Characteristics of Coral Cay Soils at Coringa-Herald Coral Sea Islands, Australia[1]

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Abstract: Coral cay soil chemical and physical properties were described from Coringa-Herald National Nature Reserve, Australia. Soil A horizons under littoral herblands and *Argusia argentea* shrubs were shallow and coarse textured. Interior soil A horizons, particularly under *Pisonia grandis* closed forest, were deeper (1.2 m) with finer textures. Average surface soil pH values ranged from pH 8.76 at the seashores to pH 8.09 in the interior. Average surface soil organic carbon ranged from 2.4% to 4.8%; and phosphorus (Colwell-P) concentrations ranged from 467 mg/kg to 882 mg/kg within the interior areas. Chemical fertility of all A horizons increased from the seashore to the island interior. The higher fertility levels are attributed to high organic matter contributed by vegetation, combined with activities of seabirds, particularly the burrowing wedge-tailed shearwater, *Puffinis pacificus.* Leaching of nutrients from surface soils is reflected in the rapid decline in soil fertility with depth. Deeper interior A horizons are interrupted by formation of an abrupt white C profile. It is speculated that the formation of this layer is the product of periodic "washing" by a seasonally high fresh/brackish water table.

Coringa-Herald National Nature Reserve (CHNNR) (Figure 1) is a remote locality of relatively high biodiversity in the northeastern Australian Exclusive Economic Zone. The soils of the five vegetated cays at CHNNR were studied as part of an ongoing assessment of resilience and vulnerability of terrestrial ecosystems. The soils of the low-lying coral cays and islets are products of physical, geological, and biological factors (Gourlay 1988). Coral cays in the Pacific Ocean formed during the Holocene period between 3000 and 5000 B.P. (Smithers et al. 2007). The coral cay soils of eastern Australia are largely composed of sediments derived from Foraminifera spp. and *Halimeda* spp. (Yamano et al. 2000) that have developed through biotic interactions with soil microbes such as bacteria and fungi. The coral cay sands across the Pacific are essentially homologous, although variability of soils is determined by factors such as latitude and climate, geometries and age of the islands, the relative sea level histories of reefs, and the diversity of reef sediments of which they are composed (Smithers et al. 2007).

Most other coral island soil publications have reported on islands where human disturbances have been high (e.g., clearing for agriculture, extensive phosphate rock mining, the detonation of nuclear weaponry, and so forth [Barry and Rayment 1997, Morrison and Manner 2005, Deenik and Yost 2006]). In contrast, the CHNNR islands have seen minimal human disturbance. Therefore, the major factors influencing soil properties and conditions at CHNNR (vegetation type, avifaunal associations, and environmental disturbance events) are entirely natural.

Coral cay soils are generally considered to be problematic for plant growth with their high porosity and low water-holding capacity, being compounded by little cation exchange capacity (Stone et al. 2000, Deenik and Yost

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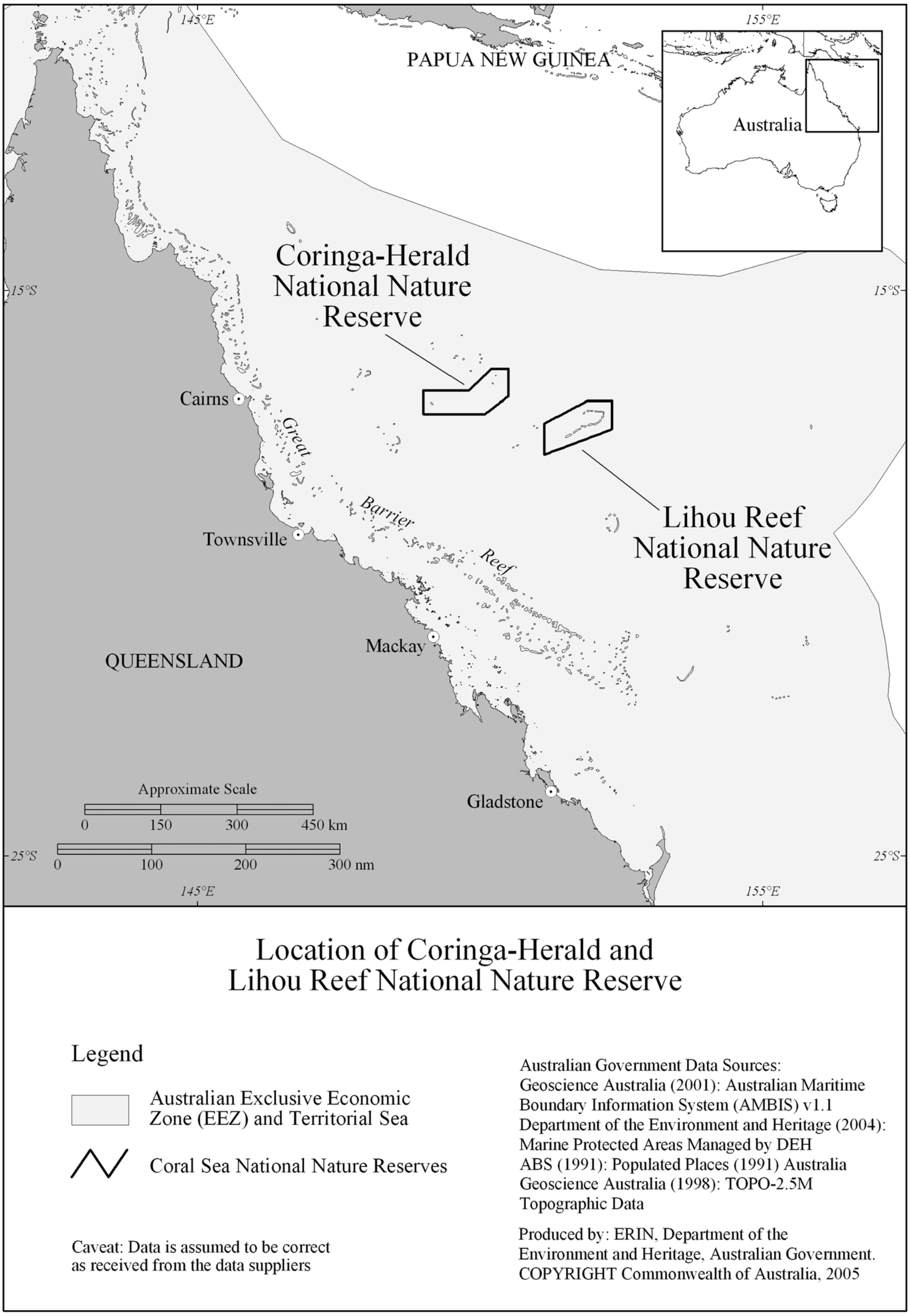

