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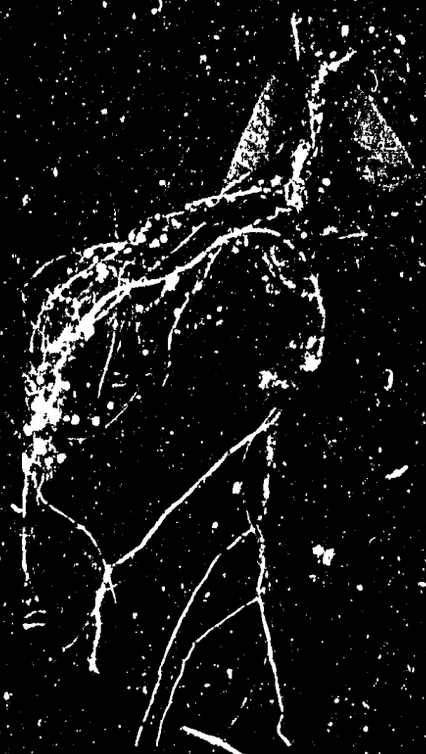
Physical Constraints to Root Growth in Savanna Oxisols



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Physical Constraints to Root Growth in Savanna Oxisols

A synthesis of investigations conducted under the collaborative agreement between Cornell University and the Cerrado Agricultural Research Center, CPAC/ EMBRAPA

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Setting

Acid savannas constitute a major portion of the tropics of South America, covering vast stretches in Brazil (known as *Cerrados*), Columbia, and Venezuela (known as *Llanos*), as well as Bolivia (known as *Pampas*) and the Guianas (Cochrane et al. 1985). In South America alone, these savannas comprise over 300 million ha. The dominant vegetation is wooded savanna, with cover types ranging from pure grasslands to closed-tree canopies prevalent along perennial streams. Total annual rainfall varies from about 900 to 2500 mm, distributed in distinct wet and dry seasons. The strong dry season of four to six months constitutes a physiological analog to temperate-region winters. The prolonged dry season can be a major resource for agriculture, diminishing pest proliferation, reducing soil biological decomposition, and acting as a natural dry fallow.

Schematic-level surveys indicate that Oxisols cover more than 50% of South American savannas. These soils are characterized by gently sloping topography, deep unobstructed profiles, and good internal drainage—all of which favor mechanized agriculture. Inherent constraints to the use of Oxisols include acidity, high aluminum saturation, low base status, low cation-exchange capacity, low phosphorus levels, and high phosphorus fixation by iron and aluminum sesquioxides.

Management strategies for overcoming chemical constraints to cultivation of adapted plant species have developed out of two decades of research on savanna Oxisols in South America, coincident with the opening of these lands for agricultural production on a large scale. Today, with less than 30% of the suitable land cleared for agriculture, the Cerrado

Native Cerrado (Neil Caudle).

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Vast fields of grain in the Cerrado (Neil Caudle).

region of Brazil already produces 40% of the nation's soybeans, 35% of its coffee, and 42% of its cattle. Much of the pioneering research that led to this growth was carried out at the Cerrado Agricultural Research Center of Brazil's Agricultural Research Enterprise (CPAC/EMBRAPA), located in the Central Plateau core region of the Brazilian savannas at 1000-m altitude. Results presented in this bulletin were obtained from studies conducted in laboratories, in growth chambers, and on farms. The studies were part of the TropSoils Acid Savanna Research Program of Cornell University in collaboration with CPAC/EMBRAPA.

The transformation of extensive rangelands to productive farmland and improved pastureland in the central Brazilian Cerrado has been a quiet social revolution since the early 1970s. Settlement of farmers new to this sparsely populated region was largely the result of individual initiative, not government intervention or massive translocation programs. (It may represent the first spontaneous settlement of a large area for sustainable agriculture with research at the forefront providing viable options for land use.) In addition, stable intensive-farming enterprises in the Brazilian Cerrado have been an effective but often overlooked buffer that keeps the agricultural frontier from advancing into the more fragile Amazon rainforests.

In contrast, prevailing social and economic conditions have limited the successful transfer of modern agricultural technology in the acid savanna Oxisols of Africa. Oxisols in what is referred to as Africa's subhumid wooded-savanna agroecological zone are estimated to cover 136 million ha (FAO, 1976). High plateaus of Cameroon, Rwanda, Burundi, and Madagascar have extensive agricultural or none at all (Pieri, 1985). Indigenous management practices often transfer fertility from a large area to a smaller one by accumulating crop residues or collecting cattle dung. While efficient in the current setting, these practices do little to improve overall soil fertility and expose large unprotected areas to erosive forces. However, even the proven effectiveness of a gradual approach to building soil fertility with low annual additions of phosphate fertilizers may be stifled by socioeconomic conditions.

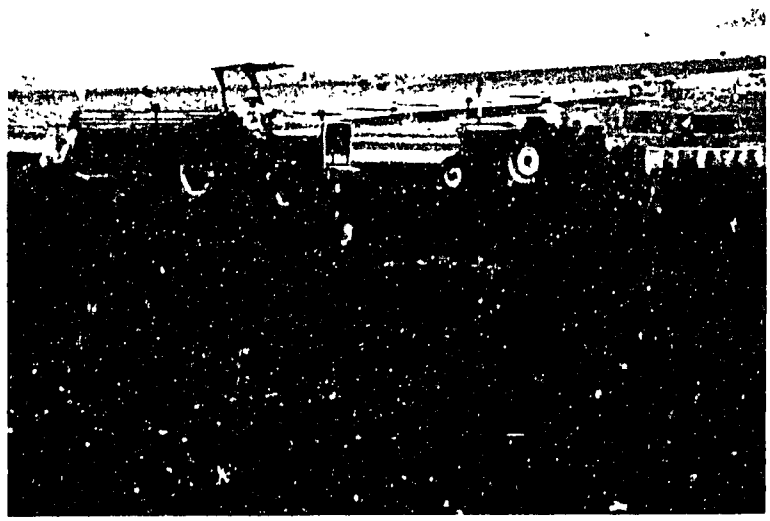
Although the combination of extreme soil poverty and the lack of modern farming skills discourages productive agriculture at present on African savanna Oxisols, empowerment to change this situation will come with education and the national will to fully use land resources suitable for agriculture. Given the great investment in human and financial resources that this represents, poor countries must understand the techniques to overcome soil infertility and other physical constraints. They must learn from experiences in similar agroecological zones where research and on-farm diagnoses have identified the problems. A strong case can be made for a collaborative research training initiative between African countries and advanced South American countries. Such an initiative would link scientists and institutions that share soil and climatic conditions as well as development experiences.

Properties and Management of Savanna Oxisols

Physical characteristics of medium- and fine-textured Oxisols of the seasonally humid savanna region of Brazil have generally been considered excellent for mechanized agriculture because of what has been described as their very stable microaggregate structure. In both water-holding capacity and tilth, these soils often behave as sands. Structural consistency allows for ease of tillage, even on clay-textured soils immediately after rainstorms. As a trade-off, the limited water-holding capacity aggravates drought stress when rainfall shortages occur during the growing season. Climatic constraints limit annual crop production under rainfed conditions to the six-month wet season. Strategies to promote subsoil use of captured rainwater through deep-root exploration of the extremely deep acid soil profile are perhaps even more important than experience has shown on temperate soils.

Over the past 15 years, experiments have identified management practices that overcome, to a large extent, those inherent chemical constraints which render savanna soils practically incapable of crop production. (Goedert, 1986). Severe nutrient deficiencies and soil-acidity problems are manageable through amendments to the tilled soil layer. Acidity, Al toxicity, and Ca deficiency are known to restrict root elongation in acid savanna subsoils (Ritchey, et al., 1982). Diagnostic tests can identify probable chemical constraints to root development in acid soils, and management practices such as deep incorporation of limestone, Ca leaching following application of gypsum, and the selection of suitable plant materials have reduced chemical barriers to deep root exploration (Bouldin, 1979; Ritchey et al., 1980).

Whereas cultivation improves chemical and microbiological conditions in Oxisol profiles, continuous tillage may degrade the favorable physical properties of native Oxisols. Natural correction mechanisms such as cracking by shrink-swell and freeze-thaw cycles that frequently alleviate



Drilling soybeans on wet soil (Eric Stoner).

