Published online August 4, 2005

Change in Physical Properties of "Terra Rossa" Soils in Paraguay under No-tillage

Aki Kubota,* Jorge Bordon, Kent Hoshiba, Toshiyuki Horita, and Kazuo Ogawa

ABSTRACT

The introduction of no-tillage farming stabilized soybean [*Glycine max.* (L.) Merr.] yields on "Terra Rossa" soils of eastern Paraguay at a yield level that is among the highest in the world. The objective of this study was to clarify the effect of long-term no-tillage in a soybean-based farming system on physical properties of "Terra Rossa" soils with different texture. Four farmers' fields of different soil texture were studied in 1990 and 2000. Two fields had fine-textured soil and other two had coarse-textured soil. A 1-m deep pit was prepared at each site at the exact same location in 1990 and 2000, and clay contents, bulk density, cone index, saturated hydraulic conductivity (K_{sat}), aggregate-size distribution, and Ap horizon thickness were investigated. To evaluate changes in Ap horizon thickness over time, data from several additional pits were included. Effects of long-term no-tillage on physical soil properties differed with soil texture. High erosion rates were associated with coarser soil texture, low K_{sat}, poor aggregate stability, and high compaction. Coarse-textured soils lost 34% (about 7 cm) of their Ap horizon in 10 yr compared with 11% in fine-textured soils. Cone index readings in the subsoil of a coarse-textured soil became extremely high (4.72 MPa). Soil compaction was furthermore associated with rapid soil drying and on the sixth day after rain reached a level that could restrict vertical root development of germinating seedlings. These results suggest that the no-tillage system as currently practiced in eastern Paraguay may not be suitable for coarse-textured "Terra Rossa" soils.

In the early 1980s, a soybean grower in Yguazú District, Alto Paraná State, Paraguay, successfully introduced a no-tillage farming system from Brazil. This technology expanded rapidly, and about 65% of soybean growers in Paraguay have been using the no-tillage system on all or part of their fields (Derpsch, 1998). Soybean–wheat (*Triticum aestivum* L.) double cropping is now the predominant cropping pattern on large-scale farms in eastern Paraguay. Most farmers use the system continuously without any tillage for both soybean and wheat crops. No-tillage was introduced to minimize soil erosion after exceptionally heavy rains in 1982 caused severe topsoil losses. No-tillage had additional benefits as it stabilized soybean yields by shortening the time needed for land preparation, thereby allowing farmers to seed soybeans when conditions are favorable.

No-tillage farming systems usually have positive impacts on soil properties. They help to maintain soil organic matter and aggregate stability (Hajabbasi and Hemmat, 2000; Rhoton, 2000), conserve soil moisture, maintain constant soil temperatures (Benegas, 1998), and improve soil structure and water infiltration rates (Gill, 1998). On the other hand, some studies indicated that long-term no-tillage farming might also cause several problems. These are accumulation of applied nutrients in the surface soil (Seki et al., 2001; Pierce et al., 1994), high bulk density (Benegas, 1998; Betz et al., 1998; Pierce et al., 1994), low water permeability (Benegas, 1998), and high soil penetration resistance (Betz et al., 1998; Vazquez et al., 1989).

The high yield of the Yguazú District has lately been affected by short dry periods at the end of the growing period. Seki et al. (2001) studied the effect of drought on yields in farmers' fields and concluded that the reduction of soybean yields was caused by poor root development associated with soil compaction in the soil profile. Similar observations were made by Busscher et al. (2000) in South Carolina where soybean yields were reduced by 1.08 to 1.81 Mg ha^{-1} for every MPa increase in mean profile cone index.

Changes in physical soil properties are therefore an important factor that may affect long-term sustainability of no-tillage systems. Monitoring these changes would consequently be important to prevent undesirable developments with negative effects on crop yields. It would furthermore be desirable to confirm that no-tillage farming, as practiced in eastern Paraguay, can indeed prevent soil erosion. Several long-term studies have been performed to investigate the effects of no-tillage farming system on physical properties of soils in Brazil (Abreu et al., 2004; Oliviera et al., 2003; Prado et al., 2002). However, very little information is available regarding physical properties of the predominate "Terra Rossa" soils of eastern Paraguay. It is also not well established whether any long-term changes in soil properties under no-tillage systems vary with different soil textures.

Objectives of this study are to clarify the effect of long-term no-tillage in a soybean-based farming system on physical properties and Ap horizon thickness of "Terra Rossa" soils in dependence of different textures. The relationship between soil hardness and soil moisture of a fine-textured "Terra Rossa" soil was investigated and changes in soil hardness after rain monitored to determine when the soil reaches a degree of hardness that taproots of germinating soybeans cannot penetrate.

MATERIALS AND METHODS

The predominant soil type found in the study area of eastern Paraguay is a red, clayey soil called "Terra Rossa" that is derived from basalt (Fig. 1). It is classified as either Ultisol or Oxisol according to soil taxonomy. Four farmers' fields with different texture in Yguazú District were studied in detail

A. Kubota and K. Ogawa, former experts of CETAPAR-JICA, Paraguay. A. Kubota, current mailing address: DAPO 7777, Metro Manila, Philippines; J. Bordon, K. Hoshiba, and T. Horita, CETAPAR-JICA, Ruta 7, km 45, Distrito Yguazú, Depto. Alto Paraná, Paraguay. Received 19 Aug. 2004. *Corresponding author (akikubota@yahoo.com).

