Point of View

SOILS AND AGRICULTURE IN CENTRAL-WEST AND NORTH BRAZIL

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ABSTRACT: Modern soil science, spearheaded by research in Brazil has facilitated the utilization of vast areas of previously uncultivated soil long considered unsuitable for human food production into highly productive agricultural land. Naturally acid soils with high contents of aluminum and iron oxides and low CEC values and organic matter contents long considered insurmountable obstacles to crop production in tropical latitudes could be extremely productive. With continued development of the infrastructure needed by commercial agriculture Brazil has the potential to lead the world in its quest to provide food for growing human populations.
Key words: Cerrado soils, Brazilian Amazon, Latossolos, Oxisols, Ultisols

SOLOS E AGRICULTURA NO CENTRO OESTE E NORTE DO BRASIL

RESUMO: A moderna ciência de solo, liderada pelas suas pesquisas no Brasil, tem possibilitado a utilização de vastas áreas de solos, durante muito tempo não cultivados por serem avaliados como inaptos para uma intensiva produção de alimentos. Hoje, ao contrário, constata-se que essas terras são altamente produtivas para a agricultura. Estas pesquisas vêm mostrando que alguns atributos naturais destes solos, como acidez, baixos teores de matéria orgânica, baixa capacidade de troca de cátions, além de altos teores de óxidos de ferro e/ou de alumínio - considerados como obstáculos à produção de boas colheitas em latitudes tropicais - podem ser superados. Com a continuação do desenvolvimento das infra-estruturas necessárias para alavancar ainda mais a agricultura comercial, o Brasil tem potencial para, em breve, liderar o mundo no que tange ao fornecimento de alimentos para as crescentes populações humanas.
Palavras-chave: solos do Cerrado, Amazônia Brasileira, Latossolos, Oxissolos, Argissolos

INTRODUCTION

Almost every major kind of soil known to soil scientists exists in Brazil with the exception of soils with permafrost (Gelisols[1]) and soils formed from recent deposits of volcanic ash (Andosols[1]). Many of the soils in the southern and southeastern parts of Brazil have long supported productive commercial production of human food. However, it has been only in recent years that commercial agricultural production has accessed the more extensive soils originally under cerrado vegetation in the Central-West region of Brazil and some tropical forested areas of the Amazon basin. It is those areas that I have had the pleasure of working with the past 40 years during many delightful trips to Brazil in company with several Brazilian graduate students studying for graduate degrees at North Carolina State University and many other outstanding Brazilian soil scientists. It has been a personal delight to see the remarkable expansion of agriculture in the Cerrado that has taken place following the research initiated by personal from North Carolina State University and Cornell University on sites I selected in 1971 and later conducted by EMBRAPA scientists near Planaltina in the Federal District.

The Cerrado is the second largest major biome, after Amazonia in Brazil originally covering some 2,032,000 km^2 and representing the most extensive area of savanna-type vegetation in South America (Figure 1a). The major areas of Cerrado are on the Central Brazilian Plateau where annual rainfall is typically between 1,100 and 1,600 mm concentrated in a period of six or seven months (October to April). Most soils in the Cerrado are deep with favorable physical characteristics on nearly level to rolling topography that permit intensive agricultural mechanization with little potential erosion hazard. These soils have Isothermic and Isohyperthermic soil temperature regimes and an Ustic

[1]U.S. Soil Taxonomy (Soil Survey Staff, 1999).

soil moisture regime[1]. This is the region of Brazil where most grain production development is taking place. In 1955 only 200,000 hectares in the Cerrado region were considered arable. In 2005 over 40,000,000 hectares were in cultivation. This phenomenal achievement over a span of less than 50 years is the world's single largest increase in farmland since the settlement of Midwest USA that began in 1850 and has been hailed as a far reaching achievement and milestone in agricultural science (SeedQuest, 2006).

The relative slowness in understanding and utilizing the agricultural potential of soils in Cerrado and Amazon areas can be understood by examining the developmental history of soil science. Academic understanding of soil as a distinct unit of the lithosphere had its beginning in the 1880's in Russia when it was determined that soils had properties that depended not only on the geologic material, but also were created by active processes controlled by climate, vegetative growth, landscape position and time of exposure. Within a very few years this concept became dominant within the United States where the observations made in Russia were readily apparent in the rapidly developing agriculture in the Midwest part of that country. Starting in about 1865 extensive federal support was forthcoming for the study of soil and tended to be focused in the most successful food crop producing areas. As a result of these studies extensive amounts of literature were written relating soil properties to high levels of crop production in the United States. The most favorable soil conditions for crop production with the technology available were identified and conveyed throughout the world in scientific publications. These observations became the criteria by which scientists judged the potential of soil to support food production. Where such soil properties were not found the soil was often considered unsuitable or incapable of agricultural production.

When we examine the origin of where these academic concepts of desirable soil properties were developed and presented in scientific publications we find in large part, although not entirely most observations were made of soils that had been formed in deposits of material left by massive continental glaciers of relatively young geologic age (Pleistocene). The most agriculturally desirable soils were formed in thick deposits of material crushed by the continental glaciers and further transported and deposited by the wind. These loess deposits were predominantly silt-sized particles and contained significant quantities of calcium, magnesium, potassium and phosphorus derived as the Pleistocene glaciers passed over several kinds of rock, especially limestone.

