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Review

A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas

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ABSTRACT

The Argentine Pampas is one of the most important cropping regions of the World. Limited tillage systems, and specially no-till, had widespread in recent years, occupying actually around 70% of the surface devoted to annual crops. We review results produced in field experiments installed along the Pampas to determine the effect of the adoption of these tillage systems on some soil properties and crops yield. It was performed a metanalysis of data from experiments where plow tillage (mouldboard plow), reduced tillage (chisel plow, disk plow or harrow disk) and no-till were compared. Treatments effects were contrasted by paired *t*-tests between groups of paired data. Soil bulk density and cone penetration resistance of the 0–20 cm layer were higher under limited tillage systems than under plow tillage. Increases of bulk density under no-till in comparison to plow tillage were generally small, averaging 4%, but cone penetration increased by 50% in many soils. The increase of bulk density was greater in soils of initial low bulk density. Neither bulk density increases nor cone penetration changes reached critical threshold for roots development. Aggregate stability and water infiltration rate were higher in soils subjected to limited tillage systems than under plow tillage. The improvement of aggregate stability was higher in poorer structured soils, with an average increase of 70% under no-till in relation to plow tillage. Under no-till infiltration rate doubled in average that of plow tillage. Soil water content during the critical periods of sowing and flowering was generally greater under limited tillage but, conversely, nitrate nitrogen levels were greater in plow tillage. Higher soil water content under no-till in relation to plow tillage may satisfied the evapotranspiration demand of 1–3 days of crops during the critical flowering period, being nitrate nitrogen in average 21 kg ha^{-1} lower under no-till. Soybean (*Glicine max* (L.)-Merr.) yield was not affected by tillage system, meanwhile wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) yields were lower under reduced tillage and no-till than under plow tillage without nitrogen fertilization. Wheat and corn no-till yields were 10–14% lower that yields under plow tillage as a mean. When fertilizers were applied, wheat and corn yield differences between tillage treatments generally disappeared. The adoption of limited tillage systems in the Pampas leads to soil improvement but also generates the necessity of increase nitrogen fertilizers utilization to sustain yields of graminaceus crops.

Contents

1. Introduction

The Pampas is a vast plain of around 50 Mha, which runs from 30° to 40°S, 57° to 68°W in Argentina (Alvarez and Lavado, 1998). The relief is flat or slightly rolling and its natural vegetation consist

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of grasslands in which graminaceous vegetation species are dominant. Mean annual rainfall ranges from 200 mm in the west to 1200 mm in the east and the mean annual temperature ranges from 14 °C in the south to 21 °C in the north. Predominant soils are Mollisols formed on loess like materials of eolian origin, which present a wide range of variation in solum depth, texture, organic matter content and fertility (Alvarez and Lavado, 1998,). Because of its extension and yield potential the region is considered as one of the most suitable areas for grain crop production in the world (Satorre and Slafer, 1999).

Cultivation began in the Pampas during the 19th Century in a central humid portion of the region, with soils of high fertility, and widespread in recent decades to the south and the semiarid west (Soriano, 1991; Hall et al., 1992). Agriculture was introduced using low external input farming systems based on cattle grazing and harvest crop rotations (Viglizzo et al., 2001). The cropped area increased gradually due to economic reasons and, partially, as the consequence of an increase in rainfall during the last few decades (Viglizzo et al., 1995). At present the classical pasture-crop rotation is being replacing by continuous cultivation, especially under humid scenarios. Agriculture is performed on well drained soils, both in the semiarid and humid portions of the region, with nearly 50% of the whole pampean area devoted to soybean (*Glycine max*), corn (*Zea mays*) and wheat (*Triticum aestivum*), the main crops (Hall et al., 1992).

Soil losses by intense erosion under conventional tillage systems that employed the mouldboard plow (Alvarez et al., 1995), and a net loss of nutrients (Bernardos et al., 2001) and soil organic carbon (Alvarez, 2001; Hevia et al., 2003; Quiroga et al., 1996a) due to negative balances occurred in some pampean areas, but despite soil degradation crops yield increased (SAGPyA, 2008). Genetic improvement lead to potential and attainable yields increases mainly of wheat (Calderini et al., 1999) and corn (Maddonni et al., 2000), possible counteracting partially soil degradation. Limited tillage systems combined with fertilization, and specially no-till, were introduced as management practices in the 1990s and were adopted at an exponential rate by farmers since them (AACREA, 2008; Fertilizar, 2008; SAGPyA, 2008). Nowadays between 60 and 80% of the planted area of main pampean crops is conducted under no-till. This evolution may be ascribing mainly to economic reasons. The phenomenon leads to public institutions studying tillage system effects on soils and crops. Many field experiments were performed along the Pampas and also many local and some international papers published but they had not been integrated in a study that resumes the changes produced on soils by the adoption of limited tillage and their possible effects on productivity. Only tillage system impact on soil organic carbon had been assessed in the region, detecting that increases of around 3 t C ha^{-1} may be expected on average when soils are cropped under no-till in relation to plowed soils (Steinbach and Alvarez, 2005). Local reports of grain yield response to tillage systems are contradictory between different experiments (Buschiazzo et al., 1998; Díaz-Zorita et al., 2002), and tillage induced changes on soil physical properties and fertility too (Buschiazzo et al., 1996; Panigatti et al., 1998). In spite of this, concern about soil erosion and fertility lead to researchers and extension services to recommend the use of conservation tillage systems in the Pampas.

A widespread idea in some production circles of Argentina is that productivity increases when no-till practices are adopted. Conversely, others suppose soil compaction under this tillage system and possible constraints to crops growth. Our objective was to integrate results from field experiments where tillage systems effects on soil physical properties, water content, fertility and yields of the main pampean crops were reported. A metanalysis of this data was performed to detect possible impacts of tillage system on soil productivity.

2. Materials and methods

Results from 35 different field experiments in which the effect of tillage system were tested on soil physical properties, water content, nitrogen availability or crops yield were extracted from published reports, with one exception in which data were available from the researcher on charge of the experiment (Tables 1–3). The experiments were widespread over the entire Pampean Region (Fig. 1), with a wide range of variation of climate, soil type and rotation. Selection of data was performed taken into account the following conditions: (1) experiments were performed by researchers from public institutions, (2) before the installation of the experiments the soil had been subjected to an uniform management, (3) all management conditions were similar between treatments which only differed in tillage systems, (4) tillage systems were clearly described, (5) experiments had replications, (6) the dates of experiment initiation and sampling were stated, and (7) crop rotations, fertilization methods, varieties and other management conditions is each experiment were representative of those usually applied by farmers in the area where the experiment was performed.

Tillage systems were grouped in three categories according to the intense of soil disruption caused by machinery during the primary tillage: (1) plow tillage, in which the mouldboard plow was the main tillage implement, usually followed by secondary tillage with harrow disk, field cultivator or equivalent, (2) reduced tillage, in which primary tillage was performed by chisel plow, disk plow or harrow disk and secondary tillage operations were implemented using similar machinery as before or were not used, and (3) no-till, in which weeds were chemically controlled and crops direct drilled. Reduced tillage systems produced a smaller disturb of soil than the mouldboard plow during primary tillage, specially when chisel plow or harrow disk were used (Unger and McCalla, 1980), and were generally followed by less intense pre-planting secondary operations. Chisel plow and harrow disk were mainly used in the experiments performed both in the humid and in the semiarid portions of the Pampas, but in some experiments located on this later region, disk plow was implemented followed by a shallow operation with harrow disk. Reduced tillage and no-till were also grouped together as limited tillage systems for the analysis. These later tillage systems usually leave 15% or more of previous crop aboveground biomass residues on soil surface decreasing soil erosion (Unger, 1994).