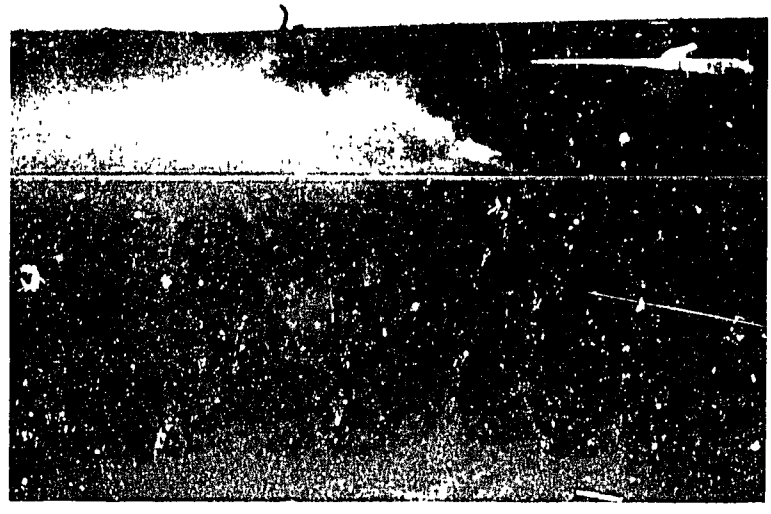


Figure 1. Tillage under excessively wet or dry soil conditions contributes to structural degradation of savanna Oxisols (Eric Stoner).

compacted conditions by restoring structure to cultivated temperate soils are absent in the wet-dry tropics, although some evidence exists that there may be slight decompaction under natural wetting and drying cycles (Mantovani, 1989). Under these circumstances, even normal farm traffic with heavy tractors and harvesting equipment is likely to cause wheel-track packing. Even more serious, however, are the possible deleterious effects of traditional disc tillage on Oxisols under monoculture cropping systems devoid of rotational or fallow periods.

The pressure-packing action of disc tillage implements adversely affects soil structure, especially when soils are tilled at high moisture contents shortly after a rain—as is often the practice in crop management on Cerrado Oxisols. Just as damaging may be the pulverizing action of disc tillage under dry soil conditions, breaking down soil aggregates and exposing protected organic matter to increased oxidation, further aggravating structural degradation through destruction of this important cementing agent (Figure 1). Proper timing of field operations, especially primary tillage, is crucial, while rainfall patterns may not provide as broad a window of optimal soil moisture conditions for field work as is commonly believed.

Decreases in soybean yields on corrected Cerrado soils after ten years of monocrop production have often been accompanied by farmer observations of superficial root development on soils which have been adequately fertilized. As a consequence of shallow rooting of annual crops, the relatively costly investments in lime and fertilizer in Cerrado soils may be underutilized. Severe soil compaction reduces the volume of soil available for root growth, limiting access to subsoil moisture as well as solutes. Nitrogen mineralized in the surface soil and applied fertilizer N may be carried quickly out of shallow rooting zones with excessive amounts of percolated water where root-restricting zones occur. Nitrogen losses can also occur from denitrification when water perches on compacted layers. Even with limited soil compaction, there may be an energy cost to the plant if roots cannot penetrate compacted layers simply by following a more tortuous path through the soil (McCoy, 1987).

Water capture on Oxisols—which in their native state have extremely high infiltration rates—may be greatly reduced under compacted conditions during the frequently brief, high-intensity storms common to the Cerrado region, thus limiting replenishment of subsoil moisture. Reduced permeability and infiltration may cause problems with water runoff and soil erosion during these same rainfall events. Severe gully erosion and washout of even carefully placed contour terraces have become a common sight on

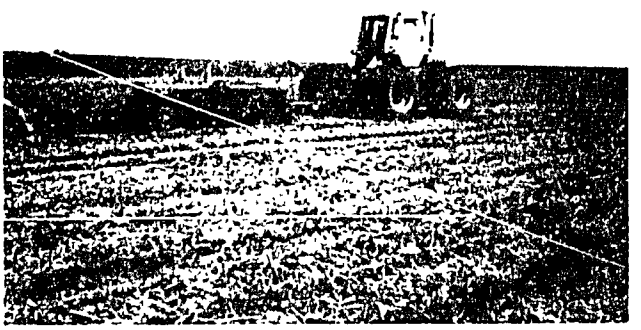
gently sloping fields, some of which have slope lengths of several kilometers.

Clearly, soil moisture acts as a control factor in root-growth restriction (Taylor et al., 1964; Mendes, 1989). The concept of nonlimiting water range has been useful in defining those optimal moisture conditions under which roots proliferate unrestricted by either aeration stress in excessively wet soils, or moisture stress or high mechanical impedance in drying soils (Letey, 1985). Measureable soil properties such as bulk density, texture, aggregate stability, distribution and size of pores, penetration resistance, permeability, and infiltration rate are helpful in portraying compacted soil conditions, but they do not by themselves explain root restriction. Phenomena such as transit pores in decomposed root channels and zones of weakness between structural units play an important role in root exploration, but they are difficult to characterize in a field setting (Freitas, 1988).

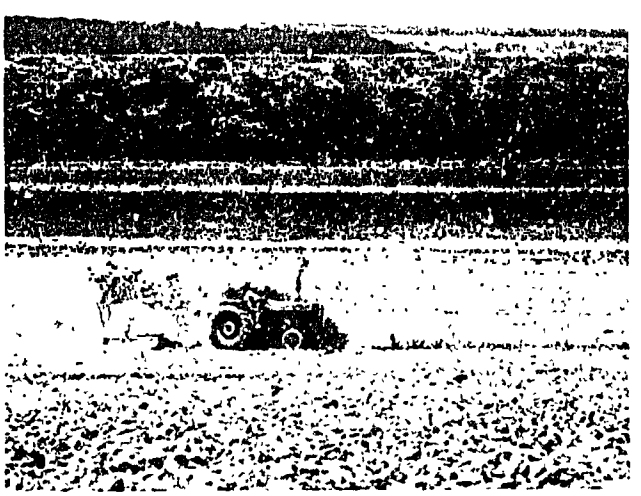
Under adverse conditions, roots may respond to penetration resistance by decreasing the rate of growth, by increasing in diameter or turning abruptly at the mechanically impeding layer, by constricting within the hardened layer, or by proliferating finer lateral roots in less compacted layers (Goss, 1977; Bowen, 1981; Taylor, 1981). In compacted soil layers, a larger percentage of the root volume is occupied by cell-wall material (Baligar et al., 1975) while mature cell length is reduced (Goss, 1977). Again, anatomical changes such as cell-wall thickening may occur without apparent alterations in root distribution and still result in an energy cost to the plant. Characterization of root anatomy and soil structural properties in the elongation zone at the root-soil interface requires understanding on the millimeter scale.

Soil micromorphological studies through thin-section analysis have been useful in explaining the microaggregate structure of Oxisols (Stoops and Buol, 1985; Embrechts and Stoops, 1987). As viewed on a microscopic level, water-stable microaggregates are formed when Fe and Al oxyhydroxides and organic matter cement randomly oriented primary particles, a process which accounts for the isotropic nature of the soil matrix (Santos et al., 1989). Recently, image analysis techniques used with soil thin sections have permitted the precise measurement of size, shape, orientation, and continuity of pore space in soils (Murphy et al., 1977a and 1977b; Bui et al., 1989). These techniques elucidate the pseudo-silt or pseudo-sand character of Oxisol microaggregates. That character influences a range of soil physical, chemical, and biological properties, not the least of which is soil susceptibility to compaction. Tillage pans formed in soil materials having smooth-surfaced sand particles restrict root growth more than those pans formed on soil materials having rough-surfaced particles, a response hypothesized to relate to particle packing geometry (Cruse et al. 1980, 1981).

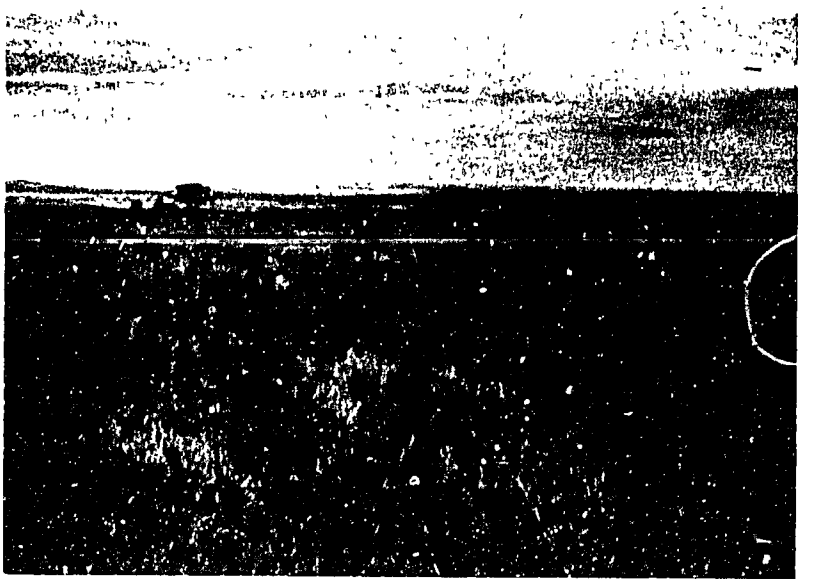
Research on soil physical constraints conducted with TropSoils support at the Savanna Agricultural



Primary tillage with a heavy disc harrow (Eric Stoner).



Secondary tillage with a light disc harrow (Eric Stoner).



Improved pasture on former cropland in the Cerrado (Eric Stoner).

Research Center (CPAC) of EMBRAPA focused on identifying soils susceptible to compaction, the variability in soil mechanical strength as a function of moisture content, bulk density, texture, yield reduction on compacted soils, and morphological evidence of root deformation as related to soil-structure micromorphology. Experimental results were obtained from controlled laboratory and growth-chamber studies as well as from on-farm paired sampling, which contrasted compacted conditions to soil parameters in the native state.

