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Soils of low elevation coral structures

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Abstract
The small islands of the South Pacific region, like many other parts of the world, arc (~\I\j riencing population growth and, more particularly, the movement of people into)11,1I1!1 urban centres. Most Pacific cities, especially the capitals of regional countries, arc locili ",I in naturally protected coastal waterways. This is a historical situation, arising from III,' need to provide protected deep-water harbours for ships, the main form of internaliol\,d travel and trade. These waters are protected by offshore barrier reefs, by islands or by ril(,1 ine deltas. However, these protective mechanisms also have the effect of limiting mix!II): of near-shore and open-ocean waters (Viles and Spencer, 1995). This provides an OPP(l1 tunity for problem materials, derived from human activities, to accumulate in the neill shore waters and the marine zone with which most people interact.

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Coastal lagoon management in three Pacific island situations: Is scientific knowledge used effectively?

Introduction

The small islands of the South Pacific region, like many other parts of the world, are experiencing population growth and, more particularly, the movement of people into major urban centres. Most Pacific cities, especially the capitals of regional countries, are located in naturally protected coastal waterways. This is a historical situation, arising from the need to provide protected deep-water harbours for ships, the main form of international travel and trade. These waters are protected by offshore barrier reefs, by islands or by riverine deltas. However, these protective mechanisms also have the effect of limiting mixing of near-shore and open-ocean waters (Viles and Spencer, 1995). This provides an opportunity for problem materials, derived from human activities, to accumulate in the near-shore waters and the marine zone with which most people interact.

Urbanised coastal lagoons represent one of the most threatened global environments. These water bodies, as a result of their adjacent populations, are subjected to human impacts from habitat modifications, poor waste management, industrial discharges, storm-water runoff and shipping activities. In some cases, the lagoons are approaching ecological collapse. The ecological behaviour of these water bodies is difficult to determine as they are constantly undergoing change due to the effects of tides and river inputs. The management of coastal lagoons is often complicated by the multi-jurisdictional nature of the legislation that frequently applies to them.

It is a common saying that 'you cannot manage what you cannot measure'. There has therefore been a significant global effort to gather scientific information about coastal areas with the stated goal of ensuring that decision-making is based on a firm knowledge base. The knowledge base should focus on ecological conditions and processes in coastal water bodies and the potential impacts of humans on them. It is also important to emphasise that planning and management should be integrated and multi-dimensional in nature, and should accommodate the technical, social and economic components of such a complex undertaking. Despite this aspiration, a number of researchers have found that an integration of science, policy and management is lacking (e.g. Hoare, 2002; Kay and Alder, 2005; van Kerkhoff, 2005; Thompson, 2006). In this context, the Pacific islands have not received much attention.

The global effort to provide management regimes for coastal lagoons

Phase 1: Evaluation of ecological processes and community expectations to create a scientific understanding of the main factors controlling lagoons and the expectations and goals of the people using them.

Phase 2: Development of a cooperative management plan using information gathered in Phase 1. This needs to be flexible and adaptable as new information becomes available.

Phase 3: Implementation and monitoring to determine whether the plan is achieving its goals.

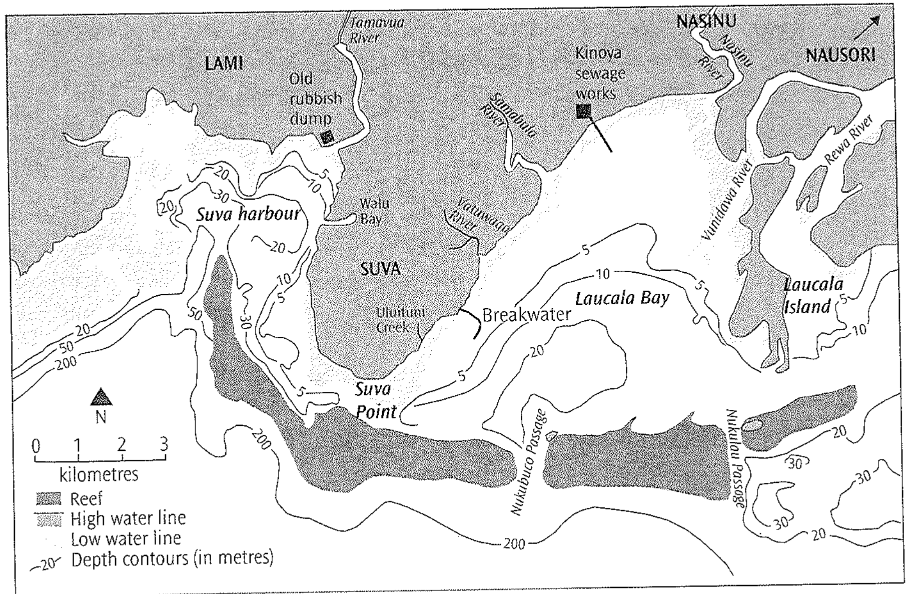
This chapter reviews the situation in three Pacific localities, Suva Lagoon in Fiji, Fanga'uta Lagoon in Tonga and Funafuti Lagoon in Tuvalu, by examining what is being done about the management of these areas, what scientific knowledge is available and how it is being utilised therein.

