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A Temporal Sequence (Chronosequence) of Soil Carbon and Nitrogen Development after Phosphate Mining on Nauru Island[1]

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ABSTRACT: Ten composite soil samples (0–15 cm depth) were collected from abandoned phosphate-mined sites on Nauru Island (Central Pacific) and analyzed for % organic C and % N. The samples represent a temporal sequence (chronosequence) of soil development spanning < 55 yr. The increase of % C and % N was fairly rapid. In recently mined sites (< 1 yr) the values of % C were between 0.41 and 0.48, and those for % N were between 0.03 and 0.04. Fifty-five years after mining, the values of % C and % N were 4.56 and 0.33, respectively, and comparable to the amounts found in undisturbed Lithic Haplustolls, Typic Haplustolls, and Lithic Ustorthents epipedons. These changes in soil properties are considered to be a function of time and the accompanying seral development of vegetation (particularly the fern cover of *Nephrolepis biserrata* and *Polypodium scolopendria*), because parent materials, climate, and other factors of soil formation are considered to be constant. Rate of soil development is faster in the unconsolidated sands and limestone rubble of the pit bottoms and slower on the dolomitic limestone pinnacle surfaces.

AT ANY POINT IN TIME, a soil is the result of the complex interaction of soil formation factors. Jenny (1941) expressed this relationship simply:

Soil = f(climate, biota, topography, parent material, time, ...)

An underlying assumption was that if all state factors save one were held constant, the changes in soil properties could then be ascribed to the varying factor. These conditions, however, have rarely been met, and there have been inherent difficulties in the interpretation of data (Jenny 1949, 1958, Crocker 1952, Stevens and Walker 1970, Birkeland 1974).

Since 1906, phosphate rock has been open-caste mined on Nauru, a small upraised coral limestone island in the Central Pacific. As a result of the mining process, a parent material of dolomitic limestone pinnacles and residual phosphatic material has been exposed to the processes of weathering and soil formation. In the absence of any attempt at land rehabilitation and human activities in the abandoned mined areas, these form a topographically rugged and almost impenetrable landscape of pits and pinnacles. These surfaces have revegetated naturally and may be considered as a temporal continuum or chronosequence (Stevens and Walker 1970) in which soil and vegetation development occurs as a function of time. A chronosequence is defined as "a sequence of soils developed on similar parent materials and relief under the influence of constant or ineffectively varying climate and biotic factors, whose differences can then be ascribed to the lapse of differing increments of time since the initiation of soil formation" (Stevens and Walker 1970). As will be shown in the present paper, parent material, climate, and topography on Nauru can be considered to be constant. The following information represents a temporal sequence of soil development attributed to time and the accompanying seral development of vegetation. In this context, time and vegetation are synonymous,

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and their particular effects on soil development are inseparable.

This paper presents the results of soils analyses of percentage of organic carbon (% C) and percentage of nitrogen (% N) from the mined areas of Nauru, spanning a time sequence of >55 yr. The changes in soil properties are mainly considered to be a function of time and the accompanying seral development of vegetation. The implications of this study are also discussed.

Nauru is located at 0° 32′ S and 166° 56′ E and measures 22.6 km^2 in area. Physiographically, the island can be divided into a narrow coastal strand and its fringing reef, a coral limestone escarpment that rises 30 m to the central plateau, and the central upraised plateau where the phosphate deposits are located. The central plateau (known locally as "Topside") is composed of rocks containing high-grade fluoro- and hydroxyapatite that overlie a dissected dolomotic limestone (karstic) base. The highest point of the plateau rises to 70 m.

The total annual rainfall for the island ranges between 104 and 4572 mm, with an annual average of ca. 2003 mm (Carter 1981). Droughts are not uncommon, and several lasting more than 12 months have occurred in this century. The average annual temperature is 27°C, with a seasonal variation of 1°C. Assuming an evapotranspiration rate of 4 mm/day, Nauru soils experience, on average, a moisture deficit for about 5 months of the year (Morrison 1987 [unpublished report on the soils of Nauru]). Given the small size of Nauru, it is unlikely that there is any spatial variability of climate; the conditions of temperature and precipitation are fairly uniform throughout the island, particularly on the upraised plateau.

The island's vegetation is strandlike in character and may be classified into the following types: (1) coastal strand vegetation modified by human activities and settlement patterns; (2) a *Ficus prolixa*–dominated forest on the escarpment; and (3) the pre-mining plateau forest, which covered 90% of the island's area and is dominated by *Calophyllum inophyllum*, with *Guettarda speciosa*, *Morinda citrifolia*, and *Lantana camara* the subdominant species; (4) successional or seral vegetation on the abandoned mined sites, characterized by pantropical herbs and pioneer species during the early stages of succession and later by indigenous shrubs and trees common to Pacific strand communities (Manner et al. 1984, 1985).

The rate of revegetation is variable and closely associated with substrate depth. The pit bottoms, which often contain a thick (i.e., 20 to 30 cm) matrix of phosphate sands and coral limestone rubble, are fairly quickly revegetated by a wide range of pioneer species, whereas relatively few species can colonize the bare and massive pinnacle surfaces. It has been suggested that *Ficus prolixa*, because of its growth habit, has a comparative advantage over other species and will become the dominant species of the mined plateau (Manner et al. 1984).

