Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
http://dx.doi.org/10.5424/sjar/2014123-5625

Spanish Journal of Agricultural Research 2014 12(3): 611-622
ISSN: 1695-971X
eISSN: 2171-9292

RESEARCH ARTICLE

OPEN ACCESS

Reduced tillage for tobacco (*Nicotiana tabacum* L.) production in East Cuba. Soil physical properties and crop yield

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Abstract

The area devoted to growing tobacco (*Nicotiana tabacum* L.) in the province of Granma, Cuba, accounted for nearly 2600 ha in the year 1997, which represented the 4% of the total tobacco plantation area on the island in that year. Tobacco is tillage-intensive since traditional production systems entail seven or eight cultivation operations before transplanting. The objective of this study was to evaluate two alternative tillage systems in comparison with conventional tillage for tobacco production with the aim to improve soil conditions, reduce the number of tillage operations for soil preparation for transplanting, and increase yields. The treatments studied were: (T1) conventional or traditional tillage, (T2) reduced tillage with a multi-tiller plough, and (T3) reduced tillage with a chisel plough. T1 consisted in disc ploughing twice and disc harrowing twice for primary tillage, while before transplanting plots were ploughed twice with a horse-drawn mouldboard plough and harrowed twice with a horse-drawn spike-tooth harrow. In T2 primary tillage was accomplished with two passes with the multi-tiller followed by disc harrowing twice before transplanting. In T3 chisel ploughing was substituted for multi-tiller ploughing. The two reduced tillage systems improved the physical conditions of the soil, which resulted in: lower bulk density, with average values across the 0-30 cm soil profile of 1.48, 1.34 and 1.30 Mg m^{-3} in T1, T2 and T3, respectively, at the end of the growing season; higher soil water content in the soil profile in all four sampling dates per season; greater porosity; and lower resistance to penetration with values of 2.48, 2.15 and 1.71 MPa in T1, T2 and T3, respectively, before crop harvesting. Tillage system T3 provided the highest crop yields (2.26 Mg ha^{-1}) compared with T2 (2.14 Mg ha^{-1}) and T1 (1.95 Mg ha^{-1}), for the plants grown on T3 plots had the largest number of leaves. The size of the leaves was similar in all three systems, however.

Additional key words: reduced tillage; soil conditions; tobacco production.

Introduction

Tobacco (*Nicotiana tabacum* L.) is an intensively tilled crop since cultivation has been used to control weeds and to improve yields. Conventional or traditional production systems comprise up to seven cultivation operations for soil preparation for tobacco plantlet transplanting (Benham *et al*., 2007). Such intensive tillage leaves the soil bare and, therefore, it can contribute to soil losses by wind and runoff erosion, and to groundwater pollution due to nutrient and pesticide leaching (Colvin *et al*., 1985; Shilling *et al*., 1986; Benham *et al*., 2007).

With the advent in the 1950s of herbicides, capable to controlling a wide spectrum of weeds, it began a slow but steady movement towards the adoption of new tillage systems for different crops that entail a reduction in the tillage operations for weed control (Lal, 2007). The latter are known as reduced or minimum tillage, and their objective is tilling the soil enough to facilitate plant establishment and subsequent plant growth. Reduced tillage systems offer the advantages

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Received: 21-01-14. Accepted: 24-06-14.

This work has 1 supplementary figure that does not appear in the printed article but that accompanies the paper online.

of soil and water conservation, a reduction in erosion potential, less energy and time spent in producing a crop, and more efficient land use (Hoyt *et al*., 1996; Knowler & Bradshaw, 2007; Derpsch *et al*., 2010). However, both researchers and the farmers themselves have largely ignored the adoption of these tillage systems for growing tobacco. The reason for this is that the "clean culture" used in the traditional tobacco production systems for keeping the soil clean and weedless is still very deeply rooted (Shilling *et al*., 1986). Although the lack of weed control has limited the adoption of conservation tillage practices for tobacco production, herbicides now available, such as sulfentrazone and clomazone, could change this (Gooden *et al*., 2008). Hoyt (2000) reported yields and quality to be similar for reduced tillage systems, strip-till and no-till, in comparison with conventional-till in a 3-year burley tobacco study. However, lower yields, but with lower alkaloids, have been observed with conservation-till tobacco when compared to conventionally produced tobacco (Gooden *et al*., 2008).

