

Chemical properties of atoll soils in the Marshall Islands and constraints to crop production

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Abstract

The sandy carbonatic soils of Pacific atolls are considered infertile and poorly suited to agriculture. The Republic of the Marshall Islands is comprised predominantly of atolls, and there is scant information on the fertility status of the Marshall Island soils. We conducted a survey of the soils to quantify chemical properties and determine significant trends related to soil distribution and climate. A total of 116 surface (0–15 cm) soil samples from 13 atolls and 42 subsoil (15–45 cm) samples from five of the atolls were analyzed for pH, electrical conductivity (EC), organic carbon (OC), total nitrogen (TN), cation exchange capacity (CEC), and nutrient levels. A missing element study in the greenhouse on a typical soil from Majuro Atoll was conducted to rank soil nutrient deficiencies. There were some strong differences in soil chemical properties between the two depths, but not necessarily between the two soil series constituting the sampled soils. Soil chemical properties were not affected by a strong rainfall gradient running from the southern (≈ 4000 mm) to the northern (≈ 1350 mm) atolls, but human activity had a significant effect on some properties. Soils located near the center of islands tend to show higher concentrations of OC than soils located along the ocean exposed shoreline. The missing element study indicated that the soil was deficient in Cu, P, N, S, and K. Potassium was the most serious nutrient constraint whereas the micronutrients Fe, Mn, Zn, and B did not limit maize growth significantly in a greenhouse pot experiment. Interpreting soil test data on atoll soils, however, remains difficult for two reasons: (i) the soil tests have not been calibrated with crop growth, and (ii) standard soil tests may not be applicable to the unique physical and chemical properties of atoll soils.

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1. Introduction

The Republic of the Marshall Islands, a remote archipelago comprised of 34 low-lying coral atolls and islands in the central Pacific Ocean, is struggling with food security issues. Rapid population growth combined with the demise of traditional agriculture since the end of World War II have left the small island nation largely dependent on imported

processed food (Sommers, 1987; Rapaport, 1990). This dependency on processed food is a significant factor contributing to declining health associated with the rise of chronic diseases like hypertension and diabetes (Schoeffel, 1992; Finney and Laukon, 1993). The government has made increasing local food production a top priority. However, several factors interact to constrain food production opportunities in the Marshall Islands. First, the Marshall Islands has a limited land area of only 181 km². The lack of water also poses a serious threat to crop production especially in the northern atolls where drought conditions prevail between December and May. One of the most serious

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constraints to good crop growth is the general infertility of atoll soils (Morrison, 1992; Stone et al., 2000). Atoll soils are considered poorly suited to intensive agriculture (Stone, 1951; Fosberg, 1954; Caiger, 1987; Finlay, 1987a; Laird, 1989; Morrison, 1990; Stone et al., 2000). Their extremely sandy texture promotes rapid drainage, low water holding capacity, and little cation exchange capacity.

The chemical properties of atoll soils have not been studied in much detail. Existing research has shown that these soils are deficient in N (Finlay, 1987b; Reddy and Chase, 1992) and exchangeable K (Bruce, 1972; Finlay, 1987a; Reddy and Chase, 1992; Gangaiya and Morrison, 1998), and that rapid drainage and low CEC demand that fertilizers be added in small frequent doses. The high soil pH resulting from the carbonate mineralogy predicts that P and micronutrient solubility in atoll soils should be very low (Morrison, 1992). However, few studies have confirmed P and micronutrient availability in atoll soils. High total soil P levels have been measured in some atoll soils and attributed to accumulation of guano from birds (Fosberg, 1954). A survey of chemical properties of soils on Tuvalu, an atoll country in the South Pacific found that Olsen extractable P concentration in the surface soil averaged 26.2 mg kg^{-1} (Caiger, 1987), but because this level was not compared with crop growth and yield, it is difficult to interpret.

The United States Department of Agriculture conducted a soil survey on five atolls in the Marshall Islands and identified two soil series (Laird, 1989). The Majuro series (Sandy–skeletal, carbonatic, isohyperthermic Typic Troporthents) occurs predominantly along the ocean side of the atolls. Its texture ranges from a cobbly, loamy sand to an extremely cobbly sand with 35–50% coarse fragments > 8 cm. The second, the Ngedebus series (Carbonatic, isohyperthermic Typic Ustipsamments) is found primarily in the interior and along the lagoon beaches of the atolls. Its texture ranges from a loamy sand to a very gravelly loamy sand with 0–25% coarse fragments > 8 cm. The Ngedebus series occupies approximately 64% of the area while the Majuro series comprises the remaining 36% of the area. According to the soil survey, surface soil pH was similar in both soil series ranging from 6.6 to 8.4. Subsoil pH in the Majuro series was similar to the surface soil, but the Ngedebus series showed higher pH values ranging from 7.4 to 9.0 (Laird, 1989). A pair of studies conducted fifty years ago investigated soil chemical properties on Arno Atoll (Stone, 1951) and the phosphate rich soils of Kwajalein, Bikar, and Jemo Atolls (Fosberg, 1954), but total nutrient analysis was determined and the data are difficult to interpret for fertility purposes because the soil test values have not been calibrated with crop growth.

Good crop production depends largely on nutrient availability in the soil. Where nutrients occur at sub-optimal levels, management strategies are required to increase nutrient availability. One of the first steps in developing a nutrient management strategy is to characterize the chemical properties of the soil and identify potential fertility constraints to crop production. The chemical properties of the Marshall Island soils have not been well characterized. The present work was conducted to characterize the chemical properties, identify any significant trends in soil chemical properties related to soil distribution and climate, and to assess the fertility status of the soils of the Marshall Islands.

2. Materials and methods

2.1. Study area

The Marshall Islands comprise 29 low-lying coral atolls and five islands spread out over 2.1 million km^2 of the central Pacific Ocean. 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 m above sea level where 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 1000 m long and 500 m wide (Wiens, 1962). The total land area of the Marshall Islands is 181 km^2 .

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 (Wiens, 1962). Precipitation in the southern atolls averages threefold higher than in the northern atolls. On Enewetok atoll in the north-west, rainfall averages about 1440 mm annually (SRDC, 2005) increasing to 2540 mm on centrally located Kwajalein (3D Research Corporation, 2005). The southern Marshalls are considerably wetter with annual precipitation on Majuro averaging 3300 mm (Marshall Islands Statistics, 2005). 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 during the winter and

spring months (Fig. 1). The atolls in the south, on the other hand, enjoy a moist climate throughout the year under normal conditions. However, drought conditions can occur on even the wettest atolls.

Large distances between the atolls, unreliable transportation, and government access restrictions prohibited sampling on all the atolls. Nevertheless, two technicians from the College of the Marshall Islands were able to travel to and collect soil samples from 12 atolls (Table 1). Six of the 12 atolls are in the Ratak Chain (eastern) covering most of the north-south distribution, and the remaining six are in the Railik Chain (western) concentrated mainly in the southern and central portion of the distribution. Access to the northern most atolls in the Railik Chain (i.e. Bikini, Enewetok, and Rongelap) is restricted due to residual radioactive contamination from atomic bomb testing in the 1940s–1960s.

