Impact of Tillage and Maize Cropping System on the Physical Properties of a Kaolinitic Soil in the Brazilian Coastal Tablelands

Marcelo Ferreira Fernandes[A], Antônio Carlos Barreto[A] and Guilherme Montandon Chaer[B]

[A] Embrapa Tabuleiros Costeiros, Aracaju, SE, Brazil, Email marcelo@cpatc.embrapa.br
[B] Embrapa Agrobiologia, Seropédica, RJ, Brazil, Email gchaer@cnpab.embrapa.br

Abstract
The objectives of this work were to evaluate (i) the effects of tillage and maize crop systems on the physical properties of a kaolinitic soil (Udic Kandiustalf) in the Brazilian coastal tablelands, and (ii) the relationship between maize productivity and soil physical quality (SPQ). The experiment was a 3 x 2 factorial replicated four times in a randomized complete block (RCB) design arranged in a split-plot layout. Three tillage methods (no-till, NT; chisel plow, CP; and conventional till, CT) and two maize cultivation systems (sole maize, SM; and maize-pigeon pea intercropping, MP) were tested. Plots fallowed for seven years, arranged in the RCB design, were also analyzed. Soil samples were collected seven years after the beginning of the experiment (0-20 cm) and analysed for water-stable aggregates (WSA), aggregate mean weight diameter (MWD), available water (AW), bulk density (ρ_b), macroporosity (MP), microporosity (mP), and saturated hydraulic conductivity (k_{sat}). Cultivation systems had no significant effects on soil properties. Fallow significantly improved all the variables studied. CP and NT had higher MP, WSA and MWD, and lower mP and ρ_b than CT. Except for a decrease in MWD, chisel subsoiling in CP did not affect soil properties, compared with NT. A significant positive correlation was observed between maize productivity and SPQ.

Key Words
kaolinitic soils, soil quality, *Cajanus cajan, Zea mays*

Introduction
Kaolinitic soils are the most widely occurring soils in the tropics. The use of kaolinitic soils for continuous cropping must overcome many physical and chemical limitations, especially those related with the compaction due to frequent tractor traffic and lack of organic inputs (Juo and Franzluebbers 2003). Therefore, soil management strategies that combine reduced or no-till and high plant residue inputs are pivotal to the long-term sustainability of these soils (Juo and Franzluebbers 2003; Juo 1980; Nyamadzawo *et al.* 2008; Nyamadzawo *et al.* 2009). Crop successions between cash crops and cover crops have been pointed as an efficient alternative to increase residue inputs in many regions (Valpassos *et al.* 2001; Machado *et al.* 2005; Bayer *et al.* 2006; Villamil *et al.* 2006; Zanatta *et al.* 2007). However, in many subhumid and semiarid regions of the tropics, the rainy season is relatively short to allow two cropping cycles in the same year. Pigeon pea presents a high temporal complementarity of resources with maize due to its slow initial growth rate (Gilbert 2004). Because of this complementarity and of its drought tolerance, pigeon pea is amenable to being intercropped with maize, and can stand the dry period after the harvest of the cash crop, therefore, contributing with the production of plant residues during the dry period in subhumid and semiarid regions.

The objectives of this work were to evaluate (i) the effects of tillage and maize crop systems on the physical properties of a kaolinitic soil (Udic Kandiustalf) in the Brazilian coastal tablelands, and (ii) the relationship between maize productivity and soil physical quality (SPQ).

Methods
Experimental Setting
This work was carried out in a kaolinitic Udic Kandiustalf at the Umbauba Experimental Station (Umbaúba, Sergipe State, Brazil). The experiment was a 3 x 2 factorial replicated four times in a randomized complete block (RCB) design arranged in a split-plot layout. Three tillage methods (no-till, NT; chisel plow, CP; and conventional till, CT) and two maize cultivation systems (sole maize, SM; and maize-pigeon pea intercropping, MP) were tested. Tillage treatments were imposed from 2002 to 2008, whereas cultivation system treatments were applied from 2006 and 2008. Before 2006 all the plots had been sown with maize and pigeon pea, in an intercropping system. Plots fallowed for seven years, arranged in the RCB design, were included as soil quality references.

