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The chemistry of lateritic soils: the search for new agricultural technology

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Abstract: Studies of heavily leached lateritic soils from the Amazon Basin and Niger Delta regions show extreme removal of at least a dozen bio-essential elements. Macronutrients such as Na-K-Ca-Mg, present at the per cent level in fertile soils are often reduced to the ppm level in lateritic soils.

Western fertilizer technology was developed for fertile soils where enhanced levels of N-P-K cause significant increase in biomass production. For tropical soils the response is often small unless very massive fertilizer doses are used. Phosphate fertilizers carry a large array of trace elements and micronutrients (Ni, Zn, Mo, Ca, Mg) and plant response may often reflect these accidental additions as much as the phosphate influences. Phosphates also carry high levels of undesirable species such as uranium (typically at the 100 ppm level).

The weathering process and the influences of aerosol, ground water, and sea water fluxes will be considered as a function of time. Experiments will be described where mineral materials and mineral-based glasses have been tested as fertilizers on infertile soils. It will be shown that for such cases, higher biomass productivity has been produced using such materials than by use of conventional N-P-K. In fact, with soils of lower buffer capacity, soluble fertilizers can produce extreme toxicity, and environmental pollution. There is need for detailed field testing of all potential fertilizer materials to isolate the significant variables in sustained biomass production.

INTRODUCTION

Lateritic soils are the products of intense chemical weathering. In the modern configuration of continents lowland tropical soils and surface sediments provide the most prominent examples (Fyfe *et al.,* 1983). During long-term leaching major and trace elements are continually removed in weathering solutions, resulting eventually in multi-elements depletions. Concentrations of bioessential elements (F, S, Na, Mg, Si, P, Cl, K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sn, I; Mertz, 1981) 1–4 orders of magnitude below those found in typical surface rocks or fertile soils have been documented in soils of the Amazon (Kronberg *et al.,* 1979) and the Niger Basins (Olorunfemi *et al.,* 1984). Extraordinary low levels of inorganic nutrients in heavily leached terrains make agricultural production in such regions precarious or impossible.

Conventional N-P-K fertilizers were not designed for highly leached soils and local failures in their use may be attributed to various problems. Besides failing to provide the necessary array of nutrients, N and K released from soluble fertilizers under high rainfall conditions have short residence times in soil solutions. In fact, ammonia derivatives may even enhance leaching of certain necessary metals. Local ground water contamination by nitrates is a problem even in regions with fertile soils (The Economist, 1984). Soluble phosphate additives may be lost by fixation processes in soils rich in aluminium and iron oxides.

Detailed soil chemical analyses of problem soils in Brazil and Nigeria are used here as a basis for discussing the need for new agricultural strategies. We also discuss results of small scale trials using simulated leached soils and a field experiment on a fertile soil designed to test the feasibility of our proposed mineral-based fertilizers for intensely leached soils.

CHEMISTRY OF INTENSELY WEATHERED SOILS

Soils develop as rocks weather at the Earth's surface (Kronberg and Nesbitt, 1981). Rain is the principal weathering agent and percolation of rain-derived waters through surface rocks leaches and eventually dissolves rock-forming minerals (feldspars, pyroxenes, etc.). Surface waters charged with rock-derived solutes Na^+, Mg^{2+}, K^+, Ca^{2+}, etc.) buffer the formation of complex clay minerals (smectites, illites, chlorite, etc.), the hallmarks of fertile soils.

Complex clays are important in conserving soil nutrients due to their capacity to incorporate metals into their layered lattices, in which there is a greater range of sites than in most primary minerals. Potassium, for example, may be concentrated during weathering in illites. Large interlayer distances in smectites enhance their capacity to store a wide range of metals and even water molecules. Furthermore, clay minerals tend to be present in soils as fine (micron-size) particles whose surfaces participate in metal uptake processes.

When surface waters lose contact with fresh rock debris, complex minerals dissolve and kaolin phases accumulate. This transition in soil mineralogy marks the change from soil fertility to infertility. Kaolin lattices do not host macro nutrient elements (Na, Mg, K, Ca) and in general have much less capacity to exchange metals than do complex clays. The ultimate product of long-term weathering is gibbsite (bauxites).