2.2. Soil sampling, sample preparation and chemical analyses

A total of 116 surface (0–15 cm) soil samples were collected from the organic rich A horizon on 13 atolls. Forty-two subsoil (15–45 cm) samples were collected from 5 of the atolls (Table 1). Sampling was conducted on the main island of each of the atolls in a zig-zag pattern at nine locations (except Likiep where eight samples were collected). Samples were labeled Ngedebus or Majuro corresponding to the two soil series. Ngedebus samples were associated with the interior sections and areas along the lagoon shoreline, and Majuro samples were associated with the ocean side of the islands. Ninety-one or 78% of the samples represented the Ngedebus series and 25 or 22% of the samples came from the Majuro series. In addition, samples were categorized as forested (unmana-

Table 1

Name, geographic location, land area, and population of the 13 atolls where soil samples were collected

Atoll	Latitude/ longitude	Chain	Land area km ²	Population ^a
Ailuk	10°13' 169°59'	Ratak	5.4	617
Ailinglaplap	7°16' 168°33'	Railik	14.7	2168
Arno	6°58' 171°33'	Ratak	13.0	2093
Majuro ^b	7°09' 171°12'	Ratak	9.7	27,776
Bikirin				
Laura				
Ebon	4°34' 168°38'	Railik	5.8	937
Jabat	7°44' 168°58'	Railik	0.6	142
Jaluit	5°47' 169°24'	Railik	11.3	2160
Kili	5°37' 169°7'	Railik	0.9	761
Likiep	9°48' 168°58'	Ratak	10.3	609
Mili	5°53' 171°42'	Ratak	15.9	1079
Mejit	10°16' 170°52'	Ratak	1.9	562
Namdrik	5°35' 108°5'	Railik	2.8	1029

^a Source: Asian Development Bank (1997).

^b Two locations on Majuro were sampled: Bikirin, a small uninhabited islet on the eastern side of the lagoon and Laura, a farming area on the northern–western tip of the lagoon.

ged native or coconut forest land) or farm (lands where human activity was apparent, i.e. gardens or lands adjacent to houses). Eight samples were collected from traditional taro pits. A subsequent sampling was conducted on Arno Atoll comprising six surface samples along three separate transects traversing uninhabited, forested lands on the main island from the ocean shoreline to the lagoon shoreline to identify the existence of specific trends in soil chemical properties.

The samples were packaged in airtight plastic containers on-site, and sent by airplane to the Agricultural Diagnostics Service Center (ADSC) at the University of Hawaii for laboratory analysis. The samples were air

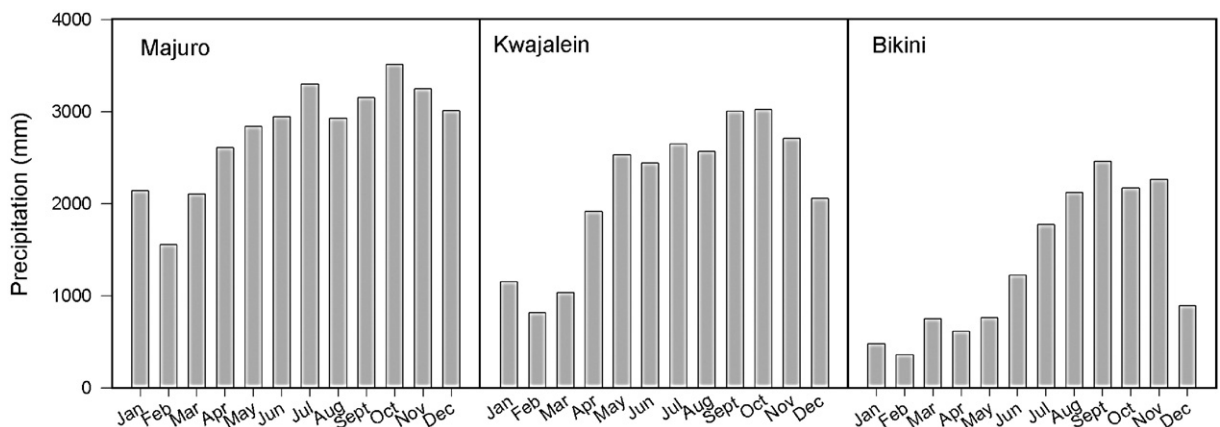


Fig. 1. Mean monthly precipitation for three atolls in the Marshall Islands illustrating the decreasing rainfall gradient from south (Majuro) to north (Bikini). (Sources: Gouveia et al., 2002; Horel, 2005).

dried and screened through a 2 mm stainless steel sieve. All samples were analyzed according to procedures developed by the ADSC to enable fertility interpretations (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 min and filtering. Soil P was determined by the Olsen P method (Kuo, 1996). Phosphorus in the filtered extract was determined by Inductive Coupled Plasma (ICP) on a Thermo Jarrell Ash, Atomscan 16 instrument. Total N was determined by Kjeldahl distillation (Bremner, 1996), and OC by a revised Walkley Black method (Heanes, 1984). Exchangeable cations (K^+ , Mg^{2+} , Ca^{2+} , 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 Lindsay and Norvell (1978). Cation exchange capacity (CEC) was determined on selected samples by the leaching method where the saturating solution consisted of a 0.4 M $NaOAc-0.1$ M $NaCl$ solution adjusted to pH 8.2 and the extracting solution was 0.5 M $MgNO_3$ to reduce Ca dissolution from the $CaCO_3$ rich parent material (Sumner and Miller, 1996). Particle-size analysis was determined by the pipette method with no additional pretreatment other than dispersion with $(NaPO_3)_6$ (Day, 1965).

2.3. Missing element study

A missing element study was conducted in the greenhouse using a surface soil from the Ngedebus series collected from Laura village on Majuro Atoll to help interpret results of the soil test in terms of nutrient availability. Soil chemical properties were determined according to the methods presented above and were as follows: pH (7.8), OC (69.9 g kg^{-1}), total N (5.2 g kg^{-1}), P (50.0 mg kg^{-1}), K (0.0 mg kg^{-1}), Ca (9455 mg kg^{-1}), Mg (221 mg kg^{-1}), SO_4-S (6.7 mg kg^{-1}), B (0.4 mg kg^{-1}), Fe (27.7 mg kg^{-1}), Mn (7.4 mg kg^{-1}), Cu (0.1 mg kg^{-1}), and Zn (3.4 mg kg^{-1}). Treatments and nutrient rates are outlined in Table 2. Nitrogen and K were added in solution form at a rate of 25 mg kg^{-1} N and K bi-weekly during the pot study for a total equivalent to 200 mg N and K kg^{-1} . The remaining elements were added separately in solution at the outset of the experiment and mixed thoroughly with 2.5 kg of soil (1.79 kg oven dry basis). Deionized water was

added to achieve approximate field capacity, and six maize (*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 maize was thinned to two uniform plants per pot seven days after planting. The maize plants were harvested 4 weeks after planting, weighed for fresh weights, dried at 70°C for 72 h, and weighed again 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, OC, and extractable P, K, Ca, Mg, B, Fe, Mn, Cu, and Zn according to the procedures outlined above.

