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Myths and Science about the Chemistry and Fertility of Soils in the Tropics

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In many scientific and popular publications, soils of the tropics are considered to be universally acid, infertile, and often incapable of sustained agricultural production (Gourou, 1966; McNeil, 1964; Goodland & Irwin, 1975; Friedman, 1977; Irion, 1978; Reiss et al., 1980; Jordan, 1985). The soil science literature shows that universal tropical soil infertility is a myth devoid of scientific validity. This myth has generated major misconceptions relevant to current global issues such as rural poverty, land degradation, deforestation, biodiversity, and climate change.

The historical development of this misconception has been recently analyzed by Richter and Babbar (1991) who traced it from the initial explorations in the tropics in the early 19th century (Buchanan, 1807), through the prevalence of broad soil genesis theories during the first half of the 20th century (Sibirtzev, 1914; Jenny, 1941), and finally to the lack of utilization of quantitative data about the diversity and management of soils in the tropics, generated largely during the second half of this century. Richter and Babbar cite telling examples of how major ecological texts still use obsolete concepts about soils, and conclude that the myth is a consequence of a major communications gap between soil scientists and other environmental scientists. Newer books, products of multidisciplinary efforts, put this misconception aside (Leith & Werger, 1989; Coleman et al., 1989).

The myth about universal soil infertility in the tropics is readily counteracted by two kinds of evidence. First, the vast diversity of soils in the tropics (Sanchez & Buol, 1975; Moormann & Van Wambeke, 1978; Drosdoff et al., 1978) which is now systematized according to quantitative soil taxonomy (Soil Survey Staff, 1975), a world soil map (FAO, 1971–1979), and numerous and

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increasingly accurate databases and geographic information systems (Sombroek, 1986). Second, the existence of successful, sustained soil management systems in many ecosystems of the tropics (Coulter, 1972; Pushparajah & Amin, 1977; DeDatta, 1981; Sanchez et al., 1987) plus the overwhelming evidence of sustained increases in per-capita food production in tropical Asia and Latin America (Swaminathan, 1982; FAO, 1986). Such successes, however, are concentrated on those soils of the tropics with superior chemistry and fertility and are certainly not sufficient to overcome world food needs or land resource deterioration in marginal areas. Nevertheless, they are successes of such magnitude that food production has outpaced population growth in two of the three tropical regions of the world.

We discuss the overall misconception about universal tropical soil infertility into three specific areas: soil fertility levels, clay mineralogy, and soil organic matter contents.

SOIL FERTILITY PARAMETERS

Soils are as diverse in tropical regions as they are in temperate regions. All 11 soil orders are found in both regions but their distribution varies (Table 3-1). Acid, low fertility soils meeting the stereotypic concept of "tropical soils" are mainly classified as Oxisols and Ultisols. Due to recent global glaciation, these soils cover only 7% of the temperate region but 43% of the tropics. Consequently, the majority of soils in the tropics (57%) does not fit the stereotype. Generally fertile soils, classified as Alfisols, Mollisols, Vertisols, and Andisols, cover a similar proportion of the temperate region (27%) and of the tropics (24%). Further generalizations at the order level are difficult; it is more relevant to examine specific soil-fertility parameters. It is also more relevant to subdivide the tropics into major agroecological zones.