Figure 1. Location of Coringa-Herald National Nature Reserve within the Australian Exclusive Economic Zone.

2006). The high carbonate, high pH soils of coral cays are predicted to be highly restrictive on phosphorus and micronutrient solubility (Morrison 1990).

This paper draws largely on the study of soils at CHNNR from 2006 to 2007 that formed part of a multidisciplinary survey of terrestrial ecology (Batianoff et al. 2009). The main aims are to report chemical and physical soil properties and describe the process of soil development from the seashore areas to the island interiors. The roles of vegetation and nesting seabirds that utilize different vegetation communities are highlighted as part of soil development from unvegetated low nesting beaches to high-usage nesting sites of *Pisonia grandis* closed forest.

Study Area

These low sand cays and islets have a maximum elevation of about 5–6 m above sea level (Batianoff et al. 2009). Island shapes range from the cylindrical South West Herald Cay (19 ha) and Chilcott Islet (17 ha), the raindrop-shaped South West Coringa Islet (13.5 ha) and South East Magdelaine Cay (41 ha), and the half-moon-shaped North East Herald Cay (60 ha) (Batianoff et al. 2009). The dominant southeasterly trade winds operating in the area lead to the development of "exposed" shores on the east to southeastern sides and "sheltered" shores on the west to northwestern sides. Lithified limestone "beach rock" platforms and rubble are common along the exposed shores, whereas the sheltered shores feature sandy beaches up to 20 m wide. On all islands, elevated beach ridge areas have formed adjacent to shores, with lower plains within the island interiors. The seashores, beach ridges, and interior plains make up the three distinct landform units described for the islands. Seventeen plant communities have been described occurring on these three distinct landforms (Batianoff et al. 2009).

CHNNR has a tropical and maritime climate characterized by seasonally variable rainfall, consistently high annual temperatures (21.9°C mean monthly minimum in July to 30.7°C mean monthly maximum in January), and high evaporation rates (Farrow 1984, Bureau of Meteorology 2008, Batianoff et al. 2010). Rainfall at nearby Willis Island (1,115 mm) occurs predominantly during the four "wet" months of January–April. A "dry" period lasts from May to December. Prolonged drought periods lasting between 2 and 6 yr are also common (Batianoff et al. 2009). Southeasterly "trade" winds dominate throughout most of the year except during summer (December to March), when the northerly "monsoonal" influence brings storms and cyclonic conditions.

MATERIALS AND METHODS

Field Studies

Fieldwork was conducted over three separate surveys from 2006 to 2007. Soils were collected during the October 2007 field survey from different vegetation communities identified at three landform units: seashores, beach ridges, and interior plains (Batianoff et al. 2009). The seashore vegetation includes ephemeral herblands of *Lepidium englerianum*, *Stenotaphrum micranthum* and/or *Lepturus repens*, and the more permanent fringing *Argusia argentea* shrublands.

On the beach ridges the vegetation consists of mainly *A. argentea* open scrubs. On North East Herald Cay (NE Herald) and South East Magdelaine Cay (SE Magdelaine), *Cordia subcordata* closed scrubs, windshorn *Pisonia grandis* closed scrubs, and immature *P. grandis* low closed forests are also found along beach ridges. The interior plains support mixed herblands and *Abutilon albescens* shrublands, with *P. grandis* forests on NE Herald and SE Magdelaine.

