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Characteristics of soils in the tropical rainforest biome of Biosphere 2 after 3 years

Harry J. Scott

Bureau of Land Management, 4610 Third St., Tillamook, OR 97141, USA

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Abstract

After 3 years in place, soils of the tropical rainforest (TRF) area of Biosphere 2 were quantitatively sampled to determine the chemical and physical properties at different depths. Analyses were made of soils from six pits to determine several physical and chemical properties of the topsoil of the lowland forest and ginger belt zones. Comparisons were made with rainforest soils in Puerto Rico and elsewhere. Soils in the rainforest area of Biosphere 2 were started with relatively homogeneously mixed organic and inorganic materials according to two different 'recipes', and then planted with tropical plant species along with additional introduced life forms. The data presented in this study reveals some soil development processes taking place (vertical differences in soil aggregates, organic matter, nitrogen, and soil-borne animals). Soils remained slightly alkaline (pH 7.4–7.5), with higher concentrations of calcium, magnesium, and potassium than in acid soils of older rainforests.

Keywords: Biosphere 2; Ginger belt zone; Lowland forest; Tropical rainforest

1. Introduction

Soil materials were introduced in 1991 during construction and start-up of Biosphere 2. One of the 'biome' areas receiving soil was the tropical rainforest (TRF). Three years later, in November 1993, physical and chemical characteristics of soils from this area were examined using six soil pits. Fig. 1 shows subportions of the TRF area and locations of the soil pits. Three pits were chosen as representative of the lowland forest area and three for the ginger belt zone. This paper contains some analyses of these soils.

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The ginger belt was mainly planted with non-woody, light-loving, edge-type vegetation from the order Zingiberales, such as species from the families, Musaceae (banana), Zingiberaceae (ginger) and Streletziaceae (bird of paradise). This area received side light through the glass walls of Biosphere 2 as well as light from directly overhead. It occupied the outermost 4 m of soil adjacent to the east-, north-, and west-facing windows and covered 451 m^2, representing 24% of the total area (1895 m^2) of the TRF (Scarborough, 1993) (Fig. 1).

The lowland forest area (Fig. 1) was at lower elevation, surrounded by the ginger belt to the north and east, the bamboo belt to the south, the cement wall 'cliff face' and varzea areas to the west, and the 'mountain' to the northwest. The lowland forest was planted with tropical woody trees, shrubs and lianas as well as herbaceous plants of a successional humid, tropical interior forest type. It occupied 641 m^2, or 34% of the TRF (Scarborough, 1993).

1.1. Introduced soils and organisms

The soils of the TRF were formulated to contain two layers, topsoil 0.9 meter (3 ft.) deep, and underlying subsoil. The TRF required $\sim$1995 m^3 of topsoil (Scarborough, 1993). Logistic and cost considerations as well as state and federal quarantine regulations restricted the importing of unsterilized tropical soils from outside Arizona or the US. To still provide a wide variety of soil conditions, different 'recipes' for soil mixtures were used in the different zones. Five different topsoil recipes were suggested by Kew Botanical Garden personnel under the direction of G. Prance for use in the seven different areas of the TRF (Scarborough, 1993). These different soils were mixed from locally available materials, collected as near as possible to the construction site of Biosphere 2.

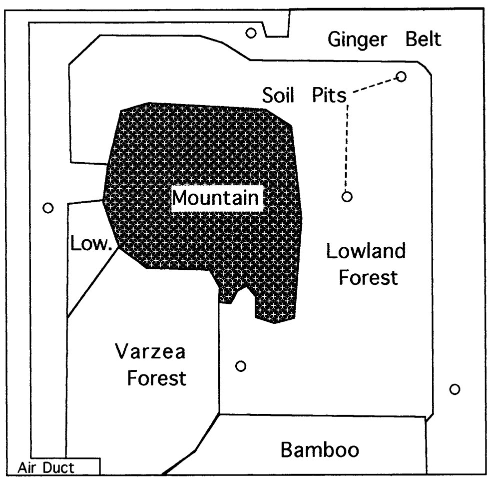

Fig. 1. Sketch of the floor plan of the tropical rainforest biome of Biosphere 2, including location of the sampling pits (not drawn to scale).

