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THE USE OF GROUND ROCKS IN LATERITE SYSTEMS: AN IMPROVEMENT TO THE USE OF CONVENTIONAL SOLUBLE FERTILIZERS?

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Abstract

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The geochemistry of lateritic terrains is discussed in terms of nutrient demand in agriculture. The data presented show a dramatic depletion of virtually all nutrients when compared to crustal levels and other soil systems. Increasing world demand for food production, particularly in tropical countries where alcohol production is also needed, has forced the agriculture frontier deep into lateritic areas. As cultivation is intensified the laterite becomes more barren and a neutral recipient for the massive doses of nutrients that are to be constantly added if production is to continue. Conventional soluble fertilizers such as NPK do not answer basic requirements. Designed for the high-nutrient and high-exchange-capacity soils of the northern hemisphere they are not held by the Fe_2O_3-Al_2O_3-SiO_2-H_2O laterite systems and, under condition of excess rain, they can be wasted and consequently polluting. Furthermore, they do not supply a variety of both macro- and micronutrient elements that are normally present in soils in equilibrium with rock debris, but that are lacking in laterites. The replenishment of the laterite to the nutrient levels of natural fertile soils can be basically attained by adding into the system ground rocks of varied composition. The thermodynamical and geochemical background of this proposition is discussed and the state of the art is presented.

1. Introduction

1.1. *Statement of the problem*

As a consequence of the exponential growth of the world population, food must also increase exponentially if famine must be avoided. The recent *Global 2000 Report* to the U.S. President summarizes the gravity of the problem (Barney, 1980). While in the next two decades population is expected to increase by 25% the increase of arable land is predicted to be only 4%. Furthermore, the overall increase of fertilizer consumption has not been accompanied by a corresponding gain in food production. Such pessimistic trends that expose the weakness of our modern fertilizer technology invite new approaches and revives old forgotten practices. But, whatever path we take, a serious limitation to all our modern agriculture practices

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(Waldrop, 1981) is that of not taking into account all the missing inorganics necessary to restore the chemically balanced environment such as found in natural fertile soils.

Successful crop production has been carried out for millennia in regions of natural fertile soils where geological processes provide a continuous supply of nutrients from the lithosphere to the soil–biosphere–hydrosphere system. The processes involve a complex geochemical balance of all 92 elements present in minerals. Significant departures from such a balanced system may turn such soil systems unfit for food production – without massive replenishment of the leached nutrients. The extreme cases are those of laterite environments where the system is reduced to water and a few insoluble hydroxides and oxides of Fe, Al and not uncommonly rarer metals as Ti, Nb, U, Th, Cr or even Au and Pt. Though such systems may yield notable enrichment of valuable metals that can be mined to the benefit of mankind, they do not respond to NPK agriculture.

The demand of new areas for agricultural expansion is opening vast and heavily leached laterite regions such as the Cerrado and Amazon of Brazil for food and energy (alcohol) production. What fertilizers systems are appropriate for such soils?

Unfortunately the standard concept and technology of soil fertilizer (I.F.D.C., 1978) is behind that of the superphosphate concept developed by J.B. Lawes in England, 150 years ago. Since then, this technology has been universally adopted and improved by NK formulas experimented and spread by the Tennessee Valley Authority (T.V.A.) in the U.S.A. and other traditional centers in the northern hemisphere. Had this technology been originally developed for the deep leached laterite soils of the tropics instead for the glacial and rock-debris-rich soils of the northern hemisphere our present fertilizers might have been quite different. Perhaps, the concept of petrofertilizer would have been well established.

