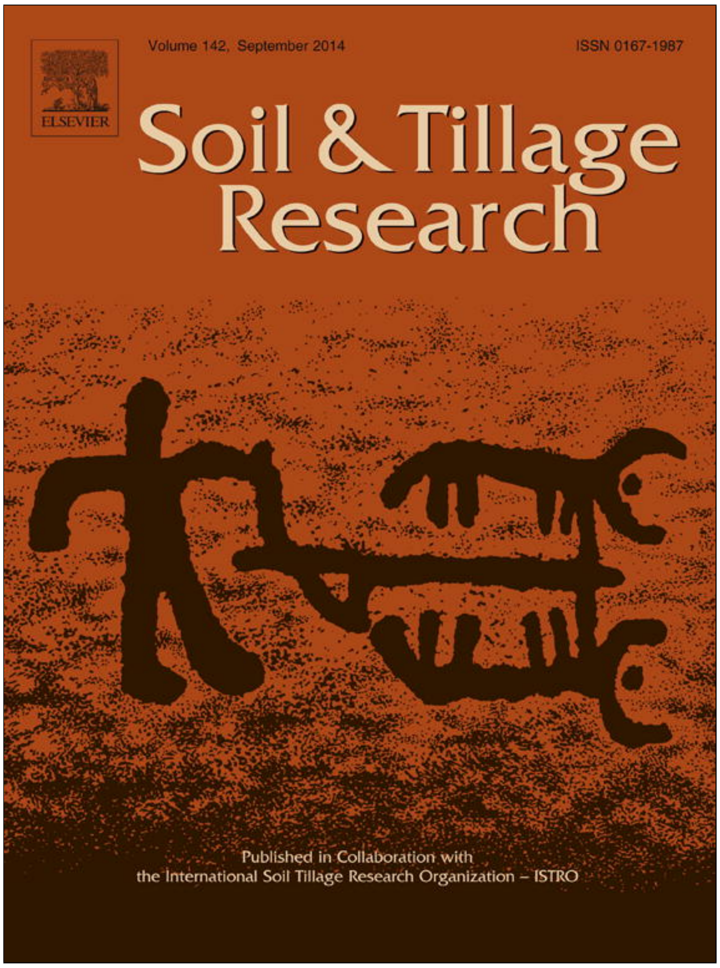
Volume 142, September 2014
ISSN 0167-1987
ELSEVIER
Soil & Tillage Research
Published in Collaboration with
the International Soil Tillage Research Organization – ISTRO

Soil & Tillage Research 142 (2014) 8–14

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Effect of conventional and no-till practices on solute transport in long term field trials

Elena Okada [a,b,*], José. L. Costa [b], Francisco Bedmar [c], Pedro Barbagelata [d,e], Alicia Irizar [f], Edgar A. Rampoldi [g,h]

[a] *Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina*
[b] *Estación Experimental Agropecuaria Balcarce – Instituto Nacional de Tecnología Agropecuaria (INTA) Balcarce, Dto. Agronomía CC 276, 7620 Balcarce, Argentina*
[c] *Facultad de Ciencias Agrarias, Universidad Nacional de Mar del Plata, Ruta 226, Km 73, Balcarce, Argentina*
[d] *Estación Experimental Agropecuaria Paraná – INTA Paraná, Ruta 11 Km. 12,5, 3101 Oro Verde, Entre Ríos, Argentina*
[e] *Facultad de Ciencias Agropecuarias, Universidad Nacional de Entre Ríos, Oro Verde, Argentina*
[f] *Estación Experimental Agropecuaria Pergamino – INTA Pergamino, Av. Frondizi (Ruta 32) Km 4,5, 2700 Pergamino, Buenos Aires, Argentina*
[g] *Estación Experimental Agropecuaria – INTA Manfredi, Ruta Nacional N 9 km 636, 5988 Manfredi, Córdoba, Argentina*
[h] *Universidad Nacional de Córdoba, Facultad de Ciencias Agropecuarias, Ciudad Universitaria, Av. Valparaíso s/n, CC 509, 5000 Córdoba, Argentina*

A R T I C L E   I N F O

Article history:
Received 19 September 2013
Received in revised form 17 March 2014
Accepted 4 April 2014