Soils that formed in the loess deposits were neutral to slightly alkaline in reaction and contained large amounts of phosphorus, calcium, potassium and magnesium both in the topsoil and in the subsoil. Many of these soils were naturally vegetated with grasses that seasonally ceased growth in response to temperate latitude winters and annually deposited large quantities of organic residue both on the soil surface and with depth as annual grass roots decomposed. The copious quantities of silt-sized particles created voids in the soil that retained large quantities of water against leaching but available to plants and the absence of transpiring vegetation during the cold winter months assured a large supply of plant available water stored in the soil at the time crops were planted as the weather seasonally warmed in the spring.

Perhaps the most unique feature of soils formed in glacial deposits is the physical and chemical nature of the mineral materials. As the massive continental glaciers moved from their more northern source areas they dislodged minerals that were deeply buried below the land surface and pulverized them into small particles. The minerals that were then widely distributed by water and wind as the glacial ice melted had not previously been subjected to decomposition by water and organic acids and were of small particle size. Thus they had large surface areas per unit weigh whereupon decomposition (weathering) could rapidly proceed and release essential elements in ionic forms needed by plants.

Within Central Brazil, and other tropical latitudes the above scenario did not take place. Within the Guiana and Brazilian shields, and other geological features the mineral material in which the present soils formed were weathered on the land surface and redistributed during many episodes of erosion, especially during the more humid climates of Cretaceous and early Cenozoic time (Orme, 2007). As a result few micas, feldspars, apatites, and other weatherable minerals containing potassium, calcium, magnesium or phosphorus remained, having long since been dissolved while in previous locations and/or during transport. Most present day Oxisols[1] (Latossolos[2]) formed in such material that had been exposed to many cycles of weathering, erosion, and deposition (Lepsch & Buol, 1988). Almost no nutrient bearing minerals were present and sand-sized quartz (SiO_2) is the dominant primary mineral remaining in the parent material within which the present soils have formed. Where sandy textured deposits were concentrated sandy textured Quartzipsaments[1] (Neossolos Quartzarênicos[2]) are now present among the Oxisols[1] (Latossolos[2]) (Buol, 2007).

[2]Brazilian Soil Classification System (EMBRAPA, 2006)

As silicon was removed from feldspars and other weatherable minerals during the cycles of erosion and deposition kaolinite clays and iron and aluminum oxides were formed. The iron and aluminum oxides have the ability to adsorb phosphorus in forms unavailable to plants. Kaolinite has a very low cation exchange capacity (CEC) and in the absence of carbonate minerals and other basic cations, aluminum ions dominate the meager amounts of negative sites on the clay and organic particles in the acid conditions that form naturally from organic matter decomposition and root exudates of hydrogen ions. Only very small quantities of silt-sized particles are present. The clay and iron oxides form fine and very-fine granules, often called 'pseudo-sand'. The result is soils with very small voids within the granules that retain water at such a great tension that plants cannot extract it and large voids between the granules that allow water to rapidly percolate under the force of gravity. Thus the soils hold relatively little plant available water per unit of soil depth when compared to the silt-rich soils formed in loess and most glacial deposits in temperate latitudes.

An often overlook, but agronomical significant contrast between soils in tropical latitudes and temperate latitudes are the seasonal temperature dynamics and how this affects the hydrologic cycle as related to crop growth. Farmers in temperate latitudes are almost always assured of a supply of plant available water in the soil at planting as the soil warms in the spring. Farmers in tropical latitudes with seasonal rainfall patterns (Isothermic and Isohyperthermic soil temperature regimes and Ustic soil moisture regimes[1]) often plant in soil with little or no stored available water. Thus early growth of seedlings is dependant on reliable rainfall following germination. This is seldom a problem in temperate latitudes.

In historical summary, the preponderance of soil science experience, literature, and training that influenced prevailing concepts of soil potential during most of the 20th century was almost totally bias toward soil properties present near the terminus of continental glaciers in Europe and the United States. When soil scientists and other agronomic professionals attempted to evaluate soils in which little or no successful agriculture had been achieved in tropical latitudes they compared them to the European and United States standards and declare them to have too little cation exchange capacity, too acid, too lacking in silt content, too lacking in weatherable minerals, too little organic matter content (often based only on their red color rather than actual measurements of organic matter content), or simply attributed the problems to amorphous concepts of 'tropical weathering' and 'laterization'. Hopelessness among many soil scientists and agronomists in tropical areas resulted from such comparisons for several generations.