1.2. Previous work

The use of rocks to improve crop yields roots in ancient times. Pliny (23–79 A.D.), for instance, presented a detailed account of the liming practice used in Gaul (Russel, 1961). In the eighteenth century, James Hutton, the father of modern geology not only recommended but used himself rocks like marl to increase the soil fertility of his farm in Scotland (Bailey, 1967). Since then, earth scientists have been calling attention to the vast nutrient potential of the majority of rock types and minerals and advocating their use in agriculture. Contrary to the current opinion among agronomists that rock-forming minerals have a soil life-time far beyond a crop cycle, rocks do have large solubility rates both in water and in weak organic acids, promptly releasing nutrients in a matter of minutes and increasing the pH of solution until the system is saturated (Keller, 1948, 1950; Stevens and Carron, 1948; Correns, 1963; Keller et al., 1963; Huang and Keller, 1970; Vandor, 1975; Portilho and Leonardos, 1976; Singer and Narrot, 1976) at nutrient levels equivalent to the "glacial milk" and groundwater composition (Keller, 1948; Vandor, 1975; Fyfe et al., 1983). Common rock-forming minerals such as feldspar and micas were early shown experimentally as efficient source of K, Ca and micronutrients for a variety of plants (Magnus, 1850; Aitken, 1887; Cushman, 1907; de Turk, 1919; Haley, 1923; Graham, 1941; Lewis and Eisenmenger, 1948; Lyon, 1955); nutrient availability considerably enhanced by micro-organisms (Eno and Reuszer, 1955; Duff et al., 1963; Mojallali and Weed, 1978). One of the most comprehensive field trials using powdered whole-rock fertilizer was carried out for sugar cane in Mauritius (d'Hotman de Villiers, 1947, 1949, 1961). The long-term trials successfully recorded the fact that basalt flour could be used profitably to rejuvenate lateritic soils, a practice that had been long recommended for the poor soils of Europe (Albert, 1938, 1940;

Gerth, 1939) and recently re-discovered (Roschnik et al., 1967; Rasp, 1974; Gillmann, 1980). Extremes of the igneous rock spectrum such as dunites and serpentinites (Chittenden et al., 1967) and granites and gneisses (Swanback, 1950; Geering, 1952) have been also successfully employed as source of Mg and K, respectively. In Brazil, independent work has advocated the use of K-rich (zeolitized) phonolites (Frayha, 1950; Ilchenko and Guimarães, 1953, 1954), ultramafic tuffs (Ilchenko, 1955), mica schists (Lima, 1969; Horowitz et al., 1978), basalt (Hardy, 1962; Paccola et al., 1974; Leonardos et al., 1982) and other rock types (Lopes, 1971; Dutra and Braga, 1976) as alternative fertilizers for lateritic soils. Past reviews of rock fertilizers (Keller, 1948; Leonardos et al., 1976; Chesworth et al., 1983; Von Fragstein, 1983) unanimously endorse them as more intelligent alternatives than NPK.

2. Petrofertilizers?

2.1. General background

Twenty years ago, the authors observed in northeast Brazil that, whenever fresh rocks were present, crops were always better than when they were not.Despite early resistance of agriculture journals, results were eventually published developing soil fertilization concepts along global geochemical approaches (Leonardos, 1973; Kronberg et al., 1976, 1984; Leonardos et al., 1976; Kronberg, 1977; Fyfe and Leonardos, 1978; Fyfe et al., 1978, 1981, 1982, 1983; Fyfe and Kronberg, 1979; Fyfe, 1981; Kronberg and Nesbitt, 1981).

As in other geological phenomena, surface processes such as those responsible for the migration and distribution of nutrient elements in the soil layer are related to the mechanisms of plate motion (plate tectonics). The lateral boundaries of the plates are defined by either opening zones where new materials arrive from the Earth's interior or by collision zones where the surface rocks return to mantle depths, recording thus a state of vigorous convection (Fyfe et al., 1983). Continents move away from or towards each other at rates of 10 cm $yr.^{-1}$ and the flux of newly arrived rocks is of the order of $4 \cdot 10^{10}$ t[*]. The velocity with which a mountain is formed or worn out, the rates of sedimentation and also the processes of soil formation in a given segment are functions of the intensity of plate motion and of the location of this segment in relation to the plate's geometry. Thus, the nature and quantity of nutrients found in a given region is the direct result of tectonic processes and its interactions with the climatic pattern.