Keywords:
Tillage
Solute transport
Soil structure

A B S T R A C T

The prediction and description of water and solute movement in soils under different tillage systems is essential to the study of pesticide contamination in soils and groundwater quality. However, the impact of tillage practices in soil physical characteristics varies across locations and types of soil. In this work we analyzed the long-term impact of no till (NT) and conventional tillage (CT) on solute transport within three different Argentinian soils. Bromide transport studies were conducted under controlled conditions in the laboratory using undisturbed soil columns. Samples were taken from long term field trials, with a history of over 16 years of NT and CT practices. The studied soils were: Paraná soil (PAR), a silty clay loam soil (<37% clay), and Mandfredi (MAN) and Pergamino (PER), both silty loam soils (<26% clay). Breakthrough curves were fitted using the non-equilibrium equation model (CDEneq). The following transport parameters were estimated from the fitted curves: velocity (ν), hydrodynamic dispersion coefficient (D), dispersivity (λ), mobile water content (β), and mass transfer coefficient (ω). The relationship between the estimated parameters and soil properties was analyzed. Also, the parameters were compared between soils and tillage practices using a mixed linear model. Parameters ν and D were positively correlated to soil clay content in NT samples. Such correlation was not observed in CT samples. This would suggest that clay content in soils under conservational tillage, favors the transport of solutes, as it increases ν and D. In this study, no differences were found between soils or tillage practice regarding the estimated ν parameter. Differences were found for D and λ between CT and NT samples in PAR soil. In this case, the magnitude of solute dispersion was higher in the NT samples. For the other soils (MAN and PER), no difference in D and λ between tillage practices was found. Effects of tillage on solute transport was not substantial in these soils, even when no till management had been applied for over 30 years. Whereas in PAR (the soil with higher clay content), soil management had an important effect on structure, and therefore on solute and water transport. These results suggest that in the PAR clayey soils studied, structure is well preserved under conservational tillage, and this could lead to an increase in the risk of leaching of solutes or chemical substances.

1. Introduction

The study of soil functions and their impact on the environment is a relevant topic nowadays. Sometimes the impact can be evident at the macroscale, but it can also be determined at the microscale based on interactions between soil architecture and the transport and transformation processes occurring in the soil infrastructure, including the pore system (de Jonge et al., 2009). The prediction

* Corresponding author at: EEA INTA, Ruta 226, Km 73, Balcarce, Argentina. Tel.: +54 2266 439100x536.
E-mail address: eleokada@yahoo.com (E. Okada).

http://dx.doi.org/10.1016/j.still.2014.04.002

and description of water and solute movement in soils under different tillage systems is essential to study the problem of pesticide contamination of soils and groundwater. Nevertheless, the relationship between agricultural practices and groundwater quality has not been addressed as extensively or effectively as have other pollution processes (Cullum, 2009).

Soil tillage has a major impact on flow and solute transport as it can affect pore size distribution and porosity (Lipiec et al., 2006). The tillage system may modify soil physical properties depending on factors such as cropping history, soil type, climatic conditions and the previous tillage system (Mahboubi et al., 1993). Also, soil management may have a significant effect on structural features of soils, which in turn, can considerably affect the macropore characteristics such as type, shape, size distribution, origin, geometry and continuity of macropores (Ersahin et al., 2002). Conventional tillage generally reduces solute transport by cutting shallow functional macropores (Jarvis, 2007). Whereas, conservational tillage systems promote the formation of continuous macropores (Locke and Bryson, 1997), favoring preferential flow of water and solutes.

In the agricultural environment, preferential flow and agrochemical transport in structured soils may significantly affect the quality of water resources (Sinkevich et al., 2005). However, it is important to highlight that the impact of different tillage practices on soil hydraulic properties is not consistent across locations, soils, and experimental designs (Schwen et al., 2011). Further research is needed to better understand and to quantify the effect of different management practices on changes in soil structure and pore functioning with respect to both water and solute transport (Vogeler et al., 2006).

Miscible displacement experiments using undisturbed soil cores are used to evaluate solute movement and estimate transport parameters, such as velocity (ν) and dispersivity (λ). As a first approach to study flow phenomena in undisturbed columns, non reactive molecules are used as tracers to model water movement. Akhtar et al. (2011) has highlighted the importance of laboratory column experiments on preferential flow for a comprehensive assessment of soil functions such as its retardation capacity for various substances and groundwater protection under field conditions.