Soil bulk density was determined by the core method (Blake and Hartge, 1986), usually with thing soil layers of 3–5 cm. Data were integrated to obtain an average bulk density value for the upper stratum of the profile (Table 1). Cone resistance was evaluated by the cone index method (Bradford, 1986). Some studies determined penetrability to 40–50 cm depth in layers of 5 cm but others only to 20 cm depth. Consequently, penetration resistance of the upper four 5 cm soil layers was averaged in all cases to obtain a mean value of resistance for the 0–20 cm soil depth. Soil structural stability was assessed by a dry-wet sieving method (De Boodt et al., 1961) usually from the 0–5 or 0–10 cm stratum. Change in mean weight diameter (CMWD) was calculated as change in diameter of aggregates after being sieved dry and them wet. As CMWD increased soil aggregates were less resistant to water effect. Cumulative infiltration was assessed by the cylinder infiltrometer (Bouwer, 1986) in all cases after 60 min from initiation of readings. For comparison of the effect of tillage system on water availability to crops, two critical sampling moments were selected, sowing and flowering. Some studies reported total gravimetric soil water content but others available gravimetric water content, and in both cases to different depths. All data were used here. At sowing stage, water content was integrated for the surface soil layer, commonly up to 30–50 cm depth. At flowering

Table 1
Main characteristic from experiments where soil physical properties were determined. PT = plow tillage, RT = chisel or disk tillage and NT = no tillage.

Reference	Soil type	Texture	Rainfall[a] (mm)	Crop rotation	Years	Sampling time	Soil depth (cm)	Pairs of comparisons		
								PT vs. NT	PT vs. RT	RT vs. NT
Soil bulk density										
Alvarez et al. (1998)	Typic Argiudoll	Silty clay loam	980	Corn–corn–corn–soybean	4	Seedling	0–15	1		
Arranz et al. (2004)	Entic Haplustoll		750	Wheat–oat	4	Growing cycle	0–20	1		
Barrios et al. (2000)			1030	Sorghum–wheat–oat	2–4.5		0–20	3	2	2
Barrios et al. (2008)	Vertic Argiudoll		1030	Wheat–soybean	0.5	Seedling	0–20	1	1	1
	Vertic Argiudoll		1030	Wheat–soybean	1	Harvest	0–20	1	1	1
Berón and Blotta (1993a)	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	12		0–16	1		
Blotta et al. (1992a)	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	6		0–24	1	1	1
Colombani et al. (2002)	Typic Argiudoll-Petrocalcic Paleudoll		900	Wheat–soybean–corn	8		3–15	1		
Chagas et al. (1994)	Typic Argiudoll	Silt loam	950	Corn–corn	15	Growing cycle	0–15	1	1	1
Díaz-Zorita (1996)	Typic Hapludoll	Sandy clay loam	820	Corn–soybean	5	Harvest	0–30	1	1	1
Díaz-Zorita (1997)	Entic Haplustoll	Sandy clay loam	820	Sunflower–corn	3	Harvest	0–20			1
Díaz-Zorita (1999)	Typic Hapludoll	Sandy clay loam	820	Corn–soybean	6	Harvest	0–30	1	1	1
Díaz-Zorita et al. (2004)	Typic Hapludoll	Sandy clay loam	820	Corn–soybean	12	Harvest	0–20	1	1	1
Elissondo et al. (2001)	Typic Argiudoll		923	Corn–wheat	0.6–1.6	Seedling	3–18			2
	Typic Argiudoll		923	Corn–wheat	1–2.1	Harvest	3–18			2
Fabrizzi et al. (2005)	Typic Argiudoll-Petrocalcic Paleudoll		923	Corn–wheat	4	Postharvest	3–18			1
Ferreras et al. (1998)	Typic Argiudoll	Silt loam	989		6	Growing cycle	0–20			1
Ferreras et al. (2000)	Petrocalcic Paleudoll	Sandy clay loam	900	Wheat–soybean	2.5	Growing cycle	3–20	1		
	Petrocalcic Paleudoll	Sandy clay loam	900	Wheat–soybean	3	Harvest	3–20	1		
Fontanetto and Vivas (1998)	Typic Argiudoll	Silty clay loam	1030	Wheat–soybean–corn	9		0–15	2	2	2
Gudej y Maseiro (2001)	Typic Argiudoll	Silt loam	950	Soybean–soybean	18	Postharvest	2–12	1	1	1
Iglesias et al. (1998)	Typic Haplustoll		780	Oat + hairy vetch–oat + hairy vetch	3		0–25			2
Küger (1996a)	Typic Haplustoll	Loam	750	Sunflower–wheat	6	Postharvest	0–25	1	1	1
Küger (1996a)	Entic Haplustoll	Loamy sand	750	Sunflower–wheat	6	Postharvest	0–25	1	1	1
Nuñez Vazquez et al. (1996)	Entic Haplustoll	Silt loam	760	Sorghum–soybean	10		0–35		1	
Torella et al. (2002)	Typic Argiudoll	Silt loam	1030	Soybean–wheat	0.5	Growing cycle	0–17.5	1		
	Typic Argiudoll	Silt loam	1030	Soybean–wheat	1	Harvest	0–17.5	1		
Tuda et al. (2006)	Entic Haplustoll	Silt loam	760	Corn–soybean	4–10	Postharvest	0–30	2	2	2
Mehanical resistance										
Barrios et al. (2008)	Vertic Argiudoll		1030	Wheat–soybean	0.5	Seedling	0–20	1	1	1
Barrios et al. (2008)	Vertic Argiudoll		1030	Wheat–soybean	1	Harvest	0–20	1	1	1
Bergh (1998)	Petrocalcic Argiudoll	Clay loam	820	Sunflower–wheat	7	Seedling	0–20	1	1	1
Colombani et al. (2002)	Typic Argiudoll-Petrocalcic Paleudoll		900	Corn–soybean–wheat	8	Fallow	0–20	1		
D'Hiriart et al. (1996)	Typic Ustipsament	Loamy sand	555		9		0–20	1		
Díaz-Zorita (1999)	Typic Hapludoll	Sandy clay loam	820	Corn–soybean	6	Seedling	0–20	1	1	1
Díaz-Zorita et al. (2004)	Typic Hapludoll	Sandy clay loam	820	Corn–soybean	12	Harvest	0–20	1	1	1
Domínguez et al. (2000)	Typic Argiudoll-Petrocalcic Paleudoll		900	Wheat–corn	3.5	Seedling	0–20	1		
	Typic Argiudoll-Petrocalcic Paleudoll		900	Wheat–corn	4	Harvest	0–20	1		
Elissondo et al. (2001)			923	Corn–wheat	0.6–2.1	Seedling	0–20			1
			924	Corn–wheat	0.6–2.1	Growing cycle	0–20			1
			925	Corn–wheat	0.6–2.1	Harvest	0–20			1
			926	Corn–wheat	0.6–2.1	Fallow	0–20			1
Fabrizzi et al. (2005)	Typic Argiudoll-Petrocalcic Paleudoll		923	Corn–wheat	2	Postharvest	0–20			1
Ferreras et al. (2000)	Petrocalcic Paleudoll	Loam	900	Wheat–soybean	2.5	Growing cycle	0–20	1		

Table 1 (*Continued*)