The global distribution of fertile soils is controlled to a large extent by global tectonic and erosional processes. Most fresh rock is transported to the Earth's surface from the upper mantle or lower crust during volcanic events. Glacial and alluvial processes may result in long-range transport of vast amounts of rock debris. The recent geological past ($<$ 3 Ma) has been a period of intense glaciation. During this time continental land masses have been concentrated in the northern hemisphere and thus the northern temperate regions have in general fertile soils. The valleys of the large Asian rivers are another example of agricultural productive lands, but intense food production in tropical latitudes is otherwise confined to recently active volcanic regions, such as Java.

The soils of the extensive Amazon lowlands (Table 1) and much of West Africa are typical of intensely weathered terrains, which have been tectonically inactive for tens of millions of years. In kaolin-dominated Amazonian soils macro nutrient reserves

(Table 1) are typically 3 orders of magnitude lower than those in a fertile soil. The gibbsitic soils of central Brazil and the quartz-rich soils of the Niger delta are similarly depleted. Occasional local concentrations of nutrients may be deceptive. Fertile soils, such as those developed on recent glacial debris (Table 1) are underlain by enormous accumulations of fresh and partially weathered rock debris. Thus new soil material is continually forming, in contrast to the situation in the lowland tropics, where soils may be intensely leached to depths of tens of metres.

Micro nutrient deficiencies are much more severe in highly leached soils than in fertile soils. Of the minor and trace elements designated as bioessential (Table 2), only Ni is strongly depleted (less than 10 times crustal levels) in the fertile soil investigated, while in the highly leached soils analysed, depletion is common for over half of these elements (F, S, Cl, V, Cr, Co, Ni, Cu, Zn, As) and depletion is often extreme (less than 100 times crustal levels). Often, too, residual concentrations may be present only in

TABLE 1

SOIL COMPOSITIONS (WT %)

	Average[1] Crust	Fertile[2] Soil	Amazon[3] Soil	Central[4] Brazilian Soil	Niger Delta[5] Soils—Central
Na_2O	3.1	0.5	.002–.09	.003–.09	.003–0.4
		(10^4)[6]	(30–1300)	(40–1300)	(40–600)
MgO	4.6	2.1	.01–0.1	.02–0.4	<.01–0.2
		(10^4)	(120–2000)	(240–8000)	(120–4000)
Al_2O_3	16	9.9	20	29	8.1
SiO_2	59	5.3	52	28	82
P_2O_5	0.3	0.2	.005–0.2	.002–.09	.003–0.2
		(10^3)	$(40–10^3)$	(20–800)	$(25–10^3)$
K_2O	2.2	2.1	0.01–0.3	0.01–0.8	.003–2.1
		(3×10^4)	(150–5000)	(150–13000)	$(50–3 \times 10^4)$
CaO	6.5	5.3	.001–.04	.004–0.1	.001–0.6
		(8×10^4)	(15–800)	(60–150)	(15–8000)
TiO_2	1.1	0.5	1.1	1.9	0.6
MnO	0.1	0.1	0.08	.001	.0003–.10
Fe_2O_3	6.5	3.6	16	9.8	5.4
Mineralogy	Feldspar, Quartz	Quartz Feldspar Chlorite Calcite	Quartz Kaolin Goethite	Gibbsite Quartz Hematite	Quartz Kaolin

[1]Ronov & Yaroshevsky, 1972
[2]Fertile Soil developed on glacial debris; S.W. Ontario, Canada.
[3]Average composition of soils collected along Amzaon highway near Maraba, in weathered shield terrians (Kronberg *et al*, 1979).
[4]Average composition of 14 soils, collected on Experimental Farm, University of Brasilia (Kronberg *et al*, 1979).
[5]Average or range of composition of 29 central delta soils (Olorunfemi, 1984 in press).
[6]Total nutrient reserves in kg ha^{-1}.