Published in Soil Sci. Soc. Am. J. 69:1448–1454 (2005).
Soil & Water Management & Conservation
doi:10.2136/sssaj2004.0277

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: CETAPAR, Centro Tecnologico Agropecuario en Paraguay; JICA, Japan International Cooperation Agency: SF, soybean field; VF, virgin forest.

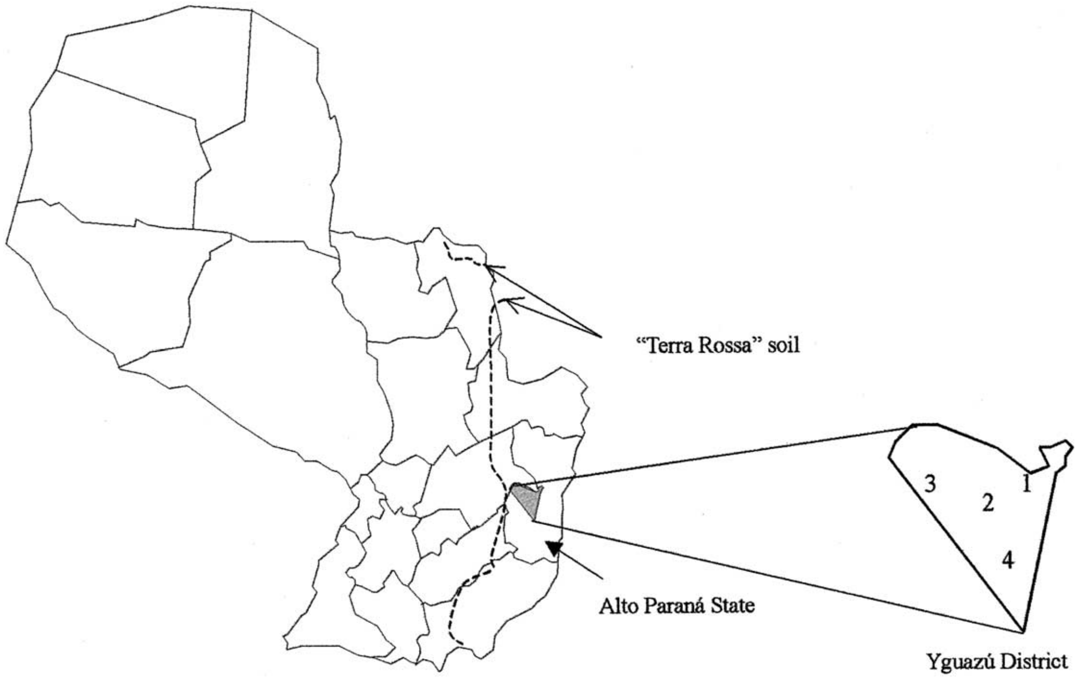

Fig. 1. Location of surveyed sites in Yguazú district and distribution of "Terra Rossa" soil in eastern Paraguay. Locations of soybean field (SF) 1, 2, 3, and 4 are 1 through 4 in the map, respectively.

over a 10-yr period between 1990 and 2000 to investigate changes in soil properties. Soybean field 1 (SF1) and 2 (SF2) are fine textured whereas soybean field 4 (SF4) had a coarse texture. Soybean field 3 (SF3) was intermediate. Soybean field 1 and 2 are classified as Rhodic Kandiudox, and SF3 and 4 as Rhodic Paleudult by the U.S. soil classification system. The soil is characterized by an udic water regime and hyperthermic temperature regime. In 2000, a virgin forest (VF) soil was included in the study to obtain comparisons between native and cultivated soils. All fields were managed by farmers that employed a soybean-based no-tillage farming system for at least 10 yr. The winter crop was wheat. Seeds were sown by drilling with row distances of 35 cm for soybeans and 20 cm for wheat.

In 1990 and 2000 1-m deep pits were prepared at the exact same location for the four fields studies in detail. Profiles were divided into horizons, and the thickness of Ap horizons was determined. To evaluate changes in Ap horizon thickness over time in more than four fields, data from several additional pits were included. For 1990, these additional pits include two fine and two coarse-textured soils. For 2000, pits of 19 fine and 8 coarse-textured soils were added. Selection of those additional 27 sites in 2000 was based on intersecting lines of a 5 by 5 km grid superimposed on the Yguazú District. Only soybean fields under no-tillage farming were selected. The mean values of Ap horizon thickness in 1990 and 2000 were compared using the LSD test as calculated for unequal replications (Gomez and Gomez, 1984). The Ap horizon thickness of four continuously investigated soybean fields were compared with the data collected in 1995 by Miura et al. (1998). Soil samples were taken after soybean harvest. For analyses of particle-size distribution and wet aggregate-size distribution, samples were collected from three spots per horizon and mixed in a plastic bag. Soil samples for physical analysis were taken by two sampling tubes per horizon with a volume of 100 cm^3 (Daiki Rika Kogyo Co., Ltd., Japan). A push-cone soil hardness meter (Daiki) with a 12° 40′ circular cone and a 1.8 cm-diam. base was used to determine the cone index. The cone index was measured four times randomly across rows by pushing the soil hardness meter horizontally at each horizon, and the mean value was presented.