The undisturbed plateau soils are classified as Lithic Haplustolls, Typic Haplustolls, and Lithic Ustorthents mainly derived from phosphatic materials and, to a lesser extent, dolomitic limestone (Morrison and Manner, in prep.). These soils are coarse-textured sands and loams, with weakly to moderately developed crumb or granular structure in their surface horizons and very weakly developed structures in their subsurface horizons. Moisture availabilty is generally low and moisture retention against 1500 kPa suction was frequently less than 10%. Soil pH (in water) ranged between 6 and 8.0, free $CaCO_3$ between 2 and 24%, and CEC between 12 and 61 cmol/kg. % C and % N in the surface horizons ranged between 3.81 and 5.64 and between 0.22 and 0.41, respectively. Mineralogically these soils are dominated by fluoroapatite and hydroxyapatite. Subsurface values for % C ranged between <0.05 and 0.51, while % N ranged from 0.03 to 0.07. Subsurface materials are mainly coarse to medium-sized structureless and friable phosphatic sands. A fuller description of these materials is presented in Morrison and Manner (in prep.).

Phosphate mining results in a dramatic change of the plateau surface and exposes the substrate to weathering and soil formation. In mining for phosphate, the forest is knocked down and the trees and litter removed for burning at a dump. The topsoil and surficial phosphate layer is scraped off by bulldozers and stockpiled. The phosphate deposits, which are usually located between the limestone pinnacles, are extracted using 0.48- and 0.76-m^3 grab buckets (Ruston Bucrus). Because the deposits are found between the pinnacles, extraction results in a dramatic change in local relief. Before mining, the plateau surface was relatively level to gently undulating. In a few places, some of the taller pinnacles and limestone outcrops were exposed by erosion. The extraction process has exposed three to five pinnacles per 100 m^2.

The use of grab buckets means that not all of the phosphate is extracted during mining. Some material remains and, with the broken pinnacle limestone, forms the loose deposits in the pit bottoms and on the saddles and scree slopes between adjacent pinnacles. The pinnacle tops and sides are relatively free of phosphatic materials.

MATERIALS AND METHODS

During the 1980 and 1982 study of the natural revegetation of the abandoned mined sites on Nauru (Manner et al. 1984, 1985), sites were identified from company records and aerial photographs according to the years of mining. These sites were marked on a 1 : 7920 scale map. Unfortunately, it was difficult to identify sites mined between 1906 and 1927 because of missing records, and inaccessibility prevented visits to all sites.

Composite soil samples from 0 to 15-cm depth were collected from 10 mined sites, which represented a soil development span of >55 yr. Each composite consisted of four subsamples taken from the pit bottoms, four from the scree surfaces, and four from the saddles between the pinnacles, if available. For each site, the samples were thoroughly mixed, composited in the field, and bagged in plastic.

The % C was determined by the Walkley-Black method, with silver sulphate added to the sulfuric acid to remove chloride ion interference. Unreacted carbon was corrected for by applying a locally derived correction factor (1.12) as determined by Lee et al. (1982). The % N was determined by the Kjehldahl method using sulphuric acid digestion and distillation of ammonia with a titrimetric finish according to Bremner (1965). All analyses were completed in quadruplicate, with the average results reported below.

RESULTS AND DISCUSSION

The results of this study are presented in Table 1 and are illustrated in Figure 1.

The data from the mined sites indicate that in the absence of further disturbance, the buildup of % C and % N is fairly rapid. Thus, 55 yr after mining, the values of % C and % N are comparable to those in the undisturbed Haplustolls and Ustorthents from Nauru's central plateau. Sites mined in 1982 had % C values that ranged between 0.41 and 0.48, while the % N values were 0.03 and 0.04. By comparison, sites mined during the 1924–1927 period had % C and % N values of 4.56 and 0.33, respectively.

The development of % C and % N in the mined sites is fairly rapid. Except for the 1982 mined site (sample no. 37), the values of % C and % N are higher than the minumum values of % C and % N from undisturbed subsurface horizons. The data indicate a rate of % C and % N accumulation of 0.07% per year and 0.005% per year, respectively. In addition, the CEC values increase with time since mining; this is expected as there is a close correlation between CEC and organic matter (% C) in the absence of significant amounts of clay minerals.