Reference	Soil type	Texture	Rainfall[a] (mm)	Crop rotation	Years	Sampling time	Soil depth (cm)	Pairs of comparisons		
								PT vs. NT	PT vs. RT	RT vs. NT
	Petrocalcic Paleudoll	Loam	900	Wheat–soybean	3	Harvest	0–20	1		
Fontanetto and Vivas (1998)	Typic Argiudoll	Silty clay loam	1030	Wheat–soybean–corn	9		0–20	1	1	1
	Typic Argiudoll	Silty clay loam	1030	Wheat–soybean	9		0–20	1	1	1
Iglesias et al. (1998)	Typic Haplustoll		780	Oat–oat	3	Growing cycle	0–20	1		
Krüger (1996)	Entic Haplustoll	Silt loam	750	Sunflower–wheat	3	Postharvest	0–20	1	1	1
Quiroga et al. (1996a,b)	Entic Haplustoll	Sandy loam	758	Wheat–wheat and wheat–sorghum	5–10		0–20	2		
Vidal and Costa (1998)			820		3	Growing cycle	0–20			1
Change in mean weight diameter										
Chagas et al. (1995)	Typic Argiudoll	Silt loam	950	Corn–corn	15	Growing cycle	0–15	1		
	Typic Argiudoll	Silt loam	950	Soybean–soybean	17	Growing cycle	0–15	1	1	1
Colombani et al. (2002)	Typic Argiudoll-Petrocalcic Paleudoll		900	Corn–soybean–wheat	8		0–20	1		
Cosentino et al. (1996)	Typic Argiudoll	Silt loam	950	Corn–corn	6		0–15	1	1	1
Díaz Zorita et al. (1999)	Typic Hapludoll	Silt loam	820	Corn–soybean	6	Postharvest	0–15	1	1	1
Ferreras et al. (2000)	Petrocalcic Paleudoll	Loam	900	Wheat–soybean	2.5		Surface soil	1		
Gudelj and Masiero, 2001	Typic Argiudoll	Silt loam	950	Soybean–soybean	18	Fallow period	0–15	1	1	1
	Typic Argiudoll	Silt loam	950	Corn–corn	18	Fallow period	0–15	1	1	1
	Typic Argiudoll	Silt loam	950	Soybean–corn	8	Fallow period	0–15	1	1	1
	Typic Argiudoll	Silt loam	950	Soybean–corn	8	Fallow period	0–10	1	1	1
Krüger (1996b)	Entic Haplustoll	Loamy sand	750	Sunflower–wheat	5		0–12	1	1	1
Nuñez Vasquez (1996)	Entic Haplustoll	Silt loam	760	Sorghum–soybean	6		0–5		2	
Quiroga et al. (1996a,b)	Entic Haplustoll	Sandy loam	758	Wheat–sorghum	10		0–10			1
Torella et al. (2002)	Typic Argiudoll	Silt loam	1030	Soybean–wheat	0.5	Growing cycle	0–10	1		
Torella et al. (2002)	Typic Argiudoll	Silt loam	1030	Soybean–wheat	1	Harvest	0–10	1		
Infiltration										
Berón and Blotta (1993a)	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	12	Seedling	Soil surface	1		
	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	12	Growing cycle	Soil surface	3		
Berón and Blotta (1993b)	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	13	Seedling	Soil surface	1		
	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	13	Growing cycle	Soil surface	2		
	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	13	Postharvest	Soil surface	1		
Blotta et al. (1992a)	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	6		Soil surface	6	6	6
Fontanetto and Vivas (1998)	Typic Argiudoll	Silty clay loam	1030	Wheat–soybean–corn–wheat–soybean	9		Soil surface	3	3	3
Marelli et al. (1987)	Typic Argiudoll	Silt loam	950	Wheat–soybean	1–2	Growing cycle	Soil surface	4		
	Typic Argiudoll	Silt loam	950	Wheat–soybean	1–2	Harvest	Soil surface	2		
Nuñez Vazquez et al. (1996)	Entic Haplustoll	Silt loam	760	Sorghum–soybean	10		Soil surface		10	
Sasal et al. (2006)	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn	20		Soil surface	1		
	Typic Argiudoll	Silty clay loam	980	Wheat–soybean–corn–spybean	8–13		Soil surface	2		

[a] Average from the 1970–2000 period.

Table 2

Main characteristic from experiments where soil water and nitrate nitrogen contents were determined. PT = plow tillage, RT = chisel or disk tillage and NT = no tillage.

Reference	Soil type	Rainfall[a] (mm)	Crop	Years	Sampling depth (mm)	Pairs of comparisons		
						PT vs. NT	PT vs. RT	RT vs. NT
Soil water content[b]								
Alvarez (2005)	Typic Argiudoll	980	Wheat	1–17	0–30	2	5	2
	Typic Argiudoll	980	Soybean	1–17	0–30	1	5	2
Alvarez et al. (2001a)	Typic Hapludoll	970	Soybean	1	0–30	1		
Alvarez et al. (2008)	Typic Argiudoll	1000	Wheat	2	0–30	1		
Aparicio et al. (2002)	Typic Argiudoll	900	Corn	1	0–100	2	2	2
Berón and Blotta (1993a)	Typic Argiudoll	980	Soybean	13	0–16	2		
Beron and Blotta (1995)	Typic Argiudoll	980	Wheat	13	0–16	2		
Bono et al. (2008)	Entic Haplustoll	760	Oat	3	0–20			6
	Entic Haplustoll	760	Corn	4	0–20			4
	Entic Haplustoll	760	Wheat	5	0–20			4
	Entic Haplustoll	760	Oat	3	0–100			6
	Entic Haplustoll	760	Corn	4	0–100			4
	Entic Haplustoll	760	Wheat	5	0–100			4
Bujan et al. (2006)	Hapludoll	1030	Wheat	1	0–100	1	1	1
Chagas et al. (1994)	Typic Argiudoll	950	Corn	15	0–50	2	2	2
Dardanelli (1998)		760	Soybean		0–30	2		
		760	Soybean		0–150	2		
Ferreras et al. (2000)	Petrocalcic Paleudoll	900	Wheat	2	0–20	4		
	Petrocalcic Paleudoll	900	Wheat	2	0–60	4		
Forjan et al. (2004)		820	Wheat		0–60	6		
Krüger (1996b)		750	Sunflower	5	0–10	1	1	1
		750	Sunflower	5	0–80	1	1	1
Leiva and Hansen (1984)	Typic Argiudoll	980	Corn	4	0–50	1	1	1
Marelli and Arce (2001)	Typic Argiudoll	950	Wheat		0–200	2		
	Typic Argiudoll	950	Soybean		0–200	2		
Marelli et al. (2005)	Typic Argiudoll	950	Corn	16	0–20	1	1	1
Melaj et al. (2003)	Typic Argiudoll-Petrocalcic Paleudoll	900	Wheat	1	0–40	1		
	Typic Argiudoll-Petrocalcic Paleudoll	900	Wheat	2	0–40	1		
Nuñez Vazquez et al. (1996)	Entic Haplustoll	760	Sorghum		0–200		1	
	Entic Haplustoll	760	Soybean		0–200		1	
Quiroga et al. (1996b)	Entic Haplustoll	760	Wheat	1–9	0–30			9
Quiroga et al. (1998a)	Entic Haplustoll	760	Sunflower	1–5	0–20			8
	Entic Haplustoll	760	Wheat	2–6	0–20			8
	Entic Haplustoll	760	Oat	3	0–20			4
	Entic Haplustoll	761	Corn	4	0–20			4
Quiroga et al. (1998b, 2004a,b)	Entic Haplustoll	760	Sunflower	1–5	0–140			8
	Entic Haplustoll	760	Wheat	2–6	0–140			8
	Entic Haplustoll	760	Oat	3	0–140			4
	Entic Haplustoll	760	Corn	4	0–140			4
Santanatoglia et al. (1989)	Typic Argiudoll	980	Soybean	1	0–16	1		
Studdert et al. (1999)		900	Corn		0–20	2		
		900	Corn		0–100	2		