TABLE 2

MINOR AND TRACE ELEMENTS IN SOILS ($\mu g\ g^{-1}$)

	Average[1] Crust	Fertile[2] Soil	Amazon[3] Soil	Central[4] Brazilian Soil	Central Niger[5] Delta Soil
B	9	15	2	500	2
F*	544	500	15	250	30
S*	340	400	10	25	5
Cl*	126	150	5	500	5
Sc	25	33	10	10	10
V*	136	120	40	25	40
Cr*	122	15	20	2	55
Co*	29	10	0.4	0.3	0.01
Ni*	99	5	0.5	15	5
Cu*	68	20	2	5	2
Zn*	76	10	40	1	1
Ga	19	5	5	6	2
Ge	1.5	0.5	0.05	2	0.5
As*	1.8	2	0.05	1	0.2
Se*	0.05	0.1	0.3	0.01	0.5
Br	2.5	0.2	0.2	0.5	0.05
Rb	78	45	15	1	0.1
Sr	384	110	30	10	3
Y	31	10	5	12	1
Zr	162	600	200	200	200
Nb	20	15	40	13	1
Mo*	1.2	0.3	1	1	1
Ag	0.08	*c*0.1	0.04	0.04	0.1
Cd*	0.16	<0.1	<0.3	<0.1	<0.1
Sn*	2.1	1	8	3	1
Sb	0.2	0.2	2	2	<0.5
I*	0.5	0.3	<1	1	<0.05
Cs	3	1	1	1	0.03
Ba	390	220	70	2	7
La	34	25	30	3	10
Ce	66	55	50	2	5
Pr	9	7	0.7	0.7	0.7
Nd	40	30	9	3	1
Sm	7	7	<2	2	<2
Eu	2	2	<1	0.2	<0.5
Gd	6	2	2	0.7	<2
Tb	1	0.3	<1	0.1	<0.3
Dy		2	2	2	<2
Ho	1	1	<1	0.1	<0.3
Er	4	3	<3	1	<1
Tm	0.5	0.5	0.2	0.6	<0.5
Yb	3	3	<1	1	<1
Hf	3	5	5	5	2
Pb	13	5	0.5	5	5
Th	8	2	6	20	<2
U	2	2	2	2	2

[1]Ronov & Yaroshevsky, 1972
[2]Fertile Soil developed on glacial debris (S.W. Ontario, Canada)
[3]Amazon top soil (FAI), from which forest had been removed by burning, and intended for agricultural use (Kronberg et al, 1979).
[4]Gibbsite-rich top soil from Experimental Farm, University of Brasilia, (Kronberg et al, 1979).
[5]Quartz-rich (98% SiO_2) soil (NN100) from Niger Delta (Olorunfemi et al, 1984)
*Bioessential Elements (Mertz, 1981).

highly refractory phases (e.g. zircon) in which elements may be chemically isolated from the biosphere. Although most of these elements are required in much smaller amounts (g ha^{-1}) than are macro nutrients (kg ha^{-1}) they are essential participants in plant growth processes. Molybdenum is a key constituent of nitrogen-fixing enzymes (Williams, 1981), and nickel has recently been shown to be essential for nitrogen metabolism in legumes and possibly in all higher plants (Eskew *et al.*, 1983). Current research is showing that there are critical levels of micro nutrients below which plant production fails. (In some regions of central Brazil nothing grows in the absence of intense fertilization.)

NUTRIENT SOURCES AND FERTILIZER STRATEGIES

The bioessential elements are rock-derived except for the biological frame work elements (H, C, N, O). Once rocks begin to weather at the Earth's surface nutrients are dispersed by geological (e.g. glacial), fluvial and atmospheric transport processes. Atmospheric deposition becomes more important as soil leaching intensifies. The rain forests of the highly leached Amazon Basin maintain themselves by nutrient scavenging largely from rainwater input and recycling. Rates of atmospheric deposition may reach kg ha^{-1} a^{-1} (Carroll, 1972). In the coastal Niger Delta local formation of complex clays appears related to incursions of marine waters.

However, intense agricultural activity involves the continuous removal of plant cover, which during its growth incoporates macro nutrients at levels of 10–50 kg ha^{-1} (Cooke, 1967). These perturbations to the natural vegetation cover including the exposure of soils to rain impact erosion makes such activities feasible only where soils nutrient reserves are vast. It is no surprise that global grain production is highly localized and the most productive regions are those which have experienced recent glacial, alluvial or volcanic activity (Loomis, 1976).

For highly leached soils conventional fertilizer technology fails to provide the array of nutrients and their high solubilities preclude their effectiveness in high rainfall regions where soils are deeply leached and highly permeable.