Fifty soil profiles were sampled using a 4 cm diameter sand auger. Soils were sampled from distinct vegetation communities within the three landform units (seashore, beach ridges, and interior plains). The seashore soil samples included ephemeral herblands ($n = 4$) and seashore *Argusia* ($n = 5$). Sampling of the beach ridge unit was from the *Argusia* ($n = 3$), *Cordia* ($n = 2$), wind-exposed *Pisonia* ($n = 6$), and immature *Pisonia* ($n = 6$) vegetation communities. The interior plains samples were from the interior herblands and grasslands ($n = 7$), *Abutilon* ($n = 8$), and healthy mature/old-growth *Pisonia* vegetation ($n = 9$).

Soil profiles were sampled according to depth/horizon. The surface soils (Ah horizons) were sampled between 0 and 20 cm. The remainder of the A horizon was sampled in 20 cm intervals (i.e., 20–40 cm, 40–60 cm, 60–80 cm, and 80–100+ cm) until the original parent material layer (C horizon) was reached. C horizons were also sampled where possible. All soil samples were placed in ziplock bags on site and oven-dried.

Analytical Studies

The dried soils were described based on soil consistency, texture, color, structure, and the coarse fragment component as outlined in Fitzpatrick et al. (1999). Soil texture was estimated by the proportions of particles that were very coarse (1.00–2.00 mm), coarse (0.50–1.00 mm), medium (0.25–0.50 mm), fine (0.10–0.25 mm), to very fine (0.05–0.1 mm). Colors of the oven-dried soils were described in accordance with the Munsell Soil Color Chart system (Munsell Color 2000). The coarse-fragment component of soils was recorded as those fragments larger than 2 mm.

The chemical properties of all soil profiles were determined by the University of Queensland's Analytical Services unit. Analyses following standard procedures from Rayment and Higginson (1992) were conducted for pH, electrical conductivity (dS/m) (using a 1 : 5 soil to water mixture), total nitrogen (wt%), total carbon (wt%), organic carbon (wt%), available phosphorus (Colwell-P) (mg/kg), extractable potassium (cmol(+)/kg), extractable calcium (cmol(+)/kg), extractable magnesium (cmol(+)/kg), extractable sodium (cmol(+)/kg), total copper (wt%), total iron (wt%), total manganese (wt%), total sulphur (wt%), and total zinc (wt%). The physical and chemical properties of soil samples were averaged for each horizon, vegetation community, and landform type. Relationships between organic carbon and other nutrients were explored with Pearsons Product Moment Correlation. Differences between landform types were compared for each nutrient according to each horizon (where $n > 3$) using parametric and nonparametric analysis of variance (ANOVA) depending on the distribution of the data. The nutrients with significant differences were normally distributed, and Tukey's test was used to compare individual means.

RESULTS

Soil Physical and Chemical Properties

The soils at CHNNR have AC profiles without B horizons. All soil profiles sampled consisted of loose and unconsolidated particles that were essentially structureless. Surface soils (Ah horizon) ranged in color from white (10YR 8/1) at the seashore areas to very pale brown (10YR 7/3) within island interiors. The A horizon layers below were darker in color than the surface soils. Generally, the Ah and C horizons had higher proportions of very coarse to coarse coral fragments than the subsurface A horizons.

The results of chemical analyses are summarized by vegetation community and landform unit in Tables 1, 2, and 3. The alkaline soil pH values declined from the seashore areas to the island interiors. Soil nutrient concentrations were higher in the surface soils than in deeper horizons for each profile and with highest concentrations recorded near the island interiors (Figure 2). The nutrients reflect typical characteristics of coral cay soils with a very high extractable P throughout that is attributable to the input of guano from the resident seabird populations. Potassium concentrations were low to marginal in the beach and ridge sites and only just adequate at the mature *Pisonia* sites. All soil nutrients were strongly positively correlated with organic carbon content (all $P < .001$, except total Cu and total Fe $P < .01$). Organic carbon was strongly negatively correlated with soil pH ($P < .001$).

SEASHORE SOILS. The beach surface soils were dominated by medium (45%) to coarse (5%) sized grains. The A horizons were up to 20 cm deep, composed mainly (50%) of fine to very fine grains, and were predomi-