Table 2 (*Continued*)

Reference	Soil type	Rainfall[a] (mm)	Crop	Years	Sampling depth (mm)	Pairs of comparisons		
						PT vs. NT	PT vs. RT	RT vs. NT
Totis et al. (1984)	Typic Argiudoll	980	Corn	1–4	0–150	8		
	Typic Argiudoll	980	Wheat	1	0–20	1		
	Typic Argiudoll	980	Wheat	1–4	0–150	4		
	Typic Argiudoll	980	Soybean	1–4	0–150	8		
Nitrate-N content[c]								
Abascal et al. (2003)		740	Sunflower	1–2	0–60			2
Bergh (1998)	Petrocalcic Argiudoll	820	Wheat	6	0–60	1	1	1
Bergh et al. (1996)	Typic Argiudoll	900	Wheat	2	0–60	2		
Bono et al. (2008)	Entic Haplustoll	760	Oat + vetch	3	0–60		1	
	Entic Haplustoll	760	Corn	4	0–60		1	
	Entic Haplustoll	760	Wheat	5	0–60		1	
	Entic Haplustoll	760	Oat	6	0–60		1	
Cordone and Hansen (1986)	Typic Argiudoll	980	Corn	1	0–60			3
Forájn et al. (2004)		820	Wheat		0–60	6		
Forján et al. (2001)		820	Corn		0–60	2		
Hansen et al. (1984)	Typic Argiudoll	980	Corn	1–4	0–60	4		
Kleine and Puricelli (2001)	Typic Argiudoll	670	Corn	1–11	0–60	3		
	Typic Argiudoll	670	Wheat	2–12	0–60	4		
	Typic Argiudoll	670	Sunflower	3–7	0–60	3		
	Typic Argiudoll	670	Barley	8–10	0–60	2		
Krüger (1996a)		750	Sunflower		0–60	4	4	4
Melaj et al. (2003)	Argiudol Típico-Paleudol Petrocálcico	900	Wheat	1–2	0–60	2		
Nuñez Vazquez et al. (1996)	Entic Haplustoll	760	Soybean	1	0–60		1	
	Entic Haplustoll	760	Sorghum	2	0–60		1	
Quiroga et al. (1996b)	Entic Haplustoll	760	Wheat	1–10	0–60			10
Santamaría et al. (2004)	Petrocalcic Paleudoll-Typic Argiudoll	900	Wheat	5	0–100	2		
Santanatoglia et al. (1989)	Argiudol Típico	980	Soybean	1	0–60	1		

[a] Average from the 1970–2000 period.

[b] Surface sampling depths correspond to sowing, menawhile deeper sampling were performed at flowering stage.

[c] Samplings performed at sowing.

Table 3
Main characteristic from experiments where crops yield was determined. PT = plow tillage, RT = chisel or disk tillage and NT = no tillage.

Reference	Soil type	Texture	Rainfall[a] (mm)	Years	Fertilizer N (kg ha^{-1})	Pairs of comparisons		
						PT vs NT	PT vs. RT	RT vs. NT
Soybean								
Alvarez and Barraco (2005)			820	1–10	0	10	10	10
Alvarez et al. (1995)	Typic Argiudoll	Silty clay loam	980	2	0		1	
Barrios et al. (2000)			1030	1	0	1		
Barrios et al. (2004)			1030	4	0	1	1	1
Bendini and Sasal (1992)	Vertic Argiudoll	Clay loam	1060	1	0			1
Blotta et al. (1992b)	Typic Argiudoll	Silty clay loam	980	1–12	0	12	12	12
Galarza et al. (2000)			950		0			1
Grazia et al. (2008)	Vertic Argiudoll		1030	1	0	1	1	1
Hansen and Zeljkovich (1984)	Typic Argiudoll	Silty clay loam	980	4	0	1	1	1
Lattanzi (1993)	Typic Argiudoll	Silt loam	950	1–9	0	9	9	9
Lavado et al. (2001)	Typic Argiudoll	Silty clay loam	980	18	0	1		
Marelli (1995)	Typic Argiudoll	Silt loam	950	1–20	0	20	20	20
Nuñez Vazquez et al. (1996)	Entic Haplustoll	Silt loam	760	1–10	0		10	
Perez et al. (2002)	Typic Hapludoll		820	4	0	1		
	Hapludoll		820	4	0	1		
Pontoni et al. (1992)			980	1	0	1		
Santos et al. (2002)	Petrocalcic Paleudoll-Typic Argiudoll		900	1	0–180	8		
Sasal and Bendini (1992)	Vertic Argiudoll	Silty clay loam	1060	1	0	1	1	1
Vivas et al. (1989)			1030		0	9		
Vivas and Sosa (1998)	Vetic Argiudoll	Silt loam	1030	1–4	0	4	4	4
Zeljkovich and Zeljkovich (1991)	Typic Argiudoll	Loam	1010	1–6	0	10	10	9
Zingaretti et al. (2004)	Entic Haplustoll		740	3	0			2
Wheat								
Alvarez et al. (1995)	Typic Argiudoll	Silty clay loam	980	2	0		1	
Bergh et al. (1996)	Typic Argiudoll	Loam	900	2	0–120		3	
Blotta et al. (1993)	Typic Argiudoll	Loam	980	9–13	0–100	4	4	4
Blotta, personal cummunication	Typic Argiudoll	Silty clay loam	980	1–12	0–100	24	24	24
Bono et al. (2008)	Entic Haplustoll	Sandy loam	760	5	45			1
Bujan et al. (2006)	Hapludoll	Loam	1030	1	0	1	1	1
Cordone et al. (1994)	Typic Argiudoll	Silty clay loam	980	3	0			1
Cordone and Rivoltella (1992)	Typic Argiudoll	Silty clay loam	980	2	0			2
Dodds et al. (1990)	Typic Argiudoll		980	1	0	1		
Forjan et al. (2004)			820		0	2		
Galarza et al. (2000)			950	7	0–70			2
Keller and Fontanetto (1998)			1030	1	0–75			16
Melaj et al. (2003)	Typic Argiudoll	Loam	900	1–2	0–120	6		
Quiroga et al. (1994)		Loam	760	1	37–46			2
Quiroga et al. (1996a,b)	Entic Haplustoll	Sandy loam	760	1–9	0			9
Santamaría et al. (2004)	Petrocalcil Paleudoll-Typic Argiudoll	Loam	900	5	0–180	8		
Sola et al. (1994)			950	1–2	0–90			16
Studdert et al. (1994)	Typic Argiudoll		900	2	0–120		18	
Venanzi et al. (2008)	Entic Haplustoll	Sandy loam	750	2–9	0–60			15
Zeljkovich and Zeljkovich (1991)	Typic Hapludoll	Loam	1010	1–6	0–80	24	22	22
Corn								
Alvarez and Barraco (2005)	Entic Haplustoll		820	1–10	0	10	10	10
Barbagelata and Melchiori (2001)	Argilic Cromudert		1130	1	0–120		2	
	Aquic Argiudoll		1130	1	0–120		2	
Blotta, personal communication	Typic Argiudoll	Silty clay loam	980	1–12	0–100	24	24	24
Blotta et al. (1992c)	Typic Argiudoll	Silty clay loam	980		0–100	4	4	4
Bono et al. (2008)	Entic Haplustoll	Sandy loam	760	4	50			1
Chidichimo et al. (1988)	Aquic Argiudoll	Silt loam	1040	2–3	0		16	
Cordone and Hansen (1986)	Typic Argiudoll	Silt loam	980	1	0–120			15
Cruciani et al. (2001)			990	1–2	0–120			6
Domínguez et al. (2000)	Petrocalcic Paleudoll-Typic Argiudoll	Loam	900	4	0–180	8		
Fontanetto and Keller (2005)	Typic Argiudoll		1030	1	0			1
Forjan et al. (2001)	Typic Argiudoll		820	2	80	2		
Galarza et al. (2000)			950	7	0–70			2
Gudelf et al. (1998)			950	8–9	0–160			10
Hansen et al. (1984)	Typic Argiudoll	Silty clay loam	980	1–4	0–80	8	8	8
Lavado et al. (2001)	Typic Argiudoll	Silty clay loam	980	18	90	1		
D'Hiriart et al. (1996)	Typic Ustipsamment	Loamy Sand	560	1–9	0	6	6	6
Marelli et al. (2005)	Typic Argiudoll	Silt loam	900	16	0	1	1	1
	Typic Argiudoll	Silt loam	900	16	74	1	1	1
Moreno (1998)	Typic Argiudoll	Silt loam	900	1	0			3
Perez et al. (2002)	Typic Hapludoll		820	4	0			5
Steinbach et al. (2004)	Typic Argiudoll	Silty clay loam	1000	3	0–325	6		