Phosphate additives present special problems. Unlike other macro nutrients phosphorus is transported in anionic form (PO_4^{3-}), which combines with many elements to form highly insoluble compounds. Al and Fe oxides which concentrate during weathering both have high affinities for phosphate and phosphate fixation problems increase as weathering proceeds. Thus soluble phosphate fertilizers may be economically unfeasible in many tropical areas. One strategy has been to use excess phosphate in order to "quench" fixation; however, these strategies may cause ground and surface water contamination. Furthermore, phosphate fertilizers mined from phosphorite deposits may contain a large array of elements, which are inherited from their depositional environments. In fact, many of these trace elements may be as much responsible for enhanced plant growth as the phosphate component which thus becomes a very expensive method of adding trace elements. We would add (Koranda *et al.*, 1981) that most natural phosphates may also add large quantities of undesirable elements such as As, Cu, U, etc.

FIELD AND GREENHOUSE TRIALS USING ROCK-DERIVED FERTILIZERS

In a series of limited field and greenhouse trials, we have made fertilizers from mixtures of common minerals and some fused products (glass) designed to provide for most nutrient requirements. The fused products were designed to have different solution rates and in the Tables that follow UWO –1, –2, –3, –4 decrease in solubility in that order.

Field Trials

Corn was grown at the University of Western Ontario Field Station on a soil formed on recent glacial debris (details of soil chemistry given in Tables 1, 2). A six by six Latin square design was used and six different fertilizer applications were tested six times throughout the field. The fertilizers were evaluated on the basis of corn grain yields (Figure 1). No drastic differences in yields were noted. While the commercial fertilizer gave the best results these yields were only 20% above those of the control plots on which no fertilizer was used. Two of the yields using glassy fertilizers exceeded those of the control and one was within a few per cent of those using the commercial fertilizer.

TABLE 3

EXPERIMENT GH-2
GREENHOUSE CORN STUDY IN QUARTZ/BAUXITE

	% dry weight normalized to U.W.O. #3 + rock
1. Control	40.9
2. Commercial	28.4*7
3. Rock	97.7
4. U.W.O. #1 + rock	0
5. U.W.O #2 + rock	93.2
6. U.W.O. #3 + rock	100.0
7. U.W.O. #4 + rock	90.0
8. U.W.O. #1	0 *
9. U.W.O. #2	15.9
10. U.W.O. #3	52.3
11. U.W.O. #4	65.9
12. U.W.O. #1 + peat	0
13. U.W.O. #2 + peat	22.7
14. U.W.O. #3 + peat	72.7
15. U.W.O. #4 + peat	61.4
16. U.W.O. #1 + peat + rock	47.7
17. U.W.O. #2 + peat + rock	95.5
18. U.W.O. #3 + peat + rock	68.2
19. U.W.O. #4 + peat + rock	70.5
20. Rock + Collophane	85.2

*These more soluble phosphate fertilizers are not effective on poorly buffered soils.