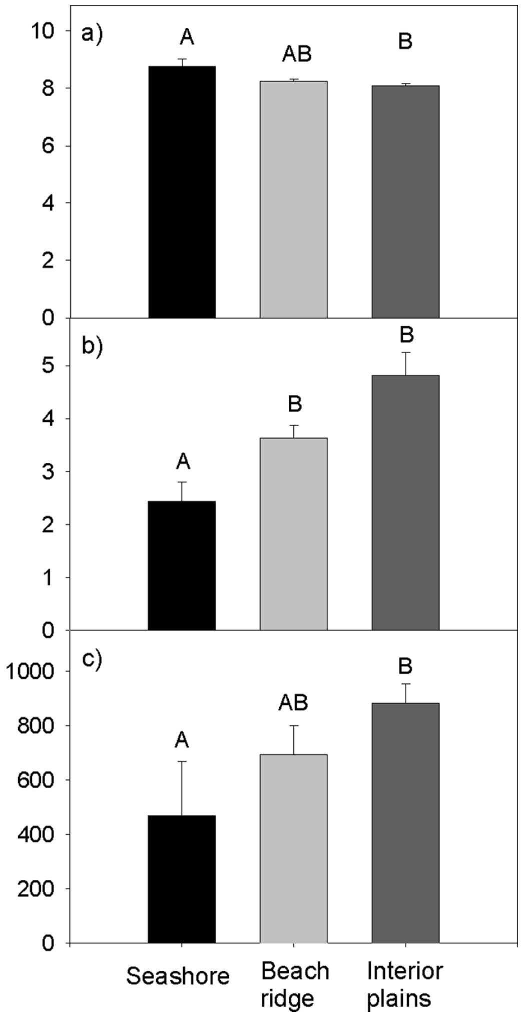

FIGURE 2. Comparison of average chemical properties of nutrients of surface soils with statistically significant difference between landforms. Individual means that are not significantly different ($P > .05$) are annotated with the same value. *a*, pH ($F = 7.41$; df = 2,43; $P = .002$); *b*, organic carbon (wt%) ($F = 6.48$; df = 2,43; $P = .003$); *c*, Colwell-P (mg/kg) ($F = 3.36$; df = 2,43; $P = .044$).

nantly white (10YR 8/1). The seashore *Argusia* soils had A horizons to a maximum depth of 30 cm, with around 10% medium to coarse grains at the surface and up to 25% at a depth of 30 cm. The fine to very fine grains proportion was about 90% at the surface to 75% at 30 cm. The dominant color was white (10YR 8/1) with a light brownish gray element (10YR 6/3). Some organic material (decomposing plant material) was visible.

The beach surface soils were strongly alkaline (pH 8.8). Electrical conductivity was low (0.32 dS/m) for nearly all surface soil samples. Mean soil organic carbon value was 2.3%, and mean total nitrogen value was 0.35%. The beach averages for total nitrogen were higher than those in the *Argusia* samples (Table 1). The mean concentration of phosphorus (P) for the surface soils of the seashore community was 467 mg/kg, though the minimum recorded for one sample was 26 mg/kg. The surface soils of the seashore communities recorded the lowest concentrations of potassium (K) of 0.11 cmol(+)/kg (Table 1).

BEACH RIDGE SOILS. The maximum A horizon depths for the beach ridge communities were as follows: beach ridge *Argusia* (0–30 cm); beach ridge *Cordia* (0–30 cm); wind-exposed *Pisonia* (0–90 cm), and immature *Pisonia* (0–80 cm). The beach ridge soils had a high fine (30–40%) to very fine grain (35–50%) component, with a lower coral fragment content than the seashore soils. The beach ridge soils from the exposed shores were often variable throughout the profile. For example, the wind-exposed *Pisonia* at NE Herald had 30–80% medium, 0–60% fine, and 10–60% very fine sized grains throughout the profiles.

The mean pH values for the surface soils of the beach ridge vegetation communities were pH 8.2. The windshorn *Pisonia* was the most alkaline, whereas the immature *Pisonia* the least alkaline (Table 2). The soil pH of the windshorn *Pisonia* C horizon was the most alkaline recorded (pH 9.28). Electrical conductivity was low: about 0.42 dS/m for surface soil samples. The mean organic carbon value for the beach ridge communities was 3.6%, with values ranging from 3.38% (immature *Pisonia*) to 4.51% (*Cordia*) (Table 2). Total nitrogen was low, averaging 0.31, apart from a value of 0.54% in the *Argusia* shrubland. Phosphorus was extremely variable, ranging from 412 mg/kg within *Cordia* surface soils to 978 mg/kg from the immature *Pisonia* surface soils. Potassium values were

TABLE 1

Comparison of Chemical Properties of Soils from Seashore Vegetation Communities Subdivided by Soil Horizon