2.4. Statistical analyses

Statistical analyses including descriptive statistics, *t*-tests, and analysis of variance (ANOVA) on soil chemical properties and dry weights from the missing element study

Table 2

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

Treatment	Description	Application rate	
		mg kg^{-1}	kg ha^{-1} ^a
Check	No nutrients applied		
Control	All nutrients applied (N, P, K, Mg, S, B, Cu, Fe, Mn, Zn)		
-N	Control without N		
-P	"P		
-K	"K		
-Mg	"Mg		
-S	"S		
-B	"B		
-Cu	"Cu		
-Fe	"Fe		
-Mn	"Mn		
-Zn	"Zn		
Nutrient	Form of nutrient	mg kg^{-1}	kg ha^{-1} ^a
N	NH_4NO_3	200	400
P	H_3PO_4	20	40
K	KCl	200	400
Mg	$MgCl_2$	35	70
S	H_2SO_4	10	20
B	$Na_2B_4O_7$	1	2
Cu	CuCl	5	10
Fe	FeEDDHA	10	20
Mn	$MnCl_2$	10	20
Zn	$ZnCl_2$	10	20

^a Conversion from mg kg^{-1} to kg ha^{-1} assumes bulk density of 1.3 mg m^{-3} (Laird, 1989) and depth of 15 cm.

were generated using SAS Analyst (SAS Institute, 1999). Soils collected from traditional taro pits were not included in analyses to investigate effects of soil type, location, and rainfall on soil chemical properties. Linear regression using Proc Reg in SAS was performed to test the effect of the north–south rainfall gradient on soil chemical properties. Because rainfall data does not exist for most of the individual atolls, we used latitude as proxy variable for rainfall. Using mean annual rainfall data (Spoehr, 1949; Wiens, 1962; Raynor, 1992) for Enewetok (1350 mm), Kwajalein (2700 mm), Majuro (3500 mm), and Jaluit (4100 mm) we conducted regression analysis with latitude as the independent variable and we found that latitude accounted for 98% of the variation in rainfall.

3. Results and discussion

3.1. Soil chemical properties

Results for the chemical properties of the soil samples collected from the 12 atolls are summarized in Table 3. The data are arranged to reflect the mean value of the different chemical determinations by depth and by soil series. Soil pH in the surface and subsoil was high in both soils with a significantly ($P < 0.05$) higher pH values in the subsoil. Lower pH values in the surface soil reflect the influence of the high organic matter content in the surface. Despite proximity to the ocean and the ubiquitous occurrence of salt laden sea spray, EC was relatively low in both soils at both depths due primarily to high infiltration and leaching rates that transport salts rapidly through the soil profile. The low values for EC indicate that soluble salt concentration in the soil profiles is low. The results for pH and EC are similar to those reported for soils of Tarawa (Morrison, 1990), Tuvalu (Caiger, 1987),

and Palmerston and Manue Islands in the Cook Islands (Bruce, 1972). There were four samples with pH values below 7.0, three of which were sampled from traditional taro pits where organic matter was very high. These three samples also showed EC values above 4.0 dS m^{-1} suggesting saltwater intrusion into the excavated pits. Our results show a similar range in pH to those reported for Arno Atoll (Stone, 1951) and Rongelap (Gessel and Walker, 1992).

Organic C contents of the surface soils were higher than the subsoil with larger differences observed in the Majuro series. Measured differences in OC in the surface and subsoil for the Majuro soils were significant ($P < 0.05$), but not for the Ngedebus soils. The occurrence of higher subsoil OC concentrations in the Ngedebus series is likely due the smaller proportion of coarse fragments than in the Majuro soil and the influence of denser vegetation towards the center of the islands promoting the accumulation of organic matter to lower depths. Surface soil OC concentrations varied from 11.0 to 490 g kg^{-1} with a median value of 44.2 g kg^{-1} . Ninety percent of the samples showed values between 11.0 and 90.0 g kg^{-1} . The three samples showing OC concentrations in excess of 300 g kg^{-1} were collected from traditional taro pits where the soil had been enriched with organic matter over many years. Mean OC concentrations (excluding soils from the taro pits) in the Ngedebus and Majuro soils are approximately 2 and 1 g kg^{-1} , respectively, greater than the concentrations recorded for the surface horizon of the Tuvalu soils (mean = 35.9 g kg^{-1}). Almost 40% of the Marshall Island soils show OC levels greater than 50 g kg^{-1} . The higher levels of organic matter in the Marshall Island soils compared with other atoll soils (Hammond, 1969; Caiger, 1987; Morrison, 1990) is likely the effect of a wetter climate that promotes and sustains denser vegetation.

Table 3

Mean values and results of *t*-test comparing depths for selected chemical properties of the Ngedebus and Majuro soil series at two depths

Soil	Depth cm	pH	EC dS m^{-1}	OC g kg^{-1}	TN	P ^a mg kg^{-1}	K ^b $\text{cmol}_c \text{ kg}^{-1}$	Ca	Mg	Na
Ngedebus	0–15	7.9	0.8ns ^c	58.3ns	4.40ns	34.7	0.13ns	30.8ns	3.05ns	0.20
	15–45	8.2	0.8	41.1	3.07	16.2	0.08	29.7	3.00	0.36
Majuro	0–15	7.8	0.8	46.9	4.25	28.5ns	0.12	29.1	3.25	0.25ns
	15–45	8.2	0.4	10.8	1.35	18.3	0.02	23.3	2.04	0.15
						B	Mn	Fe mg kg^{-1}	Cu	Zn
Ngedebus	0–15					0.6ns	2.9	11.8	1.5ns	22.1ns
	15–45					0.4	1.1	4.4	0.8	19.2
Majuro	0–15					0.6	3.2	11.4ns	2.9ns	27.6ns
	15–45					0.3	0.8	0.6	0.1	0.4

^a Olsen extractable.

^b Exchangeable cations.

^c No significant difference between depths at $P < 0.05$, pairs with no markings are significantly different ($P < 0.05$).

Total soil N concentrations followed a similar pattern to OC with significantly higher values in the surface soils for the Majuro soils, but no difference in the Ngedebus soils. The range in the surface soils varied from 1.0 to 38.6 g kg⁻¹ with approximately 90% of the samples having N levels less than 7.0 g kg⁻¹. Similar to OC, the range in total N was considerably wider than the 2.0–6.5 g kg⁻¹ reported for the soils of Tuvalu (Caiger, 1987). The samples showing very high N levels (>10 g kg⁻¹) were obtained from the organic enriched soils from the traditional taro pits. Carbon:nitrogen (C:N) ratio varied from 7.6 to 34.1 in the surface soils with 20 samples (17%) showing C:N ratio greater than 15. The high C:N showed no clear relationship to soil type, management, or rainfall.

Olsen extractable P concentrations were relatively high at both depths and in both soils, with a significant difference in the Ngedebus surface soils compared to the subsoil. There was a wide range of extractable P concentrations for both surface soils with a few very high values that inflated the mean; the median concentration was 23.0 mg kg⁻¹ for the Ngedebus soil and 21.0 mg kg⁻¹ for the Majuro series. Three of the samples with very high P concentrations were associated with the taro pits indicating the effect of management. Caiger (1987) obtained similar results for Olsen extractable P for the surface soils of Tuvalu. Based upon current fertility recommendations that use a critical P concentration of 10 mg kg⁻¹ to separate P deficient soils (Kuo, 1996), a median value of 23 mg kg⁻¹ Olsen extractable P does not suggest a P deficiency. Using the current critical level, only 15 out of the 116 surface soils sampled would fall in the deficient category. These findings appear to contradict the expectation that extractable P would be low in calcareous soils with high pH. The higher than expected P concentrations may be associated with the high levels of organic matter, but there was no correlation between OC levels and extractable P.