Soil particle-size distribution was analyzed by the pipette method (Gee and Bauder, 1986), using a Kohn-type pipette analyzer. The agent used for chemical dispersion of samples was a sodium phosphate-sodium bicarbonate solution after removal of iron oxide by a sodium hydroxide solution (Claessen et al., 1997). An ultrasonic mixer (Three-wave ultrasonic cleaner, SUS-103, Shimazu) was used for physical dispersion. Bulk density was estimated from oven-dry mass of solid phase in the core samples measured by soil three-phase meter (Daiki). Saturated hydraulic conductivity was measured by the constant-head method in 1990, and by the falling-head method (Klute and Dirksen, 1986) in 2000. Wet-aggregate distribution of the surface soil was determined by the wet sieving method (Sato, 1972) using a Yoder type aggregate analyzer (Yoder, 1936) that shakes 30 times per minute. The weight percentage of each size fraction ($>$2.0, 2.0–1.0, 1.0–0.5, 0.5–0.25, 0.25–0.1, and $<$0.1 mm) was determined. For statistical analysis we grouped aggregates into macro- and microaggregates using 0.5 mm as the cutoff point. General contrasts were computed over years for fine-textured (SF1+2) and coarse-textured (SF3+4) soils.

The relationship between cone index and soil matric water potential, and the change in cone index after rainfall (108 mm) were determined in an experimental field at CETAPAR (Centro Tecnologico Agropecuario en Paraguay), of JICA (Japan International Cooperation Agency). The soil type was identical to SF1 and SF2. The matric potential was measured by six soil water tensiometers, using a mercury tube (Daiki) for each depth (15 and 25 cm), and mean values were presented. The matric water potential at the 5-cm depth was not measured because tensiometers of this type could not be installed at this depth. The cone index was measured 6 times at depth of 5, 15, and 25 cm.

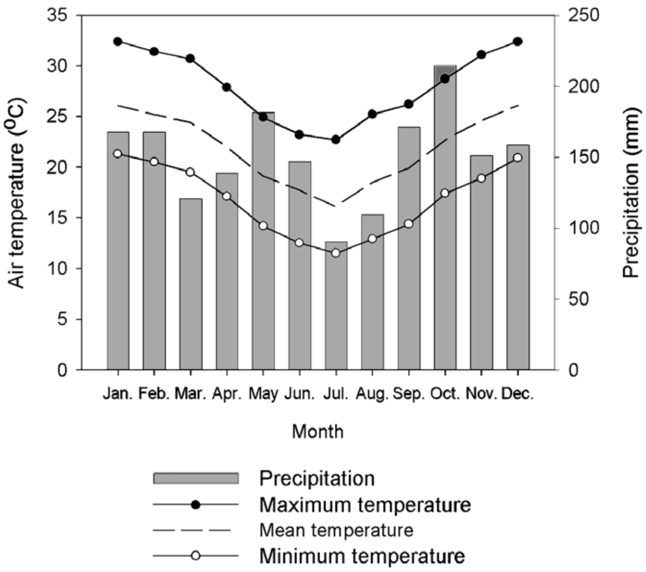

Fig. 2. Monthly average precipitation and air temperature of CETAPAR experimental station, Yguazú District, Paraguay (1990–2000). Mean annual precipitation was 1803 mm.

RESULTS

Geographic location and climatic data of the Yguazú District, Alto Paraná State, eastern Paraguay are shown in Fig. 1 and Fig. 2. Average maximum temperatures during the soybean season (November to April) exceed 30°C while minimum temperatures remain around 20°C. Mean annual rainfall was 1803 mm without pronounced dry or wet seasons. Short periods of drought lasting several weeks may, however, occur at any time of the year. Location and cropping history of the four soybean fields used in this study are given in Table 1. The clay content in the surface layer was used to differentiate between fine-textured fields with more than 40% clay (SF1 and SF2) and coarse-textured fields with <40% clay (SF3 and SF4) (Fig. 3). Throughout this study these two groups are referred to as fine-textured "Terra Rossa" and coarse-textured "Terra Rossa," respectively.

Difference in Compactness

According to the survey in 2000, VF, SF1, and SF2 had similar patterns of clay content throughout soil profiles (Fig. 3). These fields represent the dominant type of "Terra Rossa" soils in the area. Their clay content increased with depth and reached 80% at 1 m. Differences between VF and SF1/2 were observed in cone index and bulk density. The bulk density between 10 and 30 cm was higher in SF1 and SF2 compared with VF, which indicated the presence of a compacted layer just below the surface. Cone indices, on the other hand, remained low in SF1/2 throughout the profile whereas VF showed a marked increase below 20 cm. The volumetric water content at this depth of VF, SF1, and SF2 were 0.31, 0.41, and 0.52, respectively (data not presented). This could have been caused by high water uptake rates of trees as dryness is a usual cause for compactness of soils with high clay contents.

Effects of 10 yr of no-tillage farming on bulk density and cone index differed with soil texture (Fig. 3). In fine-textured SF1 and SF2, the main change observed in 2000 was an increase in bulk density at the 15- to 30-cm depths. The highest bulk density and cone index were 1.56 Mg m^{-3} and 0.98 MPa in SF1 in 2000, respectively. A similar increase in bulk density was observed with coarser-textured soils (SF3 and SF4). But in addition we detected a big increase in cone index in SF4 with a low clay contents of about 20%. Between 20 and 40 cm, the cone index increased from <1 in 1990 to 4.72 MPa in 2000. This occurred although the water content was higher when cone indices were measured in 2000 (data not shown). This value was much higher than previously reported in other studies of no-tillage systems (Busscher et al., 2000; Vazquez et al., 1989). Meredith and Patrick (1961) also observed that when soils low in clay and high in fine sand and silt are compacted, the swelling and shrinking forces that accompany hydration and dehydration are not great enough to loosen the soil over years.