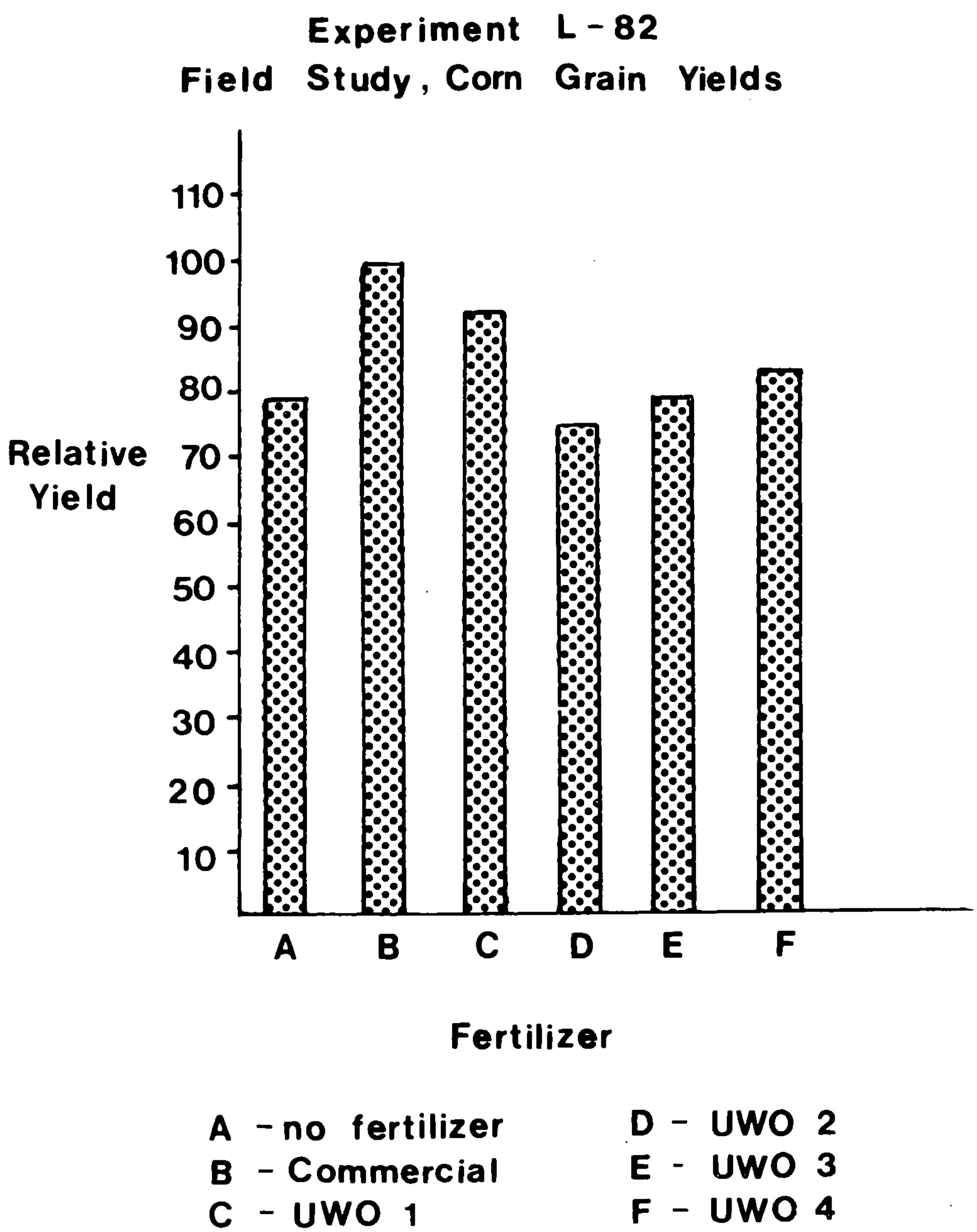

Fig. 1. Comparative yields of corn grown on extremely fertile soil in Southern Ontario. Note the overall small influence of fertilizers. In this case commercial N-P-K is the best fertilizer. UWO 1–4 are based on common minerals.

As a reconnaissance study, cob and plant ashes from different plots were analyzed to determine macro nutrient (Mg, P, Si, K and Ca) uptake (Figure 2). These results show that using one glassy fertilizer enhanced Mg, Si, K, Ca uptake by up to 3 fold more than by using commercial fertilizer. Obviously more detailed studies are needed but these results underscore the complex interplay of variables controlling plant-soil mass balances, and raise the question of plant quantity versus nutritional quality.

Green House Experiments

These experiments involved growing corn and tomato plants on artificial soils designed to simulate highly leached soils. For tomatoes grown in quartz sand (experiment T-1; Figure 3) and in soil, three of the five mineral based fertilizers were superior to commercial fertilizer. It is also clear that with the pure quartz sand, the effects of mineral fertilizers were greater than with fertile soil.

In other trials corn seeds were planted in quartz-kaolin (experiments GH-1, GH-3) or quartz-bauxite (experiment GH-2) soil media and harvested after six weeks. In GH-1 addition of Ca and Mg salts greatly enhanced the effect of the commercial fertilizer. But without these salts, the glassy fertilizers were often more effective. In experiment GH-3 designed to test the residual effects of GH-1, rock-based fertilizers out-performed the commercial fertilizers. With bauxite-quartz soils, the best results were obtained using glassy fertilizers mixed with rock and sometimes with peat as well.