Soil and crop management
Seven days before sowing, glyphosate was sprayed in NT and CP plots. CT plots were plowed with a disk plow and disked twice, immediately before sowing. CP plots were chisel subsoiled at ~30 cm depth. Nitrogen, phosphorus and potassium were provided as ammonium sulfate (90 kg N/ha), simple superphosphate (60 kg P_2O_5/ha) and potassium chloride (60 K_2O/ha), respectively, in both cropping systems (SM and MP). Maize (double hybrid AGN 3100) stand was 50000 plants/ha (80 x 50 cm, two seeds every 50 cm) in both cropping systems. Pigeon pea was sown at the same time as maize. Four pigeon pea seeds were placed 25 cm apart from maize plants, in the same row as the crop. Maize was harvested 120 days after sowing. Pigeon pea plants were left standing in the field during the dry period and killed with glyphosate (NT and CP) or plowed (CT) immediately before the maize sowing in the next year.

Soil sampling and analyses
Soil samples were collected (0-20 cm depth) in September 2008, after maize harvest, and analyzed for the following physical variables: available water between -10 e -1500 kPa (AW) (pressure plate method); soil bulk density (ρ_b) (7.5 to 12.5 cm depth); water-stable aggregates (WSA) and aggregate mean weight diameter (MWD) (Kemper and Rosenau 1986), macro- and microporosity (MP and mP) (Embrapa 1997). Saturated hydraulic conductivity (k_{sat}) was obtained in the field, at the time of soil sampling, using the double concentric ring method (Reynolds *et al.* 2002). The same sampling procedures and analyses were used for cropped and fallow plots.

Statistics
Split-plot ANOVA was used to evaluate the effects of tillage, cropping systems and the interaction between these factors on the soil variables. Whenever cropping system effects and interactions were not significant ($p > 0.10$), the following contrasts were used to compare the effects of (i) the conversion of cropping plots in fallow (NT + CP + CT vs. Fallow), (ii) the soil layer inversion in cropped areas (NT + CP vs. CT) and (iii) the chisel subsoiling in plots where no-inversion methods were applied (NT vs. CP).

Principal components analysis (PCA) was used to evaluate the treatment effects on the soil physical quality (SPQ), expressed as the combined response of the seven soil properties. Prior to PCA, data were standardized by each soil property totals. Principal components were characterized by Pearson correlation coefficients between the sample scores in PCA components and their respective values for each variable. Treatment effects on SPQ were tested using MANOVA. The same contrasts described above for the univariate analyses were used for the SPQ analysis. In this case, treatment effects were compared by *multi-response permutation procedures* (MRPP, Mielke Jr. and Berry 2007). The correlation between maize productivity and SPQ was evaluated by the Pearson correlation coefficient between productivity data and the samples scores in both components of the PCA plot.

Results
Cropping system effects and the interactions between this factor and tillage methods were not significant ($p < 0.10$) for any of the soil properties evaluated. This may be explained by the short period of application of cropping system treatments in our study (2 years). Conversion of cropped areas in fallow had a significant impact in all the soil properties (Table 1). This conversion led to increases in AW, MP, MWD, WSA and k_{sat}, and decreases mP and ρ_b. Improvements in soil physical quality under fallow have been attributed to greater residue input, higher protection of soil surface against the impact of rainfall, higher macrofaunal activity and presence of plant species with deep root systems. Soil layer inversion in CT plots lead to significant decreases in MP, MWD and WSA and increments in mP and ρb (Table 1). Except for a decrease in MWD, chisel subsoiling in CP did not affect soil properties, compared with NT. (Table 1).

Regarding the SPQ, about 89% of the original variability in soil physical properties was represented in a 2-D PCA plot (Figure 1). Differences in SPQ were mainly observed along PC1, which was associated with 56% of the variability of the original variables. PC2 explained 28% of the data variability. PC1 was highly correlated ($p < 0.001$) with all the variables, except mP. Along PC1, from the left to the right, increases were observed in MP, MWD, WSA, k_{sat} and AW; whereas ρb increased in the opposite direction (Table 2). An increasing gradient of mP and AW was observed toward the top of PC2, whereas MP varied in the opposite direction.
MANOVA indicated that SPQ was affected by tillage method ($p = 0.04$), but not by cropping system ($p = 0.55$) or the interaction of these two factors ($p = 0.24$). Contrast analyses showed that SPQ differed between

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fallow and cropped areas ($p < 0.001$), and between areas with (CT) and without (CP+NT) soil layer inversion ($p < 0.001$). Chisel subsoiling did not significantly affected SPQ ($p > 0.10$). In summary, an increasing gradient of SPQ was observed along PC1, as follow: CT → CP+NT → Fallow (Figure 1). Maize productivity was significantly correlated with shifts in SPQ along PC1, but not with PC2.