During and after the transplanting of plants from the holding greenhouses (which already had some organisms in and on their soil) into the TRF, several types of innocula were introduced including undisturbed soil cores, humus and litter containing fungal hyphae and micro- and macroarthropods. Many of the intentionally introduced arthropods also spent some or all of their lives in or on the soil, including isopods, native and tropical millipedes, cockroaches, and ants. Introductions included tens of thousands of commercially available earthworms and smaller numbers of 14 other species collected by the author in southeastern Texas.

The lowland forest topsoil was a mixture of 50% Wilson Pond soil, a silt loam which had accumulated at the bottom of a cattle pond, 25% gravely sand and 25% coarse organic material by volume. The ginger belt started with 80% Wilson Pond soil and 20% compost (Scarborough, 1993).

2. Methods

2.1. Soil sampling

The methods used to determine bulk density were based on the techniques outlined by Hamburg (1984). At each sampling site a wooden frame (50 × 50 cm) was secured horizontally above the soil surface with four stainless steel rods. The plant species composing the canopy and contributing to the forest floor litter within each frame were noted, and location was noted by measuring the distance to nearby permanently numbered and mapped plants. Live vegetation within the frame was cut at ground level and dried to yield data for live standing biomass. All dead leaves and partially decomposed organic materials on the soil surface within the frame were collected and dried to yield data on forest floor litter mass. Distance from the frame to the soil surface was then carefully measured to the nearest mm at 16 marked locations on a grid superimposed over the frame opening. The top 10 cm of soil was then excavated with a hand trowel and screened through a 1.25 cm mesh onto tarps in the field. When all the distances from the frame to the excavated soil surface were nearly 10 cm, the actual distance was recorded to the nearest mm. The distance between parallel walls was checked with a precut, 50 cm, PVC tube.

Rocks greater than 1.25 cm in diameter that did not pass through the screen were weighed (to determine the volume of rocks within that 10 cm strata at 2.65 g/cm^3). If a part of a rock was protruding into the excavated hole an approximately equal volume of rocks were weighed as a surrogate for the rock left in place. Large roots that were removed from the hole were collected and separately dried at 105°C to determine their mass and volume (at 0.3 g/cm^3). All excavated fresh soil was weighed in the field and subsamples (one handful per bucket excavated) were taken to the lab and weighed fresh and again when air dried to determine field wet-weight to air-dry-weight conversion factors. Subsequent screening of these subsamples through 2 mm mesh at Yale University was used to determine coarse fragment volume (the total volume occupied by all rocks greater than 2 mm). After drying the soil subsamples at 105°C, bulk density (total weight of material less than 2 mm

Table 1
Summary of soil macrofauna in subportions of the rainforest area of Biosphere 2, 21 December 1994

Depth (cm)		% Lowland forest[a]	% Ginger belt[a]	% Overall[a]
Surface	Worms	0	0	0
	Ants	67	100	80
	Isopods	67	100	80
	Surinam cockroach	67	100	80
	Australian cockroach	100	100	100
	Millipedes	100	50	80
0–10	Worms	100	100	100
	Ants	33	0	20
	Isopods	33	100	60
	Surinam cockroach	33	50	40
	Australian cockroach	0	33	20
	Millipedes			
10–20	Worms	67	100	80
20–40	Worms	0	100	40
40–60	Worms, arthropods	0	0	0

[a] Percent of pits which contained these invertebrates; lowland forest, 3 pits; ginger belt, two pits.

in size per volume excavated) was calculated for the total volume of soil removed minus rock and root volumes. These subsamples were retained for further chemical analyses. Notes also were made as to the presence or absence of earthworms and/or arthropod taxa in each strata of all pits after the first day (for five of the six sampling sites). Procedures were repeated for each topsoil stratum; 0–10 cm, 10–20 cm, 20–40 cm, and 40–60 cm. At the end of the day the pit was refilled.