What was often overlooked in their despair were areas of basic ion rich well-drained Oxisols, mostly Eutrustox[1] (mostly Latossolos Vermelhos Eutroférricos[3], popularly called 'terras roxas' and various Alfisols, mostly Haplustalfs[1] (Argissolos and Nitossolos[2], third category Eutrófico soils) that existed and had for many years been successfully farmed within and south of the geographically areas of Cerrado (Moura Filho & Buol, 1972). The original vegetation on these more fertile soils that had formed in residual, or locally transported basic rock material such as basalt or limestone was seasonal semi deciduous forest rather than Cerrado. However, almost all the trees had been removed by generations of farmers that had found these areas to be more fertile than those vegetated by Cerrado vegetation. In the 1960's some farmers allowed scattered palm trees (mainly *Scheelea phalerata*-"bacuri") to remain in their fields and pastures as indicators of the original forest and more fertile soils. More recently almost all of the palm trees have disappeared in cropped fields and pastures.

In the early 1970's I noted several hectares of reasonably good corn growing in a remote area of otherwise non-cultivated Cerrado of the Federal District. Upon closer examination the area was found to overlay limestone and the soil to classify as a Mollisol[1] (Chenossolo Argilúvico[2]). Within the Amazon basin recent satellite images show that some of the most extensive areas of jungle clearing correspond to areas of identified as containing Latossolos Vermelhos Eutroficos[2], and Nitossolos Eutróficos[2] (classified as Latossolo Eutrófico and Podzólico Eutrófico by (Camargo et al., 1981). Clearly not all soils in tropical areas of Brazil are affected with what many had identified as insurmountable problems related to tropical climatic conditions.

The Cerrado Region

Although vast areas in the Central-West Brazil had cerrado vegetation of small trees and grasses the natural vegetation is so chemically poor that it would not serve as domestic cattle pasture. Indeed, there are no accounts indicating that herds of native mammals as are present in similar appearing, but nutrient rich and

[3]Well drained Oxisols[1] (Latossolos[2]) are the most common soils in the Cerrado covering 46% of the area. Quartzipsaments[1] (Neossolos Quartzarênicos[2]) and Ultisols (mostly Argissolos) cover 30%, Inceptisols and shallow Entisols (Cambissolos and Neossolos Litólicos[2]) occupy 10% and the remaining 14% of the Cerrado is covered with several other soil types (Lepsch, I. F.: Personal communication).

water stressed savannas of Africa ever existed in the savanna-like but nutrient stressed Cerrado. Herds of buffalo and other mammals existed in the fertile savannas of Midwestern United States prior to European settlement. In the Cerrado domestic cattle often died from broken bones after grazing only calcium and phosphorus deficient cerrado grasses and ranchers came to refer to Cerrado as a place to loose cattle rather than graze cattle.

Although soils that support cerrado vegetation can correctly be considered as some of the most chemically infertile in the world the growing production of grain and meat we see taking place there today is the result of many components (Lopes, 1996). First there was the scientific understanding that some of the chemical properties of the soil had to be changed before grain production and cattle grazing could take place. The two primary changes needed were to provide plant available phosphorus and the replacement of extractable aluminum with calcium on the CEC sites in the soil.

Almost all soils in the Cerrado have a high content of iron and aluminum oxides at all depths. Most significantly the iron oxide content is substantially higher in the surface horizons than in almost any of the soils in Europe or the United States. Thus most agronomists had no experience with the very great capacity of these oxides to adsorb phosphate fertilizers. Numerous experiments that applied phosphorus fertilizer at rates considered economically feasible in Europe or the United States failed. Placing phosphate fertilizer in concentrated bands near the seed row to avoid adsorption by the oxides resulted in a concentration of roots in that band. This resulted in a rapid depletion of available water within the band limiting the effectiveness of the fertilizer. In view of many failed attempts to fertilize agronomic crops the Cerrado region was declared to be of little if any value for agriculture (Wright & Bennema, 1965).

In the early 1970's research determined that the amount of surface area on the iron minerals was responsible for adsorbing large amounts of P added as fertilizer (Bigham et al., 1978). Field studies determined that initial applications as great as 838 kg P ha^{-1} sustained maximum corn yields through four crops (Yost et al., 1979). Such high fertilizer rates were considered impractical but experimentally attempted in conjunction with adequate lime applications to neutralize extractable Al and provide calcium at the site of root growth (Figure 2).

However, researchers soon found that a large, one time application of soluble P when mixed into the upper layer of soil had a residual effect well beyond the first crop. Also, the initial phosphorus application required was related to the amount of clay and most often significantly less than the maximum rates of P used in the initial experiments Once the capacity of the iron oxide to adsorb P had been satisfied the annual applications of phosphorus fertilizer required were no greater than the amount exported in the harvest of the crop and comparable to annual fertilizer rates routinely used the Midwest of the United States. Although the rather massive amounts of P required at the initiation of cropping were often three times the purchase price of the land in the mid 1980's that expense could be considered a capital investment to be recovered over many years rather than an annual fertilizer expense (Göedert & Lobato, 1988). As this knowledge became available land prices have increased greatly in the Cerrado.