		Beach *Argusia*[a]		
Parameter	Unit	Ah (4,3)	Ah (5,3)	C (2,0)
pH		8.81 ± 0.50	8.72 ± 0.30	8.95 ± 0.07
Electrical conductivity	(dS/m^2)	0.32 ± 0.14	0.34 ± 0.12	0.13 ± 0.00
Total Nitrogen	(wt%)	0.35 ± 0.31	0.15 ± 0.03	0.07 ± 0.00
Total Carbon	(wt%)	8.27 ± 1.77	5.01 ± 0.61	2.55 ± 0.13
Organic Carbon	(wt%)	2.29 ± 0.83	2.54 ± 0.29	1.77 ± 0.05
Colwell-P	(mg/kg)	378 ± 241	538 ± 329	226 ± 4
Ca	(cmol(+)/kg)	14.9 ± 3.1	14.4 ± 2.3	12.2 ± 0.6
K	(cmol(+)/kg)	0.1 ± 0.06	0.16 ± 0.11	0.02 ± 0.00
Mg	(cmol(+)/kg)	1.87 ± 0.62	2.13 ± 0.8	1.12 ± 0.04
Na	(cmol(+)/kg)	0.45 ± 0.19	0.54 ± 0.27	0.09 ± 0.00
Total Cu	(mg/kg)	5.7 ± 4.6	2.0 ± 0.8	na
Total Fe	(mg/kg)	30 ± 23	8 ± 4	na
Total Mn	(mg/kg)	8.49 ± 6.21	2.44 ± 0.09	na
Total S	(mg/kg)	1,281 ± 155	1,123 ± 23	na
Total Zn	(mg/kg)	53 ± 48	8 ± 3	na

[a] Sample size is given in parentheses, with the first value relating to rows 1–10 (pH through Na) and the second value relating to rows 11–14 (Total Cu through Total Zn).

very low but variable, ranging from 0.15 cmol(+)/kg) for *Argusia* to 0.64 cmol(+)/kg) for immature *Pisonia* (Table 1).

INTERIOR SOILS. The interior soils are part of older landforms represented by sand plains and relic beach ridges and swales. The maximum depths of the interior plains soils were *Abutilon* (0–70 cm), interior herblands (0–60 cm), and mature *Pisonia* (0–110 cm). Fine to very fine grain proportions were high, with some samples from the interior herblands recording up to 100% fine to very fine grains. The mature/old-growth *Pisonia* soil profiles were the most developed at CHNNR, with A horizons up to 110 cm deep. Ah and A horizon soils in the interior were darker than other soils. The mature/old-growth *Pisonia* soils were the darkest of all samples (10YR 3/3, dark brown). The transition from A horizons to C horizons was often abrupt, with the C horizon samples resembling the white sands of the seashore. Litter cover was generally higher in the interior areas than in the beach ridge and seashore areas. Moderate surface soil compaction and patchy organic crust layers were observed on the surface of some interior soils. Surface runoff was evident in some areas of the *Pisonia* forest floor, despite the freely draining nature of unconsolidated sands.

The mature *P. grandis* surface soils at SE Magdelaine recorded the lowest soil pH values, with the lowest 7.29. The mean interior plains pH was 8.00 for surface soils. A mean electrical conductivity of 1.44 dS/m was measured in mature *Pisonia*, considered high by agricultural standards (Rayment and Bruce 1984). The mature *P. grandis* profiles recorded the highest mean organic carbon values (4.84%), with one sample recording 12.08%. The interior communities organic carbon mean value was 4.8%. Total nitrogen concentrations were well maintained throughout the A horizons (0.36% to 0.69%) of interior soil profiles (Table 3). However, the average total nitrogen concentration in the C horizons of mature *Pisonia* was considerably lower (0.28%).

DISCUSSION

Most coral island soils are described as having AC profiles with an absence of B horizon (Fosberg 1954, Catala 1957, Wiens 1962,

TABLE 2

Comparison of Chemical Properties of Soils from Beach Ridge Vegetation Communities Subdivided by Soil Horizon

	Argusia		*Cordia*		Windshorn *Pisonia*			Immature *Pisonia*		
Parameter	A (3,2)	C (2,1)	Ah (2,0)	C (2,0)	Ah (6,0)	A (2,0)	C (1,0)	Ah (5,2)	A (6,2)	C (1,1)
pH	8.26 ± 0.15	9.02 ± 0.42	8.3 ± 0.03	8.81 ± 0.36	8.37 ± 0.10	8.81 ± 0.19	9.28	8.05 ± 0.15	8.32 ± 0.09	8.10
Electrical Conductivity	0.36 ± 0.09	0.11 ± 0.03	0.29 ± 0.01	0.15 ± 0.04	0.48 ± 0.07	0.21 ± 0.07	0.15	1.16 ± 0.54	0.34 ± 0.09	0.53
Total Nitrogen	0.54 ± 0.29	0.15 ± 0.04	0.28 ± 0.09	0.1 ± 0.07	0.28 ± 0.05	0.17 ± 0.03	0.02	0.39 ± 0.12	0.40 ± 0.11	0.60
Total Carbon	7.73 ± 2.39	4.38 ± 1.07	5.97 ± 0.54	3.32 ± 0.31	6.12 ± 1.46	7.36 ± 3.5	2.59	6.79 ± 1.31	6.93 ± 1.39	6.18
Organic Carbon	4.48 ± 1.36	1.98 ± 0.32	4.51 ± 0.3	2.52 ± 0.9	3.54 ± 0.33	2.7 ± 0.96	1.67	3.38 ± 0.45	3.5 ± 0.45	3.31
Colwell-P	551 ± 121	293 ± 77	412 ± 68	288 ± 117	547 ± 74	412 ± 70	187	978 ± 220	832 ± 196	669
Ca	16.3 ± 2.9	12 ± 2.8	16.6 ± 0.6	12.1 ± 0.5	14.3 ± 0.6	13.4 ± 0.1	12.1	18.0 ± 2.3	16.9 ± 2.0	24.2
K	0.15 ± 0.05	0.03 ± 0.02	0.07 ± 0.01	0.02 ± 0.01	0.48 ± 0.23	0.17 ± 0.07	0.01	0.64 ± 0.17	0.66 ± 0.42	0.44
Mg	2.24 ± 0.74	1.13 ± 0.15	1.92 ± 0.37	1.11 ± 0.05	3.12 ± 0.56	1.78 ± 0.19	1.14	3.21 ± 0.78	2.7 ± 0.9	6.69
Na	0.52 ± 0.20	0.12 ± 0.01	0.19 ± 0.02	0.09 ± 0.02	1.1 ± 0.36	0.49 ± 0.20	0.14	1.43 ± 0.68	0.84 ± 0.46	2.92
Total Cu	9.5 ± 7.8	na	na	na	na	na	0.0	20.7 ± 7.6	27.1 ± 6.1	32.2
Total Fe	31 ± 25	na	na	na	na	na	0	88 ± 25	116 ± 17	131
Total Mn	7.07 ± 3.56	na	na	na	na	na	0.00	8.65 ± 0.39	9.96 ± 0.33	9.74
Total S	1,436 ± 219	na	na	na	na	na	0	1,802 ± 370	1,891 ± 560	2,401
Total Zn	48 ± 40	na	na	na	na	na	0	94 ± 31	120 ± 26	145