In simple terms there are two extreme situations of soil fertility: (a) plate margins, where the tectonic and geologic processes are extremely active; and (b) in the plate's interior where stable conditions favor rock decay. In the first case, crustal elements such as Si, Al, K, Na, (Ca), Be, Li, Zn, Mo, F and B are mixed with newly arrived mantle elements such as Ca, Mg, Cu, Co, Ni, S, V, Cr and Se. The residence time of a given rock at the surface is small as the rate of addition of new materials is much greater than the rate in which they decompose. When periodic rock debris is incorporated into the soil, either by volcanic, fluvial or glacial processes, natural fertile terrains result. This is the case of Java, the whole western part of North, Central and South America (volcanic), deltas such as the Nile, Mekong and Yang Tse, and glacial soils. At these sites natural processes have sustained high agriculture output during millennia! In contrast, the second case shows a dominance of sedimentary rocks, frequently formed by chemically simple rocks such as orthoquartzites, shales, limestones, evaporites, etc., with specific or virtually no nutrients, or by granitic and metamorphic rocks, with a limited nutrient spectrum. Plate centers provide the tectonic stability that leads to little erosion and high leaching. The situation becomes the more extreme when such condi-

*1 t = 1 metric tonne = 10^3 kg.

tions are superimposed in a humid tropical climate which accelerates the leaching process. This is the situation of typical laterite environment where the rock component of the soil, primary minerals and nutrients are gone. Virtually all nutrients and a balance among all elements must be restored if the high soil fertility of the first situation is to be attained. NPK is in this case an inadequate solution.

2.2. Mineralogic and geochemical constraints

Soils are formed either by accumulation of rock debris as in the aforementioned case (a) or by accumulation of secondary minerals derived through processes of rock decay. Basically these processes are chemical reactions of silicate hydrolysis that release nutrients and hydroxyl radicals. The complementary process is that of chemical titration (Chesworth et al., 1983), where the bases released during the hydrolysis are neutralized by the atmosphere and biosphere acids in the soil aqueous phase. In the initial stage, there is an excess of bases and primary minerals are incongruently dissolved, producing clay minerals of the smectite group, vermiculites, or zeolites. These minerals and the organic complexes of the soil due to their high exchange capacity or chelating properties form virtual banks on which plants can withdraw their nutrients as they deem necessary. In a second stage, the smectites, zeolites and organic complexes themselves become acidified, oxidized and leached, yielding clay minerals of the kandite group (kaolin, halloysite) and Fe-oxides, drastically reducing the amount and availability of nutrients. In a third stage, that of lateritization, the soil has already lost its primary components and the process of hydrolysis has come to an end with the hydrolyzation of the kaolin to form gibbsite or boehmite. The soil reaches stable equilibrium with the atmosphere-acids in the Al_2O_3–Fe_2O_3–H_2O systems (Kronberg et al., 1979). Many laterites are formed exclusively by gibbsite–goethite (lepidocrocite)–(quartz) and have no nutrient reserves and, what is more serious, *not any capacity to retain the nutrients* if they are incorporated in a highly soluble form. Again NPK fertilizers seem in-appropriate. We leave the reader to consider the pollution levels that would result if the same levels of NPK fertilizers used in North America and Europe were ever reached in laterite countries.

2.3. Petrofertilizer recipes

From thermodynamic considerations, laboratory experiments on dissolution rates of rocks and minerals, pot tests, field trials and geological observation of natural soil fertility (Albert, 1938, 1940; Gerth, 1939; Frayha, 1950; Swanback, 1950; Geering, 1952; Ilchenko and Guimarães, 1953, 1954; Ilchenko, 1955; d'Hotman de Villiers, 1961; Chittenden et al., 1967; Roschnik et al., 1967; Lima, 1969; Rasp, 1974; Horowitz et al., 1978; Gillmann, 1980) it is known that plants respond favorably to a supply of fine-grained rock debris. In fact, plants for hundreds of million years have evolved on rock debris and still appear to require it for a balanced diet (Fyfe and Kronberg, 1979). As the variety of rock materials that satisfy basic nutrition requirements is practically unlimited, what shall distinguish a good from a bad recipe is the return of the fertilizer investments over the life of the agriculturist's enterprise. Given a particular situation, one should be able to design the best rock combinations according to the local geological, agricultural and economic factors. A favorite recipe is the "manna" (Fig. 1) that falls after volcanic eruptions (Kronberg et al., 1979; Fyfe et al., 1981) for it brings a well-balanced diet for most crops, a long lasting productivity with virtually no pollution and what is more, no costs, within a few hundred kilometers windward of the source. However, for those not near active volcanic centers, transportation and energy costs of grinding to appropriate grain sizes, mixing and (occasion-

Fig. 1. Wheat fields being fertilized by andesitic flour from Mount St. Helens (Washington, U.S.A.), ~160 km away.

ally) costs of heating will limit possible choices of rock combinations.