The area devoted to tobacco cropping in the province of Granma, Cuba, rose considerably in the late 1990s and it accounted for nearly 2,600 ha in the year 1997. This figure represented the 4% of the total area covered by tobacco plantations on the island in that year (65,000 ha) (Rivero *et al*., 2006). That increase was achieved upon a rise in crop yields and improvements in tobacco quality, but this latter factor has not changed consumption patterns as the entire production continues to be sold on the domestic market (Parra, *pers. comm.,* 2009). However, that promising figure declined steadily in the 2000s and the Cuban office of statistics (ONE, 2012) has pointed out that the tobacco acreage in the province of Granma amounted 200 ha in 2012, but it is expected a total area of 750 ha in the year 2014 (CNCT; http://www.cnctv.icrt.cu). Around 70% of the Cuban soils are regarded to be almost unproductive or slightly productive. This includes the soils in the eastern part of the island, whose fragile ecosystems are vulnerable to the negative impact of drought and irregular rainfall (Ascanio & Pérez, 2002). Soil erosion is a problem in 97% of the tobacco cropping area in Cuba, but severe erosion and moderate erosion has been recorded in 19 and 65% of that country's land area, respectively (Vega *et al*., 2007).

Inadequate tillage may have adverse effects on the soil, including structural deterioration, decline in the organic carbon content, alteration of physical, chemical and biological properties, and accelerated erosion (Lal *et al*., 1994; Lal, 2007). These effects constitute one of the most serious problems affecting soils devoted to growing tobacco in Cuba, whose low yields can be attributed in most cases to the unsuitable use of natural resources inherent to inadequate tillage systems (Rivas *et al*., 2004).

In Granma province, soils devoted to tobacco production are subjected to long fallow periods, during which intensive tillage practices, comprising up to eight cultivation operations, remove crop residues from the soil surface, thus increasing soil susceptibility to erosion by the local intense rainfall and strong winds. The objective of this study was to evaluate two alternative tillage systems in comparison with conventional or traditional tillage for tobacco production with the aim to improve soil conditions, reduce the number of tillage operations for soil preparation for transplanting, and increase yields.

Material and methods

Site characteristics and experimental design

The experiments were conducted at the "General García" Credit and Service Cooperative (20° 23´ N; 76° 38´ W), which is owned by the "Empresa de Acopio y Beneficio del Tabaco", located in the town of Bayamo in the Cuban province of Granma. The soil of the experimental site is a Typic haplustert (USDA, 2006) with a loam-clay texture, an organic matter content of 3%, and a pH of 7 (MINAGRI, 1999). The experimental site is located 20 m asl, and has a mean annual temperature of 26°C and a mean annual rainfall of 1200 mm.

A 3-year field experiment was carried out during three months (December-February) in the dry period of years 2006, 2007 and 2008. The rainfall received between December and February during the three consecutive experimental growing seasons of 2005-06, 2006-07 and 2007-08 was about 17, 44 and 51% less, respectively, than the average rainfall of 101 mm for that 3-month period. The months of January 2007 and December 2007 received 93 and 89% less rainfall than normal values, 42 and 27 mm, respectively.

The experiment, which was begun in November 2005, compared three tillage systems for tobacco (var. Habana 2000) production following a maize-tobacco rotation. The tillage systems assessed were conventional tillage (T1), reduced tillage using a multi-tiller plough (T2); and reduced tillage with a chisel plough (T3). T1 comprised eight cultivation operations since plots under this tillage system were disc ploughed to 20 cm depth and disc harrowed to 15 cm depth. Conventionally tilled plots were then disc ploughed to a depth of 18 cm and disc harrowed to a depth of 18 cm. All these four latter tillage operations were performed in November using tractor-drawn implements. Before transplanting the tobacco plantlets, T1 plots were tilled twice with a horse-drawn mouldboard plough at 15 cm depth, but alternating each of these two operations with two harrowings to 10 cm depth, likewise using a horse-drawn spike-tooth harrow (Suppl. Fig. S1a [pdf online]). In T2, primary tillage consisted in two passes to a depth of 30 cm that were accomplished with the multi-tiller plough (Suppl. Fig. S1b [pdf online]). The latter is an implement designed and patented by the Instituto de Investigaciones de Mecanización Agropecuaria (IIMA, La Habana, Cuba) (Ríos, 1999), that consists essentially in two rigid shank subsoilers fitted with two wing shares with a maximum width of 1.2 m, although the working width was 2 m. Prior to transplanting, and as secondary tillage, the soil was disc harrowed twice to 18 and 15 cm depth, respectively. T3 substituted chisel ploughing twice to 30 cm depth for multi-tiller ploughing followed by disc harrowing twice to 15 cm depth as secondary tillage. In the two reduced tillage treatments, primary and secondary tillage were performed in November using full-size tractor-drawn implements. All tillage treatments were arranged in a randomized block design with three replications and plot size of 20 m × 30 m.

In each growing season tobacco transplanting was done manually in December to a depth of 4 to 7 cm, with rows spaced at 90 cm and plants in the row 30 cm apart, for a mean plant density of 37,037 plants ha^{-1}. Ridging was performed with a horse-drawn mouldboard plough.