At the same time as the initial P application it is necessary to neutralize the extractable Al ions that dominate the CEC in acid soil. Supplying Ca as lime and incorporation at depth in the soil is also expensive because of the transportation costs of the large amounts that must be supplied. The need for deep incorporation so as to facilitate deep root growth also requires powerful cultivation equipment. Shallow rooting depth leading to rapid water stress during the growing season was commonly observed among early farming attempts in the Cerrado (Cline & Buol, 1973). When crops only root to a shallow depth because of Al toxic conditions in the subsoil severe moisture stress limits crop growth during short rainless periods that commonly occur during the growing season

One of the most berated properties of the soils in the Cerrado turns out to be an advantage. The low cation exchange capacity of the kaolinitic clay means that only a limited quantity of extractable Al is present. It takes about one metric tons of lime per hectare to neutralize 10 mmol of aluminum per kilogram of soil (Kamprath, 1970). Most soils in the Cerrado have 20 or less mmol of aluminum per kilogram of soil in the surface horizons and less in the subsoil where less organic matter is present (Table 1).

Of the three pedons in table 1 pedon ISCW 2 has the greatest amounts of clay and organic carbon and thus the highest CEC_7 (CEC determined at pH 7) values. Extractable Al^{3+} ions unfortunately occupy most of the CEC_7 sites. To neutralize the approximately 30 mmol kg^{-1} of Al in a cultivated surface layer would require a minimum of approximately 3,000 kg ha^{-1} of lime with 100% calcium carbonate equivalent. Pedon ISCW 9, with much lower organic carbon contents and CEC_7 values has nearly the same percentage of Al saturation but a much lower amount of extractable Al. It would take a minimum of less than 1,000 kg ha^{-1} of lime to neutralize a cultivated surface layer. Greater quantities of lime are required for some aluminum sen-

Table 1 - Selected EMBRAPA-SNLCS data from soil profiles sampled in Brazil for the International Soil Classification Workshop- ISCW (Camargo et al., 1986).

Depth	Clay	OC	CEC7	$Ca^{2+} + Mg^{2+}$	K^+	Al^{3+}	Al^{3+} sat.
m		g kg^{-1}		mmol$_c$ kg^{-1}			%
ISCW 2: Humic Hapludox[1] - Latossolo Amarelo Distrófico húmico evergreen tropical forest phase[2]							
Parent material : Pelitic cover of Plio-Pleistocene sediments over granite							
0.00-0.10	550	36.4	197	18	1.4	29	59
0.10-0.43	600	26.2	163	30	0.5	32	89
0.43-1.13	640	12.9	111	10	0.1	24	96
1.13-1.55	620	8.7	78	10	0.1	15	83
1.55-2.05	650	4.0	47	10	0.1	3	60
2.05-2.80	670	0.8	24	10	0.1	0	0
2.80-3.30	670	0.6	24	10	0.1	0	0
3.30-4.30	670	0.6	24	10	0.1	0	0
ISCW 9: Typic Acrudox[1] or Latossolo Amarelo Ácrico - evergeen cerrado phase[2]							
Parent material : Sandy clay sediments from Upper Cretaceous- Bauru Group							
0.00-0.15	320	9.5	44	1	0.4	6	75
0.15-0.30	330	7.7	35	1	0.2	4	80
0.30-0.54	350	6.1	33	1	0.1	2	67
0.54-0.75	380	5.2	27	1	0.1	2	67
0.75-1.20	400	3.7	20	1	0.1	0	0
1.20-2.25	410	2.3	16	1	0.1	0	0
2.25-2.85+	420	2.1	8	1	0.1	0	0
ISCW 8: Rhodic Eutrudox[1]- Latossolo Vermelho Eutroférrico típico-Semi-deciduous tropical forest[2]							
Parent Material: Weathering residues from basalt.							
0.00-0.18	680	17.3	125	84	7.4	0	0
0.18-0.45	700	10.7	86	59	2.9	0	0
0.45-0.85	710	6.4	66	49	0.3	0	0
0.85-1.30	690	5.1	62	48	0.3	0	0
1.30-2.35	730	2.5	43	33	0.2	0	0
2.35-3.35	760	1.9	30	21	0.4	0	0
3.35-4.50	690	1.2	25	18	0.2	0	0

sitive crops in both of the above pedons. Pedon ISCW 8 is an example of naturally fertile soil within the Cerrado region that originally supported forest vegetation (Table 1). Note the absence of exchangeable Al and the abundance of exchangeable Ca^{2+} and Mg^{2+} throughout the 4 m depth sampled in pedon ISCW 8.Also, note that the percent Al saturation in both pedons ISCW 2 and 9 (Table 1) remains high well below a depth normally cultivated to mix lime into the soils. The roots of many grain species do not enter soil when Al^{3+} saturation exceeds about 60% of the CEC_7 or soil that contains only negligible amounts of exchangeable calcium. Several crop species have retarded growth if extractable Al^{3+} quantities exceed 1/5 of the CEC_7 values.