Suva Lagoon

Suva Lagoon, located in south-east Viti Levu, the largest island of the Fiji group, consists primarily of Laucala Bay and Suva Harbour (Figure 15.1).

The lagoon is one of the most commercially important water bodies in the South Pacific region. Since Suva (at 178°43'E and 18°15'S) was established as the capital of Fiji in 1882, this lagoon has been an intensive shipping centre, acting as both a national and regional hub for transport and trade. The development of Suva as a major commercial centre in the Pacific islands has also led to a rapid expansion of the local population (see

Figure 15.1. The Suva Lagoon System, Viti Levu, Fiji



the present day elevation of the prehistoric cyclone deposits, and the imprecision in calculating the wave run-up during the prehistoric event. Nott and Hayne (2001) and Nott (2003) recognize these possible caveats, and note that sea levels have fallen, due to hydroisostasy, over the period of the prehistoric record. However, if this is taken into account in the analysis of the intensity of the prehistoric storms, the older deposits (coral shingle ridges deposited between 3,000 and 5,500 years BP) should be higher in elevation than the younger more shoreward ridges. Topographic surveying of the ridges shows that this is often not the case. The coral shingle ridges compact over a period of time, and there is evidence also to suggest that the ridge crests have been overtopped by storm surge and waves, further reducing their height since deposition. Nott and Hayne (2001) suggested that this reduction in elevation of ridge crests would likely more than compensate for the effects of sea-level fall since termination of the Holocene transgression. In addition, if sea-level fall was taken into account it would suggest that the ridges deposited since approximately 2,500–3,000 years BP, or since sea levels stabilized close to their present height, would have been deposited by more intense cyclones. Such an interpretation would suggest that these storms were becoming more intense with time. Independent studies of other ridge sequences (sand and shell ridges) throughout the region and also studies using isotopic signatures of tropical cyclones in limestone stalagmites suggest that there has not been a substantial increase in the intensity of tropical cyclones in this region to the present day (Nott, 2006; Nott et al., 2007).

Summary

Coral shingle ridges form where coral reefs lie close to shore. Waves during intense storms or tropical cyclones break fragile coral species into fragments that can accumulate as a (shingle) deposit landward of the high tide mark or as an offshore deposit that may or may not be transported landward at a later date. The onshore deposits of coral shingle are shaped into a ridge by the marine inundation constituting a storm surge, tide, wave set-up, wave action and wave run-up. Successive ridges are deposited with time so that multiple shore parallel ridges can eventually form into a ridge plain. Each new ridge is deposited seaward of the previous ridge and often, but not always, one ridge can be deposited during a single tropical cyclone event.

The ridge plains can provide a valuable record of the frequency and intensity of tropical cyclones for that region over several millennia. Recent examination of several ridge plains along the Great Barrier Reef region show that these ridges are often emplaced during intense tropical cyclones and these events occur on an average every two to three centuries. This is an order of magnitude greater than that suggested by the short historical record of these events in this region.