Fertilizer was manually broadcasted in all treatments after the last tillage operations were done and before transplanting. Average rates applied were 44 kg N ha^{-1}; 44 kg P_2O_5 ha^{-1}; 44 kg K_2O ha^{-1} K; and 20 kg MgO ha^{-1}. The plots were surface irrigated six times per season, applying a water depth of 25 mm per irrigation, the first before transplanting and the others 6, 24, 37, 45 and 60 days after transplanting. Pest control was conducted as recommended in the Cuban Ministry of Agriculture's Tobacco Technical Code (MINAGRI, 2001).

Variables measured

The dry bulk density of the soil was determined with a 100-cm^3 (50 cm × 50 cm) cylinder. Six samples were taken per treatment and replication at each depth studied: 0-10, 10-20 and 20-30 cm. Sampling was timed as follows: after harvesting and before tillage (date 1), after tillage (date 2), 33 days after transplanting (date 3) and shortly before harvesting just 70 days after transplanting (date 4). These samples were also used to determine the soil gravimetric water content and soil porosity (η). This latter variable was calculated with the following expression:

$$\eta = \left(1 - \frac{\rho_b}{\rho_s}\right)100 \qquad [1]$$

where ρ_b is the dry soil bulk density (Mg m^{-3}), and ρ_s is the density of soil particles (Mg m^{-3}).

Soil particle density was determined in six samples extracted at different soil depths in each experimental plot following the procedure described by Kaurichev (1980). Average soil particle density to a depth of 0-10 cm was 2.71 Mg m^{-3}, and it was 2.72 Mg m^{-3} to depths of 10-20 cm and 20-30 cm, respectively.

Soil penetration resistance was measured with a Field Scout SC 900 SN 328 digital penetrometer (Spectrum Technol. Inc., Aurora, IL, USA) on three dates: before tillage, 33 days after transplanting and prior to the harvest. Six measurements were taken per treatment and replication. The mean weight diameter of the soil aggregates was determined after tillage in each plot by sieving the dry soil collected from an area of 1 m^2 and to a depth of 30 cm. Sieve sizes of 150, 100, 75, 50, 25, and 10 mm in diameter were used.

In the field, the length and width of tobacco leaves were measured on a total of 16 plants randomly chosen from each experimental plot, using the methodology proposed by Torrecilla *et al*. (1986). Crop yield was calculated considering the mean plant density and the dry weight of the leaves harvested manually from another set of 16 plants randomly chosen from each experimental plot at the end of February, 70 days after transplanting (Torrecilla *et al*., 1986).

The statistical design was a split-split-plot in time and space for the soil variables studied, with tillage treatments as main effects, and sampling date and soil depth as sub-treatments (Carmer *et al*., 1989), while the crop variables were analyzed with an ANOVA for a randomized block design. The STATISTICA (Stat-

Table 1. Soil bulk density (Mg m^{-3}) averaged across the three growing seasons considered for each sampling date and soil depth, as affected by tillage (T1, conventional tillage; T2, reduced tillage with multi-tiller; T3, reduced tillage with chisel plough)

Date[a]	Soil depth (cm)	Soil bulk density (Mg m^{-3})			Mean
		T1	T2	T3	
1	0-10	1.46 a[b]C[c]A[d]	1.45 aC A	1.44 bC A	1.45
	10-20	1.51 aB A	1.48 bB A	1.48 bB A	1.49
	20-30	1.55 aA A	1.54 aA A	1.54 aA A	1.55
	Mean	1.51 a	1.49 b	1.49 b	
2	0-10	1.04 bC D	1.08 aC D	1.09 aC D	1.07
	10-20	1.10 bB D	1.12 aB D	1.13 aB D	1.11
	20-30	1.13 bA D	1.15 aA D	1.16 aA D	1.15
	Mean	1.09 c	1.11 b	1.12 a	
3	0-10	1.40 aC B	1.16 bC C	1.14 cC C	1.23
	10-20	1.41 aB C	1.19 bB C	1.16 cB C	1.25
	20-30	1.41 aA C	1.21 bA C	1.18 cA C	1.27
	Mean	1.41 a	1.18 b	1.16 c	
4	0-10	1.45 aC A	1.32 bB B	1.29 cB B	1.35
	10-20	1.47 aB B	1.33 bB B	1.30 cB B	1.37
	20-30	1.51 aA B	1.37 bA B	1.32 cA B	1.40
	Mean	1.48 a	1.34 b	1.30 c	

[a] Sampling dates: 1, before tillage; 2, after tillage; 3, during crop growth; 4, before harvest. [b] Means in each row followed by the same lower case letter are not significantly different between tillage treatments at the same depth. LSD test ($p < 0.01$). [c] Means in each column followed by the same upper case letter are not significantly different between depths for the same treatment and sampling date. LSD test ($p < 0.01$). [d] Means in each column followed by the same upper case letter are not significantly different between sampling dates at the same tillage treatment and depth. LSD test ($p < 0.01$).

soft, 2006) software package was used in both cases. Differences between soil variable means were assessed using the least significant procedure (LSD) at the 1% probability level ($p < 0.01$).