Physical Properties of Native Oxisols

Textures of Oxisols of the Cerrado region range from the lower limit of 15% clay content as defined for oxic horizons to the over 90% commonly found on gently sloping to nearly level tablelands in the Central Plateau. Silt contents are usually negligible. High clay-content Oxisols are more prevalent in this region than has frequently been reported. Within the Federal District, fully 50% of the soils are mapped as latosols belonging to the clayey-surface texture class (>35% clay content), while only 5% of the soils are mapped as latosols belonging to the loamy-surface texture class (>15% clay content < 35%). Profile descriptions show surface-soil clay contents ranging from 40% to 88%, with an average of 70% for the 41 profiles studied (EMBRAPA, 1978). This figure places the majority of the latosols in the Federal Distict not just in the clayey texture grouping, but within the very-fine clayey class of soils with more than 60% clay in the fine-earth fraction.

The excellent structure of Oxisols, even with very-fine clayey texture, is attributed to stable aggregation of clay particles into sand-sized granules. Kaolinite, quartz, gibbsite, Fe oxides, and hydroxides are the dominant minerals in these soils. Soils classified locally as dark-red latosols and red-yellow latosols (both clayey, oxidic, isothermic Typic Acrustox) have hematite and goethite subsoil Fe mineralogy, while surface soils belonging to the red-yellow latosols have only the goethite Fe component (Macedo and Bryant, 1987). Amorphous iron and aluminum oxides along with organic matter play a role in cementing primary particles. The very low surface charge in Cerrado Oxisols is conducive to the agglomeration of particles and may account in part for aggregate behavior. Agricultural management practices that lead to the removal or alteration of these cementing agents or the generation of surface charge may have negative consequences for structural stability.

The amount of water-dispersible clay is often zero or near zero in Oxisol subsoils. Surface soils in the native state and under cultivation present higher amounts of water-dispersible clay. It has been

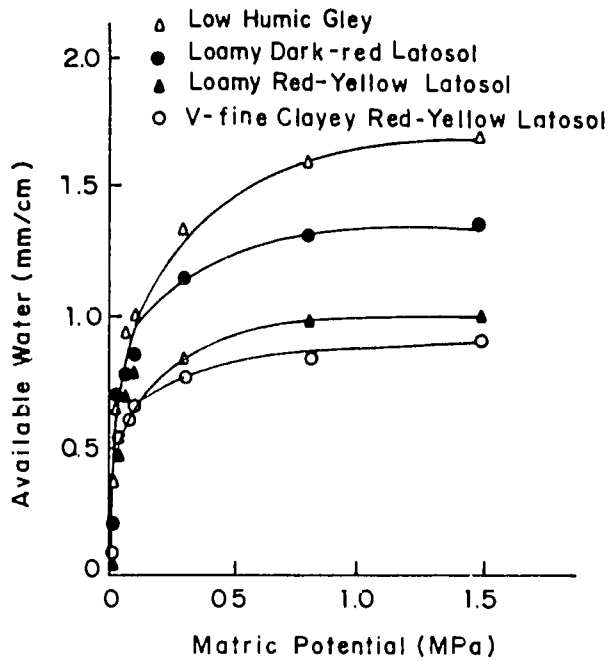


Figure 2. Available water content in different Cerrado soils (Luchiari et al., 1986).

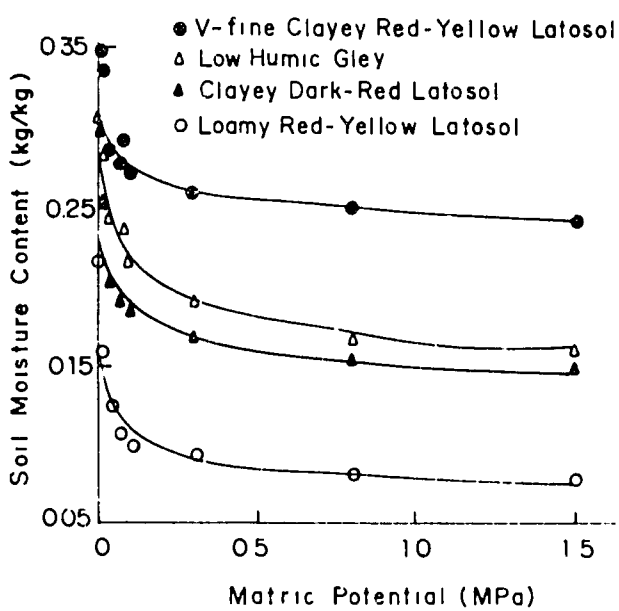


Figure 3. Moisture-retention characteristic curves for representative Cerrado soils (Luchiari et al., 1986).

reported that the decrease in water-dispersible clay in the A horizon and the increase in the B horizon upon intensive cultivation may signal clay translocation, with resulting compaction consequences (Moura Filho and Buol, 1972). Whether or not clay illuviation occurs, in-place degradation of the microaggregate structure into primary particles capable of clogging pore space is a serious management concern.

Bulk densities throughout the Oxisol profile are very low compared to many temperate soils: they range from less than 1.0 Mg/m^3 for many clay-textured soils to 1.3 Mg/m^3 for sandier-textured Oxisols. The very-fine granular or crumb structure gives the soil a fluffy appearance in the field and imparts a high level of macroporosity (pores > 0.05 mm) that commonly reaches 25 to 30% of the soil volume. Even under compacted conditions, aeration is not likely to limit root development.

Moisture retention and water-holding capacity of Oxisols do not follow patterns of temperate soils with similar clay contents. Soils common to the Central Plateau exhibit low water availability and have unique moisture-retention characteristic curves (Figures 2 and 3; Luchiari et al., 1986). Although fine-textured, these soils release water rapidly at high matric potentials because of the sand behavior of the microaggregates. At low matric potentials, water content is relatively high, a characteristic attributed in part to the presence of intra-aggregate pores in the stable microaggregate environment (Bui et al. 1989).

Wet-sieving techniques provide a reliable measure of aggregate stability in Oxisols. It is not unusual for 85 to 90% of the water-stable aggregates to be in the >2 mm size range for native soils, with 90 to 95% of the water-stable aggregates in the >1 mm range. Field testing with a double-ring infiltrometer is a pragmatic way to evaluate integrated physical properties that influence soil structure. Infiltration rates as high as 82 cm/h have been reported on newly-cleared Oxisols (Moura Filho and Buol, 1972), although rates on the order of 10 cm/h are more common.

Soil-management practices and tillage methods

Land-clearing methods in the Cerrado region vary with the density and height of wooded savanna cover. Usually, farm tractors with a simple front-blade attachment are capable of felling even the larger trees and windrowing debris onto contour strips. Such tractors also allow selective clearing and thus can preserve shade or lumber trees. Swath clearing with a logging chain pulled by two steel-track tractors is quite common. When proximity to iron foundries warrants, clearing is frequently contracted out to charcoal producers who remove native woody vegetation by hand with a minimum of vehicular traffic on the land. Heavy disc harrows are adequate for cutting low shrubs and native grass sod and for partially incorporating organic litter, most of which remains in place after tree removal.

Contrary to experience in the humid tropics, land clearing by itself has not been reported to degrade soil organic matter or provoke compacted conditions. Degradation is more likely to be a scale-related phenomenon, as when large tracts are cleared without respect to natural waterways or field-border shelterbelts or when unnecessarily large fields are formed without regard to extreme slope lengths. Also, the slash-and-burn techniques employed in the humid tropics are unheard-of on open savanna land because of the low regenerative ability of unamended soils. Slash-and-burn is incompatible with any form of sustainable agricultural production on Cerrado Oxisols.

Following land clearing and the formation of contour terraces, soil amendments such as agricultural limestone are incorporated with heavy-disc harrows or disc plows. The presence of remnant tree roots and numerous tubers during the first several years of cultivation makes moldboard plowing ineffective for incorporating amendments, at least until the first reliming. Deep placement of limestone (0 to 30 cm), although widely researched and recommended to farmers, remains mostly a matter of farmer preference, being dictated more by available tillage equipment and haste to prepare land than by an appreciation of how effective incorporation enhances crop growth.

Although primary tillage is sometimes performed with a disc plow and rarely with a moldboard plow, it is most frequently carried out with a large, offset heavy disc harrow. This operation may occur shortly after harvest at the onset of the dry season when residual soil moisture presents optimal conditions for tillage, but it is more often performed during down time at the height of the dry period. Likewise, secondary tillage with light disc harrows is often performed on dry soils before the onset of rains. Two or three secondary disc-harrow operations often precede final seedbed preparation. One or more of these operations may be principally for weed control.

Planting is done mainly on clean, smoothed seedbeds. Very little no-till or reduced tillage has been practiced, although the use of chisel plows and subsoilers is increasing with the growing awareness of compaction problems. Cultivation is also seldom used for weed control in established crops, herbicide use being widespread on fields that have developed weed problems. With the large expanse of cash grain farms, the unpredictable nature of rainfall, and good soil tilth even under wet conditions, it is not unusual for tillage and even planting to be carried out in the rain. Potential for soil structural degradation is great when tillage occurs at inappropriate soil moisture levels.