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SOILS OF LOW ELEVATION CORAL STRUCTURES

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Definition and introduction

Low elevation coral structures include atolls (essentially reefs of variable thickness built up by corals (and other organisms) resting on a volcanic base) and reef platforms having an elevation generally less than 5 m above mean sea level. They are unique to tropical and certain subtropical oceans since the reef-building organisms require water temperatures in excess of 22°C. These features are

widespread in the central and south Pacific, the central Indian Ocean, and parts of the Caribbean (Lesser Antilles and Bahamas), with a few examples in the Atlantic Ocean. Some countries consist entirely of low elevation coral structures, e.g., Kiribati, Maldives; others contain atoll groups, e.g., the outer Islands of the Seychelles; and some countries consist of mainly volcanic islands with a few isolated atolls, e.g., Ontong Java in the Solomon Islands.

Cumberland (1956) has identified six types of island (in the Pacific) partly or wholly associated with coral reefs, but in this chapter focus will be on more or less continuous emerged or slightly emerged calcareous reefs, with minimal comment on any non-calcareous structures present. The main structures will be low atolls (reefs surrounding a lagoon) where the maximum height of the emerged portion (usually less than 5 m) is made up of accumulations of broken reef material deposited by storms, or emerged coral platforms with no associated lagoon. Low-lying fringing reefs occur around many tropical islands, but these will not be considered here.

The widely varied nature of low elevation coral structures makes generalization difficult, but many have some features in common. They usually have limited land area and few natural resources. Such islands, particularly in the eastern Pacific, have limited supplies of fresh water and many are subject to prolonged droughts. The groundwater is often brackish (slightly salty). This peculiar environment has resulted in the development of a specialized flora – a plant community adapted to saline, alkaline soils, subject to water stress and salt spray. The natural vegetation is mostly strand species recruited from the Indo-Pacific or similar strand flora of the shores of islands of all kinds in the tropics. The agriculture is also rather specialized, often being restricted to coconuts, pandanus, breadfruit, and such root crops as *Colocasia* and *Cyrtosperma* grown in pits dug down to the groundwater table.

The properties of coral soils are, in general, dominated to a large extent by the calcareous nature of the parent material, whether or not this is mixed with volcanic materials. The soils tend to be shallow, alkaline, and coarse textured, having carbonatic mineralogy except where there have been relatively recent additions of volcanic material. The soils are generally of very low silica content. The fertility is highly dependent on the organic matter content. Organic matter can be high in undisturbed soils under natural vegetation, but can decrease dramatically as a result of inappropriate cultivation techniques, e.g., land clearance and weed control by fire.

As for all tropical soils, organic matter in coral soils performs an important role in the concentration and cycling of plant nutrients. In coral soils, however, a second role – that of moisture retention – is equally important. Since low coral structure soils are frequently sandy and excessively well drained, the moisture retention in the absence of organic matter is very low (see Morrison, 1990); the total amount of water retained often remains low, and plants are subject to water stress unless the rainfall is high and relatively constant or they can tap the freshwater lens.

Soil forming factors on low elevation coral structures

Soil forming factors include climate, parent material, relief, hydrology, flora (and fauna), time, and humans, although these are not independent of each other. For low elevation coral structures, many of these factors are relatively constant, but some important distinguishing features occur. For example, the climate consists of two components – temperature and rainfall. The climate for the areas of interest is relatively constant with mean annual temperatures ranging from about 22 to 35°C, while the rainfall (as expressed in mean annual terms) can vary from about 700 to over 3,000 mm/yr. The impact of rainfall variations produces significant differences in the vegetation type and quantity, and this in turn leads to different amounts of organic matter being available for incorporation into soils. The result is that soils in similar geomorphological positions in "wet" and "dry" locations can be quite different (see Figure 1).