2.2. Chemical analyses

At Yale University, two replicate subsamples of ~8 g of air-dried soil were extracted from each stratum of each pit using ~55 ml of 0.1 M $BaCl_2$ solution and a vertical vacuum extractor (Johnson et al., 1991). The exact extract volume of the combined extractant was determined gravimetrically and corrected for the specific weight of the solution. The solutions were analyzed for calcium, magnesium, and

Table 2
Summary physical characteristics of soils in the rainforest area of Biosphere 2, 21 December 1994

Depth cm		Lowland	Ginger	All Pits
0–10	Coarse fragment vol. in %	8.23	10.94	9.59
	Bulk density (g/cm^3)	1.10	0.94	1.02
10–20	Coarse fragment vol. in %	12.88	14.60	13.74
	Bulk density (g/cm^3)	1.26	1.11	1.19
20–40	Coarse fragment vol. in %	15.22	16.75	15.99
	Bulk density (g/cm^3)	1.32	1.03	1.18
40–60	Coarse fragment vol. in %	15.54	21.13	17.77
	Bulk density (g/cm^3)	1.18	1.10	1.15

potassium on a ThermoJarrell Ash Atom Scan 25 type Inductively Coupled Plasma (ICP). All data reported are on an oven-dry weight basis.

Total soil nitrogen (N) and carbon (C) were determined for an appropriate subsample from each stratum of each pit using a LEDCO CHN elemental analyzer and microsamples. These data were also used to determine soil organic matter content.

Soil pH was determined using a 1:1 slurry consisting of 5 g air-dry soil and 5 ml deionized water, in conjunction with an Orion research ion analyzer combination pH electrode. The pH value was confirmed by increasing the slurry to 0.005 M with $CaCl_2$ to mask any activity of soil-borne salts remaining in the slurry solution. There was an average difference of 0.2 pH units for both the ginger belt and the lowland soils between the two techniques. Only data from the second technique are presented here.

3. Results

Tables 1–3 contain results of the soil pit analyses for the ginger belt and lowland forest areas. Bar graphs (Figs. 2–5) show properties with depth including large-root biomass, bulk density, and chemical characteristics.

Table 3
Average soil chemistry for the rainforest area of Biosphere 2, 1 December 1994

Depth (cm)			Lowland	Ginger	All pits
0–10	pH		7.56	7.70	7.63
	Ca	meq/100 g	26.34	28.52	27.43
	Mg	meq/100 g	3.98	4.39	4.19
	K	meq/100 g	2.62	4.01	3.32
	C	% of dry weight	3.11	3.07	3.09
	N	% of dry weight	0.29	0.30	0.29
10–20	pH		7.64	7.42	7.53
	Ca	meq/100 g	25.00	27.00	26.00
	Mg	meq/100 g	3.53	3.72	3.62
	K	meq/100 g	2.75	2.41	2.58
	C	% of dry weight	2.42	2.29	2.35
	N	% of dry weight	0.22	0.24	0.23
20–40	pH		7.62	7.40	7.51
	Ca	meq/100 g	21.20	28.38	24.79
	Mg	meq/100 g	3.18	3.82	3.50
	K	meq/100 g	2.50	1.87	2.19
	C	% of dry weight	2.35	2.15	2.25
	N	% of dry weight	0.22	0.22	0.22
40–60	pH		7.59	7.40	7.52
	Ca	meq/100 g	21.83	27.66	24.16
	Mg	meq/100 g	3.42	3.95	3.63
	K	meq/100 g	2.90	1.89	2.49
	C	% of dry weight	2.50	2.12	2.35
	N	% of dry weight	0.24	0.23	0.23

Table 4
Comparison of chemical characteristics for the rainforest soils in Biosphere 2 with soils of other humid tropical forests

Site	Depth (cm)	Ca	Mg	K	Total N %	pH	Reference
		(meq/100 g soil)					
Biosphere 2 (lowland)	0–10	26.3	4.0	2.6	0.3	7.3	This study
Biosphere 2 (ginger)	0–10	26.5	4.4	4	0.3	7.5	This study
Puerto Rico (valley)	0–10	6.2	4.3	0.6	0.2	4.7	Silver et al. (1994)
Puerto Rico (ridge)	0–10	2.3	2.2	0.5	0.3	4.8	Silver et al. (1994)
Puerto Rico (N. cut)	0–12	19.2	12.5	0.5	—	5.7	Edmiston (1970)
Puerto Rico (S. control)	0–12	0.8	1.5	0.1	—	3.8	Edmiston (1970)
Puerto Rico	0–15	5.1	17.4	3.8	0.2	5.3	Cuevas et al. (1991)
Costa Rica	0–15	1.1	0.3	0.2	0.4	3.7	Heaney and Proctor (1989)
Columbia	0–20	3.4	2.8	0.7	0.2	5.4	Cavelier (1988)
Columbia	0–12	6.7	3.7	0.6	0.4	5.5	Cavelier (1988)
Panama		39.3	9.4	1.5	—	—	Blue et al. (1969)
Panama (riverine)		33.5	12.5	1.0	—	—	Blue et al. (1969)
Panama		37.4	10.9	0.2	—	—	Gamble et al. (1969)
Venezuela	0–10	3.1	2.4	0.2	0.3	5.4	Zink, (1986)
New Guinea	0–2	25.7	7.1	1.1	1.5	6.2	Edwards and Grubb (1982)
Sabah, Malaysia	0–15	7.7	24.6	0.1	—	5.7	Proctor et al. (1988)