Table 3 (*Continued*)

Reference	Soil type	Texture	Rainfall[a] (mm)	Years	Fertilizer N (kg ha^{-1})	Pairs of comparisons		
						PT vs NT	PT vs. RT	RT vs. NT
Zeljkovich and Zeljkovich (1991)	Typic Hapludoll	Loam	1010	1–8	0–80	16	16	16

[a] Average from the 1970–2000 period.

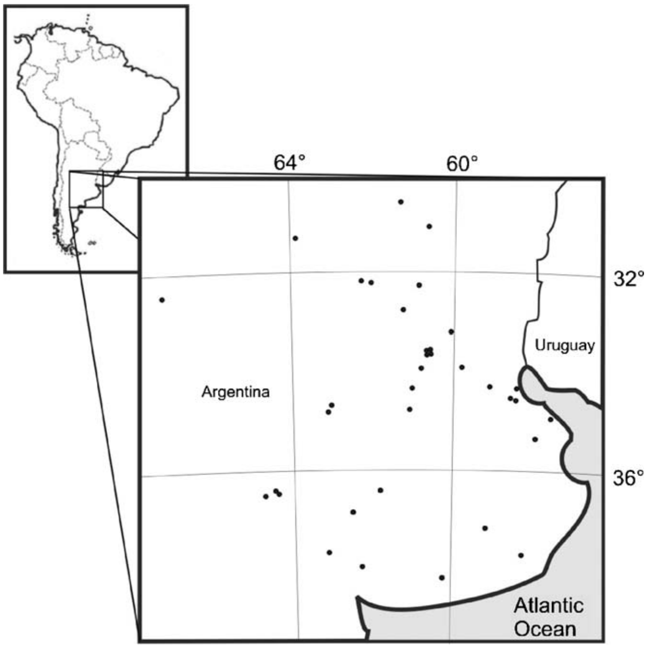

Fig. 1. Map of the Pampean Region with points indicating experiments locations.

stage, water content was integrated for the whole soil profile, usually up to 100–200 cm depth. This was done taken into account that during the initial stages of plant development water availability in surface soil is determinant of a successfully crop installation and that during the flowering stage roots can absorb water from surface and deep soil layers. Nitrate nitrogen content of soils before crop sowing was determined by colorimetric or steam distillation methods (Bremmer, 1965). In many reports, data to 60 cm depth were available, but in some of them only to 20 cm. Estimation up to 60 cm depth was performed in these later cases using equations locally developed (Alvarez et al., 2001b). Yield of crops were determined at maturity by hand or mechanical harvesting expressing results on a dry mass basis. Rainfall data were obtained from unpublished records from the Servicio Meteorológico Nacional and the Instituto Nacional de Tecnología Agropecuaria available upon request.

The analysis of data was performed by paired *t*-tests between pairs of results from the same experiment contrasting tillage systems at $P = 0.05$. All possible combinations of treatments were tested: plow tillage vs. limited tillage, plow tillage vs. reduced tillage, plow tillage vs. no-till and reduced tillage vs. no-till. A graphical analysis was also used plotting results from limited tillage systems against plow tillage, or differences between limited tillage and plow tillage were calculated and plotted against plow tillage values.

3. Results

Soil bulk density was significantly higher under no-till than in plow tillage, but no changes were detected between plow and reduced tillage (Fig. 2A). Bulk density increases in no-till were reported only for soils where bulk density was lower that 1.3 g ml^{-1} (Fig. 2B). Above this threshold, no-till had no impact on soil density. Increases of bulk density may be as high as 0.15 g ml^{-1} but averaged 0.05 g ml^{-1} for the whole data set and were not related to time since initiation of the experiment, soil type or rotation. In average bulk density increases under no-till represent a densification of only 4% related to plow tillage density mean. Significant differences were also detected when contrasting reduced tillage and no-till with greater densities under the later management system.

Limited tillage systems produced an increase of cone penetration resistance that was significant both under reduced tillage and no-till when compared to plow tillage (Fig. 3A and B). Many experiments reported great cone resistance raises that reached 0.8–0.9 MPa. In about one third of the experiments cone penetration resistance was 50% higher under limited tillage than in plowed soil. Despite these soil increases of cone penetration resistance a threshold of 2.5 MPa was not surpassed. Effects of experiment duration, soil type, texture or rotation were not observed. Soil resistance was significantly higher under no-till than under reduced tillage. This later systems presented generally intermediate values between plow tillage and no-till.

The instability of soil structure, evaluated through the CMWD, was significantly greater under plow tillage than when soil was subjected to limited tillage systems (Fig. 4A). Both reduced tillage and no-till increased soil stability with greater differences between systems in poorer structured soils (Fig. 4B). Averaging results from all experiments, structural instability was 70% higher in plowed soil. No detectable effects of time since tillage systems application, soil type, texture or rotation could be identified. Again, for this soil

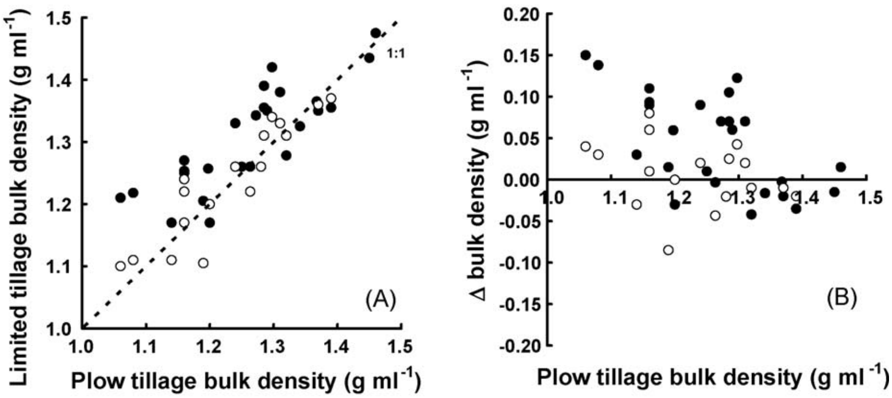

Fig. 2. (A) Relationship between soil bulk density of the upper soil layer under limited tillage systems and plow tillage system. (B) Change in soil bulk density (limited tillage—plow tillage) in relation to plow tillage bulk density: full circles: no tillage; empty circles: chisel or disk tillage.