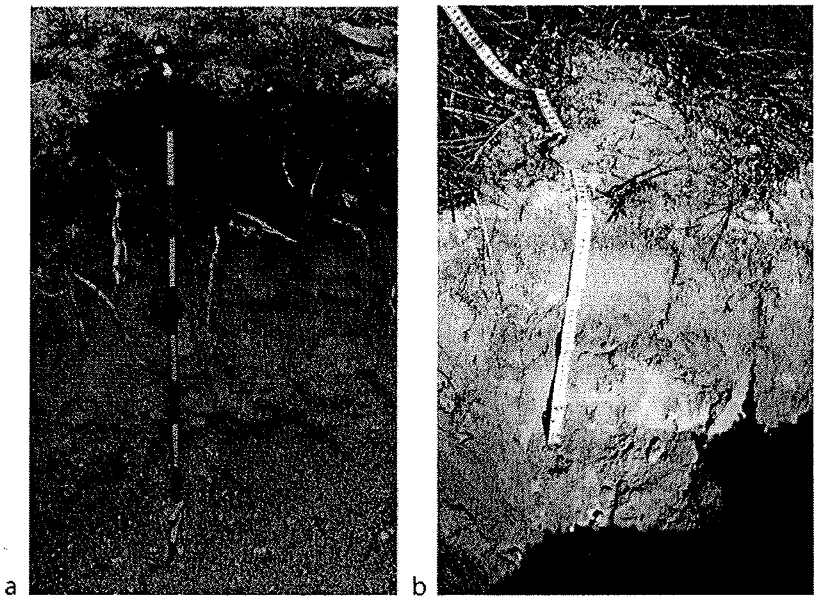
As noted above, the parent materials are dominated by calcareous solids derived from reef growth, with varying additions of ash, scoria, pumice, and guano. The materials are generally coarse-grained varying from accumulations of boulders and cobbles to materials dominated by sand with some silt material. Clay size materials are not abundant is these soils. Relief is not normally a key factor for low elevation coral soils, as the elevations are <10 m and slopes are usually very gentle.

Hydrology can be a significant factor, as the position of the groundwater table can influence soil properties, use, and management. In addition, the freshness of the groundwater may have an impact on the vegetation diversity and density and thus impact on organic matter availability for soil incorporation. As noted above, vegetation density and diversity are highly rainfall dependent, although the diversity is generally quite limited. The influence of fauna is limited with crabs digging burrows, pigs digging in soils, birds depositing guano, and some introduced species such as rats and goats damaging the vegetation. Time is also relatively constant for coral soils, as most low elevation structures have been formed in the last 5–7,000 years (Woodroffe, 2008). The influence of humans varies from place to place mainly by changing the vegetation from native species to coconut plantations or growing of other food crops.