Note: Units are provided in Table 1. Sample size is given in parentheses, with the first value relating to rows 1–10 (pH through Na) and the second value relating to rows 11–14 (Total Cu through Total Zn).

TABLE 3

Comparison of Chemical Properties of Soils from Interior Plains Vegetation Communities Subdivided by Soil Horizon

	Herblands		*Abutilon*			Mature *Pisonia*		
Parameter	Ah (7,6)	C (4,3)	Ah (8,4)	A (8,4)	C (1,0)	Ah (9,3)	A (8,4)	C (7,3)
pH	8.18 ± 0.12	8.38 ± 0.12	8.12 ± 0.08	8.38 ± 0.08	8.76	8.00 ± 0.14	8.01 ± 0.12	8.43 ± 0.16
Electrical Conductivity	0.54 ± 0.14	0.3 ± 0.09	0.59 ± 0.20	0.29 ± 0.07	0.13	1.44 ± 0.54	1.17 ± 0.33	0.54 ± 0.17
Total Nitrogen	0.65 ± 0.20	0.37 ± 0.09	0.45 ± 0.10	0.36 ± 0.09	0.05	0.69 ± 0.26	0.63 ± 0.25	0.28 ± 0.10
Total Carbon	9.56 ± 1.7	6.58 ± 1.15	7.04 ± 1.10	5.95 ± 1.08	2.60	7.06 ± 1.42	6.04 ± 1.15	5.3 ± 1.0
Organic Carbon	4.84 ± 0.8	3.13 ± 0.33	4.73 ± 0.42	3.69 ± 0.4	2.29	4.84 ± 1.01	4.24 ± 0.87	2.93 ± 0.43
Colwell-P	949 ± 207	602 ± 36	833 ± 89	718 ± 94	364	873 ± 86	861 ± 90	634 ± 135
Ca	17.4 ± 1.4	14.0 ± 0.7	16.4 ± 0.9	14.6 ± 0.8	11.6	18.5 ± 2.3	18.6 ± 2.4	15 ± 1.2
K	0.48 ± 0.15	0.16 ± 0.06	0.39 ± 0.13	0.15 ± 0.07	0.00	0.84 ± 0.29	0.58 ± 0.18	1.1 ± 0.9
Mg	3.01 ± 0.58	1.95 ± 0.25	2.66 ± 0.52	2.26 ± 0.52	0.75	2.14 ± 0.33	1.84 ± 0.33	1.53 ± 0.17
Na	0.88 ± 0.18	0.45 ± 0.13	0.62 ± 0.18	0.44 ± 0.19	0.06	0.94 ± 0.32	0.7 ± 0.19	0.39 ± 0.1
Total Cu	13.3 ± 2.7	10.4 ± 0.4	14.4 ± 3.4	17.6 ± 3.4	0.0	30.4 ± 3.2	26.5 ± 2.7	15.2 ± 9.1
Total Fe	54 ± 9	34 ± 3	60 ± 18	68 ± 14	0	111 ± 10	100 ± 8	63 ± 22
Total Mn	8.88 ± 2.5	5.35 ± 0.4	8.93 ± 1.07	8.56 ± 1.02	0.00	13.31 ± 2.01	11.05 ± 1.86	5.93 ± 2.10
Total S	1,510 ± 180	1,383 ± 74	1,568 ± 80	1,452 ± 107	0	2,916 ± 217	2,400 ± 146	1,463 ± 310
Total Zn	62 ± 11	42 ± 3	75 ± 20	96 ± 21	0	160 ± 20	123 ± 7	66 ± 37

Note: Units are provided in Table 1. Sample size is given in parentheses, with the first value relating to rows 1–10 (pH through Na) and the second value relating to rows 11–14 (Total Cu through Total Zn).

