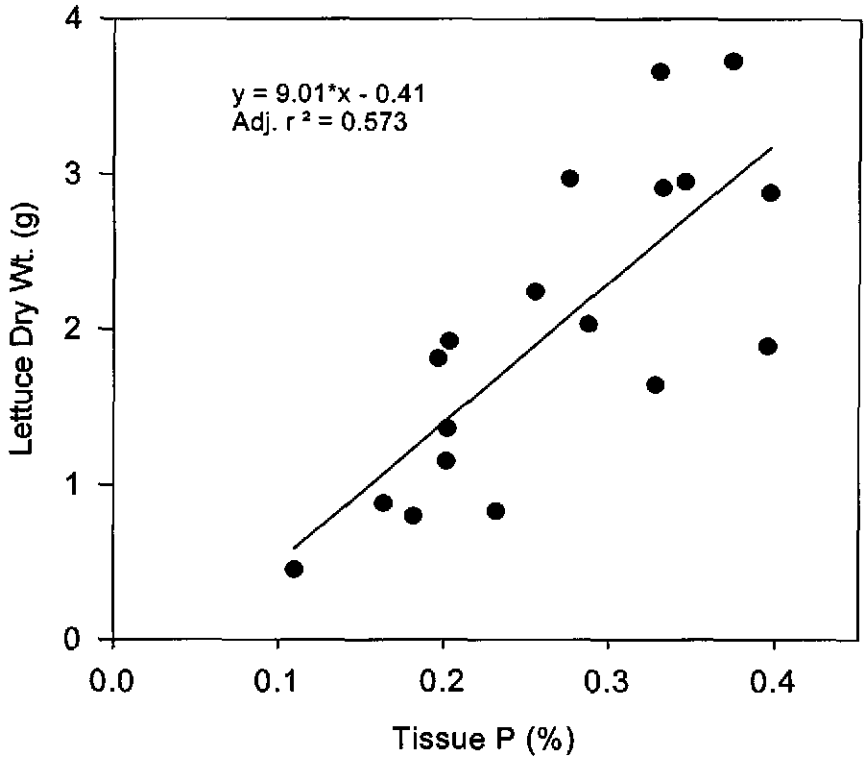


Fig. 5.15. The relationship between tissue P concentration and letuuce dry matter production.

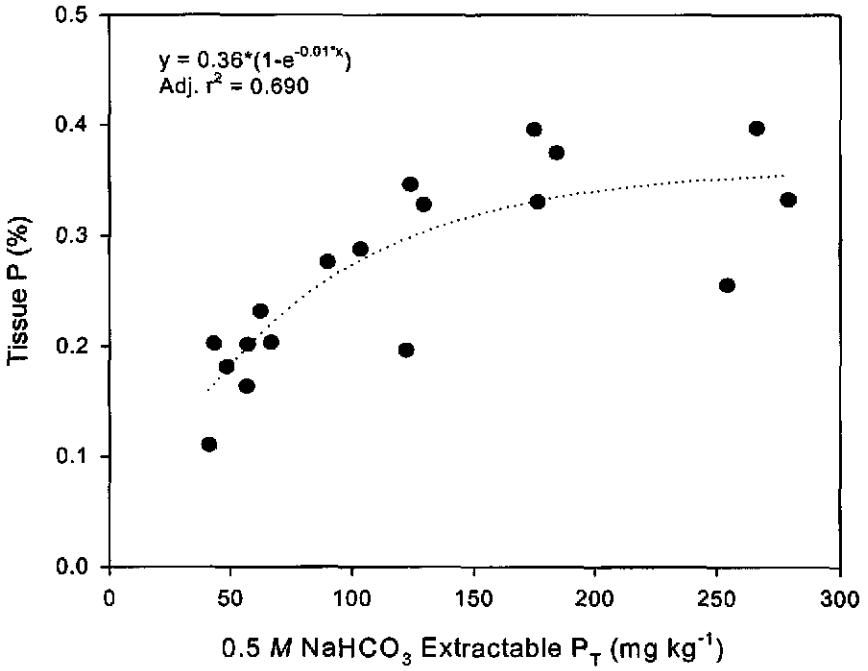


Fig. 5.16. The relationship between lettuce tissue P concentration and extractable P.

Table 5.5. Lettuce tissue concentrations with increasing rates of P in a Marshall Island soil.