In this chapter five of these zones are discussed: (i) humid tropics, (ii) semiarid tropics, (iii) acid savannas, (iv) tropical steeplands, and (v) tropical wetlands. The humid tropics have high and constant temperatures and a dry season of <90 d. The humid tropics are, therefore, defined as areas dominated by udic soil moisture regimes or isohyperthermic and isothermic soil temperature regimes. Their native vegetation is tropical rainforest or semideciduous forest. Deforestation is the main land degradation process involved. The semiarid tropics are characterized by a protracted dry season of 6 to 9 mo duration with a strong ustic soil moisture regime and isothermic or isohyperthermic soil temperature regimes. Their native vegetation are the drier savanna types (Sahelian and Sudanian in West Africa, or thorny vegetation as in the Brazilian Sertão). The acid savannas are seasonal tropics defined by a strong dry season of 3- to 6-mo duration, acid soils, and native savanna vegetation. The tropical steeplands are simply defined as those regions dominated by slopes >30%, mainly in the mountain regions of the tropics and the wetlands as regions with aquic soil moisture regimes. Major limitations in the tropical steeplands are often physical (shallow rooting depth with low available water contents) rather than fertility (Logan & Cooperband, 1987). Erosion of tropical steeplands may increase the base content of those soils formed on more basic parent materials.

Table 3-1. Approximate distribution of soil orders in the temperate and tropical regions of the world.

	Tropics†		Temperate region‡	
Soil associations dominated by:	Million ha	%	Million ha	%
Oxisols	833	23	7	--
Ultisols	749	20	598	7
Alfisols	559	15	1231	13
Mollisols	74	2	1026	11
Entisols	574	16	2156	24
Inceptisols	532	14	1015	11
Vertisols	163	5	148	2
Aridisols	87	2	2189	24
Andisols	43	1	101	1
Histosols	36	1	204	2
Spodosols	20	1	458	5

† Latitudes below 23½°.
‡ Latitudes above 23½°.

Gross estimates of the extensiveness and importance of the main soil fertility constraints are shown in Table 3-2, based on conversion of the FAO soil database into the fertility capability classification system (Buol et al., 1975; Sanchez et al., 1982). Examination of that table destroys the myth of universal tropical soil infertility, and divides the problem into specific soil fertility constraints.

Low Nutrient Reserves

About 36% of the tropics (1.7 billion ha) is dominated by soils with low nutrient reserves, defined as having <10% weatherable minerals in the sand-and-silt fraction. This constraint identifies highly weathered soils with limited capacity to supply P, K, C, Mg, and S. Soils with low nutrient reserves are more extensive in the humid tropics (66%) and in the acid savannas (55%) but are locally important in the Sahel. It is relevant to note that about two-thirds of soils in the tropics (64%) do not suffer from low nutrient reserves.

Aluminum Toxicity

About one-third of the tropics (1.5 billion ha) has sufficiently strong soil acidity for soluble Al to be toxic for most crop species. This constraint is defined as having more than 60% Al saturation in the top 50 cm of soil. Aluminum toxicity is most prevalent in the humid tropics and acid savannas but occurs in large areas of the tropical steeplands. This constraint is found mainly in soils classified as Oxisols, Ultisols, and Dystropepts, and is highly correlated with low nutrient reserves. As in the previous case, it is relevant to note that Al toxicity does not occur in two-thirds of the tropics.

Table 3-2. Main chemical soil constraints in five agroecological regions of the tropics.

Soil constraint	Humid tropics		Acid savannas		Semiarid tropics		Tropical steeplands		Tropical wetlands		Total	
	million ha and (%)											
Low nutrient reserves	929	(64)	287	(55)	166	(16)	279	(26)	193	(16)	803	(6)
Aluminum toxicity	808	(56)	261	(50)	132	(13)	269	(29)	23	(4)	1493	(32)
Acidity without Al toxicity	257	(18)	264	(50)	298	(29)	177	(16)	164	(29)	1160	(25)
High P fixation by Fe oxides	537	(37)	166	(32)	94	(9)	221	(20)	0	(0)	1018	(22)
Low CEC	165	(11)	19	(4)	63	(6)	2	(–)	2	(–)	251	(5)
Calcareous reaction	6	(0)	0	(0)	80	(8)	60	(6)	6	(1)	152	(5)
High soil organic matter	29	(2)	0	(0)	0	(0)	–	(0)	40	(7)	69	(1)
Salinity	8	(1)	0	(0)	20	(2)	–	(0)	38	(7)	66	(1)
High P fixation by allophane	13	(1)	2	(0)	5	(0)	26	(2)	0	(0)	50	(1)
Alkalinity	5	(0)	0	(0)	12	(1)	–	(0)	33	(0)	50	(1)
Total area	1444	(100)	525	(100)	1012	(100)	1086	(100)	571	(100)	4637	(100)