Difference in Saturated Hydraulic Conductivity

The saturated hydraulic conductivity (K_{sat}) showed different tendencies in profiles after 10 yr of no-tillage farming (Fig. 3), although we cannot directly compare changes of these values because different measuring methods were employed. In 1990, the K_{sat} was relatively constant along the soil profile, and SF1 and SF2 had higher K_{sat} values than SF3 and SF4. In 2000, K_{sat} values were low where bulk densities and cone indices were high. The lowest value (0.7×10^{-5} cm s^{-1}) was obtained at the 30-cm depth in SF4, which coincided with an extremely high cone index (Fig. 3). An association of low K_{sat} with high bulk density under no-tillage was also obtained in the study of Benegas (1998). The K_{sat} of VF was higher compared with soybean fields and remained relatively constant along the profile, despite high bulk density and cone index values at depth below 40 cm (Fig. 3). Other factors such as wormholes, root channels, and cracks possibly affected measurements in the undisturbed soil in VF (Reynolds et al., 2000).

Table 1. Description of studied sites.

Site	Location	Major vegetation	Duration of land management (yr) CT†	NT‡	U.S. soil classification
Virgin forest	S 25°28′31.3″ W 055°00′27.7″	subtropical trees	–	–	Rhodic Kandiudox
Soybean field 1	S 25°23′40.2″ W 054°59′15.9″	soybean-wheat	25	18	Rhodic Kandiudox
Soybean field 2	S 25°25′12.4″ W 055°03′16.8″	soybean-wheat	2	13	Rhodic Kandiudox
Soybean field 3	S 25°24′48.0″ W 055°12′46.9″	soybean-wheat	6	10	Rhodic Paleudult
Soybean field 4	S 25°32′08.0″ W 055°00′50.8″	soybean-wheat	3	15	Rhodic Paleudult

† CT, annual conventional tillage cropping before no-tillage was introduced.
‡ NT, annual no-tillage cropping.

Aggregate-Size Distribution

Differences in aggregate-size distribution of Ap horizon are shown in Fig. 4. In 1990, fine-textured soils (SF1 and SF2) had an extremely high proportion of macroaggregates (>0.5 mm) in the surface layer, while microaggregates (<0.5 mm) were dominant fractions in coarse soils (SF3 and SF4). This difference was probably caused by the homogeneous particle size of the soil and by cementation of clay minerals and Al- and Fe- oxides (Six et al., 2000) in SF1 and SF2. Over the 10-yr period we observed a slight reduction for macroaggregates in fine soils but within the class of macroaggregates, the reduction in aggregates bigger than 2.0 mm was significant (−18%, data not shown). These results indicate that even though the no-tillage farming system is thought to maintain aggregate stability (Hajabbasi and Hemmat, 2000; Rhoton, 2000), it may not be able to prevent a reduction of well-developed aggregate stability of fine-textured "Terra Rossa" soils. It should also be noted that the aggregate-size distribution of SF1 and SF2 in 1990 was identical to that of VF in 2000 (data not shown), although both fields had been farmed for more than 20 yr (Table 1).

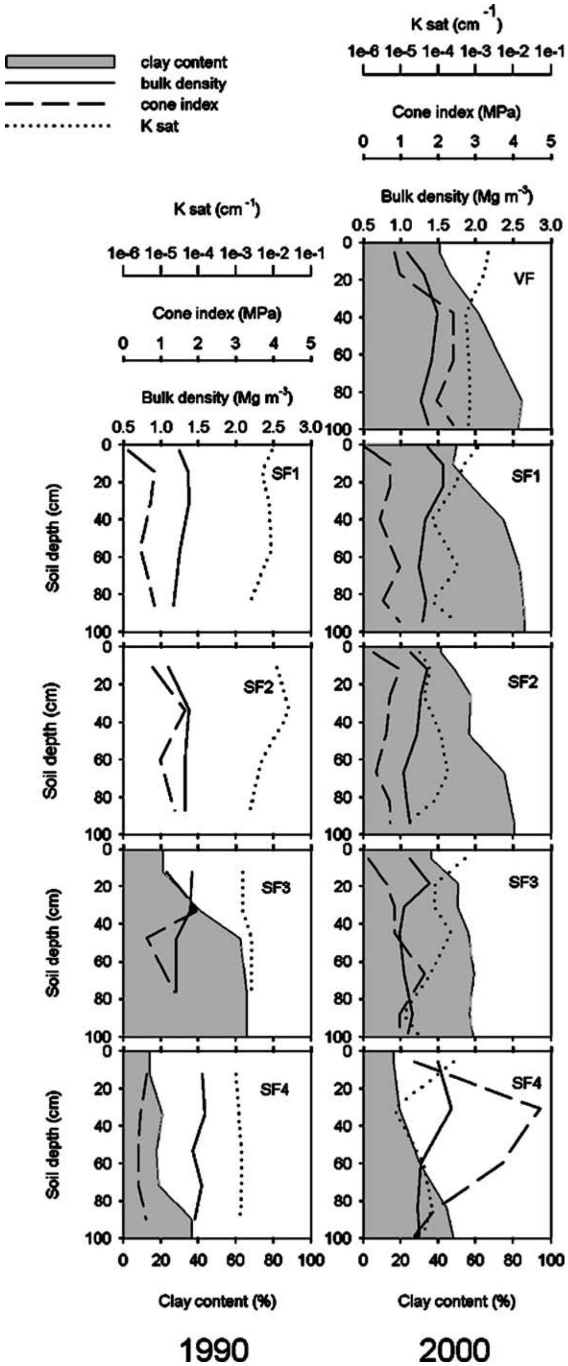

Fig. 3. Clay content, bulk density, cone index, and saturated hydraulic conductivity (K_{sat}) of the soils measured in 1990 and 2000. No data of clay content is available for SF1 and SF2 in 1990. The K_{sat} value was measured by the constant-head method in 1990, and by falling-head method in 2000 (VF: virgin forest, SF: soybean field).