As expected in soils dominated by coral sand, Ca²⁺ concentration was high in both soils at both depths with the surface soils showing slightly higher concentrations. Approximately 90% of the exchange complex is dominated by Ca²⁺ at both depths for the two soils. The significantly lower Ca²⁺ concentrations observed in the Majuro subsoil compared to the surface soil is likely associated with the lower OC contents of the subsoil. Soil Mg levels showed no difference between the surface and subsoils of the Ngedebus series, but significantly lower concentrations in the subsoil of the Majuro soils compared with the surface soils. The very low concentrations of exchangeable K in both soils stand out as a major constraint to crop growth. Low K concentrations appear to be characteristic of atoll soils (Caiger, 1987; Reddy and

Chase, 1992; Gangaiya and Morrison, 1998) due primarily to the low K content of coral parent material, the predominance of Ca²⁺, and exacerbated by the coarse texture of the soils which promote rapid leaching of K. Ngedebus subsoil Na levels were higher than in the surface soils, but showed the opposite trend in the Majuro soils. Electrical conductivity values were generally low in the surface soils with low concentrations of soluble salts. Similar results for cation concentration and distribution were reported for the soils of Tuvalu (Caiger, 1987) and Tarawa (Morrison, 1992).

We evaluated micronutrient (Fe, Mn, Cu, and Zn) availability with the DTPA soil test (Lindsay and Norvell, 1978), which was developed for calcareous soils. Extractable Fe, Mn, Cu, and Zn were consistently higher in the surface horizon for both soils with significant differences for Mn and Fe in the Ngedebus soil and Mn in the Majuro soil. Several high values tended to produce a skewed distribution of the data inflating the mean (Fig. 3). Median concentrations for Mn, Fe, Cu, and Zn in the surface soils were 2.5, 6.7, 0.2, and 4.3 mg kg⁻¹, respectively. The high concentrations for these nutrients were usually associated with samples collected from farmed areas. Extractable B concentrations were higher in the surface layer for both soils, and the occurrence of several high values in the surface layer tended to inflate the mean; median B concentration in the surface was 0.5 mg kg⁻¹. It is difficult to make fertility interpretations from these numbers alone for two reasons: first, there is no basis for comparison with previous work assessing micronutrient status of atoll soils because they measured the total micronutrient content of the soil with strongly acid extractants rather than the plant available fraction (Stone, 1951, Caiger, 1987); and second, the DTPA soil test was developed for calcareous clay soils and have not been calibrated for the sandy soils of atolls. Comparisons, however, with current ranges in critical levels (Sims and Johnson, 1991) for Mn (1.0–5.0 mg kg⁻¹), Fe (2.5 mg kg⁻¹), Cu (0.1–2.5 mg kg⁻¹), Zn (0.2–2.0 mg kg⁻¹), and B (0.1–2.0 mg kg⁻¹) reveal, surprisingly, that median micronutrient concentrations in Marshall Island surface soils fall within or above the established ranges. These findings disagree with the widely held opinion that atoll soils are deficient in micronutrients (Morrison, 1992; Widdowson and Trangmar, 1992).

The Ngedebus and Majuro soils were classified as two distinct series primarily because of measured differences in % coarse fragments (Laird, 1989). We compared both soil types to determine whether differences in particle size distribution influenced the chemical properties of the surface horizon. A *t*-test was performed on the soils located under native forest showing minimal human activity. The

Table 4

Results of *t*-test comparisons of chemical properties for Ngedebus and Majuro surface soils under forest vegetation and Ngedebus soils under forest vegetation and farm management

Property	Units	Ngedebus (<i>n</i> =69)	Majuro (<i>n</i> =20)	<i>P</i> value	Ngedebus		<i>P</i> value
					Forested (<i>n</i> =69)	Farm (<i>n</i> =15)	
pH		7.9	7.8	0.29	7.9	7.9	0.46
EC	dS m ⁻¹	0.8	0.8	0.43	0.66	0.7	0.32
Org. C	g kg ⁻¹	61.6	48.9	0.11	61.6	43.4	0.03
Total N		4.50	4.41	0.44	4.50	3.90	0.14
P	mg kg ⁻¹	33.5	31.1	0.33	33.5	40.3	0.22
K		53.7	41.0	0.18	53.7	32.9	0.05
Ca		6185	5790	0.08	6185	6005	0.26
Mg		404	375	0.68	404	329	0.23
Na		70.4	84.3	0.83	70.4	59.2	0.23
B		0.6	0.7	0.69	0.6	0.6	0.94
Mn		3.0	3.4	0.77	3.0	2.7	0.35
Fe		10.5	8.5	0.30	10.5	17.8	0.07
Cu		1.1	0.3	0.02	1.1	3.1	0.09
Zn		15.5	6.0	0.03	15.5	52.4	0.08

results of the *t*-test indicated that the Ngedebus soils were generally richer in soil nutrients compared to the Majuro soils, but the differences were not statistically significant except in the cases of Cu and Zn which showed significantly higher concentrations in the Ngedebus soils (Table 4). The higher concentrations of Zn in the Ngedebus soils may be related to higher organic matter content in these soils, which increases Zn solubility. For Cu, the explanation is less apparent since organic matter tends to depress Cu availability in soils. The relatively large difference in OC between the two soil types (12.7 g kg⁻¹ greater in the Ngedebus series) may not be statistically significant, but ($P < 0.05$), but a *P* value of 0.11 indicates that 89% of the time you would expect OC levels to be higher in the Ngedebus soils. The tendency to show a difference is important since organic matter plays such a critical role in these sandy soils. On Arno Atoll, where an additional sampling occurred along three transects crossing the island from the ocean shoreline to the lagoon shoreline, most of the soil chemical properties varied only slightly depending on relative location (Table 5), but OC concentrations were significantly higher in the center of the island (Ngedebus soils) compared with the samples collected along the ocean coastline (Majuro soils). Similar trends showing organic matter accumulation in the center of islands covered with native vegetation were reported for Arno Atoll (Stone, 1951) and Rongelap Atoll in the northern Marshalls (Gessel and Walker, 1992). Both these studies showed that soils close to the ocean shoreline tended to have lower organic matter contents. The tendency for lower OC levels in the soils along the ocean side of the islands is likely associated with the reduction in vegetation density and growth due to the negative impacts of salt spray.

Some of the sampling sites occurred on lands that had been disturbed by human activity. We conducted a separate *t*-test to evaluate whether human activity has had an effect on the chemical properties of the Ngedebus soils (Table 4). Human activity appears to have had an effect on soil chemical properties. OC and total N levels in the altered soils were lower than in the forest soils; the slight decrease reflecting the effect of removing the native vegetation. Differences in soil P and soil cations were small, but much larger differences were measured in the case of the micro-nutrients. Significantly higher concentrations for Fe, Cu and Zn were measured in soils associated with human activity. The higher metal content in the human affected soils is most likely caused by the common practice of

Table 5

Results of ANOVA showing the effect of within island location on soil nutrient concentrations for the three transects collected on Arno Atoll ($N=12$). Values represent a mean of the three transects

Determination	Units	Location			<i>P</i> value
		Lagoon	Center	Ocean	
pH		7.97	7.85	7.93	0.33
EC	dS m ⁻¹	0.31	0.30	0.29	0.95
Org. C	g kg ⁻¹	39.2	58.0	28.9	0.03
N		3.97	5.33	4.13	0.32
P	mg kg ⁻¹	15.7	34.3	35.5	0.20
K		31.6	32.5	12.2	0.08
Ca		6575	7323	7203	0.54
Mg		285	164	258	0.003
B	μg g ⁻¹	0.37	0.29	0.28	0.38
Fe		2.10	8.78	13.4	0.35
Mn		3.75	6.82	3.68	0.17
Cu		0.03	0.07	0.17	0.34
Zn		0.66	0.41	13.2	0.28