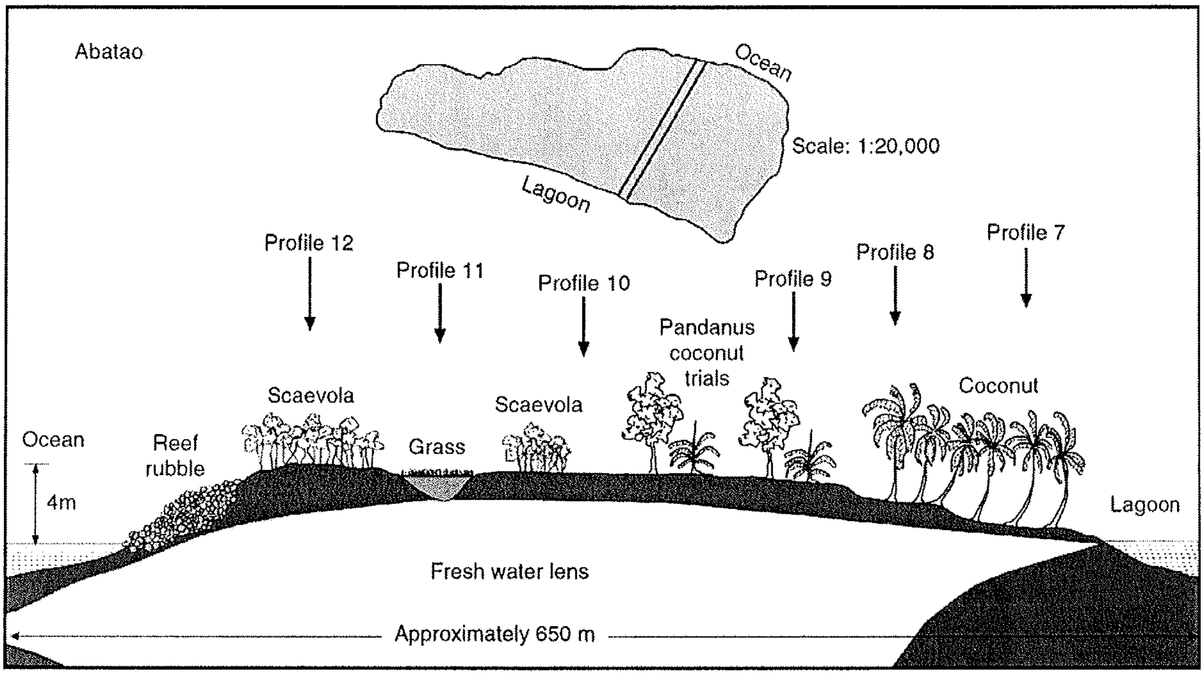
Diversity of low elevation coral soils

Given the limited variation in the soil-forming factors outlined above, it might be considered surprising that there are many variations in coral soils; this is not, however, the case. As an example, the soils of the islet of Abatao in Tarawa, Kiribati, will be described (Morrison and Seru, 1986). The survey work relating to this islet was done in the 1980s, while most of the islet was the Kiribati Government Agricultural Research Station and minimal human urban impact had occurred (see Figure 2).

On moving from the Ocean to the Lagoon, a number of different profiles were observed. Close to the ocean side,



Soils of Low Elevation Coral Structures, Figure 1 Comparison of soils in stable mid-island positions in different rainfall locations (**a**) Tarawa (wet) and (**b**) Kiritimati (dry).



Soils of Low Elevation Coral Structures, Figure 2 Cross-section of the central part of Abatao Islet, Tawara, Kiribati (modified from Morrison and Seru, 1986; soil profiles are described in the text).

Profile 12 showed minimal profile development. There was a thin surface horizon showing some organic matter accumulation, but little or no structure. This surficial layer overlay a thin, stony sand layer which, in turn, overlay coral rubble. Examination of the surrounding area indicated that the profile described represented the maximum soil development in that part of the islet. Frequently patches of coarse light grey (10 YR 8/2 dry) sand up to 30 cm thick were observed with no evidence of soil development. On moving inland, an area of soils showing significantly different vegetation was observed (dominance of grasses). This Profile 11, consisted of a silty dark brown

surface layer (10–15 cm) overlying coarse sand to a depth of at least 1 m. The surface layer was dominated by grass roots. The lower portions of the profile (below 40 cm) were permanently saturated with groundwater that moves under the influence of the tides to within 10 cm of the soil surface), and on digging into the layer below 40 cm, there was a sulfurous odor.

Profile 10 lies further toward the lagoon, and has a well-developed A horizon varying from 15 to 20 cm in depth overlying a CA horizon with minimal organic content and soil structure to about 30–35 cm. There is again evidence of groundwater variation, but the maximum depth of movement up the profile is about 75 cm. Further to the lagoon side, Profile 9, lies in a mid-islet ridge position in slightly convex, undulating terrain. This profile, formed on sand that changes from medium to coarse with depth, has a clearly developed A horizon, 15–20 cm deep with weakly developed granular structure. This organic-rich (10% organic carbon) layer overlies structureless medium and coarse sand to a depth of more than 1 m, with no contact with the groundwater being observed.

Profile 8 lies on a second sand ridge up from the lagoon, and has a clearly developed A horizon with more than 10% organic carbon to a depth about 10 cm. This overlies a lower organic content layer (approximately 10–20 cm depth), and then there is a buried A horizon (approximately 20–30 cm depth) with significantly lower carbon content (1.6%), which in turn overlies at least 1 m of stony coarse sand. The buried A horizon resembles surface soils in more disturbed parts of Tarawa (Seru and Morrison, 1985). On the sand terrace closest to the lagoon lies Profile 7. This has a very weakly developed soil profile, showing a thin (<10 cm) A horizon, with a layer below this showing minimal organic matter incorporation to a depth of 30 cm, lying on top of coarse sand to a depth of more than 1 m. Groundwater influences were noted from about 80 cm down and the groundwater (slightly brackish) was contacted at about 90 cm.

Thus, on moving across an islet of about 650 m width, there is evidence of five different soils, with the properties being influenced by depth to rock, particle size of dominant materials, organic matter content, soil structure, and influence of groundwater. In terms of soil classification (Soil Survey Staff, 1975, 1999), all the soils would be Entisols (or Regosols or Lithosols), i.e., recent soils with minimal profile development, with separation at different hierarchical levels depending on the soil properties listed above.