The rapid and high rate of % C and % N increase in the mined sites may be provisionally ascribed to the heavy fern (*Nephrolepis biserrata* and *Polypodium scolopendria*) cover of the pit bottoms; the substratum is composed of unconsolidated phosphatic sands. By way of contrast, there is little or no soil development on the massive pinnacles, where surfaces are relatively barren except along hairline cracks in which some plants, particularly ferns, have secured a foothold, and on the pinnacle tops, where strangler figs (*Ficus*

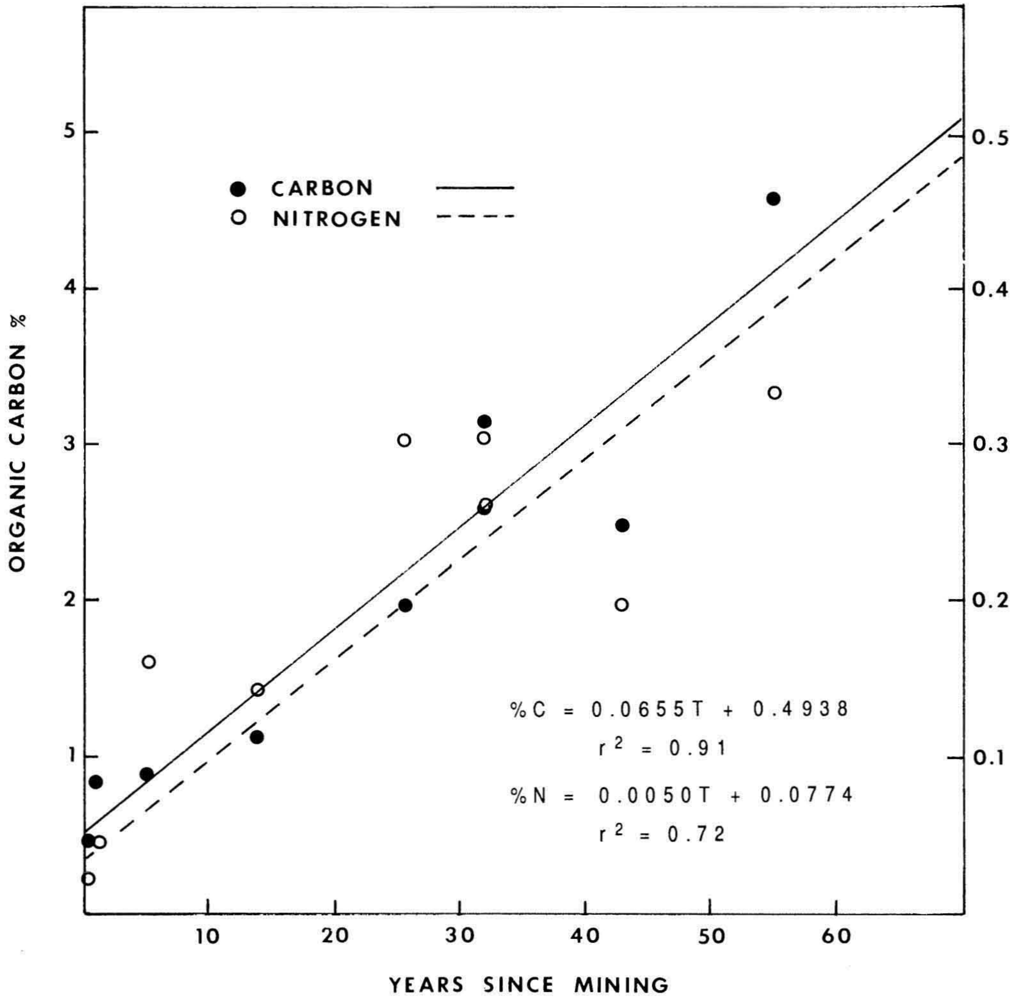

FIGURE 1. Relationship of percentage organic carbon and percentage total nitrogen with time for Nauruan soil samples after mining.

prolixa) have an ecological advantage because of their ability to colonize the bare pinnacles. In these situations, there is a developing organic mat. These observations suggest that soil development and the regeneration of the mined sites can be greatly facilitated if some unconsolidated residual materials are left behind. Of course, the unconsolidated material will not be as deep as in the original soils. This will mean reduced water-holding capacity in the profiles as a whole, and this may restrict plant growth in dry periods. It should also be noted that even in the "soils" in the oldest mined areas, structure development was minimal. The presence of significant amounts of organic matter will obviously encourage structure formation, but it appears from this study that the rate of structure development is significantly less than that of organic matter accumulation. A more rapid regeneration and use of these mined areas is possible if the pinnacles are crushed, rubble sorted according to size and covered by residual phosphatic materials, and topsoil and vegeta-

TABLE 1

CHANGE IN CARBON AND NITROGEN STATUS OF PHOSPHATE MATERIALS WITH TIME SINCE MINING

SAMPLE NUMBER	MINING DATE	NO. YEARS SINCE MINING AT TIME OF COLLECTION	% C	% N
37	1982	0	0.41	0.03
45	1982	0	0.48	0.04
29	1980	1	0.85	0.05
12	1975	5	0.86	0.16
7	1967	13	1.10	0.14
14	1953–1954	26	1.97	0.30
4	1946–1950	±32	2.69	0.26
24	1946–1950	±32	3.15	0.31
20	1930–1940	±43	2.42	0.19
22	1924–1927	±55	4.56	0.33
Undisturbed soils	—		3.81–5.64	0.22–0.41

tive regeneration encouraged. In the absence of a vigorous attempt at land rehabilitation, the jagged topography will be a barrier to future human usage of the bulk of Nauru's land area for millennia.

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