Change in Thickness of the Ap Horizon

The soil survey of 1990, 1995, and 2000 revealed a decline in Ap horizon thickness in all four soybean fields investigated (Fig. 5). In 1990, coarse-textured soils had slightly deeper Ap horizons than fine-textured soils but that completely changed over the 10-yr period. In SF1and SF2 (clay contents > 40%) a 20% reduction in Ap horizon depth was observed, while SF3 and SF4 (clay < 40%) had lost about 50% of their Ap horizon. A similar result was obtained when additional sites were included in the analysis (Fig. 6). The 34% reduction in Ap horizon thickness over 10 yr was statistically significant for coarse-textured "Terra Rossa" soils but not for fine-textured soils (loss of 11%). We also calculated Ap horizon changes on a per weight basis to account for differences in bulk density over the 10-yr period but results were essentially unaltered (data not shown). We estimated that 2280 Mg of topsoil was lost per hectare of land in SF3, using a bulk density of 1.42 and 1.13 Mg m^{-3} as measured in 1990 and 2000. These changes in Ap horizon thickness were probably due to soil erosion caused by heavy rain and strong wind in large and exposed fields. Farmers have observed soil losses from their fields particularly after heavy rains.

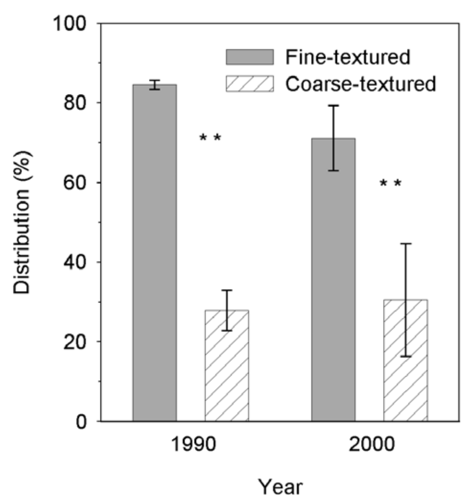

Fig. 4. Distribution of aggregates bigger than 0.5 mm in the Ap horizon of fine-textured and coarse-textured "Terra Rossa" soils. General contrast were used to determine differences between soil groups within years and groups over years. Changes over years were not significant. ** indicates significance between soil groups at $P = 0.01$. Error bars: SD ($n = 2$).

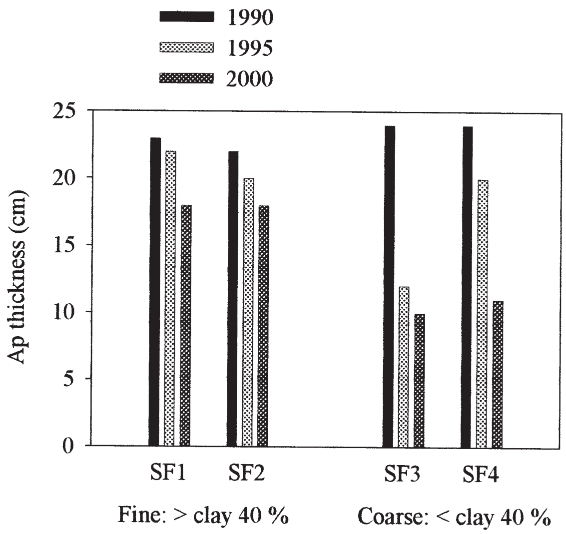

Fig. 5. Change in Ap horizon thickness of soybean fields in 5 yr, from 1990 to 2000, under no-tillage system. The Ap horizon thickness of 1995 was measured by Miura et al. (1998).

Effects of Bulk Density and Soil Water Potential on Soil Hardness

Figure 7 clearly shows that soil hardness is a function of bulk density and soil moisture condition. At a bulk density of 1.62 Mg m^{-3}, the cone index at the 15-cm depth increased exponentially when Log_{10} [−matric water potential] rose above 2.0. At this point (cone index of about 1.3 MPa) soil hardness starts restricting soybean taproot growth (Sato et al., 2001). As the soil dried further, the cone index reached values as high as 7 MPa. The increase in cone index at the 25-cm depth at a lower bulk density (1.42 Mg m^{-3}) was not as steep as at 15 cm, but 1.3 MPa was reached at Log_{10} [−matric water potential] of about 2.25. This data indicates that bulk density has more pronounced effects on soil hardness as soil becomes drier.

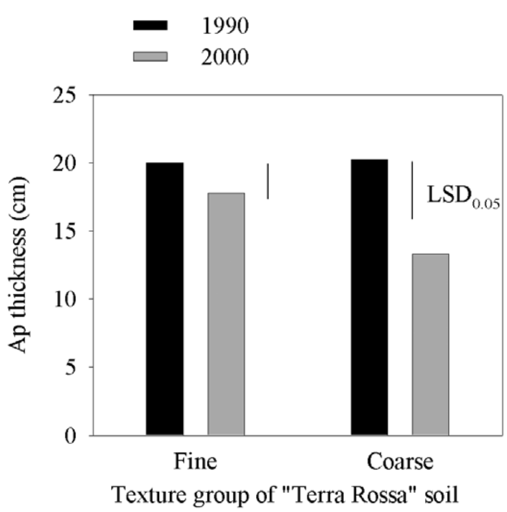

Fig. 6. Change in Ap horizon thickness of two texture groups of "Terra Rossa" soil in 10 yr. The vertical bars indicate LSD at 5% probability. Number of samples were 4, 21, 4, and 10 from the left to the right bars.