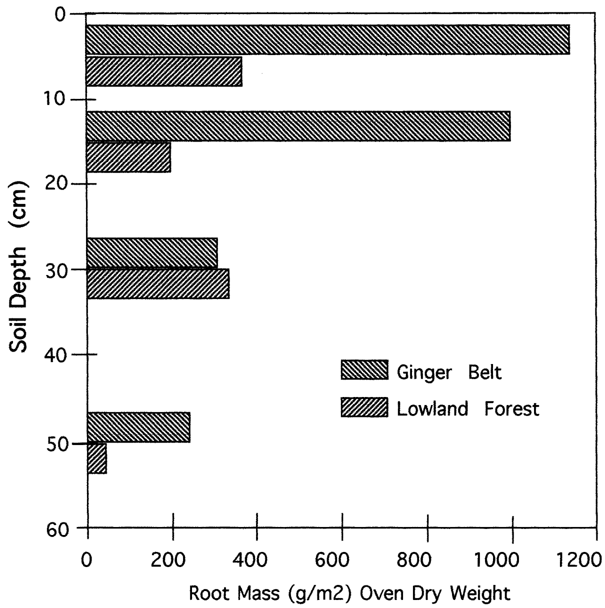

Fig. 2. Biomass of large roots in soil pits of the TRF area of Biosphere 2 after 3 years.

Table 1 contains data on animals present. No earthworms were found in the litter of any areas sampled, but the 0–10 cm strata of soil contained earthworms and arthropods in every pit surveyed ($n = 5$). No arthropods were encountered in the 10–20 cm strata or below.

Biomass of large roots ranged from 1150 g/m^2 (115 g/m^3) to 20 g/m^2 (2 g/m^3) decreasing with depth (Fig. 2), and data on coarse soil fragments are given in Table 2. Volume of coarse soil fragments ranged from 8.2 to 17.8%, increasing with depth Bulk density ranged from 0.9 to 1.3 g/m^3 (Fig. 3).

Chemical characteristics in milli-equivalents per 100 g (meq/100 g) are listed in Table 3. The soil pH remained slightly alkaline (7.4–7.7) for all strata and all soils (Fig. 4). Calcium concentrations ranged from 24.1 to 28.3 meq/100 g, magnesium concentrations from 3.1 to 4.4 meq/100 g, and potassium concentrations were 1.9 to 2.6 meq/100 g. Soil carbon ranged from 2.1 to 3.1%, and soil nitrogen from 0.22 to 0.30%. Values for carbon and nitrogen were slightly higher in the uppermost stratum.

The uppermost 10 cm of subsoil was only quantitatively sampled in one pit under the ginger belt. It contained neither earthworms nor arthropods, though it did contain roots (59 g/m^2). With much lighter color and a much more coarse texture, it remained discontinuous with the topsoil. The concentrations of basic cations remained less than for the topsoils ($Ca = 11.8$ meq/100 g, $Mg = 1.9$ meq/100 g and $K = 0.489$ meq/100 g), and the bulk density was 1.43 g/cm^3.

3.1. Comparison of the ginger belt and lowland forest soils

Samples were not numerous enough to determine statistically significant differences in most characteristics. Clearly, however, the mass of large roots was greater in the ginger belt than the lowland forest area (Fig. 2). The surface of the soil in the ginger belt also evidenced more forest floor litter than the lowland forest (1005 and 594 g/m^2, respectively). The ginger belt had a greater coarse-fragment volume in every stratum.

4. Discussion

4.1. Soil development and differentiation

In both the ginger belt and the lowland forest, vertical differences within the upper 40 cm of depth have appeared in each of the initially homogeneous mixes of materials (Tables 1–3). Organic carbon and nitrogen were now decidedly higher nearer the surface, so soil differentiation apparently had started.