As in the practice of liming, a few tons of rock flour may be needed per hectare. This means that suitable materials must be found locally – a goal not normally difficult.

However, there are cases when the nutrient content of local available rocks may be insufficient to provide a complete plant diet, and then it should be complemented by mixing with nutrient-rich materials, either in natural or glass form, brought in from other regions. Phosphate–silicate glasses of the type described in Fyfe et al. (1978) and Horowitz et al. (1978) for instance, are nutrient concentrates that keep the petrofertilizer philosophy of nutrient conservation.

Plant analysis and nutrition data show that most elements are present in plant tissues (Dutra and Braga, 1976). One-third of all elements, such as H, C, O, S, N, P, Na, K, Li, Rb, Ca, Mg, Sr, Si, Fe, Mn, F, B, Cl, Br, I, Cu, Zn, Co, Mo, Sn, Cr, Ni, V and Se, has major roles in plant nutrition mechanisms. The impressive recent growth of the number of micronutrients and of the knowledge of their role indicates that the above-mentioned list will substantially increase.

To keep a reasonable geochemical balance, nutrients should not be applied in excess of what the environment can tolerate. In laterite systems, the toleration limit is very low and unless a change in the smectite, zeolite or organic bank is gradually built up, nutrient overdoses can be harmful to the environment.

In short, to design a balanced plant diet some of the following alternatives are possible:

Alternative A

a_1 – basic rock (basalt, amphibolite, chlorite schist, etc.) to supply Ca, Mg and Na, micronutrients, and (variable) amounts of S, P and K.

a_2 – alkaline or acid rock in minor amounts to complement micronutrients and K, P. and S if not enough in a_1.

a_3 – rock phosphate (or phosphate glass) if not enough P in a_1 and a_2.

a_4 – sulphide rock or concentrate of gypsum (anhydrite) if not enough S in a_1 and a_2.

a_5 – ammonium zeolites or alternative source of N if not biologically fixed.

Alternative B

b_1 – alkaline or acid rock to supply Na, K, Li and F, micronutrients, and (variable) amounts of Mg, Ca, S and P.

b_2 – dolomite, magnesite or serpentinite to complement Mg, micronutrients, and sometimes, S (in sulphides).

b_3 – rock phosphate if not enough P in b_1.

b_4 – sulphides (Banath, 1969) or gypsum.

b_5 – ammonium zeolites.

Alternative C

c_1 – any igneous, metamorphic or sedimentary rock with mixed crustal or mantle geochemistry.

c_2 – a complementary rock to c_1.

c_3 – rock phosphate if not enough P in c_1 and c_2.

c_4 – dolomite, gypsum, sulphides depending on the composition of c_1 to c_3.

Alternative D

d_1 – petrofertilizer phosphate glass with (Na,Mg,K)-silicate matrix (fused rock and rock phosphate) and micronutrients. If N is required, the melt can be quenched in inexpensive N-rich solutions such as sugar cane effluent.

d_2 – gypsum, dolomite, vermiculite, zeolite or any rock type that can reduce amounts of d_1.

Alternative F is designed for skeptics and consists of progressively adding one of the previous recipes to NPK fertilizers already in use in a given region as the amount of NPK is being reduced.

Alternative G is the opposite of *F* and is designed for gourmet crops. It consists of one of the previous recipes to which NPK is added.