Table 1. Contrasts comparing the effects of soil tillage on the physical properties

Effect	Contrasts	Treatments	AW cm^3/cm^3	MP cm^3/cm^3	mP cm^3/cm^3	ρ_b g/cm^3	MWD mm	WSA g/hg	k_{sat} Cm/min
Conversion of cropped areas in fallow	Fallow vs. NT+CP+CT	Fallow	0.101	0.171	0.203	1.52	1.30	83	0.57
		NT+CP+CT	0.080	0.152	0.221	1.59	1.12	74	0.34
		p	<0.01	<0.10	<0.05	<0.05	<0.10	<0.01	<0.05
Soil layer inversion methods	CT vs. NT+CP	CT	0.082	0.138	0.211	1.63	0.96	71	0.26
		NT+CP	0.079	0.159	0.198	1.58	1.20	75	0.37
		p	ns	<0.05	<0.05	<0.10	<0.05	<0.10	ns
Chisel subsoiling	NT vs. CP	NT	0.082	0.160	0.199	1.58	1.31	77	0.45
		CP	0.076	0.160	0.198	1.58	1.10	74	0.29
		p	ns	ns	ns	ns	<0.05	ns	ns

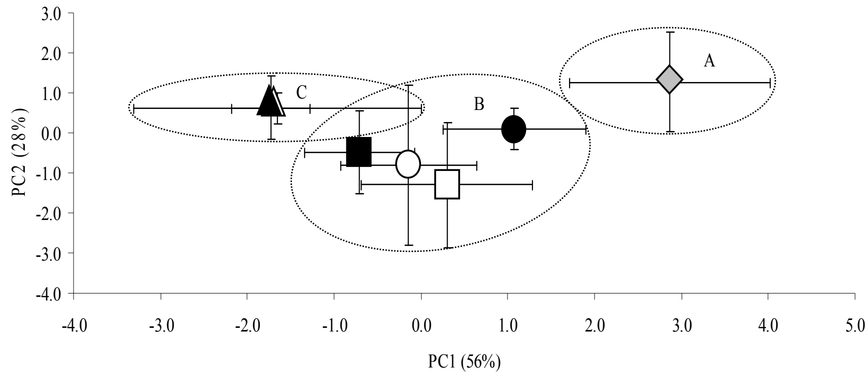

Figure 1. Changes in SPQ as a function of tillage methods and maize cropping systems. CT, CP and NT are represented by triangle, squares and circles, respectively. MP and SM systems are represented by full and open symbols. The diamond indicates fallow. Horizontal and vertical bars indicate ±1 SD. SPQ averages within the same ellipses did not differ ($p<0.05$) according with MRPP. PC: Principal components.

Table 2. Pearson correlation coefficients between soil properties and SPQ expressed as the sample scores in the principal components (PC1 and PC2) of PCA

	Soil physical variables						
	AW	MP	mP	ρ_b	MWD	WSA	k_{sat}
PC1	0.605^{***}	0.732^{***}	0.085^{ns}	-0.860^{***}	0.733^{***}	0.744^{***}	0.598^{***}
PC2	0.743^{***}	-0.568^{**}	0.972^{***}	0.037^{ns}	0.010^{ns}	-0.005^{ns}	0.074^{ns}

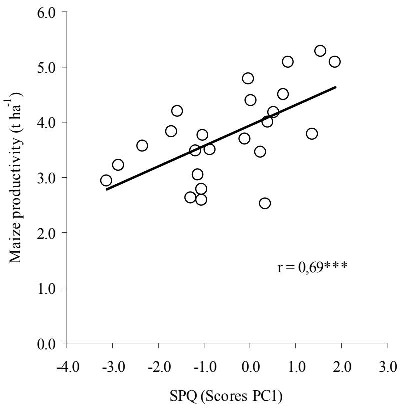

Figure 2. Correlation between maize productivity and SPQ expressed as the sample scores in the first principal component (PC1) of PCA. *** Significant at $p < 0.1\%$.

Conclusions

The maize + pigeon pea intercropping system proposed in this study does not affect soil physical quality and maize productivity in the short term (2 years). Fallow and tillage methods with no soil layer inversion promote improvements in the SPQ in the medium term (7 years). Chisel subsoiling in CP (~ 30 cm depth) does not affect soil properties, compared with NT. In the soil studied, maize productivity is correlated with SPQ.

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