To the authorś best knowledge, there exist no studies on the comparison of effects on solute transport of different tillage systems in long-term field trials (more than 16 years of no tillage and conventional tillage). Therefore the main objectives of the present study were: (i) to compare the effects of long-term tillage in different soils on solute transport, and (ii) to find a relationship between these parameters and soil physical characteristics. Studies were performed under controlled conditions in the laboratory using undisturbed soil columns from three different soils of Argentina, under long-term no-tillage (NT) and conventional tillage (CT). Transport parameters were estimated using the non-equilibrium convection-dispersion equation (CDE).

2. Materials and methods

2.1. Site description and column sampling

The present research was conducted with soil samples from three different experimental stations with long term field trials of the Instituto Nacional de Tecnología Agropecuaria (INTA).

The Manfredi (MAN) experimental site is located in Córdoba Province (31° 56′ 55″ S 63° 46 ′ 30″ W) and was established 30 years ago. The average annual rainfall of the site is 759 mm. The soil corresponds to a coarse-silty, mixed, termic Entic Haplustoll of the Oncatrivo series (INTA, 1987). Samples were taken from treatments under NT and CT with a maize-soybean rotation.

The Parana (PAR) experimental site is located in Entre Ríos Province (31° 51′ 15″ S, 60° 32′ 10″ W) and has an average annual rainfall of 1030 mm. The soil belongs to the Tezanos Pinto series (fine, mixed, termic Acuic Argiudoll) (INTA, 1998), and is characterized as deep and moderately well drained. Soil samples were taken from a long term field trial (16 years) under NT and CT, with a wheat/soybean-maize rotation.

The Pergamino (PER) site is located in Buenos Aires Province (33° 57′ S, 60° 33′ W). The annual precipitation is 946 mm and the soil is classified as fine, termic, illitic, Typic Argiduoll (Pergamino series) (INTA, 1972). This soil is well drained, with medium permeability. The field trial was established 34 years ago under NT and CT, and it has a maize-wheat/soybean rotation.

Tillage operations corresponded to the usual practices performed in each soil. For CT MAN, moldboard plowing and disc harrowing is used as primary tillage and field cultivator as secondary. In CT PAR, conventional tillage involves chisel plowing and combined vibrocultivator. And for CT PER, moldboard plowing is used as primary tillage and disc harrowing as secondary tillage.

Four replicate undisturbed soil columns were sampled in blocks from each tillage practice, resulting in 4 columns per soil per treatment (total number of columns = 24). Core samples were obtained introducing stainless steel cylinders of 8 cm wide inner diameter and 15 cm length into the top soil. Samples were then sealed with plastic lids and stored at 4 °C until transport studies.

Disturbed soil samples were also collected from each site, for physical and chemical analysis. Particle size distribution was obtained with the sieving and pipette method (Soil Conservation Service, 1972) and organic carbon content (OC) was measured by oxidation with chromic acid (Walkley and Black, 1934).

2.2. Transport experiments

Displacement studies were carried out under isothermal (20 °C) and unsaturated steady-state flow conditions using an experimental setup similar to that described by Montoya et al. (2006) and Bedmar et al. (2008). Prior to the leaching experiment, columns were slowly pre-saturated from the bottom of the column with a 0.01 M $CaCl_2$ solution. Afterwards they were sealed with a cap containing a stainless steel plate with holes on both ends of the column, which allowed a uniform distribution of the inlet flow. Columns were irrigated with a 0.01 M $CaCl_2$ solution at a constant flow of 4.16 mm h^{-1} using a syringe pump. At the lower boundary condition, the columns were connected to a vacuum chamber keeping a constant tension of −11 KPa. Inside the chamber a fraction collector was used to collect the effluent at different time intervals. When steady state flow was reached, a pulse of KBr (equivalent to 150 kg ha^{-1}) dissolved in $CaCl_2$ (0.01 M) was applied for 15 min. The columns were then leached with a 0.01 M CaC_2 solution for several pore volumes. The collected samples of the effluent were analyzed to determine bromide concentration using an ion-selective electrode (EA940 Orion) with a lower detection limit of 0.0005 mmol L^{-1}. The relative concentrations (C/C_o) of Br^- were determined by dividing the concentration of the tracer in the effluent collected by the concentration of the tracer in the stock solution.