Near the southern island of Abatao, a profile was observed that met the requirements for classification as a Mollisol (Soil Survey Staff, 1999) in that it had a deep (>50 cm), dark colored (Munsell color values 3 or less), high base status (base saturation >50%) surface layer having some structural features. This is most unusual, as Mollisols are typically the rich, productive soils of the Great Plains of North America. Their presence on Abatao further confirms the wide range of properties that can be found on low elevation coral structures.

Another area of Abatao also showed the presence of the Jemo series soil first identified by Fosberg (1954, 1957). These soils have laminated subsurface layers formed of carbonate materials cemented by phosphatic material believed to be derived from reaction between guano from birds nesting in the surrounding Pisonia trees and the underlying carbonate substratum. This genetic process has yet to be confirmed experimentally.

Such diverse combinations of soils have been observed on other low elevation coral structures in other islands of Kiribati (Jenkin and Foale, 1968; Woodroffe and Morrison, 2001; Morrison and Woodroffe, 2009), Tuvalu (Morrison 1990), Cook Islands (Bruce, 1972), Marshall Islands (Stone, 1951; Fosberg, 1956), Solomon Islands (Wall and Hansell, 1976), French Polynesia (Tercinier, 1956, 1969; Jamet, 1985), Hawaii (Foote et al, 1972), and Maldives and Aldabra (Spaull, 1979).

Soils derived from carbonate materials have a wide range of uses despite their limitations. Such materials are the only soils in several island groups (Tuvalu, Maldives) and are common soils in other groups (Cook Islands, several Caribbean Islands). Inhabitants of these islands have developed agricultural practices to produce a wide range of crops on such soils. These include coconuts, pandanus, breadfruit, citrus, and vegetables, with the specific practices and crops dependent on local factors, including the rainfall pattern. The use of mulches and pits dug down to the water table (e.g., see Figure 3) are among the practices utilized to achieve significant production (Small 1972; Chase 1992).

Physicochemical and mineralogical properties of low elevation coral soils

Physicochemical properties and plant nutrition

Many of the properties of low coral structure soils are related to the organic matter content of the topsoil. Topsoil organic carbon values vary from about 1% to 20% depending on the age of the soil, the vegetation, climate, and soil management. In subsoils, organic carbon values

Soils of Low Elevation Coral Structures, Figure 3 *Cyrtosperma* sp. ("Babai") planted in the water table in a pit dug into soils on Bonriki, Tarawa, Kiribati.

are always low (<0.5%) unless there has been considerable soil disturbance, e.g., due to the digging of *Cyrtosperma* pits. Nitrogen values usually follow the organic contents closely, and C:N ratios usually range from about 5–15 for topsoils to 8–20 for subsoils. Water retention against 1500 kPa (15 bar $\simeq$ wilting point) pressure is often closely correlated with organic matter content; values of 5–25% have been obtained for topsoils, while for subsoils the values are always low (1–4%). Cation exchange capacity is also closely related to organic matter for topsoils, with values in the range 6–60 cmol/kg, while the values for the sandy calcareous subsoils are usually less than 5 cmol/kg. Exchangeable magnesium values are generally around 3–8 cmol/kg, sodium contents are about 0.2 cmol/kg, unless there has been saltwater intrusion, but exchangeable potassium values are always low (<0.1 cmol/kg) unless there are substantial organic matter contents.

The calcium carbonate content is always high, ranging from 55% to 90% for topsoils and usually being greater than 90% for subsoils. This dominance of the environment by carbonate leads to high pH values; pH (water) values for topsoils are usually in the range 7.1–8.5 and for subsoils 7.5–9.0; pH ($CaCl_2$, 0.01 mol/L) values usually range from 7.0 to 8.0 for topsoils and from 7.5 to 8.0 for subsoils. Extractable phosphorus (Olsen et al., 1954, procedure) values are generally low (5–15 mg/kg) for topsoils and very low (<1 mg/kg) for subsoils, but can be higher (>50 mg/kg) at sites with guano accumulation. The total phosphorus contents vary considerably, ranging from 500 to 50,000 mg/kg for topsoils and from 100 to 5000 mg/kg for subsoils. Total sulfur values are fairly constant at around 4000 mg/kg.