Soil development appeared to be taking place somewhat more rapidly in the ginger belt than in the lowland forest. There was also a greater volume of coarse fragments (rock fragments and aggregated soil clusters), and earthworms were found in some of the lower strata. Absence of earthworms in the top litter and on

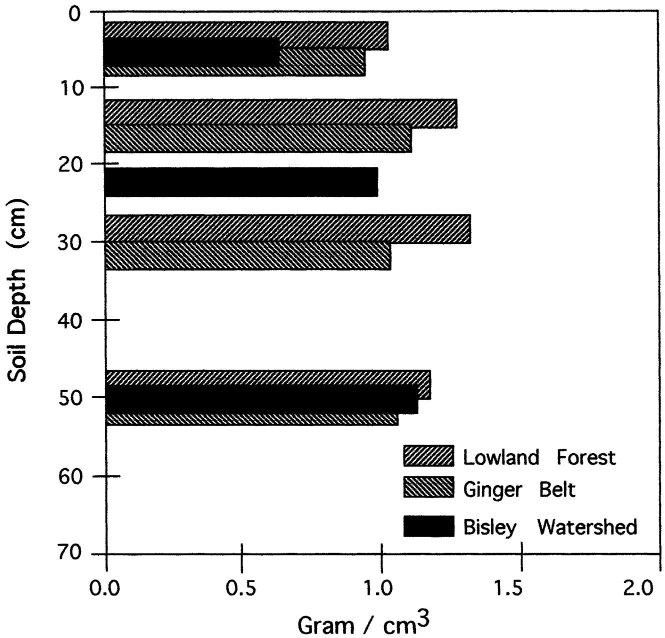

Fig. 3. Bulk density of soils in soil pits of the TRF area of Biosphere 2 after 3 years, along with values from the Bisley Watershed of the rainforest in Puerto Rico.

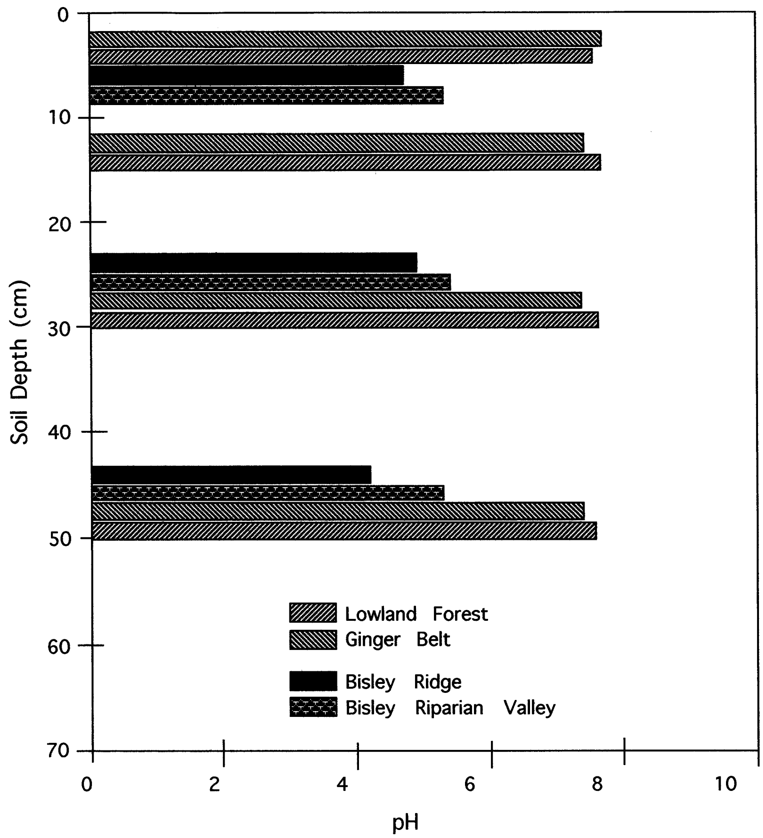

Fig. 4. pH in soil pits of the TRF area of Biosphere 2 after 3 years, along with values from the Bisley Watershed of a rainforest in Puerto Rico.

soil surface may be due to the swarms of small ants which were observed. During the course of the first 2-year closure an aggressive, surface-dwelling ant (*Paratrichina* sp.) attained very large populations throughout Biosphere 2. I observed these ants attacking and killing an earthworm emerging at the soil surface on one occasion.