Morrison and Manner 2005). The parent C horizons are derived from limestone rock or sediments from corals, forams (Foraminifera spp.), green macroalgae (*Halimeda* spp.), coralline algae, and other invertebrate shells and have a mineralogy dominated by calcium carbonate (Barry and Rayment 1997, Yamano et al. 2000). Soil development on coral islands is determined by interactions between the parent materials and the surrounding marine environment (Gourlay 1988, Gessel and Walker 1992, Rodgers 1994). Most coral islands feature freshwater or brackish lenses between 1.5 and 2 m below the surface (Wiens 1962, Gessel and Walker 1992, Deenik and Yost 2006). Such shallow-water table lenses limit soil development to <2 m depth. Depth and salinity of the freshwater lens is determined by island size and elevation, with climatic influences creating seasonal fluctuations (Wiens 1962).

The upper part of the C horizons (white sand) retained very low levels of nutrients, indicating frequent washing by tidal fluctuations of the freshwater lens. The freshwater lens salinity often increases during dry seasons, when rainfall constancy and amounts are more critical (Stone 1951, Wiens 1962). However, during higher rainfall periods, the leaching of nutrients through the soil profile is enhanced (Wiens 1962). The salinity of the freshwater lens in island interiors has been measured as up to 50% of the salinity of seawater (Gessel and Walker 1992).

A horizons form as a result of nutrient deposition on surface soils from the sea (dissolved nutrients), the atmosphere (aerosols), seabirds (guano), and organic matter (vegetation) (Morrison 1990, Gessel and Walker 1992, Rodgers 1994). The character of the A horizon in a particular area is determined by the placement in the landscape (exposure and shelter) and vegetation type (biomass), as well as the interactions with wildlife (seabirds). Variances in soil color and depth of A horizons are also believed to be dependent on vegetation type, surface coverage, and slope position (Morrison and Manner 2005).

As a result, coral cay soil fertility as well as soil structure is strongly related to plant community biomass and the rate of organic matter decomposition (Morrison and Manner 2005). Our study shows strong evidence that the structural development and nutrient enrichment of soils at CHNNR are related to the succession of plant communities. The physical and chemical properties of the various A horizon soils sampled at CHNNR act as a proxy for coral cay age and development.

The young age of the soils at the seashore and the low vegetation biomass of the ephemeral herblands, as well as the limited interactions with seabirds and the high exposure to wind and waves, is not conducive to the development of deep and fertile A horizons. The seashore and beach ridge areas with limited plant biomass had low organic carbon contents and low values of other nutrients. Disturbance by marine turtles during the nesting season also limits establishment of vegetation (Batianoff et al. 2009).

The beach ridge soils, though farther from seashores, are still subject to the dynamic physical environment. The variable grain sizes throughout profiles indicate the constant deposition of new sediments and wind sorting. The grain size variability and deeper profiles of wind-exposed and immature *Pisonia* soils are also likely due to the burrowing activities of wedge-tailed shearwaters (*Puffinus pacificus*), which were observed in moderate numbers in these communities. Along the exposed shores, *Argusia argentea* forms narrow strips of woody vegetation one to two shrubs wide. The majority of arboreal nesting species (Red-footed Booby [*Sula leucogaster*], Black Noddy [*Anous minutus*], Great Frigatebird [*Fregata minor*], and Lesser Frigatebird [*F. ariel*]) inhabit the seashore and beach ridge *Argusia* areas. Brown Boobies and Red-tailed Tropicbirds (*Phaethon rubricauda*) nest beneath shrubs.

The island interiors at CHNNR had the highest fertility (Tables 1–3, Figure 2) and greatest structural development of soil profiles and featured more dense woody vegetation (Batianoff et al. 2009). For example, mean phosphorus content for A horizon soils of the interior was 882 mg/kg, a concentration considered very high even for agricultural standards (Rayment and Bruce 1984, Moody and Bolland 1999). A sample of phosphate rock collected during surveys contained a Colwell-P concentration of 6,024 mg/kg. This is consistent with the Jemo series of soils described by Fosberg (1954) from under *Pisonia grandis* forests. Mean potassium levels within the tissue of a mature *Pisonia* sample recorded 1.92 cmol (+)/kg, also considered high by agricultural standards (Rayment and Bruce 1984, Gourley 1999). Coral cay soils have no clay, and organic matter is crucial for the retention of water and nutrients within the soil profile (Wiens 1962, Morrison 1990, Gourley 1999, Deenik and Yost 2006). The accumulation of organic matter is considered the most important process for soil formation at Nauru (Morrison and Manner 2005).