P Rate	K	Ca	Mg	Fe	Mn	Zn	Cu	B
mg kg^{-1}		%				µg g^{-1}		
0	3.59	2.22	0.53	152	25.9	96.7	11.3	31.2
40	3.99	1.68	0.50	147	22.1	78.5	7.90	31.1
80	3.99	1.43	0.46	173	23.4	78.6	7.87	29.2
160	4.48	1.46	0.5	180	21.8	61.7	6.89	29
320	4.21	1.50	0.48	121	21.7	54.6	7.42	27.5
640	4.35	1.42	0.51	176	23.9	46.2	5.71	28.9
Critical Ranges[†]	4.0-7.5	1.5-2.3	0.36-0.5	50-200	25-150	25-150	7-25	23-50

[†] Source: Mills et al. (1991)

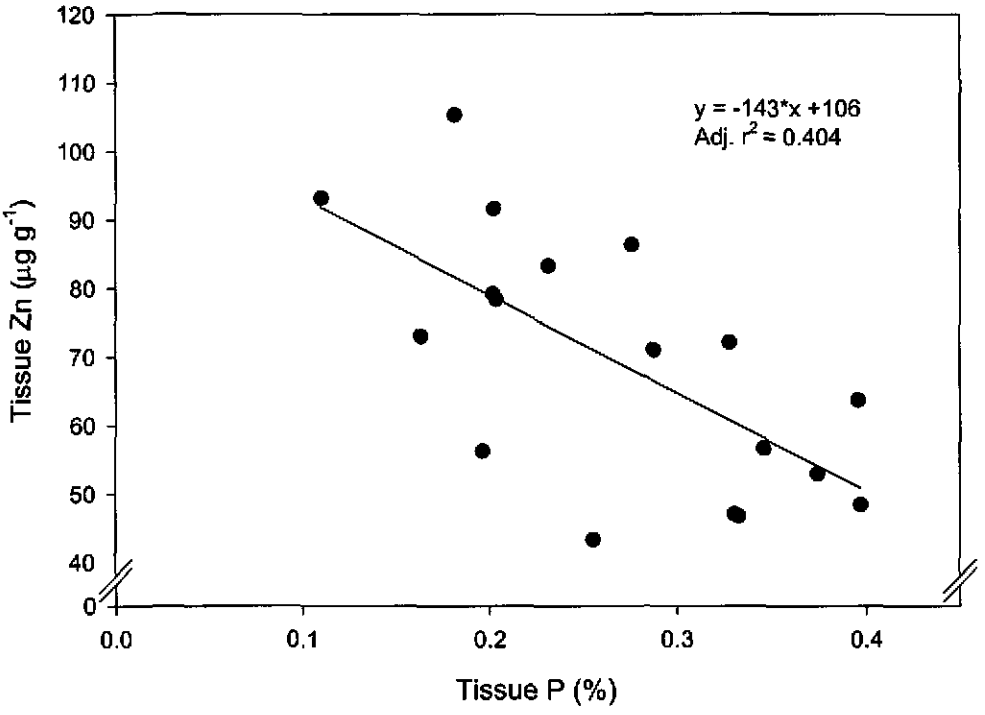


Fig. 5.17. The relationship of tissue P concentration with tissue Zn concentration in lettuce plants grown with increasing rates of P.

probably did not limit lettuce growth as the Zn tissue levels never dropped below the minimum concentration.

Conclusion

The P sorption capacity of the Marshall Island was low and similar to the carbonatic Entisols of the Everglades found in south Florida (Zhou and Li, 2001). The atoll soil exhibited low buffering capacity due probably to its very low clay content. Calcareous soils from North Africa (Amrani et al., 1999) and Pakistan (Mahmood-ul-Hassan et al., 1993) had considerably higher clay content and higher P buffering capacity than the Marshall Island soil. Because soils with a low buffering capacity cannot replenish soil solution P effectively as it is depleted by plant uptake, fertilizer requirements tend to be high (Fox and Kamprath, 1970; Black, 1993). This tendency has been observed with millet grown in a sandy North Carolina soil (Fox and Kamprath, 1970), lettuce in a sandy soil from Australia (Mcpharlin et al., 1996; McPharlin and Robertson, 1997), and a Histosol from Florida (Sanchez and Uehara, 1980).