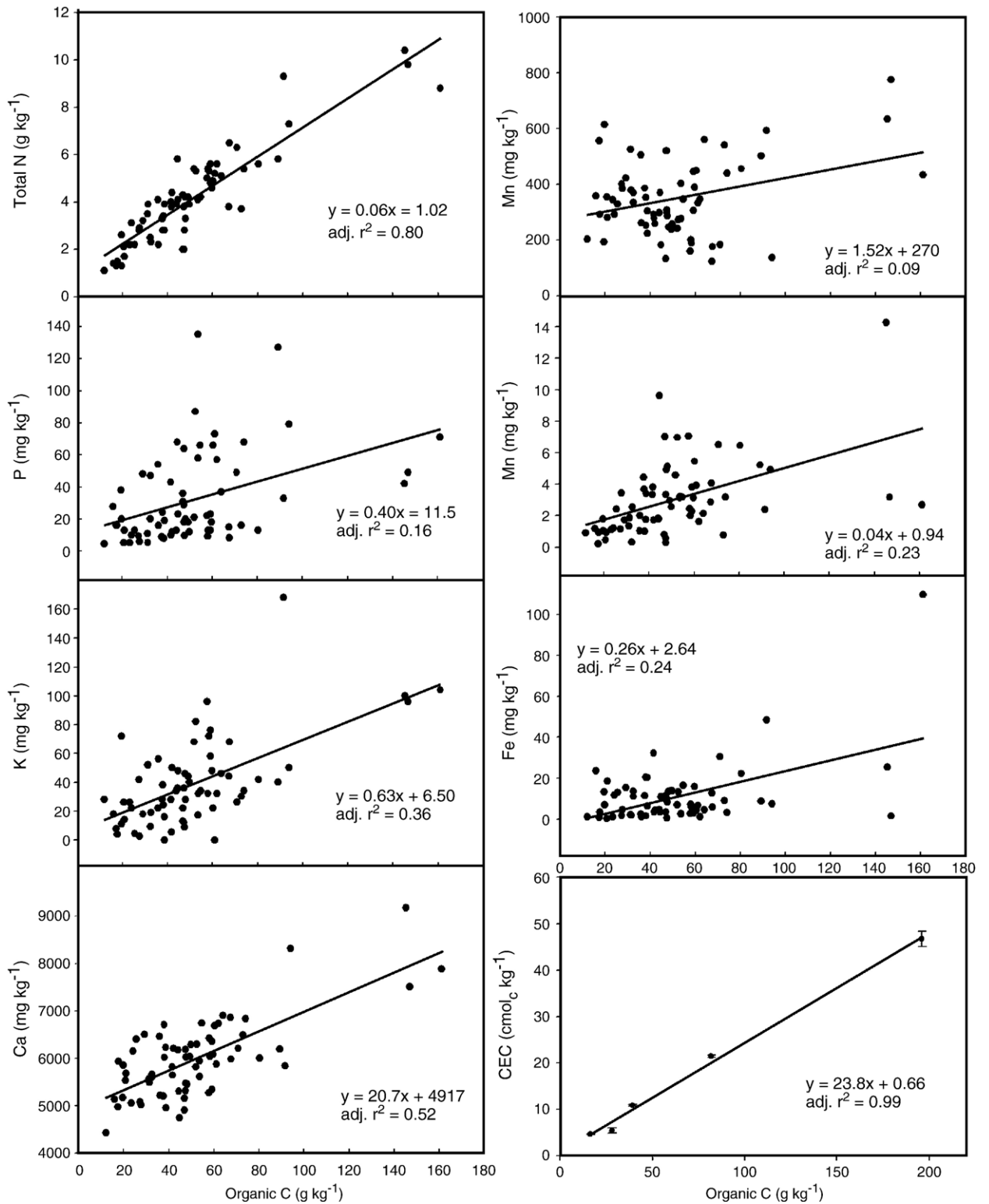


Fig. 2. Results of regression analyses for organic C and selected soil nutrients and CEC in Ngedebeus surface soils ($n=89$).

discarding metal cans in garden and farm plots to overcome soil micronutrient deficiencies. Islanders commonly mix parts of metals can and other household wastes into their garden plots and fields.

3.2. Soil organic matter

Atoll soils are characteristically sandy with minimal clay content. Particle size analysis on an Ngedebus soil from Majuro Atoll, for example, found that it was composed primarily of sand (95.2%), a small quantity of silt (3.0%), and only 1.8% clay. In the absence of a clay fraction in atoll soils, organic matter is the main source and sink of nutrients, and should theoretically show a strong relationship with the nutrient status of the soil. Results of regression analysis on Ngedebus surface soils under native forest vegetation showed that this relationship is true only for some of the soil nutrients (Fig. 2). Surface soil OC concentration was a good predictor for total N and Ca^{2+} , but showed a less robust relationship with K, Mn, Fe, P, and Mg. Organic C was a poor predictor of soil B, Cu, and Zn (data not shown). Cation exchange capacity depends on clay and organic matter content, and in atoll soils, CEC depends almost entirely on the organic matter content. We measured CEC in soils where OC concentration ranged from 16.4 g kg^{-1} to 196 g kg^{-1} and found that CEC is entirely a function of organic matter content in these atoll soils (Fig. 2). From regression we estimated that organic matter contributes $238 \text{ cmol}_c \text{ kg}^{-1}$, a reasonable number when compared with the

common number of $200 \text{ cmol}_c \text{ kg}^{-1}$ associated with the CEC of organic matter (Brady and Weil, 2004). Cation exchange capacity ranged from $4.65 \text{ cmol}_c \text{ kg}^{-1}$ to $46.7 \text{ cmol}_c \text{ kg}^{-1}$ as OC increased. Caiger (1987) found a similar range in CEC for the surface soils of Tuvalu. Measuring CEC involves multiple steps, but in atoll soils CEC can be readily estimated by exchangeable Ca^{2+} , which explains 99.2% of the variation in CEC.

Climate gradients can often have a strong influence on soil chemical properties. Soil organic matter, for example, is strongly influenced by climate showing accumulation in wet environments (Brady and Weil, 2004). Because of its importance in determining soil behavior in atoll soils, we performed regression analysis to evaluate the effect of rainfall distribution on soil OC levels. Less than 10% of the variation in soil OC levels can be explained by rainfall. A wide range of OC levels can be found on each of the islands irrespective of mean annual precipitation or seasonality of precipitation. The highest mean OC concentrations were measured on two wet southern atolls (Ebon and Mili), but the two lowest levels were also measured on two wet southern atolls (Jaluit and Namdrik), and relatively high concentrations were measured on the two northern most atolls (Fig. 3). The low C levels on Jaluit and Namdrik are puzzling, but may be related to sampling on the most populated islands within the atoll where natural vegetation patterns have been altered most. Mean Zn concentrations on Jaluit are unusually high (147 mg kg^{-1}) compared to the median value for all the atolls (2.5 mg kg^{-1}) and suggest that human activity has significantly altered these soils.