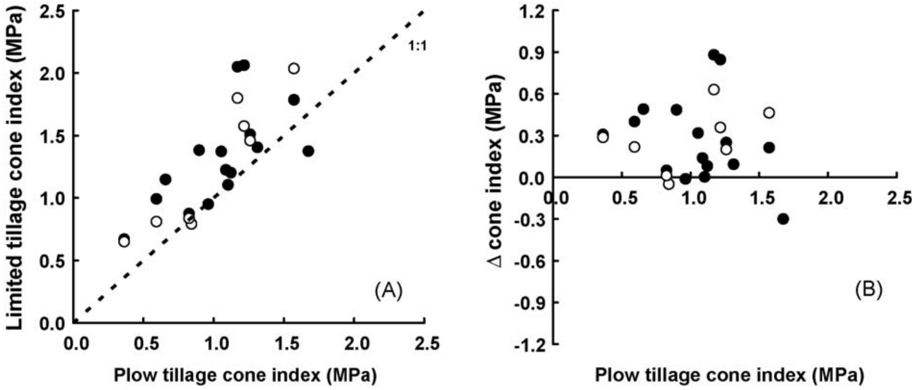

Fig. 3. (A) Relationship between cone resistance of the 0–20 cm soil layer under limited tillage systems and plow tillage system. (B) Change in soil cone resistance (limited tillage—plow tillage) in relation to plow tillage cone resistance: full circles: no tillage; empty circles: chisel or disk tillage.

property, reduces tillage had intermediate values between plow tillage and no-till.

Infiltration rate was significantly higher under reduced tillage and no-till than in plow tillage (Fig. 5A). When only infiltration under no-till and plow tillage were compared, differences between tillage systems tended to increased in soils of high infiltration rate (Fig. 5B). Variability of experiment duration, soil type and rotation was small in this data set, with nearly all results obtained from long duration experiments, installed on Typic Argiudolls under very similar crop sequences. Under no-till, infiltration was also significantly greater than under reduced tillage.

No significant differences were detected between plow tillage and reduced tillage in soil water content, meanwhile no-till had greater water content that these both tillage systems (Fig. 6A). The differences were detected at sowing and also during the flowering stage. In average, no-till water content was 16 mm higher than in treatments with tillage (Fig. 6B). In fine textured soils, located in areas with humid climate, soil water content was 9 mm greater under no-till than under plow tillage and reduced tillage as a mean of the whole data set, but this difference increased to 18 mm in coarse texture soils from semiarid scenarios. No-till had in average 13–14% more water than plowed soil both at seeding and flowering stages. When soils were wet, differences between tillage systems

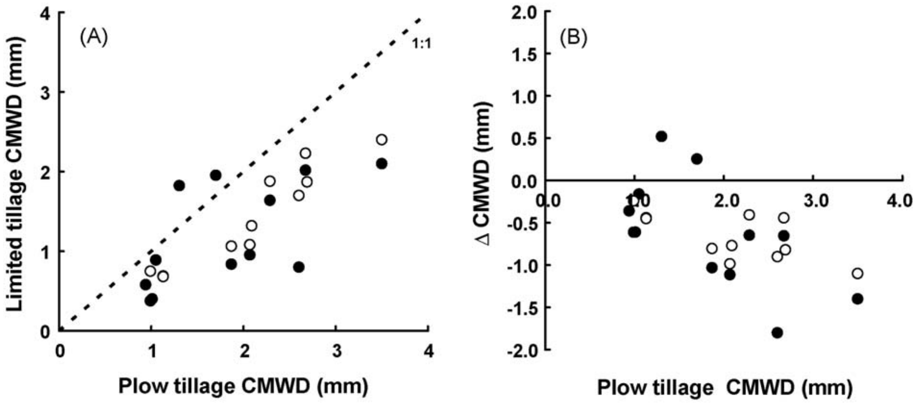

Fig. 4. (A) Relationship between change in aggregate mean weight diameter (CMWD) of the surface soil layer under limited tillage systems and plow tillage system. (B) Change in soil CMWD (limited tillage—plow tillage) in relation to plow tillage CMWD: full circles: no tillage; empty circles: chisel or disk tillage.

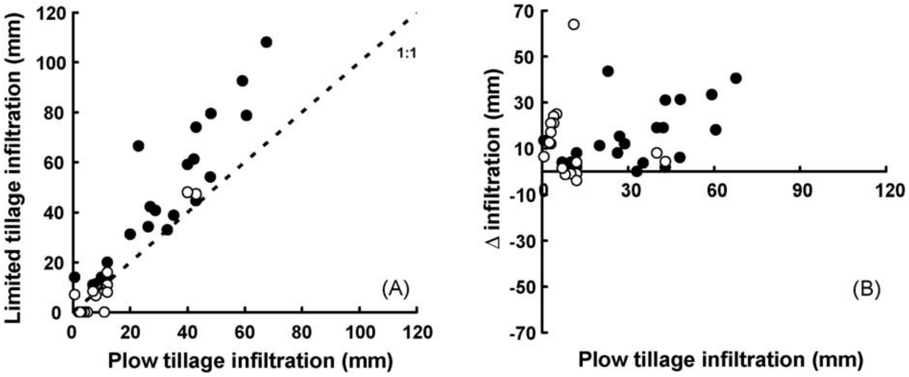

Fig. 5. (A) Relationship between soil infiltration under limited tillage systems and plow tillage system. (B) Change in soil infiltration (limited tillage—plow tillage) in relation to plow tillage infiltration: full circles: no tillage; empty circles: chisel or disk tillage.

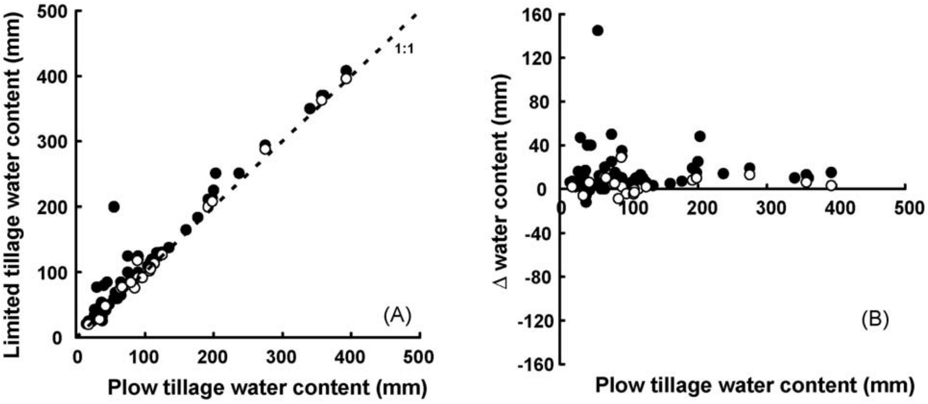

Fig. 6. (A) Relationship between soil water content under limited tillage systems and plow tillage system. (B) Change in soil water content (limited tillage—plow tillage) in relation to plow tillage water content: full circles: no tillage; empty circles: chisel or disk tillage.

were small but increased in drier soils showing that no-till effects on soil water content were more pronounced under water limiting scenarios.

