Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic Paleudoll of the southern “Pampa” of Argentina

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Abstract

Soil structural deterioration from continuous cropping systems can adversely affect crop development. Conservation tillage systems are useful to control soil degradation, but may lead to excessive soil compaction, negatively impacting crop growth. Physical measurements were made during 1994 on a Chernozemic loam soil (Petrocalcic Paleudoll) with a petrocalcic horizon at a depth of 1.2 m in Balcarce (Buenos Aires, Argentina). The experiment started in 1992 with wheat (\textit{Triticum aestivum} L.), followed in 1993 with soybean (\textit{Glycine max} (L.) Merr.) and in 1994 with wheat again. The soil had been previously cultivated for 25 years and presented structural degradation (40% of the optimum value). The aim of the study was to evaluate the effect of two tillage systems: conventional tillage (CT) and no-tillage (NT) on soil physical properties and to determine soil physical factors related to reduced growth of wheat under NT. Soil bulk density in the 3–8 and 15–20 cm layers was measured by the cylinder and the paraffin methods. There were no significant differences between treatments ($P>0.05$). Mechanical resistance measured by the cone penetrometer at emergence gave the following values ($P<0.05$): NT: 1.6 MPa, CT: 1.1 MPa at 5–10 cm depth; NT: 1.6 MPa, CT: 1.0 MPa at 10–15 cm depth; and NT: 1.3 MPa, CT: 0.9 MPa at 15–20 cm depth. The function of pore size distribution determined by the water desorption method was significantly different between tillage systems ($P<0.05$). The volume of pores with a diameter larger than 20 μm was greater under CT than under NT ($P<0.05$). Plots under CT and NT had low stability indexes (NT: 30%, CT: 26%), showing a deterioration of soil structure. The saturated hydraulic conductivity determined by a constant head technique was significantly lower ($P<0.05$) in NT plots (NT: $3.5\times10^{-7}$ m s$^{-1}$, CT: $10.9\times10^{-7}$ m s$^{-1}$). Soil water content in the topsoil measured by neutron probe was higher for NT in the early in the growth season. From anthesis to physiological maturity no significant difference ($P>0.05$) in soil water content was found between tillage systems. Data suggest that increased soil mechanical resistance under NT can decrease growth of wheat roots and reduce dry matter accumulation and wheat yield. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Tillage; Soil physical properties; Soil compaction; Mechanical resistance; \textit{Triticum aestivum} L.
1. Introduction

The southern Buenos Aires province, where this study was carried out, does not have a long cropping history. The soils of this region usually contain 60–80 g kg$^{-1}$ organic matter content and have a loam texture with high structural stability (more than 75% of their original stability) in the surface layer. However, intensive tillage has resulted in cases of severe deterioration in soil structure (Puricelli, 1985).

Different tillage systems may modify soil physical properties depending on factors such as cropping history, soil type, climatic conditions, and previous tillage system (Mahboubi et al., 1993; Chagas et al., 1994). Conservation tillage has grown in popularity in recent years as there is enough research that shows it to be an effective practice to control soil degradation on intensively farmed cropland (Larney and Kladivko, 1989; Grant and Lafond, 1993) and to increase soil water storage (Gantzer and Blake, 1978; Dao, 1993).

Nevertheless, the results of comparing different tillage systems are sometimes contradictory due to soil conditions, crop rotation and extent of the studied period. Hammel (1989) and Mahboubi et al. (1993) reported that no-tillage crop production could lead to excessive soil compaction within surface soil layers, resulting in adverse conditions for crop growth and a consequent yield reduction.

Some researchers, working on soils with different characteristics, reported that early growth of wheat and grain yield under conservation tillage systems were lower than under conventional systems, implying soil physical or biological factors as the major causes of the growth reduction (Cornish and Lymbery, 1987; Kirkegaard et al., 1994, 1995). These authors concluded that high mechanical impedance and poor aeration reduced root growth in conservation tillage systems. Root growth can be affected by high soil mechanical resistance restricting water and mineral supply (Larney and Kladivko, 1989; Oussible et al., 1992).

Transmission of water into the soil profile depends on the number of larger pores and biochannels (Unger, 1990). Chaney et al. (1985) and Carter (1992) concluded from their experiments on loamy and fine sandy loam soils, respectively, that no-tillage not only may reduce total pore space, but also may change pore size distribution, with larger pores disappearing and the finer ones predominating.

In respect to soil water content, no-tillage systems offer significant advantages over conventional tillage. The greater water storage under conservation tillage may be attributed to reduced evaporation, and to changes in pore size distribution (Gantzer and Blake, 1978; Dao, 1993).