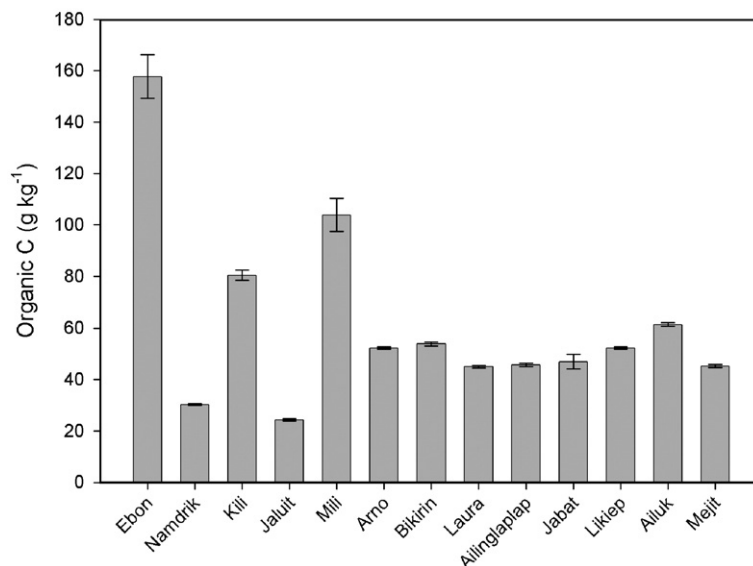


Fig. 3. Mean OC concentrations for surface soils of selected atolls in the Marshall Islands under native vegetation. Islands are arranged according to location from south to north (left to right). Error bar represents standard error of the mean.

Mean Zn levels for Namdrik are also relatively high (28.8 mg kg^{-1}) indicating the effects of human activity. Comparisons of Zn levels in samples from the uninhabited islet of Bikirin and the inhabited area of Laura from Majuro Atoll showed significantly higher ($P < 0.05$) Zn concentrations in the Laura soils (18.8 mg kg^{-1}) compared with the Bikirin soils (0.33 mg kg^{-1}) supporting the connection between human activity and effects on soil properties. These findings suggest that trend analysis across the atolls requires that sampling be limited to uninhabited islets.

Despite sampling on both human affected and unaffected soils, our results showed, as did the findings of Gessel and Walker (1992) that location within islands has a much stronger effect on soil OC levels than any variation in overall climate across the geographic region. High OC levels are generally associated with Ngedebus soils located in the center of the islands and C accumulation in these soils is associated with the historical occurrence of dense stands of *Pisonia grandis*, a common atoll tree, and other tree species, which deposited abundant litter (Manner, 1987).

3.3. Missing element study: yield and nutrient uptake

Multiple nutrient deficiencies were observed in maize grown in an Ngedebus soil from Majuro. Maize dry matter yields were significantly decreased in the $-K$, $-S$, $-N$, $-P$, and $-Cu$ treatments (Fig. 4). The $-K$ treatment showed the most dramatic decrease in maize growth; yields were 65% less than in the control treatment where the blanket nutrient solution was applied. The maize plants showed K deficiency symptoms by the second week of growth and by

harvest they were lodging. Tissue K concentration was almost an order of magnitude below the minimum critical level established for maize (Fig. 5). Our results are in agreement with earlier reports that crop growth in atoll soils is severely limited in the absence of added K (Finlay, 1987a; Reddy and Chase, 1992; Gangaiya and Morrison, 1998).

Nitrogen deficiency symptoms were apparent by the second week of growth in the $-N$ treatment, and dry matter biomass was 50% less than in the control. Our results agree with earlier studies showing that N deficiency is common in atoll soils (Reynolds, 1971; Finlay, 1987b; Reddy and Chase, 1992). Despite relatively high total N concentrations in these soils, the lower yields in the $-N$ treatment showed that the N is immobilized in the stable organic fraction and remains unavailable for plant uptake. The tissue N concentration observed in the $-N$ treatment confirms the unavailability of N in these soils (Fig. 5). Nitrogen tissue concentration in the $-N$ treatment was three times lower than the established critical level for maize, and adding N at 200 mg kg^{-1} did not raise the tissue concentration above the minimum critical level of 3.5%. Nitrogen uptake results indicated that 153 mg kg^{-1} of the added N was taken up by the plants representing 61% of the total added N.

Maize growth in the $-P$ treatment was reduced by 40% compared to the control treatment. Few studies exist documenting crop response to P in atoll soils (Weeraratna, 1992), but based on the carbonatic mineralogy and alkaline pH, P deficiency can be expected in these soils (Sample et al., 1980; Morrison, 1992). Olsen extractable P for this soil showed a relatively high concentration of

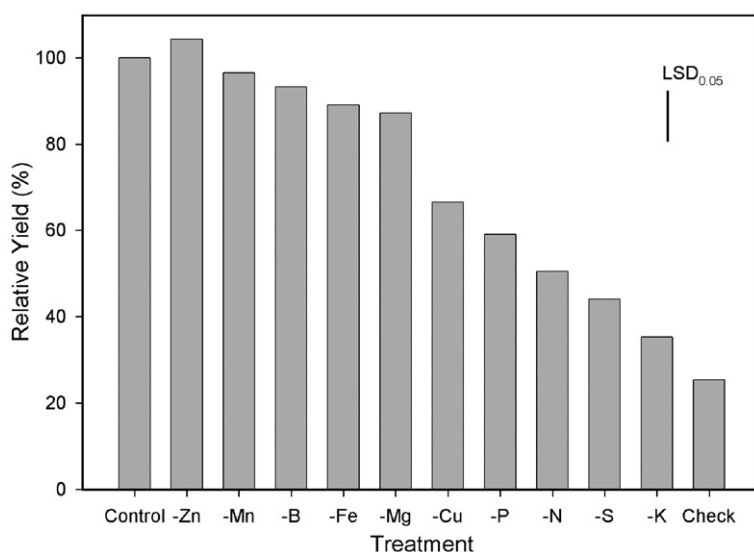


Fig. 4. Relative dry matter yield for corn tops grown in the greenhouse on a Ngedebus soil from Majuro Atoll with a soil alone treatment (check), complete fertilizer treatment (control), and with successive subtraction of each essential plant nutrient. Each bar is a mean of three replicates.