Soil texture, mineralogy, and organic matter content all interact to influence the availability of P. We have discussed earlier how sandy soils with low buffering capacity tend to require higher external P concentrations to maintain good crop growth. Soil mineralogy is a key factor governing P sorption reactions in soils. The mineral fraction of the Marshall Island soil is comprised entirely of Ca-Mg carbonates. There is abundant evidence in the literature that shows that as $CaCO_3$ content of a soil increases so does its capacity to adsorb P given the same textural properties (Black, 1993; Fox and Kamprath, 1970). On the other hand, given the

same $CaCO_3$ content, P adsorption declines significantly from a clay soil to a sandy soil (Kamprath and Watson, 1980). Zhou and Li (2001) showed that sandy soils very high in $CaCO_3$ had low P sorption capacities, and most of the observed sorption was associated with the noncarbonate clay fraction. The same study reported P buffering capacities ranging from 6.2 to 16.4 for soils under vegetable cultivation. Clearly in this system, it is the texture that is controlling P sorption rather than the $CaCO_3$ content. We observed the same phenomena in the Marshall Island soil.

The soil organic matter content influences P status of soils in two important ways. First, in terms of P sorption reactions, organic matter in surface soils reduces P fixation by forming organo-metal complexes with crystalline and amorphous Fe-Al oxide minerals blocking potential P sorption sites on the mineral surfaces (Sanchez and Uehara, 1980). In the same way, organic compounds coating carbonate surfaces in calcareous soils inhibit P sorption reactions. The Marshall Island soil has a high organic C content, and the sand particles are coated black with organic compounds. We can assume that the organic coating on the carbonate surfaces reduced the P sorption capacity of this soil. Second, P in the organic fraction of soils can contribute significantly to the available P pool byway of mineralization reactions mediated by soil microorganisms. However, P can be also be immobilized in the soil biomass with a negative effect on plant available P. Because the Marshall Island soil exhibited no net N mineralization in a previous incubation study, we can expect that P from the organic fraction does not contribute significantly to plant available P.

Results from the greenhouse experiments evaluating the P requirement of Chinese cabbage, corn, and lettuce in the Marshall Island soil were variable, but indicated

much higher Olsen P levels were required for crop growth than reported in the literature. Chinese cabbage showed no response to increasing levels of P despite having a high internal P requirement. In a field experiment in Hawaii, Chinese cabbage showed less response to applied P than lettuce, and the authors attributed the difference to the cabbage having an inherent ability to extract P from the soil (Nishimoto et al., 1977). Corn showed a response to residual P, but growth did not achieve a maximum suggesting that the external P requirement had not been satisfied despite Olsen P concentrations as high as 75 mg kg^{-1}. This level of Olsen P is considered very high if compared with sufficiency levels for Olsen P for corn on the coarsely textured calcareous arid soils of Egypt where response to P was considered improbable above 17 mg P kg^{-1} (Amer, 1995).). Maize grown on a clayey calcareous Inceptisol with pH of 8.5 and low organic matter content showed similar dry matter accumulation and P uptake response to those observed by the maize grown on the Marshall Island soil, but at Olsen extractable P ranging from 2 to 42 mg kg^{-1}, considerably lower levels than in the Marshall Island soil (Chien et al., 1996). An even lower critical level of 10.5 mg P kg^{-1} was established in a greenhouse calibration study on some Tanzanian soils (Ussiri et al., 1998). The high P addition rate required to achieve a yield plateau in the lettuce crop was caused by the combination of the sandy texture and low P sorption capacity of the Marshall Island soil.

The results of this study provide important baseline information regarding P availability in the Marshall Island soil. Phosphorus sorption did not play a significant role in removing P from the available pool despite its high pH and $CaCO_3$ content. Despite high Olsen extractable P concentrations, corn and lettuce responded to P

fertilization. Yield response to P fertilization in the pot studies indicated that the P requirement for adequate crop growth in the Marshall Island soil varies with crop, but is considerably larger than most soils for corn and lettuce. Field experiments are required to adequately describe crop response to P, and to determine whether the Olsen extraction procedure is correlated with P uptake. Due to the sandy texture of these soils and apparent high P requirement, careful management of P fertilization will be necessary to maximize P uptake and minimize P losses to leaching.

Chapter Six

Summary and Conclusions

The ever-increasing dependency on imported food has had severe social and economic impacts on the people of the Marshall Islands. Revitalizing agriculture in the atolls to increase local food production has been problematic in many of the atoll countries of the Pacific for both socio-economic and environmental reasons (Thaman, 1992b; Pollock, 1995). The unique physical and chemical properties of atoll soils are not conducive to plant growth, and comprise the primary environmental constraint to good crop growth. With a good understanding of the physical and chemical properties of soil, appropriate management strategies can be developed to increase crop production. The present study has characterized the chemical properties of the Marshall Island soils, and provided a preliminary assessment of appropriate soil management strategies to improve crop production in an atoll environment.