At the end of the leaching experiments, columns where weighed and then dried at 105 °C to estimate bulk density (ρ_b). Total porosity (ϕ) was calculated as $\phi = 1 - \rho_b/\rho_p$, assuming a particle density of $\rho_p = 2.62$ g cm^{-3}.

2.3. Model fitting

Most mechanistic models for solute transport in porous media are based on the convection-dispersion equation (CDE). The CDE is a partial differential equation representing mass continuity for movement of a given solute in a porous medium by dispersion and convection under specified initial and boundary conditions.

The mathematical form for the equilibrium model CDE (CDE_{eq}), is simple with only two parameters, D (hydrodynamic dispersion coefficient) and υ (Eq. (1)) Therefore, CDE_{eq} can be easily applied to multi-dimensional steady or transient flow, saturated–unsaturated porous media, as well as arbitrary initial and boundary conditions (Gao et al., 2009).

$$R\left(\frac{\partial C}{\partial t}\right) = D\frac{\partial^2 C}{\partial x^2} - \upsilon\frac{\partial C}{\partial x} \quad (1)$$

C is the resident concentration of the liquid phase (mol L^{-1}), D is the hydrodynamic dispersion coefficient (L^2T^{-1}), υ is average pore water velocity (LT^{-1}), x is distance (L), t is time (T) and R is the dimensionless retardation factor (Eq. (2)).

$$R = 1 + \frac{\rho K_a}{\theta} \quad (2)$$

where ρ is the soil bulk density (ML^{-3}), θ is the volumetric water content and K_a is an empirical distribution constant for adsorption (L^3M^{-1}).

The physical non-equilibrium CDE (CDE_{neq}) model considers that the liquid phase can be partitioned into a mobile and an immobile region. It is expressed as the following equation:

$$\beta R\frac{\partial C_1}{\partial T} = \frac{1}{Pe}\frac{\partial^2 C_1}{\partial Z^2} - \frac{\partial C_1}{Z} - \omega(C_1 - C_2) - \mu_1 C_1 \quad (3)$$

where $T = vt/L$, $Z = x/L$ and $Pe = vL/D$ is the Peclet number. L is the length of the column and C_1 and C_2 are the relative concentrations normalized with respect to the input concentration C_0 at the mobile (C_1) and immobile (C_2) flow regions, respectively.

The fraction of mobile water is described by the dimensionless parameter (β) (Eq. (4)) and the dimensionless mass transfer coefficient (ω) (Eq. (5)).

$$\beta = \frac{\theta_m + f_\rho K_a}{\theta + pK_a} \quad (4)$$

$$\omega = \frac{\alpha L}{q} \quad (5)$$

where θ_m is the volumetric water content of the mobile fraction, θ is the total volumetric water content, f is the fraction of adsorption sites in the mobile region (dimensionless), ρ is the soil bulk density (ML^{-3}), K_a is an empirical distribution constant for adsorption (L^3M^{-1}), α is the first-order transfer coefficient between the mobile and immobile regions (T^{-1}) and q is the Darcy water flux (LT^{-1}).

Breakthrough curves (BTC) were fitted using the computer program CXTFIT version 2.1 (Toride et al., 1999). The retardation coefficient R was assumed unity for the nonreactive bromide. Input data consisted of solute concentration ratio C_i/C_0 at the outlet and time. Model parameters, v, D, β and ω were estimated using the CDE_{neq}. Dispersivity (λ) is a characteristic property of the porous medium, and can be calculated from the relationship between D and υ (Eq. (6)).

$$D = \lambda\upsilon + D_0 \quad (6)$$

If negligible molecular diffusion is assumed ($D_0 = 10^{-6}$ cm^2 s^{-1}), λ can be calculated as D/υ (Vanderborght and Vereecken, 2007).

2.4. Data analysis

Analysis of variance and correlation between parameters and selected soil properties were performed with SAS version 9.0 software (SAS Institute, 1992). The estimated parameters were compared among soils and tillage (as fixed effects) using a mixed linear model (PROC MIXED). Mean comparisons were evaluated with a significance level of 0.05 using LSMEANS.