Results and discussion

In the three tillage systems compared, we observed no significant differences between the values of the soil variables measured in each of three years of the experiment. Therefore, we decided to average the values for each soil variable across the three years of experimentation.

Soil bulk density

Soil bulk density averaged across the three seasons considered for each sampling date and depth can be seen in Table 1. In T1, bulk density values rose with depth on all four dates. This pattern was the same but less marked in the other two treatments, for no significant differences in bulk density values were found for the 0-10 cm and 10-20 cm horizons on sampling date 4 (shortly before the harvest). After tillage (sampling date 2), the lowest bulk density values at the three soil depths considered were found in T1, while no significant differences were observed between the values for T2 and T3. In this sampling date, bulk density values averaged across the soil profile were 1.13, 1.15 and 1.16 Mg m^{-3} in T1, T2 and T3, respectively. From that date onward, soil re-compaction was more intense in the conventional tilled plots, for bulk density across the entire soil profile was higher in T1 than in T2 and T3 on all three remaining sampling dates. A comparison of these two latter tillage systems revealed that re-compaction was greater in T2 than in T3, with higher bulk density across the soil profile in the former than in the latter on sampling dates 3 and 4. Similar values of bulk density at a depth of 30 cm were not observed for the two systems until just after crop harvesting and before tillage (sampling date 1). Likewise, Table 1 shows that, in all three tillage systems, the highest level of compaction was obtained before primary tillage for the new tobacco season was performed (sampling date 1). For example, in this sampling date bulk density averaged across the 0-30 cm soil profile was 1.51 Mg m^{-3} in T1, and 1.49 Mg m^{-3} in T2 and T3. The lowest bulk density values were found for all three treatments once the different tillage operations had been applied (sampling date 2). On the following date when bulk density was measured, 33 days after transplanting (sampling date 3), soil re-compaction was more intense in T1 than in T2 and T3, especially in the upper horizon, 0-10 cm. This same pattern was identified shortly before harvest (sampling date 4), 70 days after transplanting, when the bulk density in this horizon in T1 had reverted to the value observed before tillage (sampling date 1).

Due to the large number of cultivation operations involved, T1 loosened the soil largely than reduced tillage treatments T2 and T3. For this reason, the conventional tilled soil became much more susceptible to compaction as the tobacco plants developed and required other types of cultural operations. Thirty-three days after transplanting, the mean compaction level in T1 tilled soil was greater than in the soil tilled under reduced systems T2 and T3, and this pattern remained unchanged until shortly prior to tobacco harvest.

Tillage practices have the largest impact on soil bulk density and the literature describes many studies in which the bulk density of soil tilled with reduced tillage systems was found to be greater than the density in conventional tilled soil (Hao *et al*., 2000; Gál *et al*., 2007). Hernanz *et al*. (2009), for instance, reported that soil bulk density to a depth of 20 cm was lower with conventional tillage than with reduced tillage; and Dam *et al*. (2005) observed on a 11-year field experiment in a sandy loam soil that bulk density was 10% higher in no-till than in conventional tillage. On the other hand, Álvarez & Steinbach (2009) observed in the Argentine Pampas that soil density was significantly higher under no-tillage than in conventional tillage but no differences were detected between conventional tillage and reduced tillage. Our results do not corroborate these general observations, as soil bulk density to a depth of 30 cm was lower with reduced tillage in comparison with conventional tillage except immediately after soil preparation for transplanting when the opposite situation occurred. Similarly, Ozpinar & Cay (2006) observed that reduced tillage decreased the bulk density at 0-20 cm depth compared with mouldboard ploughing, which resulted in the highest bulk density at 20-30 cm. Time is the most important source of soil bulk density variability whatever the tillage system adopted. In our case, soil consolidation after transplanting was greater in conventional tillage than in reduced tillage and it was responsible for the higher values of bulk density observed with time in the former tillage system.

Soil porosity

Table 2 gives the total soil porosity values averaged across the three growing seasons studied and for each treatment, depth and sampling date. Before tillage (sampling date 1), the highest total soil porosity for all the depths studied was found in treatment T3, followed by T2 and T1; similarly, the mean total porosity to a depth of 30 cm was significantly higher in T3 (45.18 m^3/100 m^3) and T2 (45.06 m^3/100 m^3) than in T1 (44.45 m^3/100 m^3). After tillage (sampling date 2), total soil porosity rose substantially in all three treatments, with a total porosity averaged across the soil profile that was significantly greater in T1 (59.81 m^3/100 m^3), than in T2 (58.83 m^3/100 m^3), and T3 (58.45 m^3/100 m^3). Moreover, porosity in all soil depths was significantly greater in T1 than in T2, and in this latter system was higher than in T3. On sampling date 3 (33 days after transplanting), the highest soil porosity values in all depths were recorded for treatment T3 followed by T2, while the lowest values were found for T1. Soil porosity averaged across the soil profile was significantly greater in T3 (57.23 m^3/100 m^3), than in T2 (56.24 m^3/100 m^3) and T3 (48.13 m^3/100 m^3). This same pattern was observed shortly prior to harvest (sampling date 4). On all four sampling dates, total soil porosity declined significantly with soil depth.