Moderate Soil Acidity

Acid soils with surface pH lower than 5.5 but not Al toxicity occupy one-fourth of the tropics (1.1 billion ha) and are important in all agroecological zones. Although correcting soil acidity by liming might be limited to acid-susceptible crops such as cotton (*Gossypium hirsutum* L.) and alfalfa (*Medicago sativa* L.), this constraint is generally associated with somewhat higher fertilizer requirements for these soils than those with higher pH values.

High Phosphorus Fixation

Clayey soils with iron oxide/clay ratios >0.2 fix large quantities of added P (Buol et al., 1975). This constraint, considered very typical of the tropics, is only found in 22% (about 1 billion ha) of the region. It is more extensive in the humid tropics and acid savannas but is also important in the steeplands. Successful management practices to overcome high P fixation in Oxisols have been developed for the acid savannas in Brazil (Goedert, 1985). Since high P fixation is related to high clay content, most sandy and loamy Ultisols and loamy Oxisols do not fix large quantities of P (Lopes & Cox, 1979). Phosphorus fixation is also important in Andisols because of the presence of allophane. This constraint is important in the steeplands and humid tropics where volcanic soils are found. Management practices are different from those designed to overcome P fixation by sesquioxides.

Low Cation Exchange Capacity

Soils with <4 $\text{cmol}_c\ \text{kg}^{-1}$ of effective cation exchange capacity (ECEC) occupy only 250 million ha or about 5% of the tropics. Such low ECEC values in the topsoil indicate limited ability to retain nutrient cations against leaching. This is one of the major components of the universal soil infertility myth, alleging that tropical soils are incapable of retaining nutrients. The limit of 4 $\text{cmol}_c\ \text{kg}^{-1}$ of ECEC is equivalent to 7 $\text{cmol}_c\ \text{kg}^{-1}$ of CEC at pH 7 or 10 $\text{cmol}_c\ \text{kg}^{-1}$ of CEC at pH 8.2, the other two commonly used methods (Buol et al., 1975). The main soils exhibiting such low CEC are sandy Entisols, Spodosols, very sandy Alfisols, and Ultisols and acric great groups of Oxisols. The data in Table 3-2 indicate that the vast majority of the tropics (95%) does not suffer from this problem. This is partially due to the higher-than-expected soil organic matter content of soil in the tropics, which provide a source of CEC. Cation-leaching problems do exist in the tropics like they do in the temperate regions, but not to the degree as commonly described.

In addition, many subsoils of Oxisols, Ultisols, and Andisols exhibit significant anion exchange capacity, which decreases leaching losses of nutrient anions such as nitrates and sulfates (Kinjo & Pratt, 1971). This property is also found in Ultisols of southeastern USA, but seldom elsewhere in the temperate region.

Calcareous Reaction

Soils with pH values above 7.3 and with free $CaCO_3$ within the top 50 cm are often deficient in micronutrients, particularly Fe and Zn (Lopes, 1980). Some also show imbalances between Ca, Mg, and K. Although calcareous soils occupy $<5\%$ of the tropics, their relative importance is not reflected in that figure, because they are usually intensively utilized, such as in Central Luzon, Philippines (Neue & Mamaril, 1988) and in the Cauca Valley of Colombia (Blasco & Soto, 1978; Ramírez, 1979).

High Soil Organic Matter

Organic matter levels $>30\%$ define organic soils (Histosols) and, unlike widespread beliefs, pose major soil fertility constraints. Organic soils are notoriously deficient in Cu, provide poor support for roots, and many exhibit H toxicity. There are approximately 69 million ha of Histosols and other closely related soils in the tropics, of which half are in southeast Asia (Driessen, 1978). Although organic matter is considered a desirable soil property, too much soil organic matter is definitely not (Sanchez & Miller, 1986).