3. Results and discussion

3.1. Soils

Selected physical and chemical characteristics of the soils are presented in Table 1. Clay content in PAR was significantly higher than in MAN and PER ($P < 0.001$). No differences within particle size distribution were found between tillage practices (not shown). Organic carbon (OC) content was higher in PER and PAR soils, than in MAN ($P < 0.001$). Bulk density values measured in the soil columns are shown in Table 2. In average, MAN and PER bulk density was less than PAR soil. Regarding the tillage practice, no significant difference was found between NT and CT samples in each soil.

3.2. Breakthrough curves (BTC) and model fitting

Results from the BTC obtained from the leaching experiments with Br^- are shown in Fig. 1. Only in two cases, one column from MAN-CT and another for PAR-NT, ponding occurred, so the columns had to be dismissed from the experiment. Fig. 1 shows that in PAR-NT columns there was an early solute breakthrough. The BTC also exhibited an asymmetric behavior, indicating a greater effect of macropore flow on physical non-equilibrium. Long tailing in BTC of reduced tillage column samples has also been reported by Besson et al. (2011). On the contrary, in the less clayey soils (MAN and PER), the curves were less asymmetrical, both in NT and CT. Glaesner et al. (2011) also found differences between soils of different textural composition, finding early tailing of the non-reactive solute in columns from soils of loam texture, as compared to loamy sand and sandy loam soil columns.

The BTCs where modeled using the CDE_{neq} model. This model assumes that the water in the intra-aggregate pores is stagnant and that water movement occurs in the inter-agregate region. The CDE_{noeq} model is generally considered as more powerful and versatile in modeling experimental data obtained on heterogeneous porous media (Comegna et al., 2001; Brusseau and Rao, 1990), whereas the simpler CDE_{eq} model is considered to not satisfactorily describe solute transport when preferential flow occurs.

The main reason for choosing a CDE non-equilibrium model was that the shape of the BTCs evidenced non-equilibrium flow (asymmetrical shape, peak arrival before one PV and tailing). This approach has also been taken into account in other studies such as Shaw et al. (2000) and Ersahin et al. (2002). The experimental data and the CDE_{neq} model fit are shown in Fig. 1.

3.3. Transport parameters and soil properties

The dispersion coefficient tends to increase with increasing υ as seen in the scatter diagram in Fig. 2. Other studies have reported a linear relationship between these parameters (Tabarzad et al.,

Table 1
Particle size distribution and organic carbon (OC) content of the studied soils.

Soil	Particle size distribution (%)			OC (%)
	Sand	Silt	Clay	
PAR	10b[*]	53a	37a	1.61a
MAN	23a	51a	26b	1.14b
PER	24a	51a	25b	1.78a

[*] Different letters indicate differences between soils ($P < 0.001$).

Table 2
Estimated ρ and ϕ from the undisturbed soil columns of each soil measured after the leaching experiment.

	PAR	MAN	PER
		ρ_b	
NT	1.37	1.15	1.21
CT	1.34	1.17	1.22
		ϕ	
NT	0.48	0.56	0.55
CT	0.49	0.55	0.54

ρ_b: bulk density (g cm^{-3}), ϕ: total porosity.

2011; Costa and Prunty, 2006; Shukla et al., 2003; Perfect et al., 2002). It can be observed that the highest values of ν and D were found for the NT samples; these high values suggest that the transport of Br^- is driven by the physical characteristics of the soil rather than by diffusive properties of the tracer (Ersahin et al., 2002).

The correlation between the estimated transport parameters (ν, D, β, ω) with the soil properties was analyzed separately for each tillage practice (Table 3). There was a strong positive correlation in NT columns between soil clay content with the parameters ν (r = 0.91), D (r = 0.80) and λ (r = 0.63) (Table 3). By contrast, no correlations were found for the CT parameters (Table 3). Other authors have also found a positive correlation between D and clay content, this can be inferred from data reported by Montoya et al. (2006) and it was also reported in a study that compared A, B and C horizons (Bedmar et al., 2008). Bromly et al. (2007) examined the relationship between different physical soil parameters and dispersivity. The compiled data was analyzed by a regression tree analysis, which showed that clay content was the most important factor controlling dispersivity. They found that soils with clay percentage higher than 29.8% had greater dispersion coefficients than those with less clay content. Although in the aforementioned study only repacked and sieved columns were considered, the authors note that not necessarily is the soil structure completely removed. Since the majority of the studied soils in Bromly et al. (2007) were reported as forming aggregates, they hypothesize that the repacked columns contain aggregates that are smaller in diameter than the sieve size. Therefore the intra and inter aggregate space is preserved. The higher dispersion coefficients found in more structured soils are the result of non-equilibrium transport, which occurs when the vertical flow rate through the macropores is faster than the rates of lateral equilibration of the solute concentration with the soil matrix. Other studies have reported a decrease in D values in clay loam soils compared to sandy loam and silt loam (Tabarzad et al., 2011). Also, Ersahin et al. (2002) found smaller dispersion values occurring in the E horizon due to narrow pore size distribution, even though this horizon had a higher clay content than A and B horizons.