Shortly after tillage, the greatest soil porosity to a depth of 30 cm was attained with T1, but this effect was not persistent. On sampling date 3 (33 days after transplanting), T1 plots exhibited the lowest soil porosity, a condition that remained unchanged until the beginning of the next season. The total porosity observed after tillage declined significantly with time across the entire soil profile in all three treatments.

The values of soil porosity (Table 2) attained with reduced tillage systems were higher than those achieved with the conventional tillage system, particularly in the

Table 2. Soil porosity ($m^3/100\ m^3$) averaged across the three growing seasons considered for each sampling date and soil depth, as affected by tillage (T1, conventional tillage; T2, reduced tillage with multi-tiller; T3, reduced tillage with chisel plough)

Date[a]	Soil depth (cm)	Soil porosity ($m^3/100\ m^3$)			Mean
		T1	T2	T3	
1	0-10	46.05 c[b]A[c] D[d]	46.42 bA D	46.78 aA D	46.42
	10-20	44.38 cB D	45.49 bB D	45.49 aB D	45.12
	20-30	42.91 bC C	43.28 aC D	43.28 aC D	43.16
	Mean	44.45 b	45.06 a	45.18 a	
2	0-10	61.57 aA A	60.09 bA A	59.72 bA A	60.46
	10-20	59.48 aB A	58.75 bB A	58.38 cB A	58.87
	20-30	58.38 aC A	57.64 bC A	57.27 bC A	57.77
	Mean	59.81 a	58.83 b	58.46 c	
3	0-10	48.26 cA B	57.13 bA B	57.87 aA B	54.42
	10-20	48.07 cB B	56.17 bB B	57.27 aB B	53.84
	20-30	48.07 cC B	55.43 bC B	56.54 aC B	53.35
	Mean	48.13 c	56.24 b	57.23 a	
4	0-10	46.42 cA C	51.22 bA C	52.33 aA C	49.99
	10-20	45.86 cB C	51.01 bB C	52.12 aB C	49.66
	20-30	44.38 cC C	49.54 bC C	51.38 aC C	48.43
	Mean	45.55 c	50.59 b	51.94 a	

[a] Sampling dates: 1, before tillage; 2, after tillage; 3, during crop growth; 4, before harvest. [b] Means in each row followed by the same lower case letter are not significantly different between tillage treatments at the same depth. LSD test ($p < 0.01$). [c] Means in each column followed by the same upper case letter are not significantly different between depths for the same treatment and sampling date. LSD test ($p < 0.01$). [d] Means in each column followed by the same upper case letter are not significantly different between sampling dates at the same tillage treatment and depth. LSD test ($p < 0.01$).

time period elapsed since transplanting until just before tilling for the new season, and they were more stable over time, especially in the case of T3. The total porosity of the soil increases with the intensity of soil manipulation by tillage (Ozpinar & Cay, 2006). Conventional tillage loosened the soil, thus forming more macropores at the beginning of the season. However, the increased total porosity of the conventionally tilled plots was temporary as consolidation took place after transplanting, thus reducing the pore space. According to FAO (2000), the optimal total soil porosity for tobacco is 35 $m^3/100\ m^3$ to 45 $m^3/100\ m^3$. All three tillage systems maintained those porosity levels after tillage and throughout crop growth to shortly prior to harvest.

Soil water content

Soil water content was measured in four sampling dates over the three growing seasons considered. However, in the first two sampling dates no irrigation had been applied yet, but in the third sampling date the soil had received three irrigations and in the fourth sampling date all experimental plots had received two other additional irrigations.

The pattern of variation in soil water content in the three growing seasons studied was similar in the three tillage systems (Table 3). The lowest water content was recorded in the soil profiles analyzed shortly after tillage (sampling date 2); the averaged value was significantly greater in T3 (16.70 kg/100 kg) than in T2 (14.10 kg/100 kg), being T1 with the lowest value (9.74 kg/100 kg). In each tillage system soil water content peak values were observed 33 days after transplanting (sampling date 3). In this sampling date, the highest water content was that of T3 (36.99 kg/100 kg) followed by T2 (30.71 kg/100 kg), while T1 resulted with the lowest content (26.02 kg/100 kg). From sampling date 4 onward, the water content in the soil declined significantly in all three treatments.