TABLE 4

EXPERIMENT GH-3
RESIDUAL GREENHOUSE CORN STUDY IN QUARTZ/KAOLIN

	% dry weight normalized to U.W.O. #4
1. Control	76.8
2. U.W.O. #3	88.4
3. U.W.O. #4	100.0
4. 1/2 U.W.O. #3 + 1/2 U.W.O. #4	82.6
5. 2(U.W.O. #3)	89.9
6. 2(U.W.O. #4)	92.8
7. U.W.O. #3 + U.W.O. #4	85.5
8. Commercial	97.1
9. Minerals	59.4
10. (2) + Minerals	73.9
11. (3) + Minerals	100.00
12. (4) + Minerals	62.3
13. (5) + Minerals	108.7
14. (6) + Minerals	71.0
15. (7) + Minerals	76.8
16. (8) + Minerals	68.1
17. NH_4NO_3	78.3
18. NH_4NO_3 + Minerals	63.8

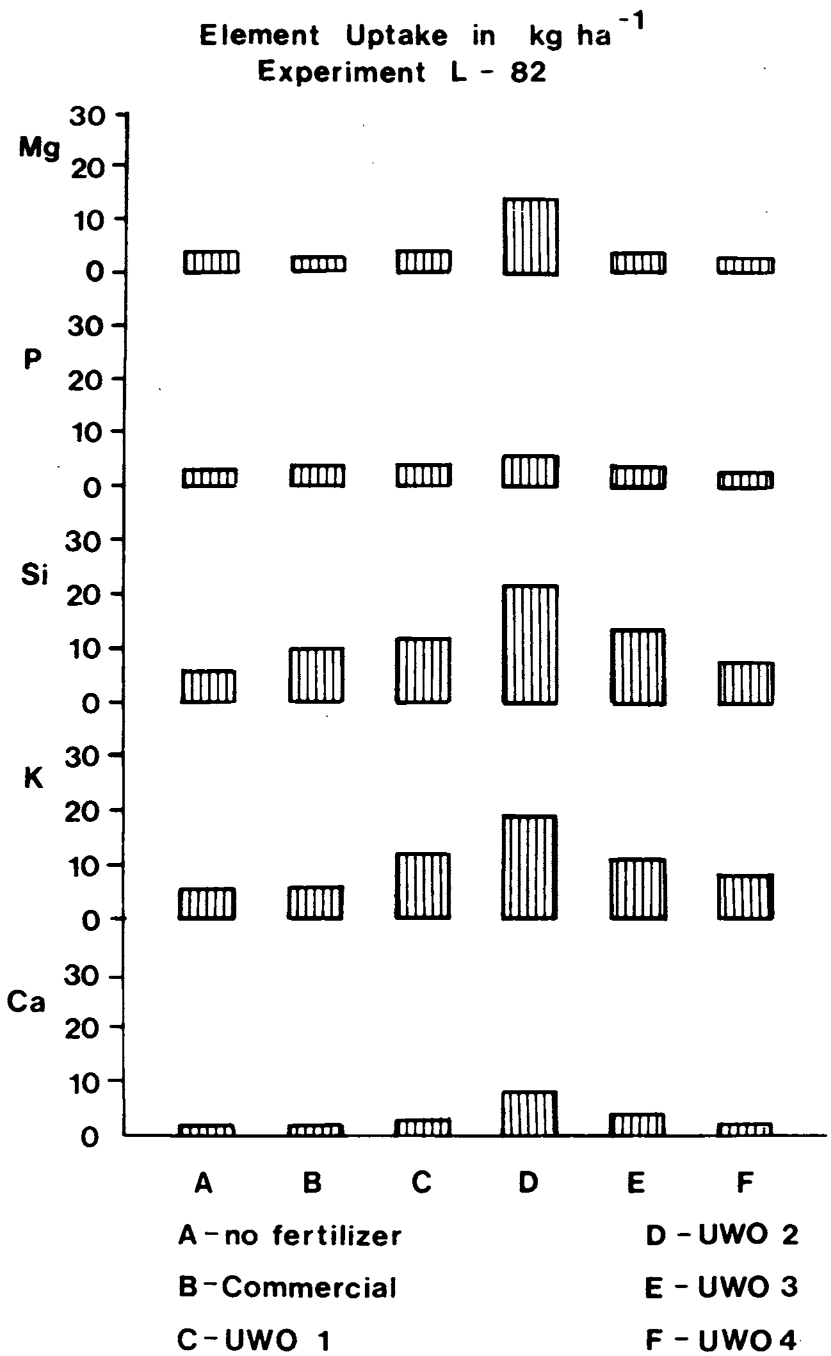

Fig. 2. Element uptake in corn cobs from the experiment in fig. (1). Note that mineral-based fertilizers produced a product with the greatest mineral content.