Research in the Cerrado of Brazil

Variability in soil mechanical strength as a function of moisture content, bulk density, and texture

Soil mechanical strength, and consequently root growth under field conditions, can be expected to vary during the growing season, especially with changing soil moisture in the profile. Cone index as measured with the cone penetrometer has come to be accepted as the most appropriate gauge of mechanical impedance in undisturbed soil (Cassel, 1982). Laboratory measurement of cone indexes for a range of soils compressed in reconstructed soil cores at controlled levels of soil saturation has increased our understanding of variability in soil mechanical strength as a function of moisture content, bulk density, and texture.

Bulk soil samples were collected from representative Oxisols of varying texture under native, cultivated, and improved pasture conditions. In the laboratory at CPAC, water was added to the samples to attain the desired degree of saturation (0.4, 0.5, 0.6, 0.7, and 0.8 m^3/m^3), an expression of the volume of water in the soil relative to the volume of pores. The moistened soil samples were placed into 10-cm diameter by 10-cm height rigid PVC rings for compression in a hydraulic press to soil bulk density levels of 1.1, 1.2, 1.3, and 1.4 Mg/m^3. Three replications were prepared for each treatment.

Resistance to penetration was measured with a spring penetrometer, and log values of the average measurement from the three replications were plotted against soil water saturation (Figures 4 and 5). For the sake of comparison with bulk-density levels frequently encountered under field situations, impedance values for five sampled soils are illustrated for a bulk density of 1.1 Mg/m^3 (Figure 4). Taking as a threshold value for unrestricted root elongation a resistance level of 1.8 MPa (1.25 on the

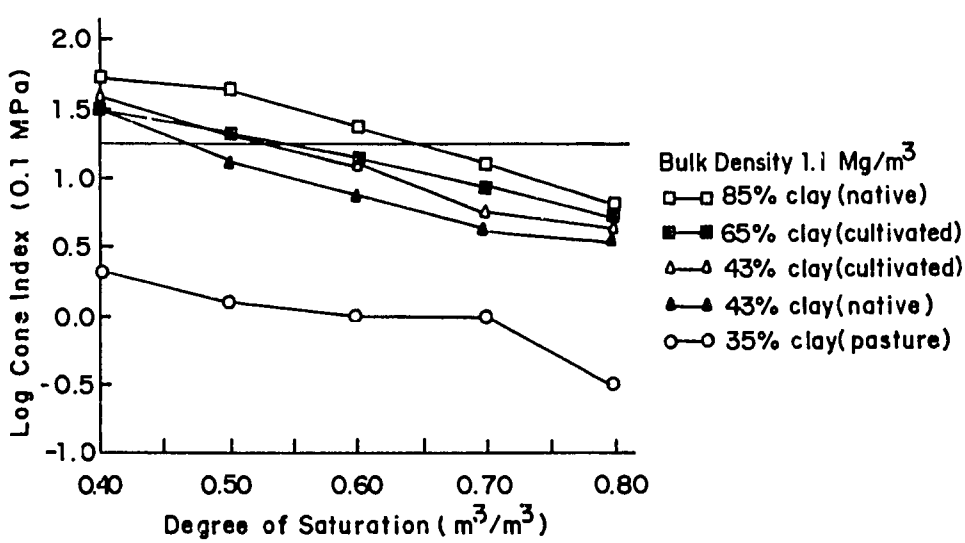


Figure 4. Soil strength as a function of soil moisture content for samples of five Cerrado Oxisols with different management histories.

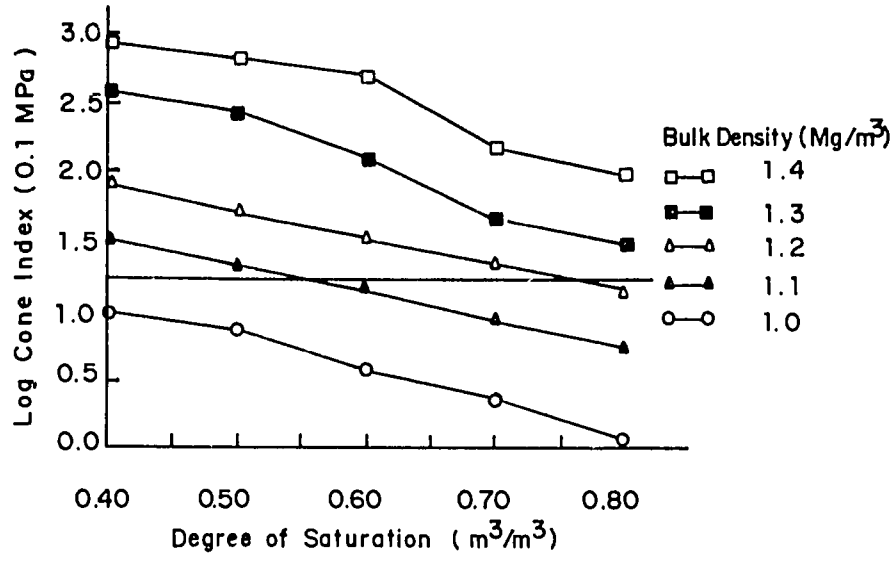


Figure 5. Soil strength as a function of soil moisture content for samples of a 65% clay content Acrustox compressed to five bulk density levels.

log scale), one finds that the 35% clay soil does not present root-restricting conditions at any degree of saturation. All five soils show resistance values below the critical limit at high soil moisture levels (0.7 and 0.8 m^3/m^3). The 85% clay soil presents impedance values above the critical limit for soil-saturation levels less than 0.65 m^3/m^3.

When the same soil (43% clay) is compared under native and cultivated conditions, higher resistance to penetration is found for the cultivated sample, its behavior under low moisture conditions resembling that of the 65% clay soil. However, susceptibility to compaction under compression forces is evident in the high clay (85%) soil even though it was sampled under native conditions with its structure intact.

Resistance values are also illustrated at five bulk-density levels for the 65% clay soil sampled under cultivated conditions, because of the wide occurrence of this soil in the Central Plateau (Figure 5). The soil bulk density of 1.0 Mg/m^3 represents a probable level in its native state, while the level of 1.1 Mg/m^3 is frequently encountered under long-term cultivation. Bulk densities of 1.2 and even 1.3 Mg/m^3 can be found near field borders or in field traffic lanes. Again a critical resistance level for root elongation of 1.8 MPa is illustrated for the resultant family of curves. At naturally occurring bulk-density levels, root-restricting conditions do not result under any of the soil moisture conditions studied, while at the 1.1-Mg/m^3 level common to cultivated fields, root-restriction could be expected to occur at water-saturation levels less than 0.55 m^3/m^3. Restriction to root penetration could be expected under even moist soil conditions in soil layers along field borders or in traffic lanes with soil bulk densities of 1.2 Mg/m^3 or greater.

Soil and crop susceptibility to root-restricting physical alterations

A screening study was conducted at CPAC to identify which of the major crop species grown in the Cerrado region are most susceptible to mechanical impedance of root development and to determine the critical soil bulk-density levels beyond which little root penetration can be expected for these crops.

Bulk soil samples of dark-red latosols were collected within the Federal District from surface soils of the sandy loam (16% clay content) and clayey (53% and 70% clay content) texture classes. Fertilizer and lime were mixed with the soil according to recommendations based on soil-test levels. Rigid 10-cm diameter by 10-cm height PVC cylinders were prepared as pots with gauze bottoms to hold the soil in place and interior walls covered with

paraffin to avoid root exploration of side walls. An appropriate amount of soil placed in the pots was compacted with a hydraulic press to a depth of 5 cm to attain the desired density levels of 1.0, 1.1, 1.2, 1.3 and 1.4 Mg/m^3. Three to 4 cm of loose soil was placed on top of the compacted layer for seed placement and to assure uniform seedling development among the compacted treatments.

Frequently planted crop varieties in the Cerrado region were planted three to a pot (thinned to two): maize (*Zea mays*, var. Cargill 111), soybean (*Glycine max*, var. Doko), wheat (*Triticum aestivum*, var. BR12), and beans (*Phaseolus vulgaris*, var. Carioquinha). Four replications were made in a randomized block design.

A system of subirrigation consisting of a 2-m by 3-m gravel-and-sand-bed tension table was devised to maintain a constant moisture tension (0.006 MPa) above field capacity throughout the one-month growing period. Plants roots were harvested by first washing and dyeing the superficial roots, followed by washing the roots in the compacted layers. The visual contrast of dyed and undyed roots served as the basis for comparison of root development among treatments.

Roots of all four crop species developed normally in the sandy-loam dark-red latosol, even at the greatest bulk density of 1.4 Mg/m^3. In the fine clayey dark-red latosol (53% clay content), roots penetrated at all bulk-density levels, although slight root restriction was noted in all four crop species at the bulk density of 1.4 Mg/m^3.

The very-fine clayey dark-red latosol (70% clay content) presented serious restrictions to root penetration for all four crop species. Critical levels of soil bulk density, beyond which little or no root penetration occurred, were as follows:

- 1.4 Mg/m^3—no root development in soybean, wheat, maize, or beans;
- 1.2 Mg/m^3—no root development in wheat, maize, or beans;
- 1.2 Mg/m^3—no root development in maize or beans;
- 1.1 Mg/m^3—no root development in beans.