Water, oxygen, temperature, mechanical resistance and these factors in combination directly affect seedling emergence and root growth. Bulk density, aggregation, aggregate stability, and pore size distribution are important soil physical properties in relation to crop production through their effect on water, aeration, temperature, and mechanical resistance (Letey, 1985).

The aim of the present study was to evaluate tillage effects on soil bulk density, mechanical resistance, pore size distribution, aggregate stability, saturated hydraulic conductivity, soil water content, and water consumption in a Chernozemic loam soil under no-tillage (NT) and conventional tillage (CT), to characterize soil physical factors related to reduced wheat growth under NT after 2 years.

2. Materials and methods

2.1. Site description

The study was carried out in the Tillage System Research Experiment at the Agriculture Experimental Station of INTA Balcarce, Buenos Aires, Argentina (37°45′ S, 58°18′ W) during the 1994 on a wheat crop. The tillage experiment was established with wheat in 1992, and followed by soybean in 1993. The soil is a moderately well drained Chernozemic loam — series Balcarce fine, mixed, thermic (USDA soil classification), a Petrocalcic Paleudoll — series Balcarce fine, mixed, thermic (USDA soil classification). It has a petrocalcic horizon at a depth of 1.2 m and a clay horizon in the 33–74 cm depth. A brief description of the soil properties at the start of the experiment is shown in Table 1. Before the beginning of the study, the experimental site had been under conventional cultivation for 25 years and the soil presented 40% of the original structural stability. This value was determined by dividing the change in mean weight diameter (CMWD) of an old prairie used as control by the CMWD of the site and expressed as a percentage.
The climate of the region is humid–subhumid mesothermal. The annual mean temperature is 14.5°C and the annual average rainfall is 954 mm (average from 1970–1993) with 80% of rainfall during spring–summer. Climatic conditions for 1994 and a long-term average (1970–1993) are shown in Table 2.

### 2.2. Tillage experiment

The experimental design was a split-plot with four replications. The main treatments were NT and CT. The sub-treatments comprised two levels of nitrogen (0 and 120 kg ha⁻¹ N) applied as urea immediately before sowing. The sub-plots were 120 m². The CT plots were disked to a depth of 10 cm after soybean harvest (2 June), followed by moldboard plowing at a depth of 19 cm (9 June). Final bed preparation was done by disk (10 cm) and tine harrow. The NT treatment was sprayed with glyphosate (4.5 L ha⁻¹) and dicamba (0.25 L ha⁻¹) (12 July). Wheat cv ProINTA Oasis was drilled on both treatments on 19 July 1994 with a density of 410 seeds m⁻². Residue covering at sowing was 73% in NT and 0% in CT. During tillering, both treatments were sprayed with metsulfuron methyl (8.4 g ha⁻¹) and dicamba (0.15 L ha⁻¹) to control weeds. Soil physical measurements were made on 0 kg ha⁻¹ N plots, except water content and water consumption that were made on 0 and 120 kg ha⁻¹ N plots.

### 2.3. Soil measurements

Soil bulk density was determined by the cylinder method (Blake and Hartge, 1986). The cores were taken between rows at 3–8 cm and at 15–20 cm soil depths. Six samples (50 mm i.d.×50 mm) from each plot were taken prior to fall disk (26 May), and three samples from each plot were taken at both depths at emergence (11 August) and at harvest (19 December). Data were processed by a Repeated Measurements Analysis (De Andrade and Da Motta Singer, 1986).

The density of individual air-dried soil clods (diameter of 30–60 mm) was determined by displacement after coating with paraffin (Blake and Hartge, 1986). 10 clods were randomly selected from the soil surface midway between rows in each plot on 23 August.

Mechanical resistance was measured using a proving-ring penetrometer (Bradford, 1986) at 5 cm increments from the soil surface to the 20 cm depth, in the row and between rows. The cone used had a 30° angle, 40 mm long, and a diameter of 21.5 mm (CN-970, SOILTEST, Lake Bluff, Illinois). Eight measurements were made for each position at emergence (17 August) and at harvest (19 December). Concurrent with the mechanical resistance measurements, soil water content was determined gravimetrically at 0–10 cm and at 10–20 cm depths.

Pore size distribution was measured by the water desorption method (Danielson and Sutherland, 1986), using Tempe Pressure Cells (1400 A, Soil Moisture Equipment, Santa Barbara, CA). Six undisturbed soil cores (54 mm i.d.×30 mm) were obtained from each plot at 4–7 cm soil depth at harvest (19 December).