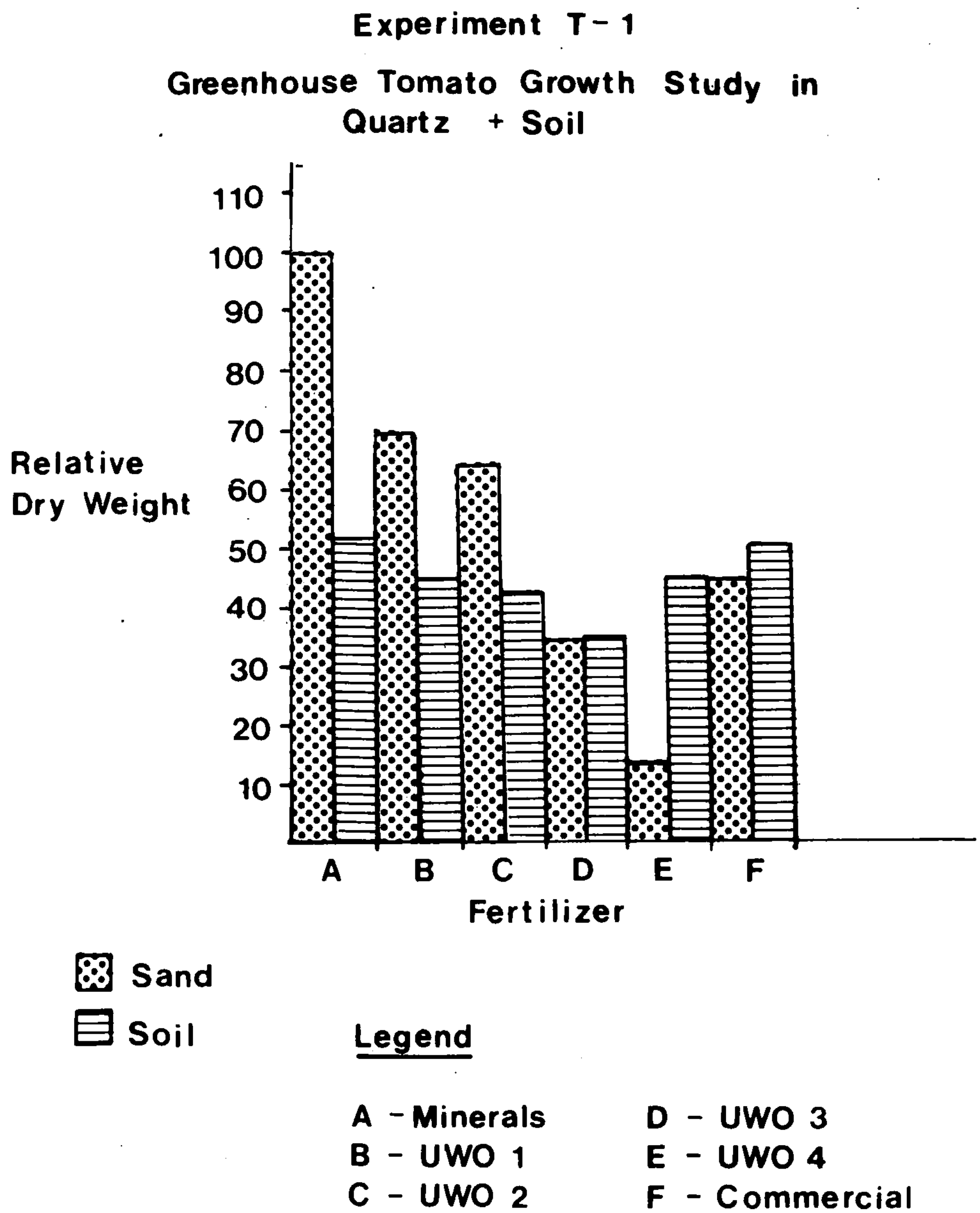

Fig. 3. Greenhouse experiments of a tomato crop grown on quartz sand and soil. Note that mineral-based fertilizers produce up to twice the yield as commercial fertilizer.