In our study, a positive relationship of clay content with ν and D parameters only occurred in NT samples. It is expected that as the clay content increases the soil structural effects become more important. But on the other hand, tillage disturbance in soils causes a reduction in aggregate size (Mc Vay et al., 2006), decreasing inter-aggregate porosity, and thus affecting flow pathways. The long-term plowing and harrowing activity in the conventionally tilled fields most likely destroyed structural differences between the different soils and produced a more homogeneous soil structure, regardless of the textural composition. On the contrary, in the no-till samples, structure is well preserved, by maintaining shrinkage cracks, worm channels, root holes and pore continuity.

3.4. Solute transport parameters

The transport parameters obtained with the CDE_{neq} model are shown in Table 4. In this study, no differences were found between soils or tillage practice regarding the estimated ν parameter. The estimated values ranged from 1.05 to 1.72 cm h^{-1}. Although no statistical difference was found, the highest ν corresponded to PAR-

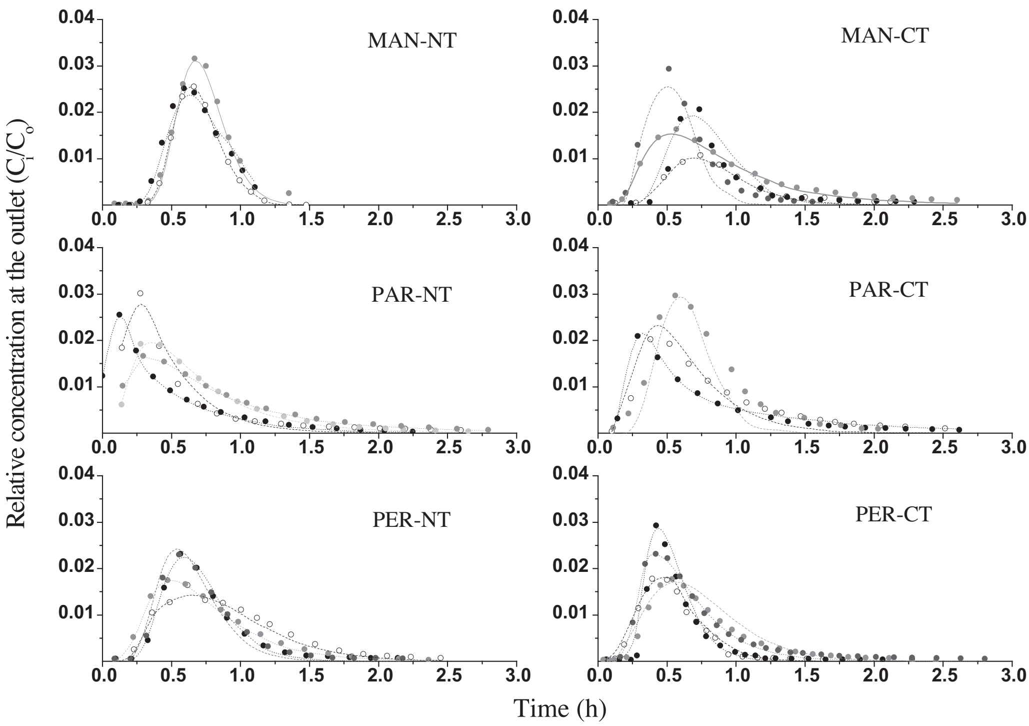

Fig. 1. Experimental (dots) and estimated (dotted line) bromide BTC using CDEneq model for different soils, under no till (NT) and conventional tillage (CT) for Manfredi (MAN), Paraná (PAR) and Pergamino (PER) soils. Different colored dots represent a different experimental column. C_i/C_o: relative concentration.