Table 3. Soil water content (kg/100 kg) averaged across the three growing seasons considered for each sampling date and soil depth, as affected by tillage (T1, conventional tillage; T2, reduced tillage with multi-tiller; T3, reduced tillage with chisel plough)

Date[a]	Soil depth (cm)	Soil water content (kg/100 kg)			Mean
		T1	T2	T3	
1	0-10	22.23 c[b]C[c] C[d]	22.94 bC C	23.48 aC C	22.88
	10-20	23.47 bB C	24.39 aB C	24.60 aB C	24.15
	20-30	24.02 cA C	25.12 bA C	25.97 aA C	25.04
	Mean	23.24 c	24.15 b	24.68 a	
2	0-10	9.26 cC D	12.00 bC D	15.58 aC D	12.28
	10-20	9.81 cB D	14.30 bB D	16.56 aB D	13.55
	20-30	10.15 cA D	16.01 bA D	17.96 aA D	14.70
	Mean	9.74 c	14.10 b	16.70 a	
3	0-10	24.52 cC A	29.86 bC A	36.02 aC A	30.14
	10-20	26.07 cB A	30.91 bB A	36.82 aB A	31.27
	20-30	27.46 cA A	31.36 bA A	38.12 aA A	32.31
	Mean	26.02 c	30.71 b A	36.99 a	
4	0-10	23.59 cC B	26.11 bC B	29.14 aC B	26.28
	10-20	24.16 cB B	27.31 bB B	29.89 aB B	27.12
	20-30	25.24 cA B	29.09 bA B	30.94 aA B	28.42
	Mean	24.33 c	27.50 b	29.99 a	

[a] Sampling dates: 1, before tillage; 2, after tillage; 3, during crop growth; 4, before harvest. [b] Means in each row followed by the same lower case letter are not significantly different between tillage treatments at the same depth. LSD test ($p < 0.01$). [c] Means in each column followed by the same upper case letter are not significantly different between depths for the same treatment and sampling date). LSD test ($p < 0.01$). [d] Means in each column followed by the same upper case letter are not significantly different between sampling dates at the same tillage treatment and depth. LSD test ($p < 0.01$).

Water content was systematically highest on all four sampling dates and at the three soil depths in T3, followed by T2 and T1. This was due to the greater total porosity exhibited by the two reduced tillage systems compared with the conventional system, which resulted in larger infiltration and, therefore, in less water loss through runoff. Soil moisture declined significantly with soil depth in all treatments. The lower soil water content observed in T1 on all sampling dates in comparison with the other two tillage systems, was the result of the excessive soil pulverization attained due to the large number of cultivation operations performed. Tillage systems that convey less soil manipulation lead to smaller moisture loss that is attributed to less evaporation compared to tillage systems that involve soil inversion (Shaxson & Barber, 2003; Fabrizzi *et al*., 2005). In this regard, the present results coincide with the findings reported by Navarro *et al*. (2000), who observed that in clayey soils sown with maize moisture loss under conventional tillage was 45-62 kg/100 kg, but only 35-44 kg/100 kg under reduced tillage.

Soil penetration resistance

Soil penetration resistance averaged across three experimental growing seasons considered for each tillage system studied and sampling dates can be seen in Table 4. Data in Table 4 reveal that the greater the depth, the higher the penetration resistance in all three treatments. In each tillage system the penetration resistance showed a similar pattern to that observed with soil bulk density. With this respect, the lowest values of this variable were obtained 33 days after transplanting (sampling date 2 for this variable), when soil penetration resistance averaged across the soil profile was significantly greater in T1 (2.16 MPa) than in T2 (1.77 MPa), and it was significantly greater in T2 than in T3 (1.53 MPa). These values rose signi-

Table 4. Effect of tillage system (T1, conventional tillage; T2, reduced tillage with multi-tiller; T3, reduced tillage with chisel plough), soil depth and sample date on mean soil resistance to penetration in the three growing seasons considered

Date[a]	Soil depth (cm)	Soil penetration resistance (MPa)			Mean
		T1	T2	T3	
1	10	2.55 a[b]C[c] A[d]	2.47 bC A	2.44 bC A	2.49
	20	3.46 aB A	3.35 bB A	3.24 cB A	3.35
	30	4.00 aA A	3.92 aA A	3.72 bA A	3.88
	Mean	3.34 a	3.25 a	3.13 b	
2	10	1.55 aC C	1.41 bC B	1.20 cC C	1.39
	20	2.29 aB C	1.72 bB C	1.51 cB B	1.84
	30	2.66 aA B	2.19 bA C	1.90 cA C	2.25
	Mean	2.16 a	1.77 b	1.53 c	
3	10	2.19 aC B	1.48 bC B	1.40 bB B	1.69
	20	2.54 aB B	2.43 bB B	1.52 cB B	2.16
	30	2.70 aA B	2.56 bA B	2.22 cA B	2.49
	Mean	2.48 a	2.15 b	1.71 c	