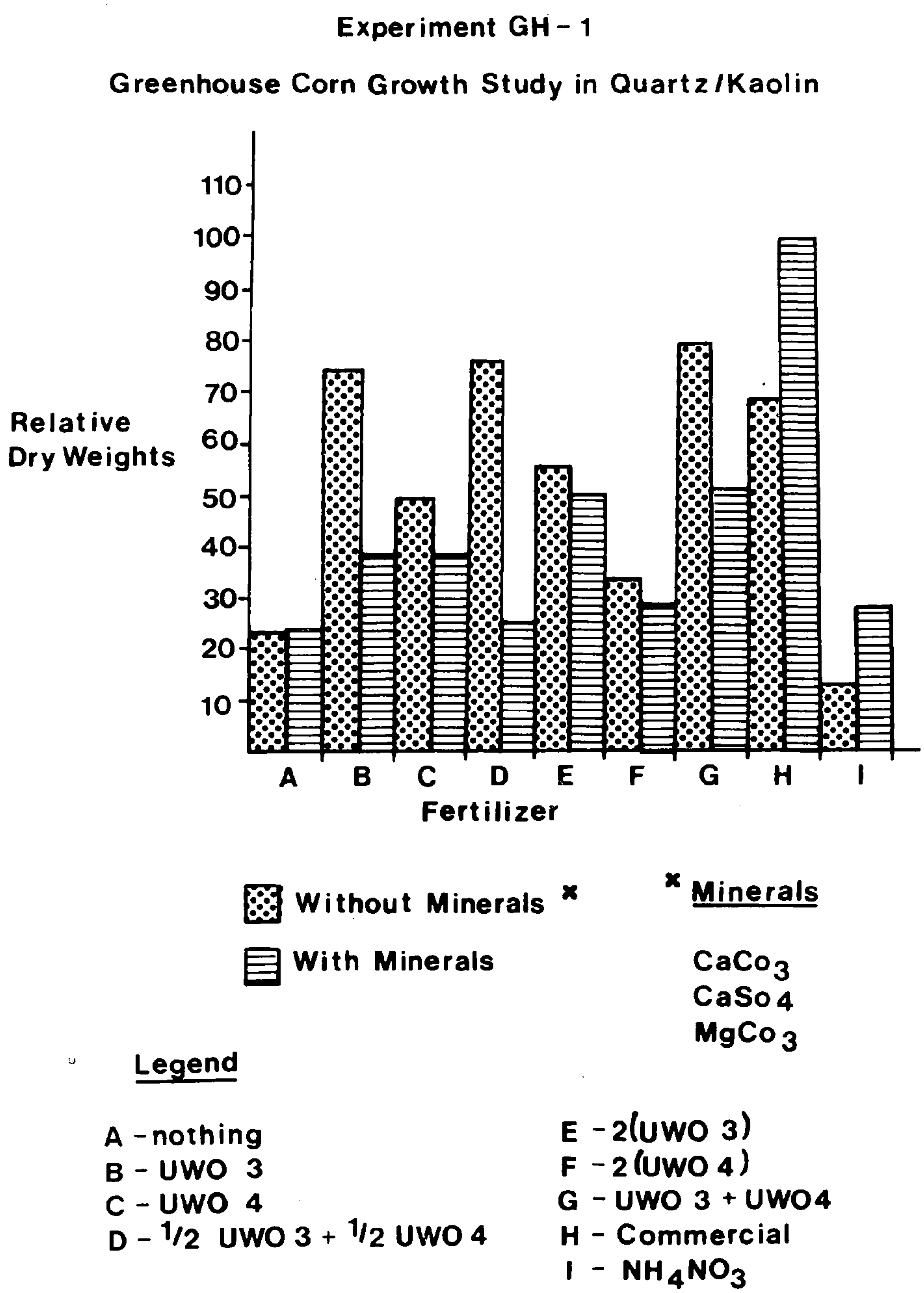

Fig. 4. Greenhouse experiment of corn grown on pure quartz + kaolin soil. Note, ammonia has little influence. Highest yields are obtained with minerals and commercial fertilizer.

CONCLUSION

From the data presented here the indication is that for lateritic soils, mineral based fertilizers are both economically and technologically superior to conventional N-P-K fertilizers. To confirm this requires full scale field trials in a range of tropical movements.

It is also clear that there are large gaps in our knowledge of geochemical cycles of nutrient elements and in particular of the processes governing their partitioning across the rock-soil-biosphere interfaces.

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