The level of nitrate nitrogen in soils was significantly higher in plow tillage than in reduced tillage and no-till (Fig. 7A), averaging these differences 11 kg N ha^{-1} when contrasted with reduced tillage and 21 kg N ha^{-1} against no-till. Reduced tillage had intermediate values between the other two tillage systems, being significantly different from no-till. Generally, more nitrate nitrogen was present at sowing under plow management in all the crops sampled and in the different types of soils studied. When nitrate nitrogen level of soil was low, differences between tillage systems were also low and increased as nitrate nitrogen level rose, reaching to differences as high as 60–80 kg N ha^{-1} (Fig. 7B).

Yield data of all crops were generated in experiments performed in around 95% of the cases on fine textured soils from the humid portion of the Pampas. Rainfall during the fallow and crop growing season summed ranged from 400 to 1200 mm with averages of 730 mm for soybean, 620 mm for wheat and 680 mm for corn. Soybean yield was not significantly different between plow tillage and no-till and also between this tillage system and reduced tillage (Fig. 8A and B). Conversely, yield of wheat and corn was significantly greater under plow tillage than under limited tillage systems by 13 and 6%, respectively, as average of all data (Figs. 9A and B and 10A and B). If the data sets were partitioned into

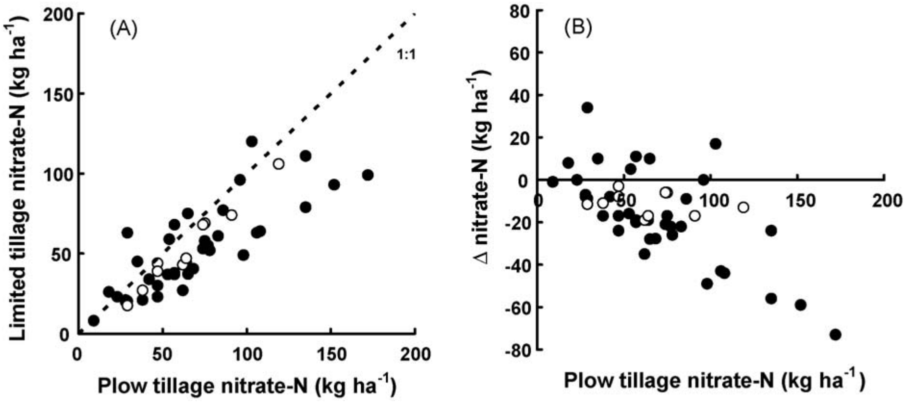

Fig. 7. (A) Relationship between soil nitrate nitrogen content before crop sowing under limited tillage systems and plow tillage system. (B) Change in soil nitrate nitrogen content (limited tillage—plow tillage) in relation to plow tillage nitrate nitrogen content: full circles: no tillage; empty circles: chisel or disk tillage.

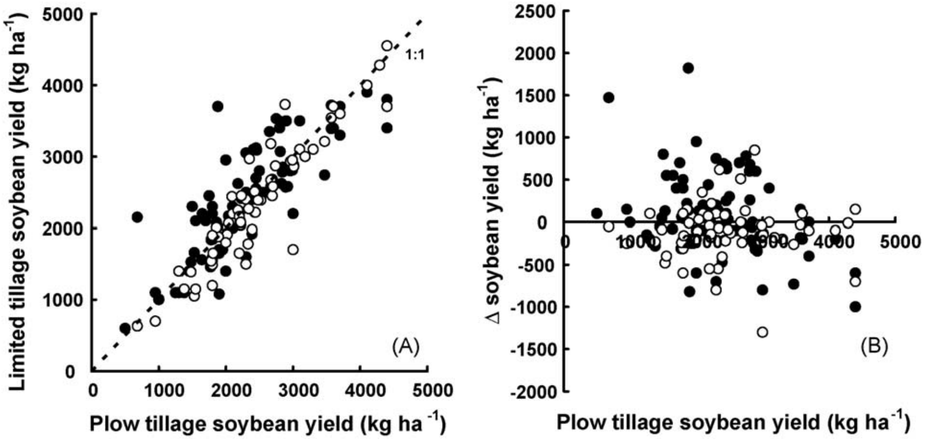

Fig. 8. (A) Relationship between soybean yield under limited tillage systems and plow tillage system. (B) Change in soybean yield (limited tillage—plow tillage) in relation to plow tillage soybean yield: full circles: no tillage; empty circles: chisel or disk tillage.

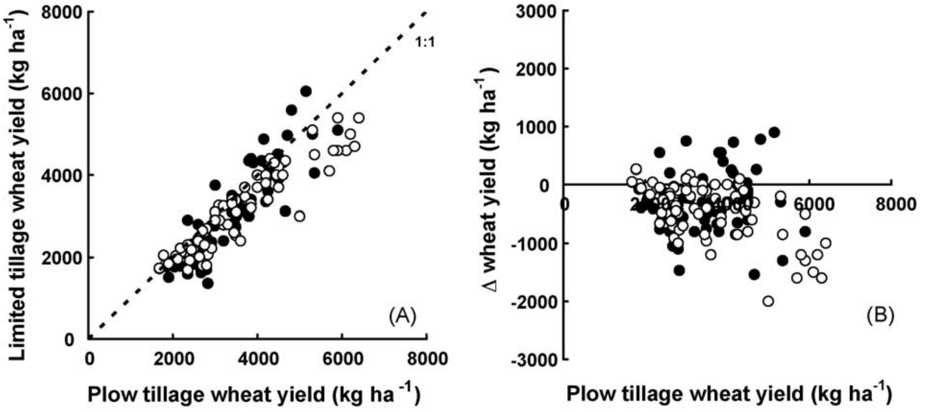

Fig. 9. (A) Relationship between wheat yield under limited tillage systems and plow tillage system. (B) Change in wheat yield (limited tillage—plow tillage) in relation to plow tillage wheat yield: full circles: no tillage; empty circles: chisel or disk tillage.

nitrogen fertilized and unfertilized managements, yields were generally similar between tillage treatments when graminaceus crops received nitrogen, with the only exception that wheat yield cropped under plow tillage was significantly higher (13%) than under reduced tillage. In unfertilized situations wheat and corn yields were in average 9–12% significantly lower under limited tillage systems than when soil was plowed, with no differences between reduced tillage and no-till. Consequently, crops productivity was generally unaffected by tillage management when nitrogen was not a limiting resource under humid climate scenarios.

4. Discussion

Contradictory results had been obtained when tillage systems effects on soil bulk density had been reviewed. Some studies found that bulk density increased under no-till in relation to plow tillage (Tebrügge and Düring, 1999) or reduced tillage (Mc Vay et al.,

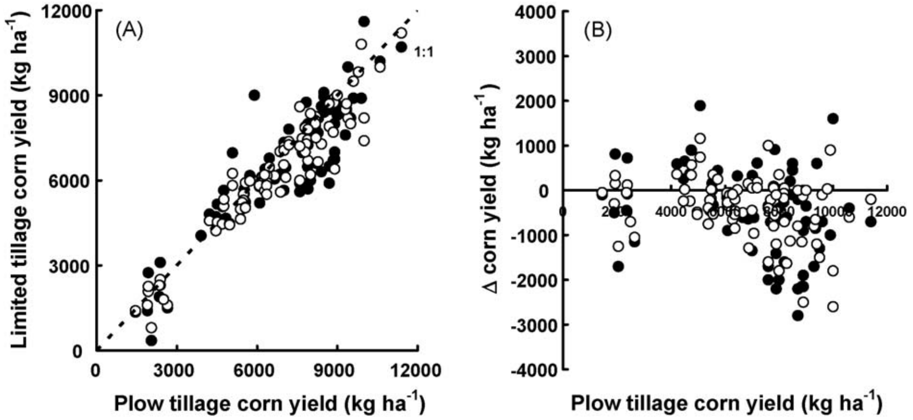

Fig. 10. (A) Relationship between corn yield under limited tillage systems and plow tillage system. (B) Change in corn yield (limited tillage—plow tillage) in relation to plow tillage corn yield: full circles: no tillage; empty circles: chisel or disk tillage.