Salinity and Alkalinity

Sixty-six million ha of the tropics have serious salinity problems, with electrical conductivity >4 and 5 dS m^{-1} in the top 1 m. Fifty million ha are alkaline with more than 15% Na saturation within the top 50 cm. Although each of these constraints occupy $<1\%$ of the tropics, they are locally important (Aguilera, 1979; Ponnamperuma & Bandyopadhya, 1980). They occur primarily in the humid tropics, semiarid tropics, and wetlands.

Geographical Distribution

The extent of these soil-fertility constraints in the developing world is shown in Table 3-3 for tropical and subtropical areas of Latin America, Africa, and Asia. Their relative importance varies with continental constraints. For example, problems related to soil acidity are more extensive in Latin America than in Africa or Asia. Examination of Tables 3-2 and 3-3 give little support to the myth of universal tropical soil infertility.

CLAY MINERALOGY

A second major myth about the chemistry and fertility of tropical soils is that they are dominated by kaolinite, iron oxides, and other highly weathered clay minerals. Such minerals are now classified as variable charge clays, where CEC increases with soil pH, as opposed to permanent charge minerals such as smectites, illite, vermiculite, and chlorites (Theng, 1980).

Table 3-3. Main chemical soil constraints in the developing world by geographical region (includes tropical and subtropical regions).

Soil constraint	Latin America		Africa		South and southeast Asia		Developing world	
	million ha and (%)							
Low nutrient reserves	941	(43)	615	(20)	261	(16)	1817	(27)
Aluminum toxicity	821	(38)	479	(16)	236	(15)	1527	(23)
High P fixation by Fe oxides	615	(28)	205	(7)	192	(12)	1012	(15)
Acidity without Al toxicity	313	(14)	471	(16)	320	(20)	1104	(16)
Calcareous reaction	96	(4)	332	(11)	360	(23)	788	(12)
Low CEC	118	(5)	397	(13)	67	(4)	582	(9)
Salinity	62	(3)	75	(3)	97	(6)	234	(3)
Alkalinity	35	(2)	18	(--)	7	(--)	60	(1)
High P fixation by allophane	44	(2)	5	(--)	7	(--)	56	(1)
High soil organic matter	9	(--)	12	(--)	23	(1)	44	(--)
Total area	2172	(100)	3011	(100)	1575	(100)	6758	(100)

Uehara and Gillman (1981) calculated the distribution of soils with variable, mixed, or permanent charge. Given the fact that mixtures of clay minerals is the norm rather than the exception in soils anywhere, Gillman and Uehara defined variable-charge soils as those where more than 60% of the ECEC is variable, mixed as those between 40 and 60%, and permanent as those where $<40\%$ of the charge is variable. Also given the fact that the ECEC of soil organic matter is entirely variable, all soils exhibit some degree of variable charge. Their data, shown in Table 3-4, indicate that 60% of soils in the tropics have variable charge, while only 10% have permanent charge. In contrast, 10% of the temperate region soils have variable charge while 45% has permanent charge. There is no question, therefore, that variable charge is the dominant feature of soils of the tropics, but it is certainly not a universal characteristic of the tropics. The 820 million ha of soils with variable charge in the temperate region are found in high latitude Spodosols and Histosols, but also exist in large Ultisol areas such as southeastern USA and southeastern China, and in Andisol regions of Japan, Alaska the Pacific Northwest, and New Zealand.

Table 3-4. Extent of soils classified as variable, mixed, or permanent charge. Source: Uehara and Gillman (1981).