Of the four crop species tested, the susceptibility to mechanical restriction of root growth was greatest for beans and decreased in this order: maize, wheat, and soybean. By far the most problematic soil was the very-fine clayey latosol, which impeded penetration of bean roots under moist soil conditions at the bulk-density level of 1.1 Mg/m^3, a level frequently encountered in the field. In general, the higher the clay content, the more susceptible the soil to root-restricting compaction for the crops studied.

A follow-up study was conducted to quantify the effect on root growth density of variations in soil bulk density and soil moisture for what previous studies had identified as a compaction-prone, high-clay Oxisol (Mendes, 1989). The same 10-cm diameter by 10-cm height PVC rings served as pots for a factorial-design plant-seedling test with treatments as follows: six soil bulk-density levels (1.00, 1.05, 1.10, 1.15, 1.20, and 1.25 Mg/m^3); six soil water-saturation levels (0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 m^3/m^3); and two plant species (soybean, var. IAC 8, and maize, var. Cargill 111). The soil studied was the same 70% clay Oxisol used in the screening study. Four sample rings were prepared for each treatment, three used for root and plantlet growth measurements and one used for spring penetrometer measurement.

Pregerminated seeds were planted in the sample rings, covered with 1 cm of fine sand and a plastic disc to prevent moisture loss. The seeds were later thinned to two plants per pot. Pots were placed in a growth chamber adjusted to a 14-hour photoperiod with maximum temperatures of 32°C and minimum temperatures of 23°C. Water was replaced daily. Soybean plants were left in the growth chamber for nine days, and maize plants were left for seven days.

Roots harvested with the compacted soil layer were left in a solution of 0.05N NaOH for 24 hours at 4°C to facilitate the washing of soil particles and the separation of organic residues. Roots were separated in running water over a 0.05-mm seive and preserved in flasks of pure water at 4°C until counted. Root length density was measured by the line intersection method (1-cm grid).

Measured root length density was inversely proportional to soil bulk density at a given degree of saturation and directly proportional to the degree of saturation at a given density for both soybean roots (Figure 6) and maize roots (Figure 7). As expected, soil bulk density alone did not explain root growth

restriction, although the drop-off in the root length density of soybeans at low soil moisture levels (Figure 6) is quite striking as density increases from 1.10 to 1.15 Mg/m^3. A similar drop-off in root length density is seen in the transition from bulk density 1.15 to 1.20 Mg/m^3 for maize (Figure 7).

Root length density was significantly correlated with soil water potential and with volumetric water content, but not with degree of saturation of the soil pores (Table 1). The single factor most highly correlated with root length density was penetration resistance as measured with a cone penetrometer (correlation coefficients of -0.914 for soybeans and -0.884 for maize). Root length density was reduced to a threshold of 70% of the maximum observed value when cone index values reached 1.6 MPa for soybeans and 1.8 MPa for maize. Reduction to 50% of the maximum observed value of root length density was reached at cone index levels of 2.6 MPa for soybeans and 3.0 MPa for maize.

Table 1. Linear correlation coefficients between average root length density and soil parameters (Mendes, 1989).

	Root length density	
Parameter	**Soybean**	**Maize**
Bulk density	-0.734**	-0.740**
Degree of saturation	0.318	0.382
Soil strength (cone index)	-0.914**	-0.884**
Volumetric water content	0.618**	0.654**
Soil water potential	0.521*	0.630**
Air-filled porosity	-0.187	-0.246

* Significant at the 0.05% level.
** Significant at the 0.01% level.

Early experimental evidence of high mechanical impedance in cultivated savanna soils

Some of the early observations of soil compaction were made in fields of the Guided Settlement Plan for the Upper Paranaíba (PADAP) near São Gotardo, Minas Gerais State, under cultivation since the early 1970s. The soil is a Typic Haplustox with 43% clay content. A study was undertaken in response to farmers' concerns over declining yields of soybeans and wheat in spite of adequate lime and fertilizer inputs.

Six locally available tillage operations were performed on the already compacted area prior to planting wheat in February 1984. Mechanical impedance profiles (Figure 8) reveal the severity of compaction immediately beneath the depth reached

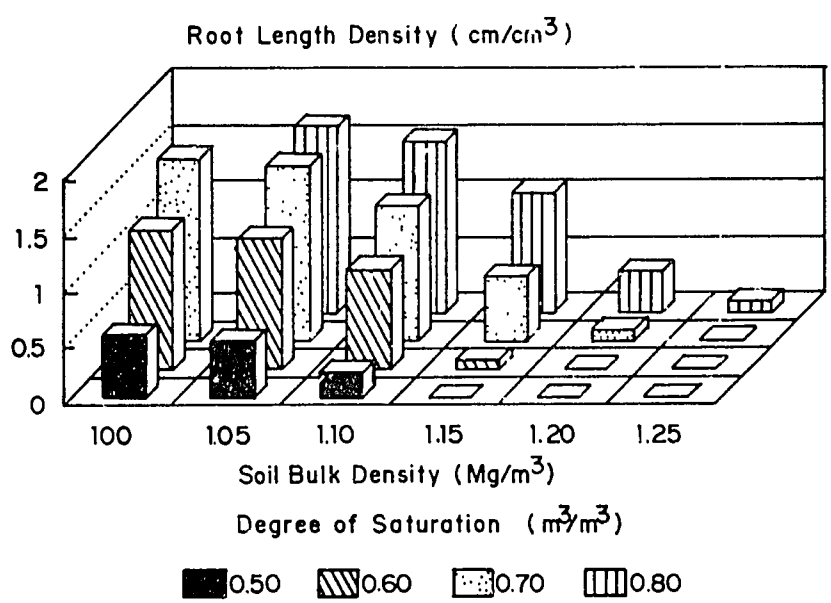


Figure 6. Root length density of nine-day-old soybean plantlets at six soil bulk-density levels and four degrees of saturation in a very-fine clayey Acrustox (Mendes, 1989).

by disc tillage implements. Ten years of tilling exclusively with disc plows and disc harrows in a rainfed soybean/wheat rotation created a zone of high mechanical impedance. Additional tillage with disc implements in year 11 only aggravated the situation. Chisel plowing and cross chiseling (repeat chiseling at 90°) alleviated the mechanical impedance for the wheat crop.

Direct-drilled wheat is used as a basis for comparison because it represents the compacted state of the soil after ten years of disc tillage. Even though offset, heavy-disc tillage shows a higher root-density index than chisel tillage (Figure 9), the critical difference in favor of chiseling is the development of roots deeper in the profile, where subsoil moisture reserves are available to the plant.

Wheat yields (Table 2) clearly indicate the benefit of the two chisel-plowing operations. It should be pointed out that low yields for direct drilling do not rule out this practice, but merely emphasize that reduced tillage or no-till systems will not work on already compacted soils unless something is done to alleviate the problem.

On-farm sampling of changes in crop-root environment

Paired sampling of soils in their native state and under cultivation has proven useful for characterizing the range in soil physical properties that can be expected given the chemical and physical alterations brought on by cropping (Kashirad et al., 1967). Many of these alterations are best observed under actual farm conditions of soil fertilization and tillage. Soil physical properties for five paired soils sampled in June 1987 in the Federal District are listed in Table 3. In each case, culti-

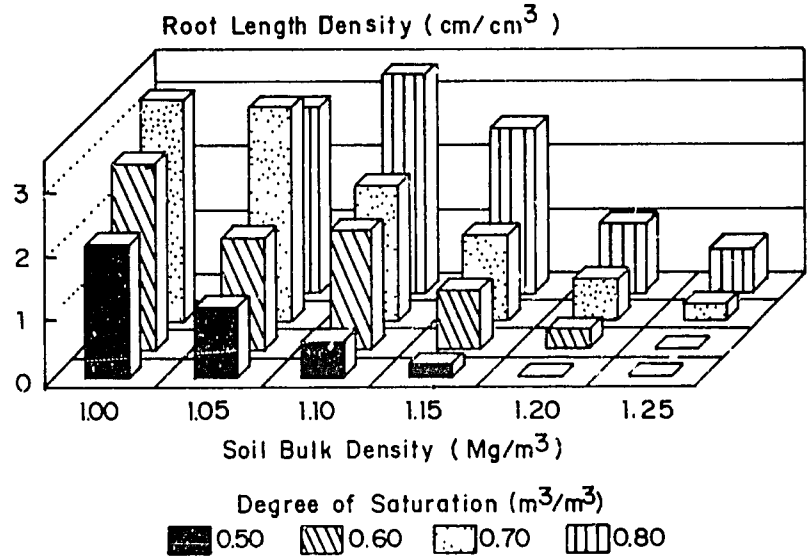


Figure 7. Root length density of seven-day-old maize plantlets at six soil bulk-density levels and four degrees of saturation in a very-fine clayey Acrustox (Mendes, 1989).