Soil Hardness after Rain

The soil hardness measured in the CETAPAR experimental field remained constant for 5 d after rain (108 mm) at depth between 5 and 25 cm (Fig. 8). Cone indices at 25 cm were lower than at shallower depth. After the fifth day, cone index readings at the 5-cm depth started to increase and reached 7.8 MPa on the ninth day, while the cone index stayed constant at the 15- and 25-cm depth. The rapid soil moisture loss at a depth of 5 cm resulted in high soil hardness that exceeded levels crop roots can penetrate after only 6 d following rain.

DISCUSSION

Data presented here shows that the typical soils of eastern Paraguay, commonly referred to as "Terra Rossa" soils, can vary substantially with regard to soil properties. This variation needs to be considered in evaluating the long-term sustainability of current agronomic practices even in no-tillage systems that are generally considered more sustainable (Hajabbasi and Hemmat, 2000; Rhoton, 2000; Gill, 1998). We distinguished between fine and coarse textured Terra Rossa soils based on the clay content in the topsoil and detected marked differences in aggregate-size distribution between the two types. Coarse-textured soils were characterized by a low proportion of macroaggregates (30%) and this property was associated with unsustainably high rates of topsoil losses due to erosion (34% or 7 cm of the Ap horizon in 10 yr, Fig. 6). This compares with 11% (<3 cm) for fine-textured soils with a higher proportion of macroaggregates (>70%). Even these lower rates may be a cause of concern as soil losses accumulate over longer periods of time. We therefore intend to monitor changes in Ap horizon thickness at 5- to 10-yr intervals.

Our survey over a 10-yr period furthermore showed a decline for macroaggregates in fine-textured soils from 85% in 1990 to 71% in 2000. This trend could also increase erosion rates in fine-textured soils if not reversed or at least halted. No-tillage systems are generally thought of as beneficial for aggregate structure (Hajabbasi and Hemmat, 2000; Rhoton, 2000). That such a positive effect was not detected under conditions of the present study is likely due to the soybean–wheat double cropping system in large scale predominantly practiced in eastern Paraguay. However, in absence of a tilled control we cannot exclude the possibility that the change in aggregate stability would have been greater with conventional tillage farming system. Soybeans can have a negative effect on soil aggregate stability (Fahad et al., 1982) because of the rapid decomposition rate of nitrogen-rich soybean residues. As a consequence, erosion rates from soybean fields were found to exceed rates of other crops such as corn (Alberts et al., 1985; Laflen and Moldenhauer, 1979). Using a winter crop that improves aggregate stability could compensate for the negative effect of soybeans; however, the winter crop wheat itself may have been largely responsible for the erosion problem. Due to cool and dry periods in winter, wheat does not produce enough biomass for rapid ground cover and leaves little biomass after harvest to maintain

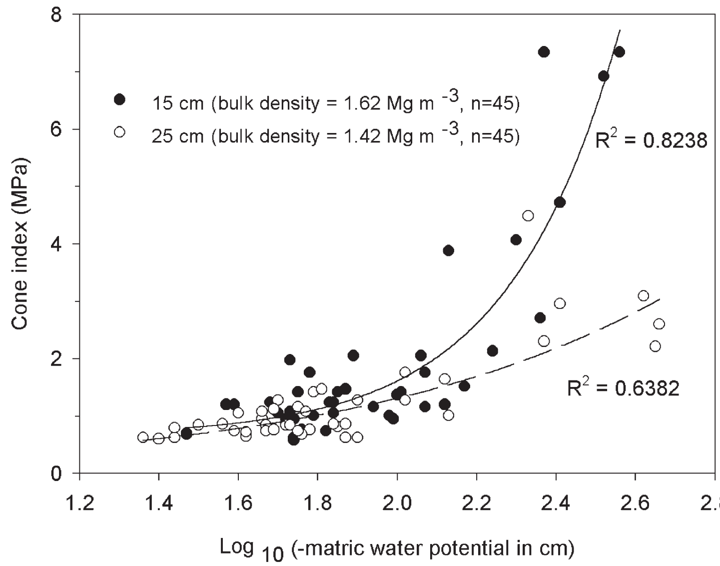

Fig. 7. Relationship between matric water potential and cone index measured at 15 and 25 cm (CETAPAR experimental field).

a protective layer. The risk of surface runoff occurring under wheat is therefore high, particularly since more than 50% of the annual precipitation occurs during winter months from April to October (Fig. 2).

A change in the cropping pattern may be necessary to overcome this problem. Soybeans are the major cash crop in eastern Paraguay because of their high yield. Reducing the cropping frequency of soybeans is therefore not economically feasible as a way to control erosion. Wheat cultivation on the other hand, has not been economically successful due to unfavorable climatic conditions in winter. Attempts to improve the soybean-based cropping pattern should therefore focus on alternative winter crops. Recently, promising results were obtained with some green manure crops that produce enough biomass to rapidly cover the soil surface, and that stabilize aggregate structure through addition of organic matter with a wider C-N ratio.