Since plants cannot internally move calcium into growing roots it is essential that exchangeable calcium ions be present at the location in the soil where plant roots are attempting to elongate. To better assure the availability of water during any rainless period during the growing season it is necessary to have crops root as deeply as possible to obtain water. This is especially critical for well-drained Oxisols[1] (Latossolos[2]) with their limited plant available water holding capacity. Rapid movement of calcium ions below a depth that can be reached by incorporating lime with tillage equipment is desirable to deepen the root system of crops. Soils with low CEC_7 values are less restrictive to the downward movement of calcium than soils with high CEC_7 values. Some soils, mostly Acrustox[1] in the Cerrado have no CEC in the subsoil (Buol & Eswaran, 2000). A study of Kandiudults[1] with low CEC values in the United States has found that after several years of lime applications significant quantities of Ca^{2+} have moved downward and replaced Al^{3+} thus enhancing deeper root growth (Buol & Stokes, 1997). In Brazil, calcium when supplied as gypsum ($CaSO_4 \cdot H_2O$) has been found to move downward more rapidly than calcium carbonate forms (Ritchey et al., 1980). All indications are that with continued applications of lime and gypsum the naturally calcium deficient and aluminum toxic subsoil will acquire exchangeable calcium below the depth of cultivation and provide for deeper rooting and thus better buffer crops from drought damage.

There are several micro nutrient, Cu, Zn, B, S, etc. deficiencies that frequent many areas in the Cerrado region and have to be diagnosed and treated with timely applications of the needed element(s) that could be cited but the roles of phosphorus and calcium in transforming soils in the Cerrado and enabling them to sustain food crops and pastures are the most critical.

Perhaps the most important lesson successful farming experience with the Oxisols[1] (Latossolos[2]) in the Cerrado has demonstrated to soil scientists around the world is the fallacies related to a requirement of high CEC values for agricultural production. Conventional dogma often states that high CEC values are needed to hold nutrients in the soil and that organic carbon is needed to increase CEC values. If a soil is to be used to grow a crop it should not 'hold' nutrients but 'release' them to the crop. Further, CEC has no reaction with nitrate (NO_3^-) or phosphorus, two of the most critical plant essential elements. When a soil is acid or becomes acid and Al^{3+} ions occupy the majority of the CEC sites greater CEC simply means more lime is required to reduce acidity and the more difficult it is to move Ca^{2+} ions downward to deepen the root system and thereby increase the amount of water available during rainless periods in the growing season. However, low CEC values dictate that management must more frequently monitor and amend the chemical properties of the soil. Although small in comparison to acid soils with higher CEC values lime applications need to be more frequent to avoid Al^{3+} accumulation that should not be allowed to exceed about 20 percent of the CEC value for many crops. Frequent monitoring the chemical dynamics in low CEC soils is critical for sustained crop production.

Well-drained Oxisols[1] (Latossolos[2]) almost universally have a strong grade of fine and very fine granular structure and a low bulk density throughout their profiles. Consequently infiltration and permeability rates are much greater than would be expected in other soils with similar clay contents but of different mineralogical composition. Their low content of silt-sized particles is responsible for a paucity of medium sized pores to retain plant available water per unit of soil depth. Reoccurring problems of compaction that increases bulk density, and slows infiltration leading to increased run off and erosion on sloping land is prevalent when these soils are cultivated (Moura Filho & Buol, 1972). Although compacted layers near the surface can be effectively treated with appropriate chisel equipment it is best to avoid excess traffic when the soils are in a rather moist condition.

An often over looked advantage tropical latitudes with a seasonal rainless period (Isothermic and Isohyperthermic soil temperature regime and Ustic soil moisture regime[1]) have is a long period of time at the onset of the dry season in which grain crops can be harvested. In most temperate latitudes (Thermic and Mesic soil temperature regimes[1]) the growing season is determined by seasonal temperatures that confine grain growing to a relatively short warm season followed by cold and often moist or even snowy winter season permitting only a short period of time during which grain can be planted and harvested. These temperate latitude conditions dictate a need for rapid planting, harvest, transport, and storage that also includes facilities to dry harvested grain. By taking advantage of the warm dry season in the Cerrado region Brazilian farmers can harvest their grain at a more leisurely pace thus more efficiently utilize their harvest and transport equipment while delivering drier grain to storage facilities, a definite financial advantage. In some parts of the Cerrado two crops, usually soybeans followed by sorghum, are possible each year.

The Amazon region

Although there are some soils in the Amazon that have fertility problems similar to soils under Cerrado most soils under rainforest have slightly greater fertility and lesser problems of phosphorus fixation. Unlike the Cerrado where natural fires frequently burned the dormant grass during the dry season natural fires are rare in the jungle vegetation. At any one time large amounts of essential elements are present in the above ground biomass. As leaves fall from the trees and decompose the essential elements they contain recycle through the soil back to the vegetation. The plant available amounts of essential elements within most soils are small and only small reserves of essential elements are present in the soil minerals. Acidity and high extractable Al contents are rather universal throughout the basin with major exceptions in areas where soils have formed from basic sediments or basic rock outcrops. Large areas of deep sandy soils with organic and aluminum rich subsoil layers, Spodosols[1] (Espodossolos[2]) are present mainly in the Rio Negro