Thus it can be seen that in the low coral islands the soils are alkaline, with most of the soil "fertility" related to the accumulated organic material. Under these conditions, nitrification is favored but toxic accumulations of nitrate are unlikely unless there are unusual hydrological conditions. Volatilization of nitrogen as ammonia from ammonium and urea fertilizers will occur, with particularly large losses occurring if these materials are not incorporated. The availability of phosphorus is controlled by calcium activity; much fertilizer P will be precipitated as calcium phosphates or adsorbed on the surfaces of the carbonates. K availability is decreased by high Ca and/or Mg levels; the low levels of K in the coral limestone parent materials mean that this element will always be in short supply.

Supplies of available Ca and Mg are plentiful in low elevation coral soils but imbalances with K and micronutrients cause significant plant nutrition problems. Sulfur is usually available in small quantities from solution of limestone and from rainwater, but if crops with large S requirements are grown intensively, external additions will be required. Solubilities of Cu, Fe, Mn, and Zn decrease with increasing soil pH. Cu deficiencies are less related to soil pH than to the other micronutrients. Zn forms relatively insoluble zincates in calcareous soils and Fe uptake is reduced by high bicarbonate concentrations in the soil solution. With the relatively low contents in coral limestone, all of these elements are likely to be highly deficient in low elevation coral soils (Deenik and Yost, 2006; Morrison, 1992).

Mineralogy

As the soils of the low elevation coral structures are dominated by calcium carbonate, the dominant minerals are calcite and aragonite, which are the common forms of calcium carbonate deposited by reef-forming and reef-living organisms. Calcite contains varying amounts of magnesium (substituting for calcium in the mineral structure). If the magnesium content is >1%, the mineral is described as high magnesium calcite (HMC); other forms are referred to as low magnesium calcite (LMC). Variations in the relative aragonite/HMC/LMC contents depend on the origin of the carbonate material base for the soils. For example, Hammond (1969) found on Kiritimati (Kiribati) that aragonite was the dominant component, this mineral being present in the greatest amounts in the coarse fragments. Calcite was more abundant where foraminifera dominated the deposits. Most calcite was high in magnesium but LMC was present mainly in the coarse sand, very fine sand, and silt fractions. Aragonite, which forms the hard parts of corals or algae, and HMC from algal skeletal material, are more abundant in most shallow water marine environments than LMC, but among deep sea oozes rich in calcitic foraminifera and coccoliths, the more thermodynamically (under Earth-surface conditions) stable LMC is the predominant phase (Chave, 1962). In soils where guano deposits have been incorporated, apatite is usually found.

Conclusions

Soils of low elevation coral structures around the globe display many similarities. The soils usually show minimal profile development, and are highly calcareous and heavily dependent on organic matter for moisture, nutrient retention and availability. Despite the limited variation in soil-forming factors, a range of soil profiles has been observed with organic matter content, particle size, depth to rock, and the influence of groundwater, leading to differences in profile features and potential utilization of the soils. The soils are usually classified as Entisols (Regosols or Lithosols), the major differences being in the soil moisture regime and the particle size class. Micronutrient and potassium deficiencies are encountered widely.

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Cross-references

Atolls
Coral Cays, Vegetational Succession
Low Wooded Islands
Vegetated Cays

SOLUTION PROCESSES/REEF EROSION

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Definition

Calcium carbonate is soluble in water containing carbon dioxide, and thus, there has been focus on the chemical processes that take place in water, given the term "solution processes." However, much erosion of calcium carbonate found in reef situations is actually effected by biological and mechanical processes, hence the wider term "reef erosion" is used to cover the range of processes involved.

Solution processes

Much interest has been expressed in the question of whether or not limestones can be dissolved in seawater. The crux of the issue is that chemical analyses of surface seawater in open areas around reefs usually show that the waters are not frequently acid (with a pH often around 8.2) and are saturated with respect to calcium carbonate. If this is so, then it is difficult to envisage how calcium carbonate can move into solution in seawater from limestones (conversely, of course, it helps facilitate explanations of the formation of carbonate rocks by processes involving chemical precipitation). However, in intertidal situations, delicate, sculptured rock surface occur which, by analogy with freshwater situations, would appear to owe their origin to solution processes. An observer might conclude that these surface forms are produced by processes other than solution (for example, salt weathering or biological action), and the analogy with freshwater solution forms is both misleading and fortuitous. Alternatively, the conclusion can be that there are actually solution processes which facilitate the dissolution of limestones in