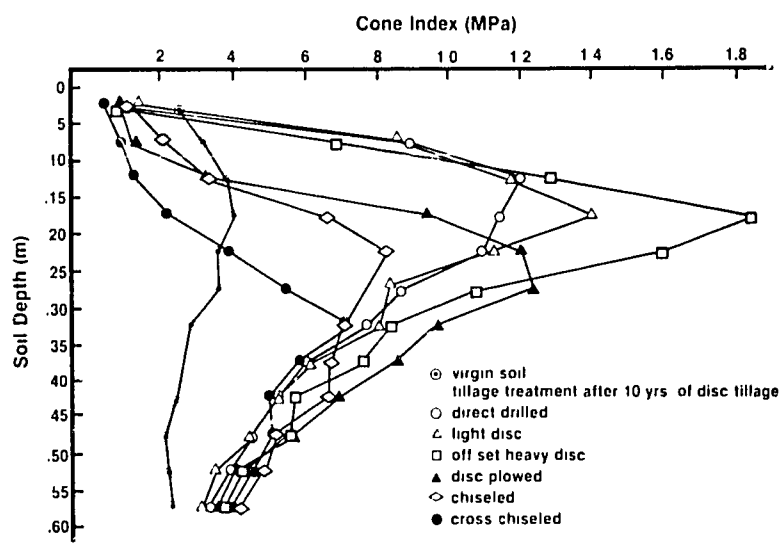


Figure 8. Mechanical impedance profiles of six tillage treatments on a Typic Haplustox, Minas Gerais, Brazil, compared to native soil conditions.

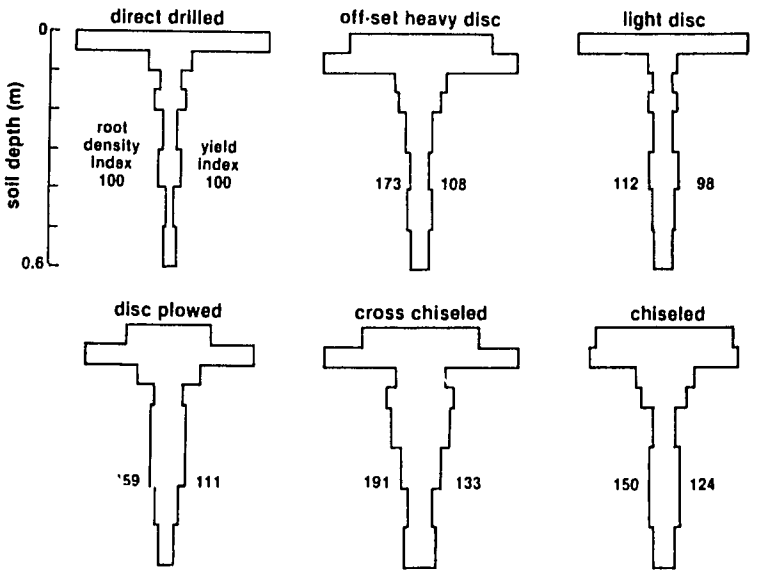


Figure 9. Root-density profiles (cm root/cm³ soil) for six tillage treatments on a Typic Haplustox, Minas Gerais, Brazil, with root and yield indices.

vated sampling sites were chosen on the basis of proximity to uncleared native savanna undisturbed by vehicular traffic or trampling by grazing animals. All cultivated sites had a history of disc harrow primary and secondary tillage, with the exception of the site at Fazenda MAE, which was moldboard plowed six months prior to sampling.

Very-fine clayey Oxisols in the native state showed bulk densities ranging from slightly lower than 0.9 Mg/m³, to slightly more than 1.0 Mg/m³. With as little as two years of cultivation, bulk densities reached their maximum observed level for very-fine clayey Oxisols, 1.10 Mg/m³ (Fazenda Fatima, 20- to 30-cm layer). With time, even very shallow layers presented high bulk densities with drastically increased soil strength and decreased permeability (Fazenda Vereda, 10- to 20-cm layer). At the same time, longer-term cultivated soils showed greatly reduced porosity and macroporosity as measured in undisturbed core samples.

Conversely, under the one situation in which a moldboard plow was used for primary tillage (Fazenda MAE), soil bulk density actually decreased, while permeability increased to a depth of 40 cm, when compared to soil in the native state. Soil strength in the important 10- to 20-cm layer was greatly reduced compared to disc-tilled sites. Apparently, deep incorporation of crop residue and rapid decomposition alleviated compaction and resulted in further cementation of primary particles.

On lower clay-content Oxisols (CPAC center pivot, 68% clay), bulk densities as high as 1.2 Mg/

Table 2. Wheat yield by tillage treatment on a compacted Typic Haplustox, Minas Gerais, Brazil.

Tillage treatment	Wheat yield	Yield index	C.V. (six reps)
Cross chiseled	2260	133	9.3
Chiseled	2108	124	10.1
Disc plowed	1887	111	7.5
Offset heavy disc	1840	108	9.7
Light disc	1672	98	10.3
Direct drilled	1702	100	6.6

m^3 were observed after ten years of cultivation with soil strength greatest and permeability lowest in the 20- to 30-cm layer. Lower clay content (57% vs. 68%) was observed in the paired native site even though it occurred just 50 m downslope from the field sampling site. Bulk densities for the 57% clay-content soil were as high in their natural state (1.1 Mg/m^3) as the most severely compacted 80% clay-content cultivated soils. The 50% clay-content soils maintained low soil strength, good permeability, and high porosity.

In June 1988 sampling was repeated on the high-clay Acrustox with the intent of characterizing possible shallow compaction on long-term cultivated soils. Soil pits were opened at locations close to the 1987 sampling sites (Table 3) after saturating soils to facilitate core sampling. Soil mechanical impedance was measured with a spring penetrometer at 1-cm intervals in the profile face to determine the precise location of high soil strength in the tilled layer. The 7- to 15-cm layer at Fazenda Vereda was determined to possess potentially root-restricting high mechanical impedance. While the pit was being opened, a large native tree root was found intact at the 18-cm depth, indicating that after 14 years of cultivation, with initial liming and three relimings, none of the tillage operations attained sufficient depth to dislodge this root.

In 1987, a second cultivated site was chosen for sampling at a location adjacent to the site sampled at Fazenda MAE in 1987 (Table 3), but with the difference that this field had been tilled solely with disc tillage implements. In addition to core and bulk samples taken at four depths (0-7, 7-15, 15-23, 23-31 cm), undisturbed soil samples for micromorphological analysis were collected at the three sites at the 7- to 15-cm depth. These samples were prepared for thin section analysis at Cornell University and were studied under a light microscope at magnifications of 20, 40, and 100

Soil physical and chemical properties are summarized in Tables 4, 5, and 6. Of note is the drastically reduced permeability in the 7- to 15-cm layer for both the long-term cultivated (Fazenda Vereda, 14 years) and the shorter-term cultivated soils (Fazenda MAE, 6 years) (Table 4). Infiltration tests were performed on-site with a double-ring

Figure 10. Soil erosion results as a consequence of decreased infiltration of compacted soil layers during high-intensity rainstorms with subsequent runoff and rupture of contour terraces. Note soil removal to depth of disc-tillage marks (Eric Stoner).

infiltrometer, yielding the following basic infiltration rates upon equilibrium: native soil, 44 mm/h; Fazenda Vereda, 6.3 mm/h; Fazenda MAE, 15 mm/h. These rates are considerably lower than those reported for other Oxisols, although the decrease in infiltration rate with cultivation is of the same order of magnitude (Moura Filho and Buol, 1972).

The very low infiltration rates on the highly compacted soil at Fazenda Vereda, cultivated 14 years for soybeans, may be the best single indication that root-restricting physical conditions exist. Because rainstorms of 50 mm/h are not unusual in this region, the low infiltration rates for cultivated very-fine clayey Oxisols constitute an erosion hazard when these soils occur on even slightly sloping terrain. Removal of the tilled layer in strips has been observed where rainfall exceeded water intake and runoff water concentrated to gouge out contour terraces (Figure 10). Innundation of recently-planted fields was also observed on one occasion during a high-intensity rainstorm, while nearby native savanna strips showed no signs of water ponding on a tableland site with less than 1% slope. Even though reduced percolation and leaching of mobile nutrients could be considered beneficial, problems such as reduced water capture, erosion, and root restriction are far more severe constraints to overall farm management. Management strategies

Table 3. Selected soil physical properties from on-farm paired sampling of cultivated and native soils in the Federal District.