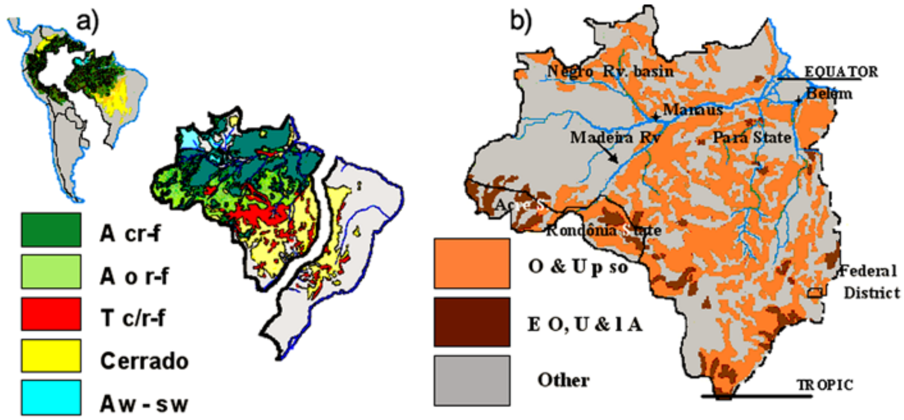

Figure 1 - (a) The original extent of the Brazilian Cerrado and main Amazon kind of vegetations: A c r-f = Amazon closed canopy rain-forest; A o r-f = Amazon open canopy rain-forest; T cerrado = Transition cerrado/forest; Cerrado; & A w-s c = Amazon "white-sand campinarama" (mainly over Spodosols); (b) The agricultured and/or potentially arable soils within North and Central Brazil regions: O & U s u r = Oxisols and Ultisols (well drained and mostly on slight undulating or almost level relief phases[2]); E A &U: Eutrophic soils (Eutrustox or Eutrudox, Alfisols & some Ultisols). (Adapted from IBGE 1992 & 2004).

Figure 2 - Photo of the first crop of soybeans growing in a demonstration plot on Oxisol[1]soils (probably Latossolo Vermelho Distrófico[2]) in the Distrito Federal, 1974. Note the two rows of soybeans in the foreground growing on unfertilized soil are only a few centimeters high and will not survive while plants more distant from the camera, growing where adequate lime and phosphorus fertilizer were added, are healthy and on their way to producing a good yield. Natural 'cerrado' vegetation is seen in the background.

watershed (IBGE, 2001) (Figure 1b). Within the basin a distinct contrast in soils occurs west of the Negro and Madeira rivers (Figure 1b). To the east of these rivers Oxisols[1] (Latossolos[2]) dominate. To the west and extending into Peru most parent materials contain more weatherable primary minerals and appear to be sediments derived from erosion in the Andean mountains. Most of the soils are Ultisols and Alfisols[1] (Argissolos, Nitossolos and Plintossolos[2] or Podzólicos in Camargo et al., 1981).

Where Eutrófico great groups or phases[2] are present (Figure 1b) they significantly contrast from the Distrófico[2] great groups and phases. The differences are most evident during the first few years after land has been cleared and cultivated, even if adequate lime and fertilizer are applied. Although both require additions of lime and fertilizer if agricultural production is to be sustained failure to adequately address the lime and fertilizer needs of the Distrófico[2] soils is more critical and crop failures followed by early abandonment of farming efforts is more frequent than on the Eutrófico[2] soils that are more forgiving.

The hierarchical arrangement with Eutrófico and Distrófico only in a third level category[2] tends to cause scientists not fully aware of the relationship of soil properties to land use to further discount the significance of base saturation, i.e. acidity. The practical significance of high base saturation percentage to settlement and cultivation within the basin is readily apparent by the more extensive deforestation that has taken place in Rondônia, Acre and Pará (Figure 1b) where the 'solos eutróficos' are rather extensive components of the small scale map units (Camargo et al., 1981; IBGE, 2001).

Another significant difference within the Amazon basin is a pronounced dry season (Ustic soil moisture regime[1]) from east of Manaus to west of Belém the presence of a lesser dry season (Udic soil moisture regime[1]) west of Manaus (Van Wambeke, 1981). The soil moisture and temperature regimes are not identified as criteria in the Brazilian classification system (EMBRAPA, 2006) however, the vegetation phases as used in most Brazilian soil surveys legends (scale > 1:1,000,000) gives some indication of them (e.g. semi deciduous and deciduous forest phases[2] closely relate to the Udic and Ustic soil moisture regimes[1], respectively).

Table 2 - Approximate Elemental Content in some Crops and Trees. (Sources: Remember, 1972; Sanchez, 1976; Tew et al., 1986).

Crop	Yield	N	P	K	Ca	Mg
	kg ha^{-1}			kg ha^{-1}		
Corn (grain)	9,408	151	26	37	18	22
Corn (stover)	100,800	112	18	134	32	19
Rice (grain)	4,032	56	10	9	3	4
Rice (straw)	56,000	34	5	65	10	5
Soybeans (grain)	2,688	168	18	52	8	8
Soybean (straw)	3,360	20	2	22	-	-
Sugarcane	67,200	108	27	251	31	27
22-Yr pine (stem)	64,736	57	4	36	52	13
(total tree)	84,672	180	19	90	178	35
60-Yr pine (stem)	194,880	173	13	136	310	49
(total tree)	224,000	256	24	194	477	69

NOTE: Where both grain and stover or straw values are presented, the values must be combined to estimate the amount of each element that must be taken by the total plant during its growth. These values do not include the elements contained in unharvested roots. Also, age of trees data is for trees grown the southern part of the United States. The growth period for trees of equal mass is probably shorter in tropical Brazil.