The Marshall Island soils share many of the chemical characteristics of other low-lying atolls in the Pacific such as Kiribati. They are alkaline with a mean surface soil pH value of 7.8, which increases to 8.2 in the subsoil. Like neighboring Kiribati, exchangeable Ca levels are high, and K is extremely low. The range in organic C and total N levels are also similar between the two atoll nations. Mean concentration for Olsen P in the surface soils is also similar. Unlike previous research, the present study provided an assessment of the plant available pool of micronutrients. Contrary to the information in most papers on atoll soils, which states that the micronutrient status of these soils is low, the results of the DTPA soil test indicate that the

concentration of micronutrients in the Marshall Island soil is generally within the established sufficiency ranges. Soil Cu levels were the only micronutrient that appeared to be deficient. The north to south rainfall gradient did not affect the chemical properties significantly. Location within the island appeared to have a stronger influence on certain soil nutrient levels. Potassium concentrations were significantly lower along the ocean shoreline where the soils contain a higher percentage of coarse fragments compared with the center and lagoon areas.

The results of the missing element study provided a preliminary interpretation of the soil test results since these tests had never been calibrated to atoll soils. Corn dry weight response indicated the following nutrient deficiencies (in decreasing order of severity): K>S>N>P>Cu. Despite a soil chemical environment that inhibits micronutrient solubility, no significant effect was observed when Fe, Mn, B, and Zn were left out of the nutrient solution indicating that native levels of these elements were sufficient to maintain corn growth. However, micronutrient tissue concentrations favored the low end of the sufficiency range; a trend that indicates potential deficiency levels, and warrants future research to characterize micronutrient response. Phosphorus deficiency was severe in the Marshall Island soil despite a relatively high Olsen P soil test result.

The suitability of a soil test for predicting the nutrient status of a soil, probable response to fertilization, and nutrient supply capacity is generally evaluated by correlating the amount of nutrient extracted with various crop growth parameters (Kamprath and Watson, 1980). In the absence of such correlations, the value of a soil test is limited. The correlations are achieved by conducting field experiments to

measure crop response to increasing rates of fertilization. This can be an expensive and time consuming practice because soil tests are often crop and soil specific. In the Marshall Islands, however, where the soil is relatively uniform in chemical and mineralogical composition throughout the atolls, a well-planned research program selecting a small number of important vegetable crops and correlating crop response to standard soil tests can be done at one location, and the information can be applied to all the atolls. Developing such a database would be an invaluable guide to nutrient management for the Marshall Islands and the low-lying coralline atolls in general. The present study has begun the process by conducting soil tests on soils from all 25 inhabited atolls. The next step would involve a series of field studies to measure crop response to N, P, K, S, and the micronutrients.

The resource poor farmers inhabiting the isolated atolls of the Marshall Islands cannot rely on imported chemical fertilizers to correct the nutrient deficient soils. Traditional Micronesian agricultural systems relied on organic matter inputs to sustain a tree-based production system. Nitrogen supply is often first used to assess the suitability of an organic material as a fertilizer. In Chapter Three, we evaluated the N mineralization potential of four organic materials available in the Marshall Islands in a controlled incubation experiment. The N mineralization potential of *V. marina*, an indigenous leguminous vine, and fishmeal was higher than chicken manure and copra cake in a 27-week incubation study. Copra cake showed the lowest mineralization potential of the four materials.

Through a series of greenhouse experiments we showed that *V. marina* was as good a fertilizer material as the chemical control and chicken manure. It provided

adequate nutrient supply to correct previously identified soil N, P, K, S, and Cu deficiencies. Comparisons of Relative Growth Rate of the cabbage plants with Relative Accumulation Rate for the macronutrients showed that *V. marina*'s supplying capacity matched the plants nutrient demands. Fishmeal could not supply adequate amounts of K, and therefore its use as a stand-alone fertilizer is unadvisable. Copra cake improved cabbage growth compared with the soil alone, but it showed lower yield improvements than the control, *V. marina*, and chicken manure. Mixing copra cake with either chemical fertilizers or *V. marina* did not significantly improve crop growth. These results suggest that copra cake may not be a suitable fertilizer material in atoll soils. Adding fresh coconut leaves to the soil as a fertilizer material induced N deficiency and caused very poor crop growth.