Site	Depth	Clay content	Bulk density	Soil strength§	Permeability	Porosity	Macroporosity
	cm	%	Mg/m³	MPa	mm/h	%	%
Fazenda	0-10	80	0.94	0.33	227	65.2	26.2
Vereda	10-20	79	0.94	0.38	256	65.2	26.8
Native¶	20-30	79	1.01	0.49	134	62.6	25.3
	30-40	79	0.99	1.26	153	62.3	26.4
Fazenda	0-10	80	1.04	1.43	14	61.5	18.6
Vereda	10-20	79	1.08	4.27	47	60.0	20.7
Cult. 13	20-30	83	1.07	3.04	101	60.4	23.9
years	30-40	81	1.08	2.12	55	60.0	22.2
Fazenda	0-10	46	0.92	0.33	525	65.9	25.8
MAE	10-20	47	0.90	0.47	489	66.7	25.5
Cult. 5	20-30	65	0.98	1.02	158	63.7	24.1
years	30-40	79	1.00	1.28	237	63.0	26.7
Fazenda	0-10	76	0.86	0.56	468	68.1	24.1
Triaca	10-20	78	0.90	0.85	270	66.7	25.9
Native#	20-30	79	0.99	1.52	144	63.3	24.4
	30-40	82	1.02	1.00	123	62.2	24.0
Fazenda	0-10	64	0.94	3.44	129	65.2	22.4
Triaca	10-20	75	1.08	3.01	65	60.0	21.9
Cult. 9	20-30	77	1.08	3.04	58	60.0	20.6
years	30-40	81	1.02	1.40	81	62.2	25.0
Fazenda	0-10	72	0.89	0.14	177	67.0	25.7
Fatima	10-20	69	0.97	0.63	122	64.1	20.7
Cult. 2	20-30	76	1.10	1.61	26	59.2	23.2
years	30-40	81	1.01	1.00	134	62.6	24.1
CPAC	0-10	53	1.06	0.50	303	60.7	27.7
Center	10-20	51	1.09	0.75	437	59.6	28.1
Pivot	20-30	55	1.10	0.73	421	59.2	28.6
Native	30-40	57	1.08	0.90	346	60.0	29.6
CPAC	0-10	67	1.16	1.08	146	57.0	21.4
C. pivot	10-20	68	1.18	1.03	136	56.3	24.0
Cult. 10	20-30	65	1.18	1.47	62	56.3	23.3
years	30-40	66	1.12	1.35	86	58.5	25.6

§ Cone index measured with soil moisture near field capacity.
¶ Native site in close proximity to both Fazenda Vereda and Fazenda MAE.
# Native site in close proximity to both Fazenda Triaca and Fazenda Fatima.

Table 4. Selected soil physical properties of a very-fine clayey Acrustox under different management systems.

Site	Depth	Clay content	Bulk density	Soil strength	Permeability	Porosity	Macroporosity
	cm	%	Mg/m³	MPa	mm/h	%	%
Fazenda	0-7	30	0.82	0.28	713	68.0	24.4
MAE	7-15	79	0.88	0.43	425	66.0	24.9
Native§	15-23	80	0.87	0.48	396	66.4	25.9
	23-31	81	0.94	0.39	173	63.7	23.3
Fazenda	0-7	68	0.96	0.07	230	62.2	21.6
MAE	7-15	72	1.04	0.71	83	59.8	20.4
Cult. 6	15-23	77	1.00	0.41	134	62.0	22.7
years	23-31	80	0.99	0.36	131	62.8	25.4
Fazenda	0-7	79	1.03	0.53	31	59.3	15.5
Vereda	7-15	82	1.05	1.48	17	59.3	17.3
Cult. 14	15-23	82	1.08	1.34	36	58.3	18.1
years	23-31	83	1.09	2.69	17	57.9	18.9

§ Native site in close proximity to both Fazenda MAE and Fazenda Vereda.

Table 5. Selected soil chemical properties of a very-fine clayey Acrostox under different management systems.

Site	Depth cm	pH (H2O)	Al	Ca	Mg	K	P (Mehlich) mg/kg	O.M. g /kg
			cmol (+)/ kg					
Fazenda	0-7	5.1	1.06	0.20	0.20	0.08	0.7	44.1
MAE	7-15	5.4	0.68	0.12	0.06	0.07	0.4	37.3
Native§	15-23	5.3	0.54	0.14	0.22	0.06	0.4	32.4
	23-31	5.3	0.48	0.08	0.08	0.04	0.3	28.9
Fazenda	0-7	6.2	0.00	3.40	0.90	0.29	2.5	21.3
MAE	7-15	6.2	0.04	2.52	0.86	0.10	1.8	28.7
Cult. 6	15-23	6.1	0.10	1.34	0.48	0.13	0.7	26.7
years	23-31	6.0	0.18	0.36	0.24	0.12	0.6	21.3
Fazenda	0-7	5.3	0.16	1.96	0.58	0.08	5.9	36.8
Vereda	7-15	5.1	0.56	0.90	0.32	0.03	4.0	35.3
Cult. 14	15-23	4.9	0.56	0.20	0.22	0.03	0.7	29.4
years	23-31	4.7	0.34	0.18	0.03	0.03	0.4	24.5

§ Native site in close proximity to both Fazenda MAE and Fazenda Vereda.

Table 6. Distribution of water-stable aggregates in a very-fine clayey Acrustox under different management systems.

Aggregate size (mm)	Distribution (%)											
	0- to 7-cm layer			7- to 15-cm layer			15- to 23-cm layer			23- to 31-cm layer		
	a§	b¶	c#	a	b	c	a	b	c	a	b	c
>2	84	80	27	86	70	32	88	84	51	88	85	61
2-1	7	8	15	6	12	18	7	12	22	7	8	18
1-0.5	4	5	23	5	10	21	3	1	15	3	1	12
0.5-0.25	2	2	16	2	4	14	1	1	7	1	0	6
0.25-0.1	1	2	12	1	3	11	1	0	2	1	0	3
<0.1	1	3	6	1	1	4	0	2	4	0	6	0

§ a = Fazenda MAE, native condition.
¶ b = Fazenda MAE, cultivated six years.
# c = Fazenda Vereda, cultivated 14 years.

that encourage deep root exploration also promote storm-water penetration into subsoil, reducing erosion.

Soil chemical status on the cultivated sites is such that nutrient deficiencies would not be expected to cause root restriction (Table 5). However, low pH levels, high Al saturation, and low Ca levels in the Fazenda Vereda subsoil (15 to 31 cm) indicate inadequate liming and underincorporation of soil amendments. Again, this points out the failure to attain adequate soil depth during primary tillage and the tendency of disc harrows to ride on top of ever shallower hardened layers.

Wet-sieving of bulk soil samples may be the best indicator of degradation of soil structural integrity. The distribution of water-stable aggregates gives a clear picture of the changes in aggregation with increasing cultivation (Table 6). Only 27% of the aggregates in the 0- to 7-cm layer from Fazenda Vereda were in the > 2 mm size fraction, while this figure was 84% for the native soil and 80% for the short-term cultivated soil. This same trend of

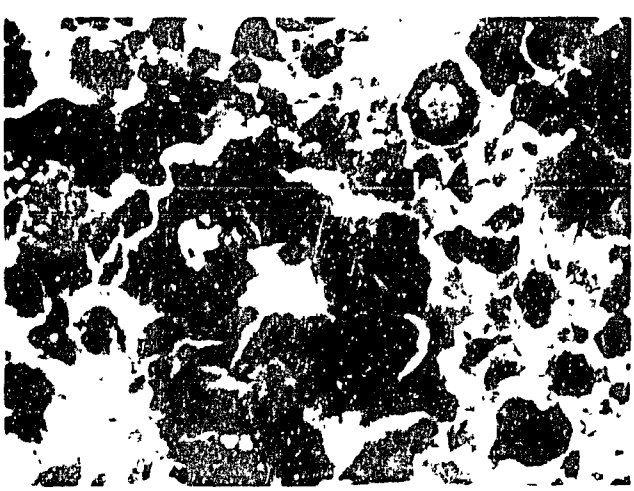


Figure 11. Soil thin section (20X) from 7- to 15-cm layer of native very-fine clayey Acrustox shows ample pore space and irregular shape of microaggregate structure (Eric Stoner).

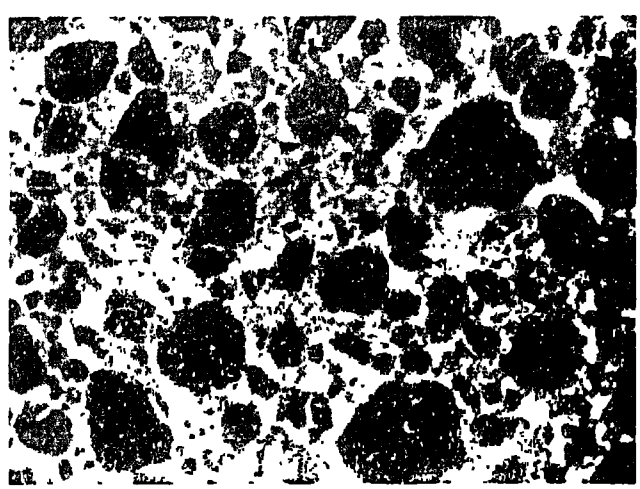


Figure 12. Soil thin section (20X) from 7- to 15-cm layer of long-cultivated, very-fine clayey Acrustox shows rounding of microaggregates and reduced pore space packed with pseudo-silt and pseudo-sand-sized particles (Eric Stoner).

reduced aggregate size held true for the 7- to 15-cm tilled layer, while even those deeper layers beyond the zone of engagement of the disc-tillage tools showed reduced aggregate size, indicating that alteration in aggregate size distribution may not be merely a mechanical process.

Thin-section analysis of soils sampled in the 7- to 15-cm layer confirmed the reduction in aggregate size for cultivated soils. Aggregates in the native soil showed large irregular-shaped granules with ample pore space between individual units (Figure 11) Aggregates from Fazenda Vereda were much reduced in size and were considerably more rounded. Numerous silt-sized granules sloughed off in this rounding process and occupied what had been macropore space (Figure 12). Shape factor analysis of digitized aggregate outlines in which a factor of 1 means circular, revealed a shape factor of 14.8 (average for 53 particles) for soil in the native state, while the soil from Fazenda Vereda had a shape factor of 5.5 (average for 280 particles).