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental site</th>
</tr>
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<tbody>
<tr>
<td>Organic carbon (g kg⁻¹)</td>
<td>30.5</td>
</tr>
<tr>
<td>Sand (g kg⁻¹) (2–0.02 mm)</td>
<td>360</td>
</tr>
<tr>
<td>Silt (g kg⁻¹) (0.02–0.002 mm)</td>
<td>390</td>
</tr>
<tr>
<td>Clay (g kg⁻¹) (&lt;0.002 mm)</td>
<td>250</td>
</tr>
<tr>
<td>P (Bray) (mg kg⁻¹)</td>
<td>10.2</td>
</tr>
<tr>
<td>pH (H₂O) (1:2.5)</td>
<td>5.6</td>
</tr>
<tr>
<td>CEC (cmol kg⁻¹)</td>
<td>33.9</td>
</tr>
<tr>
<td>Slope (%)</td>
<td>3.5</td>
</tr>
<tr>
<td>Bulk density (Mg m⁻³)</td>
<td>1.31</td>
</tr>
<tr>
<td>Particle density (Mg m⁻³)</td>
<td>2.58</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean temperature (°C)</th>
<th>Mean precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>9.2</td>
<td>8.1</td>
</tr>
<tr>
<td>July</td>
<td>7.4</td>
<td>7.5</td>
</tr>
<tr>
<td>August</td>
<td>8.9</td>
<td>8.7</td>
</tr>
<tr>
<td>September</td>
<td>11.4</td>
<td>10.7</td>
</tr>
<tr>
<td>October</td>
<td>12.5</td>
<td>13.0</td>
</tr>
<tr>
<td>November</td>
<td>17.5</td>
<td>15.6</td>
</tr>
<tr>
<td>December</td>
<td>20.9</td>
<td>18.5</td>
</tr>
</tbody>
</table>

*Source: Meteorological Service of Agriculture Experimental Station of INTA Balcarce.*
The samples were saturated by wetting from the bottom, and the volume of water removed between consecutive drain steps was determined. The effective pore sizes corresponding to different pressures were estimated using the capillary rise formula (Danielson and Sutherland, 1986). Pressure values applied were: 1.56, 2.8, 4.76, 7, 10, 14 kPa. Pore size distribution data were log-transformed prior to analysis (Biggar and Nielsen, 1976). The functions of pore size distribution were analyzed by using the Smirnov test (Conover, 1980). The Smirnov test is useful to determine whether two distribution functions associated with two populations are identical or not. This test is consistent against all types of differences that may exist between the two distribution functions.

Structural stability of aggregates was measured by De Leenheer and De Boodt (1959) index. Six undisturbed samples from each plot were dry and wet sieved, obtaining the CMWD. A structural index was obtained by dividing the CMWD of an old prairie used as control by the CMWD for each treatment and expressed as a percentage.

Saturated hydraulic conductivity was determined using a constant head technique (Klute and Dirksen, 1986). Three undisturbed soil cores (85 mm i.d. x 70 mm) were obtained from the soil surface for each plot. Hydraulic conductivity data were log-transformed prior to analysis (Biggar and Nielsen, 1976).

Soil water content was determined using a neutron probe (Gardner, 1986). Data were taken periodically in 0.10 and 0.15 m increments to a depth of 1 m during the growing season. An access tube was installed in the interrow of each 0 and 120 kg ha$^{-1}$ N plots to determine in situ soil water content with a depth moisture gauge (4300 Series, Troxler Electronic Laboratory; Research Triangle Park; Raleigh, NC). Water use was calculated taking into account soil water content measures, using the following formula (Jensen, 1973):

\[
\text{Water use} = \sum (1\Phi v - 2\Phi v)DS + P + DH,
\]

where \((1\Phi v - 2\Phi v)\) is the volumetric water content measured between two consecutive sampling dates, DS the width of each soil layer (mm), \(P\) the precipitation (mm), and \(DH\) the height variety in water layer multiplied by 0.1.

2.4. Statistical analysis

Data were analyzed using the Statistical Analysis System (SAS Institute, 1985). The analysis of variance was determined using the General Lineal Model (GLM). Mean separation among treatments was obtained using the Least Significant Difference (LSD) test.

3. Results

3.1. Soil bulk density

No statistical differences in soil bulk density were found between tillage treatments. Soil bulk density at the 3–8 cm depth prior to fall disking, at emergence and at harvest yielded the following values: NT = 1.44, 1.44, 1.52 Mg m$^{-3}$, and CT = 1.40, 1.46, 1.46 Mg m$^{-3}$, respectively. Soil bulk density at the 15–20 cm depth at emergence and at harvest yielded the following values: NT = 1.43, 1.43 Mg m$^{-3}$, and CT = 1.44, 1.46 Mg m$^{-3}$, respectively.