High nutrient concentrations in the interior are due to the influence of more long-term deposition of seabird guano, higher organic material from woody vegetation, and the cycling of organic litter from soil surfaces to the rest of the profile with digging by burrowing wedge-tailed shearwaters. Bioturbation processes increase the infiltration of water and incorporation of organic matter through increased porosity and the mixing of litter from both the surface and the root biomass (Field and Little 2008). The higher nutrient values in the interior soils reflect the higher biomass of woody plants (Rodgers 1994), which in turn delivers higher organic matter to the soil profile. Forests provide nesting habitat for seabirds, which then input extra nutrients into the soil through guano (Woodroffe and Morrison 2001). The greater depth of A horizons, the highest amounts of soil organic matter (indicated in the field by their darker color) and other nutrients, and the highest proportions of fine to very fine grains reflect the greater stability of the soils on the interior plains at CHNNR. The assimilation of nutrients from the relatively fertile interior soils is enhanced by mycorrhizae on *Pisonia grandis* roots (Ashford and Allaway 1982, Sharples and Cairney 1998). Vesicular-arbusicular mycorrhiza associations between plant roots and fungi have been shown to greatly improve the uptake of minerals such as zinc, phosphorus, and potassium, especially when supplies are deficient such as at CHNNR (McGee 1989, Chambers et al. 2005, Fomina et al. 2005).

Activities of the burrowing wedge-tailed shearwaters (*Puffinis pacificus*) within the *Pisonia* forests have an important influence on soil development on coral cays (Bancroft et al. 2005). According to Jones et al. (1994), these birds are considered "ecosystem engineers" because they displace at least 11.5 t ha^{-1} (8.5 m^3 ha^{-1}) of soil annually (Jones et al. 1994). Bancroft et al. (2005) estimated annual soil displacement of at least 22.0 t ha^{-1} (16.3 m^3 ha^{-1}). This bioturbation is an important regolith process, comparable with soil formation, and enriches the A horizon with nutrients captured from aerosols, marine debris, guano, and plant litter from the marine ecosystem (Field and Little 2008). However, for bioturbation to occur, suitable habitat for wedge-tailed shearwaters is required (i.e., well-compacted soils with a high proportion of fine roots that stabilize burrows). Although nutrient enrichment by seabirds may be substantial (Ellis 2005), nutrient availability to plants may be low if other factors are limiting uptake, such as the high carbonate content, soil pH, and moisture-stress (Morrison 1990). For example, the availability of zinc is markedly reduced in alkaline soils especially when phosphorus concentration is high (Armour and Brennan 1999), and both of these conditions are exaggerated on coral cays.

Soil organic carbon is determined by distance from the shore and vegetation productivity (Gessel and Walker 1992, Morrison and Manner 2005, Deenik and Yost 2006). Organic carbon was highly correlated with N and Ca in the Marshall Islands and less highly correlated with other soil nutrients (Deenik and Yost 2006). Organic carbon concentration was most highly correlated with soil N values ($R^2 = 0.74$). Moderate correlations ($R^2 < 0.5$) were also found for Ca and Mn with organic carbon concentration. Given the neglible clay content of these soils, increases in organic carbon generally lead to greater water storage and high nutrient content (Stone et al. 2000).

High alkalinity has been shown to retard the uptake of Zn, Mn, Fe, and other nutrients by plants (Armour and Brennan 1999, McFarlane 1999, Uren 1999). Organic carbon reduces soil pH values; however with the lowest recorded value 8.0, nutrient uptake is likely to be restricted (Stone 1951, Morrison 1990). The high calcium levels of coral cay substrates have also been shown to affect potassium levels, which are generally very deficient (Morrison 1990, Stone et al. 2000). N deficiency is also reported as common in atoll soils (Deenik and Yost 2006).

In this study, we found that the organic carbon values were at the lower end of the range recorded for atoll soils in the Pacific Ocean (Morrison 1990); however the nutrient levels of CHNNR were twice as high as levels recorded at Capricornia Cays in central Queensland (G.N.B., unpubl. data). Climate is also an influence, because organic matter accumulation is better in wetter soils. Wetter climates promote and sustain denser vegetation, giving higher levels of organic matter (Deenik and Yost 2006).

CONCLUSIONS

The soils of the CHNNR cays exhibit the characteristic features of coral cay soils: an absence of clay, alkaline conditions, low potassium and nitrogen concentrations, and the overabundance of phosphorus. Soil fertility increases from the seashore to the island interiors, which feature woody vegetation with higher biomass. The parallel development of soils with increasing vegetation structure shows that high vegetation biomass assists in soil development. This is through the input of organic matter from the vegetation but enhanced by the input of excreta from nesting and/or burrowing seabirds. The depth of soil development is enhanced by the burrowing wedge-tailed shearwaters' activities but is limited by the shallow water table. A seasonally high fresh/brackish water table causing periodic "washing" is probably responsible for the formation of the abrupt white C horizons.

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