Observers of the massive native biomass on the soils in the Amazon basin often lament the slash and burn management practices of the indigenous farmers and conclude the soils are not usable for continuous farming. In so doing they overlook a comparison between the quantitative requirements for essential elements by a forest and those of a food crop (Table 2). Mature trees take several years to acquire approximately the same amount of phosphorus in their biomass as a high yielding grain crop requires in less than 100 days. Thus a soil that slowly releases small quantities of essential nutrients from organic matter decomposition and/or decomposition of primary minerals will support the growth of large trees but will have inadequate fertility for grain crops.

In the absence of fertilizers to provide for the rapid nutrient requirements of grain and most other food crops indigenous farmers throughout the world have relied on fire. Fire quickly oxidizes the carbon in organic biomass and releases the essential elements that are unavailable to new plant growth while in organic molecules as inorganic ions that are immediately available for their food crops (Sanchez, 1976). After one or two crops of grain following the burn farmers without access to fertilizers cease to plant and a succession of weeds followed by trees invade the site. The length of time required for forest growth after fields are abandoned and again burned for crops is variable but is approximately 20 years.

Subsistence farmers relying on slash and burn techniques often have much shorter forest fallow periods on soils with a high base saturation percentage (Eutróficos[2]) than on soils with low base saturation percentage (Distróficos[2]) (Buol, 2008). Although large amounts of essential elements are lost in slash and burn fires the immediate abundance of inorganic forms of N, P, K and other essential elements in the ash provides the high concentrations of inorganic ions needed to grow one or two food crops (Fernandes & Matos, 1995).

One of the primary conditions limiting the effective agricultural use of soils in Brazil is the large distances and present paucity of transportation into the developing areas of the Cerrado and Amazon basin. While reliable, all weather roads are relatively easy to build and maintain on the stable soils in the Cerrado region the many rivers with seasonal flow amplitudes of up to 15 m are severe impediments to road construction and maintenance throughout much of the Amazon basin. Other confounding factors when building roads within the Amazon basin are the relatively high content of 2:1 expanding clay minerals in the seasonally flooded boarders of many rivers, especially rivers that transport sediments from the Andean mountains and a paucity of locally available gravel and other coarse aggregate needed for stable road construction. In the absence of reliable roads cattle production has an advantage over grain production in these areas because the market value per unit weight of meat is much greater than grain. Also, live cattle can be herded through areas were reliable roads are not available.

Brazilian Soil Classification[4]

I have some reservation about the new (EMBRAPA, 1999; 2006) soil classification system. In my opinion a soil classification system is a tool wherein soil scientists can and should communicate to others the most important soil properties of significance to vegetative growth and other soil uses. In this regard the extensive use of red to yellow soil color as a second order criterion communicates far less information about soil use than degree of subsoil base saturation percentage which is considered only in the third level or family category. Red and yellow soil colors represent relative proportions of hematite and goethite present but convey little information of significance to soil use or potential except for slightly greater phosphorous adsorption per weight of iron in yellowish colored soil rich in goethite (Bigham et al., 1978). Goethite rich material also has greater stability in reductive environments than more reddish colored hematite rich material (Macedo & Bryant, 1989; Bryant & Macedo, 1990). It is generally true that the darker red colors are associated with a higher base saturation percentage but a quantitative relationship has not be established.

While meeting with international environmental scientists it has been my unfortunate experience to find that upon viewing small-scale soils maps of Brazil they tended to disregard soil science. Everyone can see soil color and environmental scientists attempting to gain insight into future land use tend to disregard soil scientists and place little confidence in a classification that emphasizes something as obvious to all as soil color.

With extensive areas of soils with low CEC values and therefore requiring careful management of chemical parameters through lime and fertilizer inputs to sustain agronomic and forestry production scientists not fully aware of the functions of soil in supporting vegetation are inclined to ignore soil maps that identify soil color as a more significant soil property than base saturation percentage. The definitions of Distróficos and Eutróficos as used in the third level of Argissolos and Latossolos are well conceived and convey critical information relative to the presence of aluminum toxic conditions that limit the rooting depth of many plants. I find it unfortunate that this information is presented only as third category criteria and too often overlooked by users of small-scale soil maps. Base saturation percentage, and the converse covariant Al saturation information is of greater importance to soil use than soil color and should be elevated to a higher category in the system and thereby more prominently displayed on small scale soil maps. However, the utility of soil color in communicating with local users of more detailed large scale soil maps should not be neglected and after intense debate by the International Committee on Classification of Oxisols (Buol & Eswaran, 1988) both Rhodic and Xanthic Subgroups, i.e. fourth category level units, were defined in the Soil Taxonomy (Soil Survey Staff, 1999).