2.4. Experimental work at Brasilia

Pot experiments and field trials were carried out at the University of Brasília on the lateritic soils described in Kronberg et al. (1979) with the objective of testing local and inexpensive rock materials that were already available in ground form as the residual by-product of the quarrying industry. Rock powders were of three types: (a) pigeonitic basalt; (b) muscovite–biotite–chlorite–carbonate schist; and (c) phonolite. Grain size was less than 80 mesh, with ~50% less than 200 mesh. Abrasion pH of basalt was 9.6, phonolite, 9.4 and mica schist, 9.9 in 60–90 s. NPK, rock phosphate, FTE micronutrients and dolomitic limestone were used in the experiments for comparative purposes.

*2.4.1. Pot experiment on the growth of beans (*Phaseolus vulgaris, *L.)*

This experiment was carried out in greenhouse conditions. Each of the 126 plastic vases was filled with 12 kg of the lateritic virgin soil from the University farm [chemical compositions given by samples *75-5* in (Kronberg et al., 1979)] taken at depths of 10–30 cm. The experimental design involved 42 treatments as given in Table I with respective results; each treatment was repeated three times.

The materials used in the experiments and their respective doses were the following:

N – ammonium nitrate (N=35%); 84.5 kg/ha or 0.32 g/vase applied 15 days after germination.

P – triple superphosphate; 174 kg/ha or 80 kg P_2O_5/ha or 1 g/vase.

K – potassium chloride; 100 kg/ha or 0.5 g/vase.

Amounts of N, P, K, m and limestone were used according to current agriculture practice (Mascarenhas et al., 1967). Amounts of rocks were the same as for limestone.

2.4.1.1. Results. Quantitative statistical treatment of green weight, amount of roots, plant height, number of beans, nodulation and leaf composition is the subject of a further paper by O.H. Leonardos and F.P. Cupertino. The preliminary results, shown in Table I, illustrate the positive effect of ground rocks on the growth of bean plants. Highest values were recorded for $NPK_C(c)$ – NPK + m(c), $NPK_C(b)$, $NPK_A(c)$ treatments, all with values expressively higher than single NPK(a) treatment, which also showed considerably less residual effect than the rock treatments. Rocks and trace-element addition had a much larger nodulation of *Rhyzobium* than other treatments. Productivity increase due to liming was considerably lower than using basalt. Basalt among the other rock types gave the best results, followed by mica schist. Despite a large residual effect, phonolite did not show a very significant effect, probably due to the presence of K in the soil and the fact that beans do not demand high K amounts. Results also illustrate that beans cannot grow in a virgin lateritic soil without replenishing it with nutrients.

2.4.2. Pot trial with napier grass.

This involved a greenhouse experiment to evaluate the effect of several rock types and the silicate–phosphate glass of Fyfe et al. (1978) when added to the laterite soil of the previous experiment. A total of 27 pots were filled with 12 kg of soil, divided into 9 different treatments with 3 repetitions. Except for treatment *3* where superphosphate was added, in all other treatments phosphate was added as sedimentary phosphate rock (P-rock) from Patos de Minas. Rocks were added in doses equivalent to 3 t/ha. In treatments *4, 5* and *6*, doses of 5 t/ha were

TABLE I

Average weight (in grams) of green mass by treatment

Treatment	(*a*) single		(*b*) with dolomitic limestone		(*c*) with basalt	
	1st crop	2nd crop	1st crop	2nd crop	1st crop	2nd crop
000	8.0	1.6	5.7	2.8	12.0	3.3
N00	3.3	1.2	3.7	1.8	11.3	1.8
N0K	4.3	1.6	3.0	1.7	9.3	3.7
$N0K_A$	5.0	2.2	6.0	3.5	20.0	4.2
$N0K_C$	11.0	2.3	10.0	2.8	8.3	2.5
NP0	109.3	9.8	96.7	9.9	259.3*	36.5
NP_E0	47.3	14.8	44.6	17.5	47.6	14.0
NP_EK	53.0	12.3	50.0	17.0	55.0	15.3
NP_EK_A	41.0	16.1	34.0	14.3	39.2	21.8
NP_EK_C	45.5	24.6	43.7	27.3	35.0	16.0
NPK	136.7	15.7	170.3	17.5	223.0	43.5
NPK_A	126.0	16.6	144.3*	18.0	259.6*	80.0*
NPK_C	249.3	27.8	260.3	40.5	308.3*	48.8
NPK+m	116.3*	8.0	150.2*	11.7	260.6*	56.5