The missing element study identified a soil P deficiency despite high Olsen extractable P. The last chapter explored P dynamics in the Marshall Island soil through a P sorption study and a series of pot studies evaluating crop response to P fertilization. The Marshall Island soil exhibited low P sorption capacity at soil solution P concentrations considered high in terms of plant P requirements. Chinese cabbage showed no response to increasing P rates. Corn, on the other hand, showed a response to increasing P in the soil. Lettuce required high rates of P to achieve a plateau of growth. The pot studies indicated that these sandy soils require significant P additions to correct their inherently low capacity to supply P to plants.

The present research has generated baseline data on the soil chemical properties of the Marshall Islands, a preliminary evaluation of some promising organic materials to correct soil nutrient deficiencies, and an initial characterization of plant P

requirements in an atoll soil. The enormous differences in growth dynamics obtained from plants grown in pots under a controlled environment in the greenhouse and plants grown in the field, preclude using the results from greenhouse work to recommend management practices directly to farmers. Nonetheless, the results from the greenhouse experiments described in this study have shown that there are clear advantages to using organic materials to increase crop growth. Specific recommendations regarding addition rates, placement of the amendment, and timing of application cannot be transferred directly to farmers because plant and soil interactions in pots are significantly different than conditions in the field. Rather, the results can be used to develop clear, logical hypotheses that can be tested with field trials in the Marshall Islands. The questions and hypotheses developed from this research need also be germane to the issues facing Marshall Island farmers specifically.

Future research in the Marshall Islands needs to address the needs of at least two types of farmers: the subsistence farmers inhabiting the isolated outer atolls, and the potential commercial vegetable farmers of Majuro and Arno. The farmers on the outer atolls are limited to using locally available resources because an inadequate transportation system and lack of finances combine to prohibit importing materials. Their primary focus is on producing food for local consumption. On the other hand, farmers on Majuro and Arno are close to the commercial center where there is a market for fresh vegetables and other food crops. These farmers can also access a wider range of fertilizer materials. Information generated by this study can be used to guide a research program for each category of farmer.

At present, farmers on the outer atolls have few options to correct the fertility problems that constrain crop growth. The results of this study show the beneficial effects of using *V. marina* as a fertilizer to increase crop growth. A number of questions remain unanswered: (i) What are the field responses to the rates tested in the pot study? (ii) Are these addition rates sustainable based upon the occurrence of the plant? (iii) Does splitting the application dose improve nutrient uptake efficiency and improve growth? (iv) What happens when stems are included in the amendment? Do the labor requirements offset potential yield improvements and discourage adoption? A carefully planned field experiment can provide the information to answer these important questions, and this information would form the basis of a recommendation for Marshall Island farmers.

Fish is still an important component of the diet for rural Marshall Islanders. Fish wastes are often discarded. This study showed that fish wastes are a significant source of N and P, but need to be supplemented with a material high in K in order to correct soil nutrient deficiencies for good crop growth. Processed fish emulsions are common organic fertilizers in the developed world, and composted fish wastes have been used to improve crop growth (Jellum et al., 1995). Adding fresh fish waste to soil may not be a suitable practice due to the production of foul odors and attraction of unwanted pests and pathogens as the material decomposes. Composting discarded fish wastes with household wastes or with organic materials around the household offers a nutrient rich fertilizer material to overcome soil nutrient deficiencies and increase crop production. Composting initiatives have not been adopted in the Marshall Islands presumably because it is time consuming and labor intensive. With

fish waste, which is rich in N, the composting process may be accelerated. Farmers on the atolls would benefit from a research project testing a variety of composting methodologies to identify the most rapid and efficient process coupled with a field trial assessing the nutrient supply capacity of the material.

Farmers located on Majuro have easy access to a large commercial market for fresh vegetables. The Taiwanese government runs a vegetable farm in Laura Village one hour from the commercial center of Majuro. The farm produces a variety of vegetables that are sold in Majuro town. A mixture of chicken manure, fishmeal, and copra cake is tilled into the soil prior to planting. Once the crop has established, NPK and micronutrients are added as a top dressing. The farm has also initiated an outreach program assisting local farmers with commercial vegetable production. The site offers a unique opportunity to conduct field experiments to develop fertilizer recommendations for atoll soils. The extension service of the College of the Marshall Islands has its field office three miles away where they are in the process of re-building their facility. In partnership, the two organizations could initiate an agricultural research program and obtain funding to acquire basic laboratory equipment for soil and plant analysis. This type of collaboration could have long-term impacts on agricultural development in the Pacific.

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