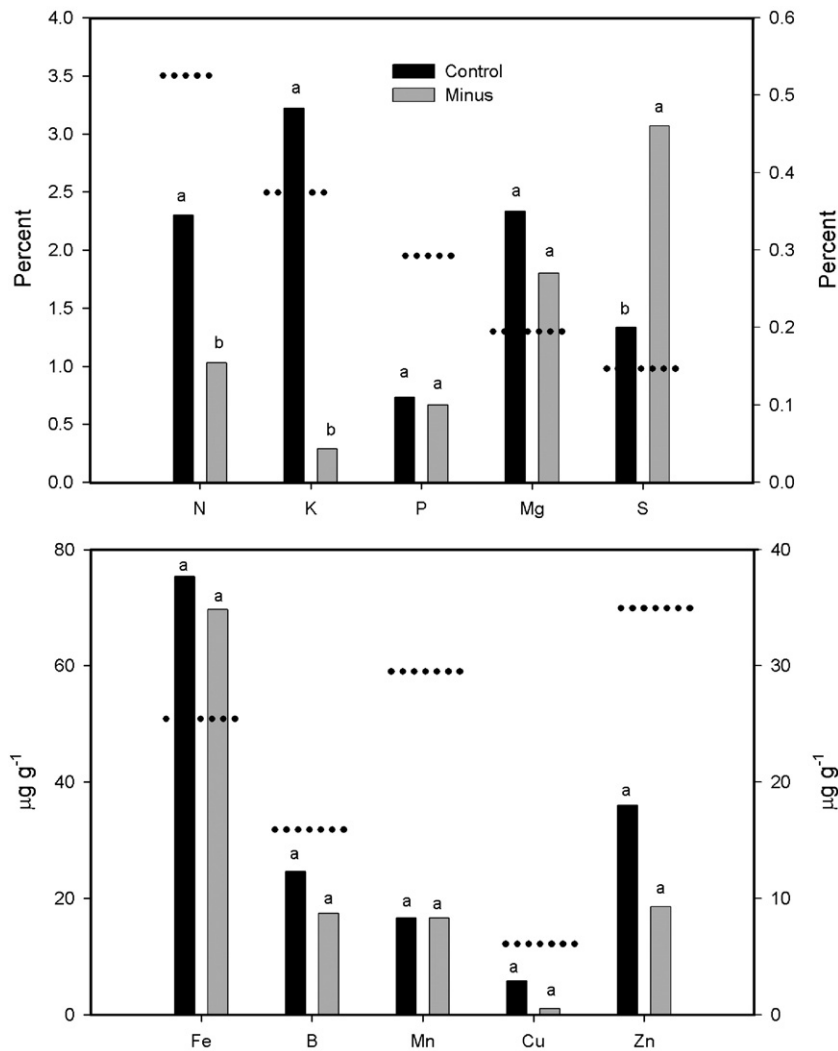


Fig. 5. Treatment effects on above ground biomass nutrient concentration for greenhouse grown corn on an Ngedebus soil. Bars with the same letter are not statistically different ($P < 0.05$). Dashed lines above each set of bars represent minimum critical concentration (Mills and Benton Jones, 1996). The second y-axis in the top graph corresponds to tissue concentrations for P, Mg, and S. In the lower graph, the second y-axis corresponds to B, Mn, Cu, and Zn.

50 mg kg⁻¹, which is considerably higher than the critical level of 10 mg kg⁻¹ established for the Olsen soil test on calcareous soils (Kuo, 1996). The observed yield response to added P compared with the control treatment indicated a P deficiency and suggests that the established critical levels may not apply to atoll soil conditions. The exact mechanism contributing to the deficiency is not clear from the data. Previous research has shown that sandy soils with low P buffering capacity require higher levels of available P to maintain adequate plant growth (Fox and Kamprath, 1971; Zhou and Li, 2001), and may explain the observed P response in the Marshall Island soil. Phosphorus levels in the maize tissue from both the control and -P treatments showed no difference suggesting that the P addition rate was insufficient (Fig. 5).

In both treatments, P tissue concentration was well below the critical levels for maize. Low P in the tissue in both the control and the -P treatment despite a relatively high value for extractable P makes it questionable to apply the current critical level for calcareous soils to atoll soils.

The -S treatment decreased yields by 56% compared with the control treatment. These results are difficult to explain from the data. The reason for the growth reduction cannot be assigned specifically to an S deficiency in the soil because S concentration in the maize tissue from the -S treatment was more than twice that of the control treatment. Isolating S deficiency is difficult, especially because it is often accompanied by N and P deficiency (Fox and Blair, 1986). The -S treatment also showed tissue N and P concentrations below the minimum critical level.

The following three properties of the Marshall Island soils may contribute, however, to a potential S deficiency: (i) the majority of the S derives from the organic fraction where it may be immobilized in stable organic substances resistant to microbial decomposition, (ii) the sandy texture of these soils and the absence of clay minerals capable of adsorbing SO_4 promotes rapid leaching and loss of SO_4 ions from the root zone, and (iii) the high CaCO_3 content will cause a certain amount of inorganic S to co-precipitate with CaCO_3 possibly making it unavailable for plant uptake (Trudinger, 1986). Under field conditions S deficiency in Marshall Island soils may not be a serious problem considering the continual deposition of SO_4 -S from sea spray.

There was no significant difference in dry matter yield between the -Mg treatment and the control. Lower amounts of Mg was detected in the tissue of the -Mg treatment compared with the control, but Mg tissue concentration was above the minimum critical level in both treatments. Soil Mg levels are usually reported as percent saturation of the CEC or the concentration of exchangeable Mg; the generally accepted saturation critical level is 5% and yield response is not expected when exchangeable Mg concentrations approach 100 mg kg^{-1} (Haby et al., 1990). The Marshall Island soil had a Mg saturation percentage of 3.8%, which is below the 5% associated with optimum yields. On the other hand, exchangeable Mg concentrations in this soil was 221 mg kg^{-1} , which is more than double the concentration where crop response to added Mg is no longer expected. The absence of a significant growth response to added Mg and adequate concentrations of Mg in the tissue suggest that Mg deficiency is not likely to be a serious constraint to crop production.

The -Cu treatment was the only micronutrient treatment to show a significant yield decline compared to the control. Maize yields dropped by 34% when Cu was not added to the soil. Maize Cu tissue concentration was more than fivefold less in the -Cu treatment compared to the control, but showed no significant difference due to high variability between the replicates (Fig. 5). Adding Cu to the Laura soil raised the Cu concentration from 0.13 to 0.63 mg kg^{-1} and the rise in soil Cu levels was accompanied by an observed yield increase. There is considerable uncertainty regarding a critical level for Cu (Martens and Lindsay, 1990), but the current range in critical concentration for DTPA extractable Cu in calcareous soils is 0.1 to 2.5 mg kg^{-1} (Sims and Johnson, 1991). Using this range, we would expect a response to added Cu in the Laura soil. Given the low Cu concentration of the tissue in the control treatment, it appears that that a higher rate of Cu fertilizer is necessary.

Contrary to the widely held belief that micronutrient deficiencies are expected in atoll soils, our results showed

no significant effect on yields when Fe, Mn, B, and Zn were not added to the Laura soil (Fig. 4). The initial Fe concentration in the Laura soil was 28 mg kg^{-1} , which is more than four times higher than the current upper limit of 5 mg kg^{-1} for the DTPA soil test (Sims and Johnson, 1991). The Fe concentration in the tissue was above the established critical limit in both the control and -Fe treatments with slightly higher concentrations in the control treatment. The high soil test values and adequate tissue levels combined with the lack of a yield decline in the -Fe treatment all suggest that native Fe levels in the soil were not limiting growth. The results for B, Mn, and Zn are less clear. Although initial soil concentrations for each of the nutrients fall within or above the established minimum critical ranges and there were no significant declines in corn yields in the minus treatments for each nutrient, tissue concentrations for the three nutrients were considerably lower than the established minimum levels for both the control and minus treatments (Fig. 5). The low tissue concentrations in the control treatments suggest that insufficient B, Mn, and/or Zn could have limited growth and explain why no differences were observed between the control and minus treatments. Amending the soil with B and Zn, however, significantly ($P < 0.01$) increased the mean soil B and Zn concentrations from 0.37 to 0.71 mg kg^{-1} for B and from 3.4 to 4.8 mg kg^{-1} for Zn, but the increase in extractable nutrient was not reflected in significantly higher plant uptake (data not shown).