A second problem detected in this study is that of soil hardness. The soil with the lowest clay content showed an extremely high cone index of 4.72 MPa in the subsoil. High cone index values were, however, also detected in the surface layer of a fine soil and our data showed a clear association of increasing hardness with decreasing soil matric water potential. Soybean taproot growth was reported to decrease at a soil hardness of 1.27 MPa (Sato et al., 2001). A short dry period of 6 d was sufficient to increase the cone index above this threshold. Taylor and Ratliff (1969) observed that cotton roots could not penetrate soil with a soil strength 2.9 MPa, and this value was exceeded on the seventh day in our study. Five or six days are usually not enough to complete sowing in areas as large as 200 ha and to have roots elongate past the 5-cm topsoil layer, even with no-tillage farming. This can explain the finding of Seki et al. (2001) that more than 50% of soybean taproots did not elongate vertically whereas lateral roots grow vigorously near the surface. The authors concluded that this shallow root system made plants susceptible to drought stress even when drought periods were short.

Due to the limited sample size used in this initial study it is difficult to make generalization with regards to the extent of problems described here and their potential solutions. Our results do, however, highlight the need to conduct more detailed studies on the dangers of erosion, particularly as they relate to soil texture and aggregate structure. Soil hardness and the associated risk of incurring drought stress is a second problem that needs to be addressed to maintain a high yield potential. It has been suggested that soil management problems of no-tillage systems, such as soil hardness and high bulk density, can be corrected by periodic tillage (Pierce et al., 1994). Despite some potential benefits for soil structure, plowing may cause other problems such as increasingly difficult weed control, more rapid loss of soil moisture and high soil temperatures (Doran et al., 1984; Wilhelm et al., 1986) that can negatively affect germination. Plowing would furthermore increase exposure of the soil surface to rain and wind, which would be counterproductive in terms of erosion control (McGregor and

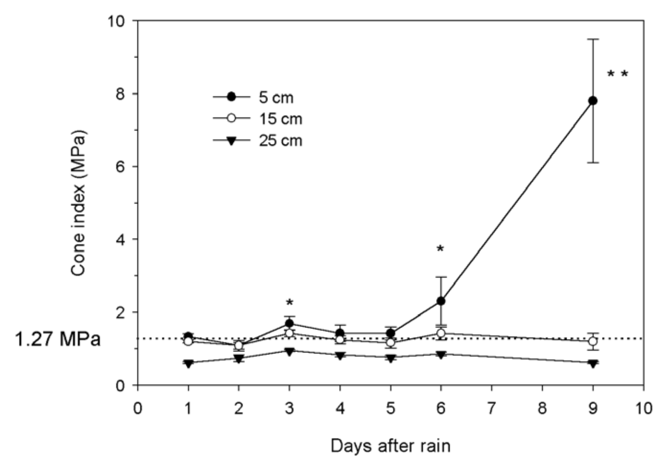

Fig. 8. Change in cone index at different depths after rain (108 mm) on 14 Dec. 1999 (CETAPAR experimental field). Error bars: SD (*n* = 5). The dotted line indicates a cone index of 1.27 MPa, which was found to restrict soybean taproot growth (Sato et al., 2001). *greater than 1.27 MPa at *P* = 0.05. **greater than 1.27 MPa at *P* = 0.01.

Mutchler, 1992; Wilson et al., 2004). We therefore prefer biological to physical or mechanical methods in solving the problems associated with no-tillage farming in eastern Paraguay.

A potential solution is the right choice of alternative winter crops that are capable of alleviating the specific problems encountered at a site. Several winter crops have already been evaluated in Brazil and results indicated that some produce substantially higher root mass than wheat with positive effects on reduction of soil compactness (Kemper and Derpsch, 1981). In eastern Paraguay it has been observed by farmers that oats (*Avena sativa* L.) softens the soil with their well-developed root system, whereas green manure radish (*Raphanus sativus* L. *var. oleiferus* Metzg.) can break hard layers and form biopores in the soil while also providing good ground cover. These practical observations, however, need to be augmented by scientific experiments on green manure crops to evaluate them under controlled experimental conditions that take soil variability into account. This is an urgent issue for crop production and soil conservation alike as soil losses of the magnitude observed in this study are not sustainable.

ACKNOWLEDGMENTS

We thank Dr. Amano and Dr. Fukumura for their technical support in soil surveys and laboratory measurements conducted in 2000. The assistance provided by Mrs. Aureliana Franco and Mr. Santiago Bogado is greatly appreciated. We are grateful for the support of farmers who offered their fields for this study. This study was carried out in CETAPAR, an agricultural institute that is run by the Japan International Cooperation Agency (JICA), Tokyo.

REFERENCES

Abreu, S.L., J.M. Reichert, and D.J. Reinert. 2004. Escarificação mecânica e biológica para a redução da compactação em argissolo franco-arenoso sob plantio direto. Rev. Bras. Cienc. Solo 28:519–532.

Alberts, E.E., R.C. Wendt, and R.E. Burwell. 1985. Corn and soybean cropping effects on soil losses and C factors. Soil Sci. Soc. Am. J. 49:721–728.

Benegas, C.P. 1998. Effect of no-tillage system on chemical and physical characteristics of soil in Paraguay. p. 19–28. *In* M. Kokubun (ed.) No-tillage cultivation of soybean and future research needs in South America. JIRCAS Working Report No.13. MAFF, Tsukuba, Ibaraki, Japan.

Betz, C.L., R.R. Allmaras, S.M. Copeland, and G.W. Randall. 1998. Least limiting water range: Traffic and long-term tillage influences in a Webster soil. Soil Sci. Soc. Am. J. 62:1384–1393.