[a] Sampling dates: 1, before tillage; 2, 33 days after transplanting; 3, before crop harvest. [b] Means in each row followed by the same lower case letter are not significantly different between tillage treatments at the same depth. LSD test ($p < 0.01$). [c] Means in each column followed by the same upper case letter are not significantly different between depths for the same treatment and sampling date. LSD test ($p < 0.01$). [d] Means in each column followed by the same upper case letter are not significantly different between sampling dates at the same tillage treatment and depth. LSD test ($p < 0.01$).

ficantly 70 days after transplanting (sampling date 3 for this variable) and again prior to tillage in the following season (sampling date 1). On all three sampling dates and soil depths, the soil penetration resistance values obtained for T1 were significantly higher than those observed for T2 and T3. A comparison of the latter two tillage systems revealed that immediately after transplanting (sampling date 2) the resistance values were significantly lower in T3 than in T2. However, on the other two sampling dates soil penetration resistance at a depth of 10 cm was similar in the two treatments, but at the other two depths the T2 values were significantly higher than the T3 data.

Soil penetration resistance shortly after tillage could not be determined. Nonetheless, the 3.2 MPa regarded to be the limit for root development (Dexter, 1998; Micucci & Toboada, 2006) was not exceeded after tillage or even 33 days after transplanting with any of the treatments or at any depth. The greatest increase in the resistance to penetration was recorded between the third and first sampling dates. Shortly before tillage (sampling date 1), the mean penetration resistance at the three depths studied was higher than the 3.2 MPa limit in treatments T1 (3.34 MPa) and T2 (3.25 MPa) but not in T3 (3.13 MPa). Our results were not consistent with those of other studies that have reported greater soil penetration with no-tillage and reduced tillage compared with conventional tillage (Carter *et al*., 2002; Singh & Malhi, 2006). However, other authors have not observed differences between tillage systems (Kirkegaard *et al*., 1994). Soil loosening with inversion tillage reduces soil strength temporarily, but machinery traffic and natural consolidation, in addition with slowly declining soil organic matter content, can result in greater soil resistance to penetration in the long term (Franzluebbers & Stuedemann, 2008).

Mean weight diameter of soil aggregates

The mean weight diameter of soil aggregates to a depth of 30 cm in the three growing seasons was determined in each tillage system after tillage (Table 5). As Table 5 shows, the lowest mean weight diameter values, both in every season and averaged across seasons, were observed for T1 followed by T2 and T3. The large number of cultivation operations performed in T1 resulted into greater soil pulverization and therefore

Table 5. Effect of tillage system (T1, conventional tillage; T2, reduced tillage with multi-tiller; T3, reduced tillage with chisel plough) on soil aggregates mean weight diameter

Season	Aggregate mean weight diameter (mm)			Mean
	T1	T2	T3	
2005/06	16.40 c[a]A[b]	32.71 bA	45.70 aB	31.61
2006/07	16.04 cA	30.51 bB	47.24 aB	31.26
2007/08	15.85 cA	32.98 bA	49.98 aA	32.94
Mean	16.10 c	32.07 b	47.64 a	

[a] Means in each row followed by the same lower case letter are not significantly different between tillage treatments in each growing season. LSD test ($p < 0.01$).
[b] Means in each column followed by the same upper case letter are not significantly different between growing seasons for the same tillage treatment. LSD test ($p < 0.01$).

smaller aggregates than in the other two treatments. The mean weight diameter in T2 was significantly smaller than in T3 in all three seasons. This fact may be attributed not to the utilization of the multi-tiller for primary tillage but to the use of the disc harrow twice before transplanting.

When averaged across the three tobacco seasons considered, mean weight diameter of soil aggregates in T3 (47.64 mm), T2 (32.07 mm) and T1 (16.10 mm) was higher than the limiting value of 10 mm established by Hoyos *et al*. (1999) as the minimum required in tropical soils to ensure good tobacco growth while avoiding any soil erosion risk. Tillage systems that entail intensive use of machinery due to the large number of cultivation operations required deteriorate soil structure, raise its compaction and destabilize soil aggregates (Barzegar *et al*., 2000; Guérif *et al*., 2001). Moreover, since the mean weight diameter of the aggregates in these soils is small, a surface crust may form that hinders the emergence of certain crops (Mrabet *et al*., 2001; Hernanz *et al*., 2002).