P_E= Araxá rock phosphate (P_2O_5 ~28%) 28 kg/ha or 1.42 g/vase; K_A= phonolite (K_2O=5%) 60 kg K_2O eq./ha or 6 g/vase; K_C=mica schist (K_2O=3.5%) 60 kg K_2O eq./ha or 8.75 g/vase; m=FTE micronutrients, 50 kg/ha; (*b*) =dolomitic limestone - 6 t/ha or 30 g/vase; (*c*) =basalt - 6 t/ha or 30 g/vase.
*Very high *Rhyzobium* nodulation.

also tried (results between parentheses). P-rock and glass were used in amounts of 1 t/ha, and superphosphate in 300 kg/ha. Results in Table II refer to the cumulative weight of grass (green mass) collected every three months for a 1-yr. period.

2.4.2.1. Results. In this experiment rocks produced gains of 10–29% while our special phosphate glass showed 75% increase. Neither a change from rock phosphate to superphosphate or a dosage increase from 3 to 5 t/ha showed significant gains in the mass of the grass.

2.4.3. Field trial with Eucalyptus pellita

Within a multi hectare forestation experiment carried out by the Agriculture Department at the University of Brasilia experimental

TABLE II

Average weight of grass treated with rock and glass

Treatment No.	Description	Weight (g)	Yield increase relative to *1* (%)
0	blank soil	63.5	-
1	P rock	80.4	0
2	limestone + P-rock	100.9	17
3	limestone + superphosphate	102.7	19
4	*Bambui verdette* (Lopes, 1971) + P-rock	93.3 (105.4)	9
5	olivine basalt + P-rock	94.1 (100.9)	10
6	mica schist + P-rock	104.2 (103.5)	20
7	migmatite + P-rock	112.5	29
8	glass	144.1	75

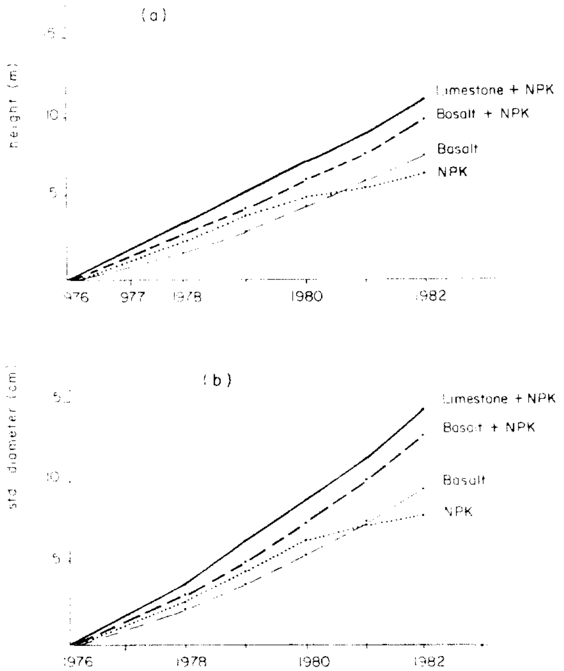

Fig. 2. Height (a) and standard diameter (b) of *Eucalyptus* trees as function of age and treatment

farm of Agua Limpa, our trial occupied a small plot where 12 rows of 9 *Eucalyptus* were planted. The plot consisted of 4 treatments, each with 27 plants distributed in 3 trials. Treatment *1* (NPK) used 170 g of NPK(5-10-2) per hole. Treatment *2*, (basalt) used 2 kg of coarse-grained basalt powder (grain size up to 1 cm and only ~30% below 200 mesh). Treatment *3*, limestone (2 kg) + NPK and treatment *4*, basalt + NPK. Results were plotted in Fig. 2. for gains in height and in standard diameter of trunk (measured at 1.60-m height). The data presented show that the use of basalt alone produces higher gains than NPK.

3. Final conclusion

The use of petrofertilizers consisting of rock mixtures or rock-derived glasses provides an intelligent alternative for lateritic soil agriculture where soil conservation is the strategy.

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