Soils with:	Tropics		Temperate		World	
	billion ha	%	billion ha	%	billion ha	%
Variable†	3.00	60	0.82	10	3.82	29
Mixed charge‡	1.50	30	3.68	45	5.18	39
Permanent charge§	0.50	10	3.68	45	4.18	32

† 60% of the CEC is variable.
‡ 40-60% of ECEC is variable.
§ <40% of CEC is variable.

SOIL ORGANIC MATTER CONTENTS

It is commonly believed that soils of the tropics have lower organic matter (SOM) contents than soils of the temperate region (McNeil, 1964; Gourou, 1966; Bartholomew, 1972; Jordan, 1985). The red color of many soils in the tropics, high temperatures, and high rainfall are among the reasons cited in support of this generalization. This assumption, however, happens to be wrong. There are no major differences in SOM contents between the two regions (Sanchez & Buol, 1975; Lathwell & Bouldin, 1981; Sanchez & Miller, 1986). Interest in the world C cycle has resulted in many recent estimates of soil C reserves in the humid tropics to answer the question of whether tropical forests are a source or sink of C for the world. Empirical estimates of the soil organic C reserves in the tropics, such as those developed by Schlesinger (1979) and Brown and Lugo (1980), vary widely. Reserves are calculated by multiplying organic C data from a few soil profiles by the land area represented by such soils or by the land area of the ecological region in which they are found. Schlesinger and Brown and Lugo recognized these weaknesses and urged some precise estimates. The soil science literature, however, has many reports indicating that soils of the tropics are not generally low in organic matter. Kellogg (1950) made this point very clear more than 30 yr ago. Studies of several hundred topsoil samples from Hawaii (Dean, 1930), Puerto Rico (Smith et al., 1951), and East Africa (Birch & Friend, 1956) showed average topsoil values on the order of 2% C, a figure that compares favorably with temperate region contents.

Studies involving large numbers of pedons (Post et al., 1982; Zinke et al., 1984; Sanchez et al., 1982) now confirm the prevalent view that soil organic matter contents vary equally in temperate and tropical regions (Duxbury et al., 1989). For example, data from 61 randomly chosen profiles from the tropics and 45 from temperate regions and classified as Oxisols, Mollisols, Alfisols, and Ultisols, showed no significant differences in total C and C/N ratios between soils from tropical or temperate regions at depth intervals up to 100 cm (Table 3-5). Total N contents, however, were significantly higher in the tropical samples while the coefficients of variability were similar. No significant differences in SOM contents were observed between Alfisols from the tropics vs. Alfisols of the temperate region, Ultisols from the tropics vs. Ultisols of the temperate region and Mollisols of the tropics vs. Mollisols of the temperate region (Sanchez et al., 1982). Furthermore, no significant differences in organic matter contents were found between the classic black Mollisols or Chernozems of the temperate region and the red, highly weathered Oxisols of the tropics (Table 3-6).

A recent analysis of well-classified pedons from the National Soil Survey Laboratory database with 282 pedons from the tropics (having isotemperature regimes) and 486 pedons from the temperate regions (non isotemperature regimes) suggest that soils from the tropics may have significantly higher SOM contents to 30-cm depth than soils from temperate regions (Buol et al., 1990). The data shown in Fig. 3-1 is arranged according to the mean annual temperature of the four main soil temperature regimes in soil

Table 3-5. Mean organic matter contents in 61 soils from the tropics vs. 45 soils from the temperate region. Source: Sanchez et al. (1982).

Parameters	Depth, cm	Tropical soils	Temperate soils	Significance	CV% Tropics	CV% Temperate
%C	0-15	1.68	1.64	NS	53	64
	0-50	1.10	1.03	NS	57	69
	0-100	0.69	0.62	NS	59	75
%N	0-15	0.153	0.123	*	62	57
	0-50	0.109	0.090	NS	57	57
	0-100	0.078	0.060	**	54	52
C/N ratio	0-15	13.7	13.6	NS	79	35
	0-50	11.3	11.3	NS	46	32
	0-100	9.6	10.0	NS	46	35

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

Table 3-6. Mean total C and N reserves of soil orders by geographical regions. Source: Sanchez et al. (1982).