Crop development

The values of tobacco leaf length and width in the tillage treatments compared and in the three seasons studied are given in Table 6. The data in this latter table show that the longest leaves were found in T3 plots, but no significant differences were observed between treatments T2 and T1. Comparison of the mean leaf length values in the three seasons revealed no significant differences in the three treatments, but leaf length in T3 exceeded to those of T2 and T1. It is assumed that leaf width increases with leaf length; however, data in Table 6 show that, in two out of three seasons, leaf width in T3 was not significantly greater than in T2 and T1. Similarly, leaf width in T2 exceeded to that of T1 in one of the three growing seasons, but the opposite occurred in other of the three seasons. Leaf size is a key factor in determining crop harvest quality, for leaves must be healthy and of a suitable size if they are to make good cigar wrappers. In this regard, the leaf size in the three treatments reached what the MINAGRI (1998) code recommends for the Habana 2000 variety, namely 50-55 cm long and 34-35 cm wide.

The mean number of leaves per plant in the three growing seasons under each treatment is depicted in Table 6. The results clearly show that T3 was the treatment with the largest number of leaves per plant in the three seasons, followed by T2 and T1 in that order. The 18 leaves per plant in T3, compared with 16 leaves per plant in T2 and 14 leaves per plant in T1 were conclusive for the differences observed in tobacco yield between tillage systems, which was 14% greater in T3 than in T1. The larger number of leaves per plant in T3 was directly correlated with the higher moisture content, greater soil porosity and lower soil penetration resistance under that tillage system than under the other two.

The mean crop yield for the three seasons (Table 7) was significantly higher in T3 (2.26 Mg ha^{-1}), than in T2 (2.14 Mg ha^{-1}), and T1 (1.95 Mg ha^{-1}). Obviously, this same distinction between the three tillage systems was recorded in all three seasons, with no significant inter-seasonal differences. The yield obtained with T3 was 3% higher than those reported by López (2005) and Olivet *et al*. (2007) for reduced tillage systems in

Table 6. Effect of tillage system (T1, conventional tillage; T2, reduced tillage with multi-tiller; T3, reduced tillage with chisel plough) on tobacco leaf length and leaf width, and on the number of leaves per tobacco plant

Season	T1		T2		T3		Mean
			Leaf length (cm)				
2005/06	53	ab[a]A[b]	52	bA	54	aA	53
2006/07	53	bA	53	bB	54	aA	53
2007/08	53	bA	53	bA	54	aA	53
Mean	53	a	53	a	54	a	
			Leaf width (cm)				
2005/06	33	a[a]A[b]	34	aA	34	aA	34
2006/07	34	bAB	34	bB	35	aA	34
2007/08	35	aA	34	aA	35	aA	35
Mean	34	a	34	a	35	a	
			Number of leaves per plant (leaves/plant)				
2005/06	14	c[a]A[b]	16	bA	18	aA	16
2006/07	14	aC	16	bA	18	aA	16
2007/08	14	cA	16	bA	18	aA	16
Mean	14	c	16	b	18	a	

[a] Means in each row followed by the same lower case letter are not significantly different between tillage treatments in each growing season. LSD test ($p < 0.01$). [b] Means in each column followed by the same upper case letter are not significantly different between growing seasons for the same tillage treatment. LSD test ($p < 0.01$).

Table 7. Tobacco crop yield in each tillage system (T1, conventional tillage; T2, reduced tillage with multi-tiller; T3, reduced tillage with chisel plough) and growing season

Season	Crop yield (Mg ha^{-1})						Mean
	T1		T2		T3		
2005/06	1.97	c[a]A[b]	2.14	bA	2.26	aA	2.12
2006/07	1.94	aC	2.14	bA	2.26	aA	2.11
2007/08	1.94	cA	2.15	bA	2.26	aA	2.112
Mean	1.95	c	2.14	b	2.26	a	

[a] Means in each row followed by the same lower case letter are not significantly different between tillage treatments in each growing season. LSD test ($p < 0.01$). [b] Means in each column followed by the same upper case letter are not significantly different between growing season for the same tillage treatment. LSD test ($p < 0.01$).

a vertisol, and 11% higher than that achieved by Gonzáles & Jiménez (2003) in a fluvisol, after chisel ploughing.

The results obtained from the present comparison of three tillage systems for tobacco production in the province of Granma (Cuba), allow us to conclude that reduced tillage involving chisel plough and disc harrow (T3) or a multi-tiller and disc harrow (T2) provided better soil physical conditions than traditional tillage (T1): *i.e.,* lower bulk density, higher moisture content, greater porosity and lower resistance to penetration. Tillage treatment T3 resulted with the largest diameter of soil aggregates thus favoring larger soil moisture content than the other two tillage systems. Even though the size of the leaves was similar in all three tillage systems, the soil physical conditions obtained with T3 led to the highest crop output, for the plants grown with this system had more leaves.

Acknowledgements

The authors wish to thank the *Comisión Interministerial de Ciencia y Tecnología* (CICYT) of the Spanish Ministry of Education and Science for the financial support given (Grant no: AGL2007-65698-C03-01).

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