4.2. Comparison with another humid tropical forest soil

Comparisons also were made between soil characteristics in the TRF area of Biosphere 2 and within the Bisley watershed of the Tabonuco forest type in the Luquillo mountains of Puerto Rico. Although the Bisley forest has had larger trees removed from time to time and has been impacted by hurricanes, it has never been clear-cut.

The Bisley watershed in the Luquillo Experimental Forest of Puerto Rico has been studied intensively since establishment of the long term ecological research (LTER) project (Scatena, 1989). Silver et al. (1994) dug quantitative pits using the same methodology and a similar protocol to that used in this study. Values from Bisley watershed are included with Biosphere 2 data in Table 3 and Figs. 3–5.

Silver found mean forest-floor biomass for the Bisley watershed to be 7×10^6 g/ha compared to a value of 8×10^6 g/ha, the mean for the ginger belt plus lowland. Concentrations of carbon and nitrogen decreased quite rapidly with depth in the Bisley watershed but not in the Biosphere 2 rain forest area (Table 3).

Soil chemistry of the riparian valley of Bisley was compared to the ginger belt, and soil chemistry of Bisley's ridge was compared to Biosphere 2's lowland forest. Chemical concentrations were corrected for coarse-fragment volume and bulk density. Soil organic matter in the Biosphere 2 area was assumed to be 50% C.

After these corrections had been made, 154×10^6 g/ha of soil organic matter was estimated to be within the first 60 cm of soil depth for the Bisley watershed (Silver et al., 1994) compared to 284×10^6 g/ha in the Biosphere 2 rain forest (Fig. 5). The differences in available cations were even more striking (Table 3).

The TRF area of Biosphere 2 had ~ 1.8 times more organic matter, 10.6 times more calcium, 1.7 times more magnesium, and 13.6 times more potassium per unit volume of soil than the Bisley watershed soils. Furthermore, the Bisley soils were acidic compared to the alkaline soils in Biosphere 2 (Fig. 4).

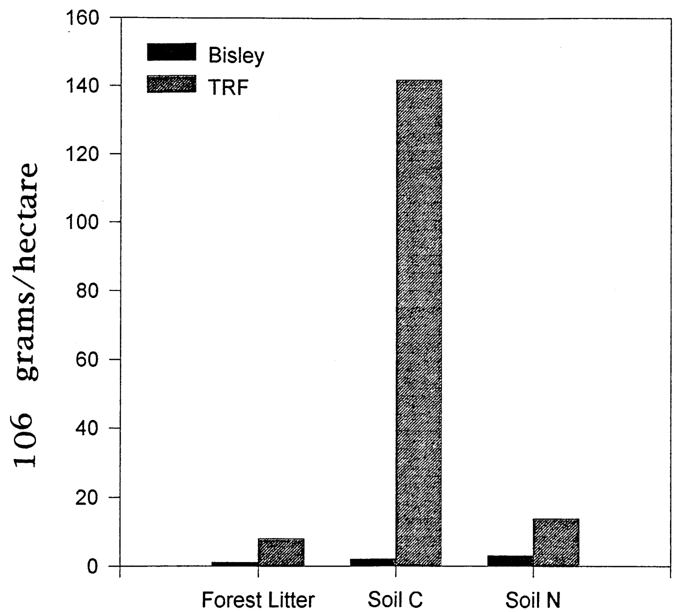

Fig. 5. Comparison of litter, carbon, and nitrogen contents of soils of the TRF area of Biosphere 2 with average for the Bisley Watershed area of a rainforest in Puerto Rico.

Whereas the soils of the rainforest at Bisley were well differentiated and in quasi-equilibrium with climate and geologic inputs, the soils of the rainforest area of Biosphere 2 still retained alkaline characteristics of the desert area from which they had been transferred.

Comparisons were also made with other humid tropical forests that receive a minimum of 2000 mm of rainfall (Table 4). Neutral to slightly alkaline pH soils, such as those of the TRF, allow a much greater amount of Ca, Mg and K to remain in the soil matrix (Brady, 1990). In Table 4 the cation composition in soils with more neutral pH most closely resemble the TRF soils, such as the 'North Cut Center' pit studied by Edmiston (1970), the New Guinea surface soil, and the soils from Panama where a sharp dry season helps retard cation leaching.

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