Busscher, W.J., J.R. Frederick, and P.J. Bauer. 2000. Timing effects of deep tillage on penetration resistance and wheat and soybean yield. Soil Sci. Soc. Am. J. 64:999–1003.

Claessen, M.E., W. De Oliveira, J. Lopez, and M. Nascimento. 1997. Analise granulometrica. p. 27–34. In Manual de metodos de analise de solo, 2a. Edicao. EMBRAPA-CNPS, Rio de Janeiro, RJ.

Derpsch, R. 1998. Historical review of no-tillage cultivation of crops. p. 1–17. *In* M. Kokubun (ed.) No-tillage cultivation of soybean and future research needs in South America. JIRCAS Working Report No.13. MAFF, Tsukuba, Ibaraki, Japan.

Doran, J.W., W.W. Wilhelm, and J.F. Power. 1984. Crop residue removal and soil productivity with no-till corn, sorghum, and soybean. Soil Sci. Soc. Am. J. 48:640–645.

Fahad, A.A., L.N. Mielke, A.D. Flowerday, and D. Swartzendruber. 1982. Soil physical properties as affected by soybean and other cropping sequences. Soil Sci. Soc. Am. J. 46:377–381.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Gill, R.C. 1998. Effect of no-tillage on physical and chemical characteristics of soils in Argentina. p. 29–33. *In* M. Kokubun (ed.) No-tillage cultivation of soybean and future research needs in South America. JIRCAS Working Report No.13. MAFF, Tsukuba, Ibaraki, Japan.

Gomez, K.A., and A.A. Gomez. 1984. Comparison between treatment means. p. 187–240. *In* Statistical procedures for agricultural research. John Willy & Sons, Inc. Canada.

Hajabbasi, M.A., and A. Hemmat. 2000. Tillage impacts on aggregate stability and crop productivity in a clay-loam soil in central Iran. Soil Tillage Res. 56:205–212.

Kemper, B., and R. Derpsch. 1981. Results of studies made in 1978 and 1979 to control erosion by cover crops and no-tillage techniques in Paraná, Brazil. Soil Tillage Res. 1:253–267.

Klute, A., and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p. 687–734. In A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Laflen, J.M., and W.C. Moldenhauer. 1979. Soil and water losses from corn-soybean rotations. Soil Sci. Soc. Am. J. 43:1213–1215.

McGregor, K.C., and C.K. Mutchler. 1992. Soil loss from conservation tillage for sorghum. Trans. ASAE 35:1841–1845.

Meredith, H.L., and W.H. Patrick, Jr. 1961. Effects of soil compaction on subsoil root penetration and physical properties of three soils in Louisiana. Agron. J. 53:163–167.

Miura, S., W. Asada, and J. Sordon. 1998. Soil survey in Yguazu District. p. 20–24. *In* Effects of soil properties and long-term crop rotation on soil productivity. CETAPAR-JICA, Paraguay.

Oliviera, G.C., M.S. Dias Junior, and N. Curi. 2003. Compressibilidade de um Latossolo Vermelho argiloso de acordo com a tensão de água no solo, uso e manejo. Rev. Bras. Cienc. Solo 27:773–781.

Pierce, F.J., M.C. Fortin, and M.J. Staton. 1994. Periodic plowing effects on soil properties in a no-till farming system. Soil Sci. Soc. Am. J. 58:1782–1787.

Prado, R.M., C.G. Roque, and Z.M. Souza. 2002. Sistemas de preparo e resistência à penetração e densidade de um Latossolo Vermelho eutrófico em cultivo intensivo intensivo e pousio. Pesq. Agrepec. Bras. 37:1795–1810.

Reynolds, W.D., B.T. Bowman, R.R. Brunke, C.F. Drury, and C.S. Tan. 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Sci. Soc. Am. J. 64:478–484.

Rhoton, F.E. 2000. Influence of time on soil response to no-till practices. Soil Sci. Soc. Am. J. 64:700–709.

Sato, T., K. Yamawaki, and M. Nakano. 2001. Effect of dry bulk density, soil water contact and hardness of volcanic ash soil on the growth pressure of soybean taproot. Jpn. J. Soil Sci. Plant Nutr. 72:175–179.

Sato, Y. 1972. Soil aggregate analysis. p. 59–63. *In* Measurement of soil physical properties. society of soil physical properties measurement. Yokendo, Tokyo.

Seki, Y., K. Hoshiba, and J. Bordon. 2001. Root distribution of soybean plants in no-tillage fields in Yguazú District of Paraguay. Jap. J. Trop. Agon. 45:33–37.

Six, J., E.T. Elliott, and K. Paustian. 2000. Soil structure and soil organic matter: II. A normalized stability index and the effect of mineralogy. Soil Sci. Soc. Am. J. 64:1042–1049.

Taylor, H.M., and L.F. Ratliff. 1969. Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Sci. 108:113–119.

Vazquez, L., D.L. Myhre, R.N. Gallaher, E.A. Hanlon, and K.M. Portier. 1989. Soil compaction associated with tillage treatments for soybean. Soil Tillage Res. 13:35–45.

Wilhelm, W.W., J.W. Doran, and J.F. Power. 1986. Corn and soybean yield response to crop residue management under no-tillage production systems. Agron. J. 78:184–189.

Wilson, G.V., S.M. Dabney, K.C. McGregor, and B.D. Barkroll. 2004. Tillage and residue effects on runoff and erosion dynamics. Trans. ASAE 47:119–128.

Yoder, R.E. 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. J. Am. Soc. Agron. 28:337–351.