Soil moisture and temperature regimes are vital soil properties, albeit they are closely related to climatic data and reflected in natural vegetation phases of the Brazilian soil classification system. Seasonal temperature dynamics determine the potential of soil for important crops like coffee and sugar cane within Brazil. Seasonal moisture dynamics determine probable needs for irrigation and potential for either one or two rain fed crops per year. Both moisture and temperature are significant factors in timber production. Although natural vegetation phases proxy for soil moisture and temperature conditions users are inclined to view such phases as simply a classification of vegetation and fail to appreciate the relationship to soil.

A category with quantitative criteria of soil temperature and moisture dynamics, defined by criteria related to specific agronomic practices in Brazil would enhance the information scholars can relate to present land use and compare with land use in both similar and contrasting areas of the world. The class limits of soil moisture and temperature regimes in Soil Taxonomy (Soil Survey Staff, 1999) were mainly developed for conditions in temperate latitudes. Brazilian soil scientists may well find soil moisture and temperature dynamic criteria that are better suited to identify natural ecosystems and land use decisions within the broad range of tropical latitude conditions present in Brazil.

Overview

Perhaps the greatest advantage the soils in the Cerrado and Amazon basin regions in Brazil have for agricultural development over similar soils in other tropical countries is the availability of farmers experi-

[4]The central concepts of the old American system (Baldwin et al., 1938 & Thorp & Smith, 1949) formed the basis for the current Brazilian soil classification (Embrapa, 2006). Modifications of this old system began in the fifty's, with the implementation of the first reconnaissance soil surveys with focus directed at great soil group category. Changes in taxonomic criteria were done in parallel with the approximations of the new American Soil Classification System, then under development in the USA, and also with reference from the scheme of the World Soil Map of FAO (FAO/UNESCO, 1974) and the FAO World Reference Basis for Soil Resources.(FAO, 1998). The effectiveness of this classification was made by means of four approximations (1980 to 97) supported by correlation field trips, one of which (in 1984), Prof. S. W. Buol had the opportunity to participate. At the 3rd category level (Great Groups) soil color in conjunction with total iron oxide content in the clay fraction is widely used as a diagnostic criteria (e.g. Red Yellow Latosols - hue between 5YR and 10YR and Fe_2O_3 content between 18 and 36% in the major part of the B horizon). (Lepsch, I. F.: Personal communication)

enced in the management talents needed for commercial farming. Most of the new settlers that come to farm the sparsely populated developing areas of the Cerrado and Amazon basin have been schooled by many generations of successful commercial farming experience in other regions of Brazil. This new generation of farmers with family traditions of commercial agriculture is able to quickly apply their farming talent to tasks of planting, harvesting, marketing of products, and utilization of chemical technology so imperative for successful production on the inherently infertile soils that must be prepared and maintained in a condition compatible with sustained food crop production. Such farming skills are seldom found among indigenous populations with only subsistence farming experience.

With an understanding of the fundamental requirements needed to convert soils previously considered unproductive because of dogmatic concerns of 'tropical weathering' Brazil is in position to take full advantage of the only factor common to all tropical areas, i.e. no seasonal coldness that limits the production of many useful and commercially desirable crops in temperate latitudes. Many of the disease problems associated with an absence of annual freezing are now being chemically controlled. The recent movement of coffee production northward from the naturally more fertile soils in the freeze prone 'traditional' coffee growing areas in Brazil is one example. As the fertility constraints of naturally infertile soils have been addressed extensive development of sugar cane production for bio fuels in Brazil is yet another example of the advantage tropical latitudes have over temperate latitudes where sugar cane cannot be grown.

Brazil is also far ahead of many other countries in having achieved a large number of highly capable soil and agronomic scientists to do the research necessary to develop and teach the principles and practices necessary to attain high levels of production per unit area of the soils in Brazil that contrast in so many ways from most soils in Europe and North America. They are in the forefront of advances in soil science as related to the sustained utilization of soils long thought to be useless for human food production. They clearly understand that the utilization of such soils cannot rely on inherent fertility but requires a reliable infrastructure of commerce, transportation, and on farm management talent as they develop site-specific technologies that alter the inherent properties of the soils into properties that sustain high levels of commercial food crop production.

Continued success in sustained high levels of food, fiber and fuel production on the low CEC and naturally acid soils in tropical Brazil will ultimately depend on the societal support of high yielding agriculture by the Brazilian people. Reliable supplies of lime and fertilizer and infrastructure necessary to efficiently link farm production to urban markets are imperative for sustainability. The naturally infertile soils in Brazil can only sustain high levels of production if their chemical and physical properties are closely monitored by reliable scientific methods and if those observations are communicated to responsive and economically viable farmers. Individual farmers are not able to see the chemical demands of their crops. Scientific expertise in soil chemistry and soil testing is required. Individual farmers cannot maintain reliable infrastructure needed to obtain farm equipment and market food products. It is only with the cooperation of the societal, economic, and political segments of the Brazilian population that infrastructure needed for commercial food production can be maintained and enhanced in the future.

As human populations increase worldwide requirements for food and fiber also increase. In this regard the preservation of natural ecosystems and highly productive farming are intimately linked. Only if high yielding production of food crops on cultivated land is sustained and enhanced will the need for excessive encroachment into virgin ecosystems be reduced and conservation of those natural ecosystems enhanced.

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