Region	Soil order	No. of profiles	Total C 0-15 cm	Total C 0-100 cm	Total N 0-15 cm	Total N 0-100 cm
Tropics	Oxisols	19	3.8a*	11.3a	0.32a	1.13a
	Alfisols	13	2.9a	6.4b	0.29a	0.85b
	Ultisols	18	2.1b	6.4b	0.18c	0.69b
Temperate	Mollisols	21	3.3a	10.1a	0.27a	0.95a
	Alfisols	16	2.8ab	5.8b	0.20bc	0.56c
	Ultisols	8	2.4b	4.2b	0.15c	0.44c

* Numbers followed by the same lower case letter are not significantly different at the $P < 0.05$ level.

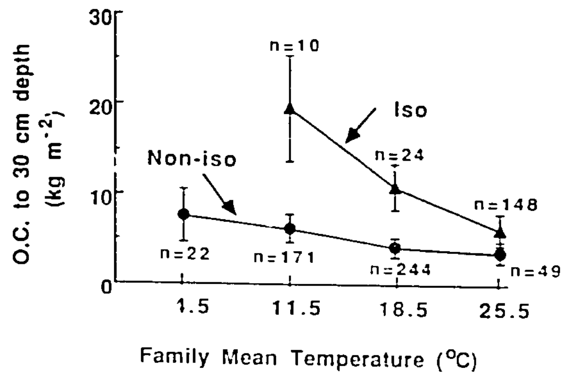

Fig. 3-1. Soil organic C contents as a function of soil temperature regime in iso (tropical) vs. non-iso (temperate) regions. Source: Buol et al. (1990).

taxonomy: frigid (4.5 °C), mesic (11.5 °C), thermic (18.5 °C), and hyperthermic (25.5 °C). Although there is a general decrease in SOM content with increasing temperature, those soils with little seasonal temperature variation indicative of the tropics (isomesic, isothermic, or isohyperthermic regimes) show higher SOM contents than those with strong seasonal temperature variation in mesic, thermic, and hyperthermic regimes.

Soil is a temporary repository for organic C (Buol et al., 1990). Soil organic matter content, therefore, is a function of additions and decomposition rates. Calculations from Greenland and Nye (1959) suggest that generally higher SOM decomposition rates found in the humid tropics caused by high temperatures and ample moisture are balanced by higher litter input, both factors being about five times higher in soils from tropical forests than from temperate forests (Sanchez, 1976). Many processes operating at site-specific rates affect actual input and decomposition rates and provide a wide range of equilibrium SOM contents (Anderson & Swift, 1984). It is safe to assume, therefore, that the range in SOM contents in the tropics is as variable as in the temperate region.

Unfortunately, there is no direct correlation between SOM contents and soil fertility as measured by crop productivity, other factors being constant (Sanchez & Miller, 1986). Mollisols shown in Table 3-6 supported many crops of corn (*Zea mays* L.) without fertilization for years in midwestern USA, Europe, and Argentina (Stevenson, 1984). But many Oxisols with similar SOM contents will definitely not be able to keep one corn plant alive without fertilizer additions (Lopes, 1983). This discrepancy is related to deficiencies of nutrients other than N, and Al toxicity in Oxisols.

CONCLUSIONS

Soils of the tropics are variable in their chemistry and fertility, ranging from the most fertile to the most infertile in the world. Although there is a larger proportion of acid soils in the tropics, they are not even in the majority. The chemical processes involved are the same regardless of latitude. What is different is their management, because of different climate, crop species, and socioeconomic conditions found in the tropics.

Given the expanding databases available from the tropics on inherent soil characteristics, and on their management, it is no longer acceptable to continue the myths of the past that were understandably caused by a lack of systematic study. Site-specific management will be increasingly necessary as demands grow on soils of the tropics for food and fiber production.

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