Even though there was an increase in water-dispersible clay in the soil pulverized by tillage, there were no signs of clay coatings that would provide evidence of clay translocation. Micromorphological evidence of clogged macropores and reduced aggregate size is in accordance with measured macro-physical properties of soil porosity and aggregate size distribution (Tables 4 and 6). Thin-section analysis also confirmed the lack of pore continuity in what resembled a uniformly packed mass of randomly arranged granules the size of sand and silt. The ultrafine microaggregate arrangement of rounded pseudo-sand and pseudo-silt granules in the tillage-pulverized soil presents an ideal geometry for the packing of voids in a manner analogous to the particle-packing geometry of smoothed sand grains, which has been hypothesized to impart mechanical resistance to certain U.S. Coastal Plain soils (Cruse et al., 1980; 1981).

In order to verify actual root restriction in the field, the same cultivated sites were revisited in January 1989 during the flowering stage of soybeans. A presampling evaluation of root anatomical response to compacted conditions in these fields (Figure 13) led to the formulation of a diagnostic Root Deformation Index (RDI) to qualify morphological evidence of lateral deviation, constriction, and thinning of the axial (tap) soybean root (Table 7). RDI values of 0 to 1 represent unimpeded root development, while RDI values of 2 to 3 indicate that seasonally high-strength conditions exist (the root may still penetrate when soil moisture conditions are optimum), and RDI values of 4 to 5 signal severe compaction with reduced penetration of high-strength soil layers. Secondary roots were not taken into account in this index, although there was a marked tendency for proliferation of fine roots at the point of strangulation (RDI = 4 to 5).

Figure 13. Visual evidence of soybean root deformation in a compacted very-fine clayey Acrustox: multiple deviation, strangulation, and thinning of tap root (Eric Stoner).

Field sampling of soybean roots and mechanical impedance was conducted when the soil was near field capacity. Roots were sampled at 1-m intervals in 10 m of two adjoining rows after measuring cone index with a penetrograph, 5 cm to either side of each sampled plant. Length to point of first devia-

Table 7. Field-measured soybean Root Deformation Index (RDI) and root length parameters as a function of soil strength.

		Root length (cm)		Cone index (MPa)	
RDI§	Observations	1st deviation point	Maximum length	1st deviation point	Maximum length
0,1	7	7.2	22.3	1.4	1.7
2,3	9	5.7	19.9	1.3	1.8
4,5	24	6.3	19.6	1.5	1.9

§ RDI=0—Vertical axial root development with no evidence of strangulation or thinning.
RDI=1—Axial root with slight deviation from vertical but no strangulation or thinning.
RDI=2—Axial root with 90° deflection but still no sign of strangulation or thinning.
RDI=3—Axial root with multiple deflections in a corkscrew fashion as root seeks path of least resistance, but still no strangulation or thinning.
RDI=4—Vertical axial root development, but with defined strangulation point, root thickening, and fissuring above this point and marked thinning beneath it indicating restricted radial root expansion.
RDI=5—Axial root with 180° deflection with defined strangulation point and marked thinning.

tion and maximum root length were measured, and the corresponding cone index values at these depths were later verified. Subsoiling at Fazenda Vereda in October 1988 reduced compaction conditions at least temporarily and produced extreme variations in rooting observations. Still, 52% of the roots sampled at Fazenda Vereda showed evidence of root deformation (RDI = 2 to 5).

Fully 60% of the soybean roots (cultivar Doko) at Fazenda MAE showed severe root deformation (RDI = 4 to 5). Although deformation and defined strangling occurred at a depth of 6.3 cm, roots attained a maximum length of 19.6 cm (Table 7). Less than 20% of the plants exhibited unimpeded root development. Evidence of root deviation was observed at cone index values as low as 1.3 MPa, and root growth termination occurred at values as low as 1.7 MPa, values close to the threshold level defined by Mendes (1989) for unimpeded root elongation in soybeans. Root deformation occurred at an extremely shallow depth, and even though many roots penetrated this hardened layer, few proliferated beyond the tilled zone.

Root length and cone index values were highly variable, and it was evident that even though penetration resistance was measured very close to the soybean tap root, actual impedance conditions and possible zones of weakness were difficult to confirm for each root. Nevertheless, patterns of root deformation were clearly related to conditions of high soil strength and did not represent natural root tortuosity or reaction to toxic soil conditions. Soybean roots evidently possess a wide range of adaptation mechanisms to compacted soil conditions. A full understanding of root deformation and possible energy consequences for the plant would require monitoring root growth and soil conditions throughout the growing season, especially in the critical first weeks of establishment.

Management Considerations and Implications for Future Research

Development of root-restricting physical constraints is evident on high clay-content savanna Oxisols. Compaction is especially harmful for susceptible crops such as beans. The formation of high soil-strength conditions appears to be a direct consequence of the degraded microaggregate structure so characteristic of these soils. A better understanding is needed of how the prolonged dry season influences natural decompaction forces and acts as a brake on biological activity, favoring the build-up of organic matter. There is a need for field-scale understanding of these phenomena at the root-soil interface level. Image analysis of soil thin sections from field compacted zones and video imaging of actual root elongation under controlled conditions should further explain the mechanics of root restriction.

Farmers in the savanna region must know and understand their own soils. Soil maps and soil testing contribute to this understanding. Soil-survey activities at a scale suitable for farm management decisions must be accelerated, soil maps at this level being almost totally absent even in the most advanced savanna farming regions. Soil maps should distinguish very-fine clayey texture class Oxisols (> 60% clay content) as distinct mapping units because of the added risk to structural degradation these soils represent. In the absence of soil-survey information, easily observable collateral soil parameters such as soil color may provide clues to soil mineralogy and organic matter. Furthermore, soil-testing programs should augment chemical analyses with estimates or actual measurements of soil clay content to gauge soil susceptibility to aggregate disruption and soil compaction. Such a procedure has already been recommended and put into effect for predicting the phosphorus fertilizer requirement, taking into account increased P adsorption capacity with increasing clay content in savanna Oxisols (Lins and Cox, 1989).

Alleviation of soil compaction over the long run will require changes in farmer attitudes towards the role of soil tillage. Measures to alleviate compacted conditions may yield very short-lived results if these efforts do not act to rebuild soil structure. Alleviating compaction through subsoiling or chiseling also carries a high energy cost.

The well-researched practice of deep incorporation of soil amendments frequently is not followed by Cerrado farmers because they often attempt to manage land areas larger than available equipment, manpower, and time will allow. Poor timing of field operations and the view that equates tillage with weed control aggravate the problem. Disc and moldboard plow implements—which are readily available and adjustable to local soil conditions—are much more effective at incorporating soil amendments and crop residues than the offset heavy-disc harrow. Unfortunately, the notion persists that the heavy-disc harrow can perform these primary tillage tasks, even though it often cuts to a mere 15-cm depth and is ineffective at incorporating crop residue.

Perhaps any long-term solution to compaction problems on susceptible savanna Oxisols must include some biological means of regenerating soil structure. Little is known about the probable role of organic matter in maintaining and regenerating soil structure in the Oxisols of seasonally humid regions. Incorporation of crop residues has been observed to

be effective at reducing soil strength and increasing permeability. Tropical legumes grown as green manure crops during the dry season may be part of the solution. Deep-rooting perennial crops or pasture species can be expected to introduce organic residues and resulting transit pores to subsoils beyond the depth of tillage. Although the reworking action of soil insects contributed to the formation of these soils and possibly to their structural arrangement, cultivated Cerrado soils are notably devoid of macrofauna. The success of introducing earthworms in no-till fields in southern Brazil suggests that this could be an effective strategy if the challenge of dry-season survival is solved.

Soil moisture content plays a vital role in determining the severity of root-restriction, in agreement with the concept of drought-induced soil hardening proposed by Taylor et al. (1964). An understanding of the time profile of soil moisture conditions in the rooting zone is needed to monitor the severity of root growth restriction at different crop growth stages. The concept of short-term drought (*veranico*) in the Cerrado region should probably be rethought to include parameters for soil mechanical impedance with depth to establish possible cutoff limits for availability of moisture stored in the soil profile. It is clear that any successful strategy for crop production on savanna Oxisols under rainfed conditions must encourage root proliferation beyond the tillage zone for effective water and solute uptake.

Soil mineralogical properties and charge characteristics along with organic-matter levels determine the structural stability of Oxisols. A better understanding is needed of the beneficial or deleterious changes that occur with soil fertilization. Research should attempt to establish relationships between colloidal dispersibility and soil amendments needed to maintain soil fertility in savanna Oxisols.

Transforming native savanna Oxisols to productive agricultural land is one of the triumphs of modern soil science. Prior attempts to use these soils without the benefit of locally developed technological inputs placed the land and the people working it in an untenable situation. No farming enterprise is without risks, but modern farming in selected areas of the wet-dry savanna poses considerably less risk to the soil and to the environment than does farming in the humid tropics. Soil changes in cultivated savanna Oxisols are not unexpected based on long-term cultivation experience with soils in much more fragile circumstances. Given the relatively short history of cultivation on these soils, there is no reason to believe that farmers cannot make the necessary adaptations to assure sustained productivity, as long as research continues to focus on second-generation problems.

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