The Repeated Measurements Analysis give statistically significant differences \((P \leq 0.05)\) between sam-

Fig. 1. Variation of soil mechanical resistance with depth at emergence (August 1994) and at harvest (December 1994), averaged for measurements in the row and in the interrow for NT and CT. (*) Indicates significant differences between treatments at the 0.05 level of probability at emergence. (+) Indicates significant differences between treatments at the 0.05 level of probability at harvest.
pling time in each treatment in the 3–8 cm depth but there was no significant difference in the 15–20 cm depth.

Results of soil bulk density obtained from individual soil clods (1.45 and 1.47 Mg m$^{-3}$ for NT and CT, respectively) were in close agreement with those obtained from the cylinder method corresponding to the sampling on 11 August.

### 3.2. Soil mechanical resistance

At emergence, mechanical resistance under NT was significant greater ($P \leq 0.05$) than under CT at the depth of 5–10, 10–15 and 15–20 cm (Fig. 1). For each treatment, differences in mechanical resistance due to relative position of crop row or interrow, were not significant both at emergence and at harvest. No difference in water content was observed between tillage systems at sampling time.

Mechanical resistance measurements at harvest were corrected by water content. At the 0–10 cm depth, water content was significantly different (NT: 0.23 kg kg$^{-1}$ and CT: 0.25 kg kg$^{-1}$, $P \leq 0.05$), thus, mechanical resistance values needed to be adjusted to a similar water content. The soil mechanical resistance values under NT were corrected by using an exponential regression equation relating soil mechanical resistance at different water contents under CT.

### 3.3. Pore size distribution

Analysis of variance for any given pore diameter interval indicated there was no significant tillage effect on pore size distribution. However, significant
tillage effects \((P \leq 0.05)\) were found when pore diameter intervals were partitioned in terms of pores with diameter >20 \(\mu m\). Soil under CT had a larger amount of its pore volume in larger pores (>20 \(\mu m\)) than soil under NT (CT: 26.1% and NT: 16.8%). When the Smirnov test was applied to the pore size data, they showed significant differences between both distribution functions.

3.4. Aggregate structural stability

No significant differences in aggregate structural stability were found. The CMWD obtained for NT and CT was 0.89 and 1.05 mm, respectively. The corresponding values for stability index were 30% in NT, and 26% in CT.

3.5. Hydraulic properties

The saturated hydraulic conductivity values were 3.5\( \times 10^{-7}\) and 10.9\( \times 10^{-7}\) ms\(^{-1}\) in NT and CT, respectively \((P \leq 0.05)\).

No-tillage showed a trend towards a higher volumetric water content than CT to a depth of 5–30 cm at emergence and at tillering (Table 3). From anthesis to physiological maturity no significant differences were found between tillage systems, but statistical differences were found between fertilizer rates. Water content in CT and NT with 120 kg ha\(^{-1}\) N was lower than with 0 kg ha\(^{-1}\) N (Table 3). No difference in soil water content was observed between treatments in the 50–100 cm depth.

Water consumption under NT (0 and 120 kg ha\(^{-1}\) N) was lower than CT from emergence to tillering.
When comparing the rate of N applied, water consumed at the beginning of the crop was similar, but from stem elongation onward, plots containing N used more water with significant differences in some cases.

4. Discussion

As regards soil bulk density, there was no difference between tillage treatment, which is in line with results reported by Chang and Lindwall (1989) for a long term cropped Chernozemic clay loam soil. However, an increase in topsoil bulk density was observed in both NT and CT from sowing to harvest.

Soil bulk density measured in our trial was higher than values measured by Bermejo and Suero (1981), who reported values of bulk density from 1.22–1.26 Mg m\(^{-3}\) for plowed soils at EEA INTA Balcarce in Buenos Aires.

The lack of differences in soil bulk density between treatments was probably due to the fact that the trial had started 3 years ago and there was insufficient time for an equilibrium value to be achieved. Voorhees and Lindstrom (1984) studied soil physical properties under different tillage systems in a silty clay loam soil and reported soil bulk density values were in equilibrium after 3–5 years.

Soil compaction may be evaluated by soil bulk density and mechanical resistance measurements. Mechanical resistance, as measured with a penetrometer, has been observed to be more sensitive than bulk density to differentiate tillage management systems (Bauder and Black, 1981; Hammel, 1989). Although tillage systems had no effect on soil bulk density, in our experiment mechanical resistance in both sampling times was found to be higher in NT than CT; this probably may be due to the lack of soil disturbance. Mechanical resistance measured on NT plots (at 5–15 cm depth was 1.5–1.6 MPa) during early growth could have reduced growth of wheat roots. Eavis and Payne and Eavis et al. (cited in Whiteley et al., 1981) reported that root penetration of a young seedling would be restricted at pressures above 1.3 MPa. Several authors concluded that high mechanical resistance reduced root growth in conservation systems (Cornish and Lymbery, 1987; Kirkegaard et al., 1994) and affected water and nutrient uptake (Oussible et al., 1992).