3.4. Fertility assessment using soil test results

We have used the results from the missing element study as an initial step to assess the reliability of correctly diagnosing nutrient deficiencies in atoll soils using standard soil tests. Table 6 summarizes the performance of the various soil tests in diagnosing soil nutrient deficiencies based upon the observance of a growth response in the greenhouse study. For K, Mg, B, Cu, Fe, Mn, and Zn expected response based on established soil critical levels and observed yield response determined by experiment were in agreement. For Mg, however, Mg sufficiency or deficiency can also be defined by the percent Mg saturation of the CEC where sufficient Mg concentrations are often achieved at 5–6% Mg saturation (Haby et al., 1990). According to the percent saturation approach, a yield response to added Mg was expected in the Laura soil with Mg saturation of 3.8%. For Zn and Mn, clear discrepancies between tissue concentrations and yield response as discussed in the previous section shed some doubt on the reliability of current critical levels for the DTPA soil test in atoll soils.

Table 6
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 ^a	50.0	No	Yes
K	NH ₄ OAc pH 7.0	270 ^b	21.3	Yes	Yes
Mg	NH ₄ OAc pH 7.0	100 ^b	221	No	No
SO ₄ ²⁻ -S	H ₂ O extractable	40 ^c	66.7	No	Yes
B	Hot H ₂ O Extractable	0.1–2.0 ^d	0.73	No	No
Cu	DTPA Extractable	0.1–2.5 ^d	0.13	No	Yes
Mn	DTPA Extractable	1.0–5.0 ^d	7.37	No	No
Fe	DTPA Extractable	2.5–5.0 ^d	27.7	No	No
Zn	DTPA Extractable	0.2–2.0 ^d	3.40	No	No

^a Kuo, 1996.

^b Haby et al., 1990.

^c Fox et al., 1964.

^d Sims and Johnson, 1991.

Expected response and observed response were not in agreement in the case of P. The critical level below which a P deficiency is expected under field conditions has been established at 10 mg kg⁻¹ for the Olsens extraction (Thomas and Peaslee, 1996). Initial Olsen extractable soil P concentration in the Laura soil was 50 mg kg⁻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 maize growth. The established critical level was developed on clayey calcareous soils extremely low in OC found in dry climates (i.e. Colorado). The soils in the Marshall Islands bear little resemblance to the soils for which the test was developed; they have little to no clay, high OC, and have developed in a wet climate. Sandy soils with low buffering capacity require higher concentrations of P in solution to satisfy crop P requirements (Fox and Kamprath, 1971), and this is a likely explanation for the observed response to added P despite relatively high initial extractable P. Clearly, 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.

The observed yield response to added S was not expected given that the Laura soil had water extractable SO₄-S above the minimum critical level set for the test. 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 SO₄-S was below 40 mg kg⁻¹. They reported slight deficiency between 40 to 60 mg kg⁻¹. The Laura soil showed extractable SO₄-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 SO₄-S sorbed on clay surfaces is desorbed. In the Laura soil, however, there is no clay fraction capable of replenishing S taken up by the plant, and therefore, potential S deficiency is more likely. Like P, 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).

Based upon the results of the missing element study and the evaluation of the soil test results, we have some basis to make a fertility interpretation of the soil test data from each island. We have used the median value for each island because a few large numbers in the dataset tend to inflate the mean. Median P concentrations (Table 7) are lower than the 50 mg kg⁻¹ measured in the Laura soil used in the missing element experiment, and therefore, we would expect P deficiency on all the islands even though they are all above the established critical level of 10 mg kg⁻¹. Soil K is very low on all the islands with concentrations similar to that measured in the Laura soil; K is probably the most severe nutrient deficiency across all islands. Median Mg concentrations are always above 100 mg kg⁻¹ and %Mg saturation averages around 9% for

Table 7
Median concentrations for selected nutrients in the surface soils from the sampled atolls

Atoll	P	K	Mg	B	Mn	Fe	Cu	Zn
mg kg ⁻¹								
Mili	20.0	50.0	388	0.73	3.24	4.46	0.73	6.20
Likiep	16.5	31.0	334	0.72	2.68	13.2	0.74	52.8
Jobot	23.0	44.0	246	0.42	4.48	4.62	0.11	0.33
Arno	19.0	28.0	274	0.43	6.44	21.4	0.13	0.25
Ailuk	71.0	22.0	402	0.64	3.26	3.90	0.07	0.14
Ailinglaplap	13.0	32.0	286	0.46	2.12	2.46	0.07	0.16
Jaluit	28.0	19.0	334	0.50	1.07	15.7	10.0	122
Majuro (Laura)	31.0	34.0	342	0.46	2.12	4.40	0.19	5.66
Majuro (Bikirin)	13.0	68.0	344	0.60	3.52	3.56	0.13	0.26
Namdrik	20.0	19.0	336	0.37	1.26	11.6	0.18	5.06
Kili	56.0	72.0	418	0.82	2.84	3.44	0.29	4.04
Mejit	18.0	12.0	372	0.56	0.76	2.88	0.08	0.23
Ebon	33.0	36.0	352	0.36	2.68	12.6	0.56	16.9

all the islands suggesting that Mg is not likely a constraint to crop production.

For the micronutrients there is a range of concentrations below the levels which a response is expected. Median micronutrient concentrations for all the islands were usually above the minimum critical limit except for the islands of Ailuk and Ailinglaplap where Cu and Zn concentrations were below the minimum critical limit. Median B and Mn levels on Mejit were also below the minimum critical level. The concentrations for the micronutrients on all the islands, with the exception of Fe, were not above the upper range of critical limits. Although the results of the missing element study did not show obvious micronutrient deficiency, the low concentrations of these elements in the maize tissue, combined with the tendency for micronutrient concentrations to be close to the deficiency range, suggests that good crop growth will require fertilization to increase micronutrient availability in the Marshall Island soils.

4. Conclusions

Despite distinct differences in the physical properties of the Majuro and Ngedebus soils, their chemical properties do not differ dramatically. Our results indicate that Ngedebus soils located in the central portion of the islands tend to show higher levels of organic matter than Majuro soils along the ocean shoreline, but Ngedebus soils found close to the lagoon shoreline show similar organic matter contents to the Majuro soils. In agreement with the findings of Gessel and Walker (1992), our results indicate that vegetation density and distance from the shoreline are key factors determining organic matter content in atoll soils. The strong rainfall gradient across the Marshall Islands does not have a significant effect on soil chemical properties. Local vegetation cover and geographic location within the island override any climatic differences.

Our results provide further evidence highlighting the critical role of organic matter in atoll soils. We show that it is the primary source of CEC, it is highly correlated with soil N and Ca^{2+} , whereas soil K levels show a moderate relationship. Organic C levels, however, do not show a strong relationship with the other soil nutrients. Our work shows that organic matter levels tend to be highest in Ngedebus soils located in the center of the islands. With the combination of these data and the knowledge that soil moisture retention is proportional to organic matter levels (Morrison and Seru, 1986), we can explain why traditional agricultural activities were concentrated in centrally located areas (Thaman, 1992). Managing organic matter was and will continue to be fundamental to cropping systems in atoll soils.

The Marshall Island soils suffer from multiple nutrient deficiencies with N, P, K, and S being the most serious. Copper appeared to be the only micronutrient showing clear deficiency, but low concentrations of Mn and Zn in the corn tissue may indicate possible deficiencies also. Interpreting soil test data on atoll soils, however, remains difficult for two reasons: (i) the soil tests have not been calibrated with crop growth, and (ii) standard soil tests may not be applicable to the unique physical and chemical properties of atoll soils. Field experiments will be required to determine the boundaries between sufficiency and deficiency for P and the micronutrients. Increasing crop production in the Marshall Islands will require considerable nutrient inputs, which may be satisfied by identifying suitable locally available organic materials.

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