2006), and also that different limited tillage managements may induced soil densification of the upper soil layers when compared to intense tillage methods (Rasmussen, 1999). Conversely, in other reviews, inconsistent effects of tillage systems were observed on soil bulk density and total porosity (Strudley et al., 2008). More consistent are results from reports of cone penetration changes induced by tillage managements, with a generalized increase of the surface soil layer cone index under no-till in relation to plowed (Tebrügge and Düring, 1999; López-Fando et al., 2007; Franzluebbers and Stuedemann, 2008) or reduced managements (Vetsch and Randall, 2002; Siri-Prieto et al., 2007; Vetsch et al., 2007). We observed increases of soil bulk density and cone index under no-till in the majority of the studies generated in the Pampas when it was contrasted with plowed soil. Densification under no-till occurred mainly in soils of bulk density lower than 1.3 g ml^{-1} and thereof soils seemed to be insensible to compaction by no-till. Lower bulk density values were reported generally for fine textured soils in which no-till produced some compaction, with small or null effects of tillage system in coarser soils, but more data are needed to confirm this result. Conversely, no-till effects on cone index were similar in fine and coarse textured soils. The changes produced by no-till adoption on soil bulk density and cone index probably did not restrict severely roots growth. Crops roots growth can be depressed when soil bulk density reaches 1.5 g ml^{-1} (Hassan et al., 2007) and cone resistant overpasses a threshold of 2.5–3.0 MPa (Hakansson and Lipiec, 2000; Hamza and Anderson, 2005). These limits were generally not exceeded in pampean soils.

Soil tillage usually induces a reduction in aggregates size (Mc Vay et al., 2006) and stability to wind erosion (Singh and Malhi, 2006) or water effects (Franzluebbers and Stuedemann, 2008) in relation to no-till management. Differences in aggregate stability are very deep when no-till is compared with soil tilled by the mouldboard plow (Hernanz et al., 2002; Martínez et al., 2008), and intermediate when it is compared to reduced tillage systems, like chisel tillage (Alvaro-Fuentes et al., 2008). We found in the Pampas similar results to those yet described in the literature, but with a tendency to a greater improvement of soil stability in poorer structured soils under limited management. In experiments in which soil structural stability was higher (low CMWD under plow tillage) little or no soil improvement was observed under no-till or reduced tillage. Aggregation improvements under limited tillage are associated to macropore connectivity, which affects near-zero infiltration rates and hydraulic conductivity (Strudley et al., 2008). In some cases, increases of infiltration rates had been observed under no-till (Nielsen et al., 2005), but in others water infiltration may be greater when soils are tilled (Rasmussen, 1999). These conflicting results can be attributed in some cases to temporal variability of the soil infiltration rate, which is very high immediately following tillage application, but diminish rapidly some weeks later, being greater under no-till than in tilled soil, some times even after the first wetting-drying cycle (Strudley et al., 2008). Aggregates stability and infiltration rate in our pampean set of data were generally greater under limited tillage systems than under plow tillage independently of the time elapsed since tillage application. Textural variability in the data set from experiments were CMWD and infiltration were assessed was small, with a predominance of medium textured soils for the former and fine textures soils for the later, so generalization of results to other types of soil is difficult.

The enhance of soil infiltration under no-till, joined to a lower evapotranspiration rate of soils covered by straw under this management, conducts many times to greater soil water contents (Martens, 2000; Nielsen et al., 2005) and also to higher water use efficiencies (Hatfield et al., 2001), than under managements with tillage application. In the Pampas, during the critical flowering period, water content was usually higher under no-till than in plowed soil, with differences in average of 7 mm in soybean, 11 mm in wheat and 19 mm in corn. These water layers can cover an evapotranspiration demand ranging from 1 to 3 days of these crops during the flowering stage (Doorenbos and Pruitt, 1977; Totis and Perez, 1994), representing a beneficial effect of no-till, especially in drier areas with higher atmospheric demands and lower capacity of coarse soils to retain available water. Conversely, lower nitrogen mineralization intensity and nitrate nitrogen is generally available for crops when they are managed without tillage (Silgram and Shepherd, 1999; Malhi et al., 2001). This determines that nitrogen fertilizer requirements increase (Martens, 2000). A higher temperature of uncovered soil (Grant et al., 1990), disruption of soil aggregates with exposition of protected organic matter to mineralization (Oorts et al., 2006) and a more rapid residues decomposition and nitrogen liberation (Lupwari et al., 2006) are the main causes to which greater nitrogen mineralization rates can be attributed to, in tilled soils. In our data set nitrate nitrogen levels were in average 22 kg ha^{-1} greater at the time of wheat and corn sowing when soil was plowed. This difference represents 10–20% of the nitrogen requirements of medium to high yielding crops. As nitrate nitrogen content of plowed soils increased, differences between no-till and tilled soil increased too, a possible consequence of an enhance of tillage induced mineralization in soils with greater potential for nitrogen generation.

Many papers had been published related to the effects of tillage systems on crops yield during the last 40 years, most of them from the North Hemisphere. Revisions of these reports shown that the adoption of no-till had small impact on yields in well drained soils under adequate nitrogen fertilization of Canada (Zentner et al., 2002) and USA (Martens, 2000; Triplett and Dick, 2008), with better results than managements that involucres tillage in arid environments (Unger and McCalla, 1980; Triplett and Dick, 2008). In experiments performed in China similar results had been observed, meanwhile increases of 5–7% of rice-wheat systems production had been reported in India (Erenstein and Laxmi, 2006). Tillage systems impacts on yield depends on the crop considered (Vetsch et al., 2007) and the interactions with rotation (Pedersen and Lauer, 2003; Ribera et al., 2004), management conditions like planting date (Sainju and Singh, 2001) or fertilizer application (Halvonson et al., 2000), site properties (Popp et al., 2002) and year (Halvonson et al., 2000; Pedersen and Lauer, 2003). Some experiments showed that yield can be higher using tillage methods in wet years but this difference may be inverted in dry years in the same site with better results under no-till (De Vita et al., 2007; Ordóñez-Fernández et al., 2007). Our data set showed that adoption of no-till and other limited tillage methods had no impact on soybean yield in humid pampean agroecosystems. Equal yields of wheat and corn can be also attained in this portion of the Pampas with different tillage managements if nitrogen fertilizer counteracts the lower nitrate nitrogen levels usually founded under limited tillage when compared to plow tillage. This humid portion of the Pampas is responsible for 70–80% of the grain production of the whole region. Yield results generated in experiments performed in the Semiarid Pampas are very scarce. Wheat yield tended to be 6% higher under no-till when fertilizer nitrogen was applied compared with managements that applied tillage, as average of the data extracted from only four experiments located in the region ($n = 13$), but this differences was not significant. Soybean and corn data are nearly unavailable for comparison. Consequently, more results must be integrated in the future to evaluate the effect of tillage systems on yields in this area. Crops yield increases obtained during the last decades in the Pampas seem not to be related to the massive no-till adoption but to the application of fertilizer technology, genetic gains and other management strategies improvements.

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