As regards pore size distribution, differences between the obtained functions showed a distinctive soil behavior in relation to water and air movement between CT and NT.

Carter (1992), working on a sandy loam soil, found, in line with our results, that macro pore volumes were significantly greater in moldboard ploughing in respect to NT. However, he also found that these pore volumes were less efficient in the conduction of air than in NT, thus reflecting the limited continuity of pores under moldboard ploughing system.

The pore size distribution values indicated a significantly greater percentage of $>20\mu m$ pores in CT compared to NT. Saturated hydraulic conductivity, an indirect measure of macroporosity, was also higher in CT. The results of soil bulk density and structural stability showed a decrease of soil porosity in both CT and NT. Saturated hydraulic conductivity for both treatments was low in comparison with soils of similar characteristics (Vidal, 1997).

The soil of the experimental site showed structural degradation due to the intensive agricultural use before the experiment began. The reduction in soil porosity as a result of the loss of structural stability and decrease of soil organic matter may explain the high soil bulk density values in the plots studied. Statistical differences in structural stability are reported in several studies among different tillage systems, showing greater structural stability values in soils under NT or with minimum tillage. In these cases, the experiments had 15 or more years since they had started and the rotations generally included crops that leave quantities of plant residues and have a root system favoring soil structure, such as corn (Mahboubi et al., 1993; Chagas et al., 1994). For this experiment, no recovery of structural stability under NT was observed. This might be due to the fact that the NT practice started from a degraded soil condition and was only in the third year of our trial. These factors should be considered for possible changes in the long term.

The presence of small pores could have favored a greater water retention (Gantzer and Blake, 1978; Dao, 1993) and together with the lack of soil disturbance and less evaporation as a result of plant residues contributed to maintain greater soil water content under NT (Chagas et al., 1994).
The decrease in water consumption under NT may be attributed in part to a lower evaporation rate, and also to the low plant growth reported by Bergh et al. (1995) for the same period of time in this trial. These authors measured dry matter at tillering, stem elongation and physiological maturity, and crop yield. Dry matter was significantly less in NT plots than in CT plots (50, 83, and 71% of the CT, respectively), while yield in NT plots was 59 and 83% of that obtained in CT plots for 0 and 120 kg ha$^{-1}$ N (4952 and 6406 kg ha$^{-1}$, respectively).

Low values of mineral nitrogen at emergence and the high mechanical resistance observed could have restricted water and nutrient supply. Bergh et al. (1995) also determined N$^{\text{NO}_4^- + \text{NO}_3^-}$ at the depth of 0–60 cm. It was 42% lower under NT than under CT at wheat sowing.

Schmidt and Belford (1994) found in wheat crop under NT that a decrease in root growth as a consequence of greater soil compaction was directly related to decreased crop yields. Denitrification and immobilization could have occurred too. Some authors have mentioned these processes as factors limiting the availability of nitrogen for crops under NT (Haugen-Kozyra et al., 1993).

5. Conclusions

Two years from the initiation of the experiment, both NT and CT soils showed high bulk density and low aggregate stability, therefore, they are susceptible to increased structural damage in continuous cropping. The low soil porosity and greater percentage of small pores (<20 μm) in NT affected soil saturated hydraulic conductivity. Mechanical resistance measurements indicated that soil compaction occurred under NT, and this problem may be associated with previous tillage and structural conditions, and the lack of soil disturbance.

Even though the crop under NT accumulated a greater water content, its development and yield was lower than under CT due to poor soil physical conditions and low mineral nitrogen in the early stages of development (Bergh et al., 1995). From the results of structural stability we conclude that soil degradation, due to intensive agricultural practices carried out for 25 years, increased soil compaction. Conservation tillage systems may be effective for maintaining a desirable soil physical structure but when the condition of soil structure is not good enough, as in this trial, these systems would seem not to be effective for structure improvement, at least in the short term. For soils with structural degradation, it seems necessary to ameliorate compacted zones to improve the soil physical conditions before starting the NT system. A rotational scheme including periods in grass would seem desirable to improve organic matter content and encourage aggregate formation and stabilization. The addition of stubble and the reduction of topsoil compaction would prove to be useful practices to take into account since success in the use of NT depends on the initial physical condition of the soil used.

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