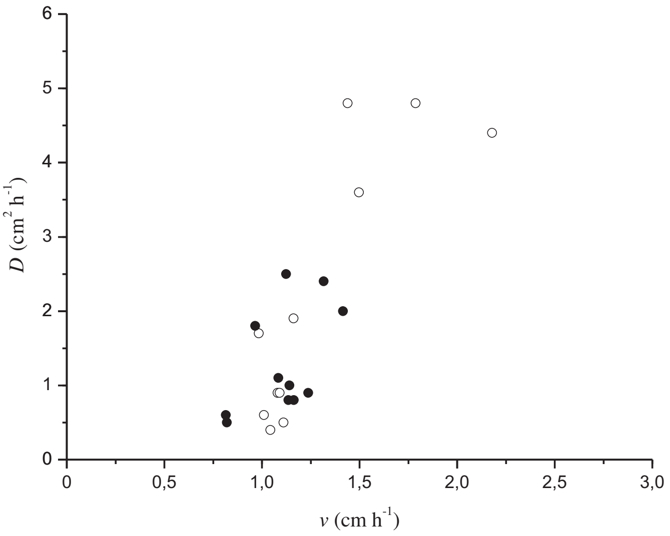

Fig. 2. Relationship between velocity (v) and hydrodynamic dispersion coefficient (D) obtained from all the undisturbed soil columns. In the graph, samples are differentiated in NT (○) and CT (●).

NT columns; this could indicate the presence of larger macropores conducting the water (Kung et al., 2000; Jaynes et al., 2001).

As for the estimated D, PAR-NT had significantly higher values than the other NT soil samples ($P < 0.005$) (Table 4), whereas no differences between soils were found in CT samples. The D in MAN and PER did not differ statistically between treatments. Nevertheless PAR-NT had a significantly higher D than PAR-CT (4.40 and 1.68 $cm^2 h^{-1}$, respectively). The asymmetrical BTC exhibited in PAR columns (Fig. 1), along with the high D values (Table 4), suggest a strong non-equilibrium transport. In general, the macropore flow is the main cause for an early breakthrough, and intra-aggregate diffusion causes tailing (Ersahin et al., 2002), therefore differences between D are strongly related to differences in soil structure.

As mentioned in Section 3.3, D was strongly correlated to the clay content. In this sense, PAR is the soil with the highest clay content (Table 1), corresponding to a silty clay loam texture, while MAN and PER have a silt loam texture. Clay content plays an important role in soil structure, favoring the formation of aggregates that can result in a more stable pore network. Particularly in PAR, which is a fine mixed type of soil (with equal proportion of illite and montmorillonite), clays tend to swell and shrink, causing cracks or bigger aggregates.

Table 3
Linear correlation coefficients between estimated CDE_{neq} parameters (v, D, λ, β and ω) and selected soil properties from CT and NT samples.

Parameter	Sand	Silt	Clay	OC	ρ	ϕ
CT						
v	−0.01	−0.16	0.12	−0.38	0.37	−0.35
D	−0.01	−0.47	0.36	−0.30	0.54	−0.53
λ	−0.10	−0.04	0.14	−0.27	0.39	−0.37
β	0.42	0.03	−0.43	0.11	−0.30	−0.08
ω	0.62	0.14	−0.31	0.09	0.27	−0.06
NT						
v	−0.59	−0.29	0.91***	0.10	0.63*	−0.62*
D	−0.74	0.02	0.80**	0.40	0.88**	−0.87**
λ	−0.70	0.16	0.63*	0.55	0.91***	−0.92***
β	0.14	0.06	−0.21	−0.01	0.24	−0.25
ω	0.25	−0.58	0.22	0.41	0.18	0.18

OC: organic carbon; ρ: bulk density; ϕ: porosity.
* $P < 0.05$.
** $P < 0.005$.
*** $P < 0.0001$.

Aggregate stability is an indicator of soil structure (Six et al., 2000). In general, tillage disrupts aggregates by affecting factors that contribute to soil aggregation, e.g., SOM, CEC, nutrient content and microbial and faunal activities (Plante and McGill, 2002). No-till management preserves larger and more stable aggregates (Castro Filho et al., 2002), increasing the volume of storage pores (0.6–50 μm) and aggregate stability (Pagliai et al., 2004). Soil aggregation values from the studied PAR fields show that stability is significantly higher in NT samples than in CT ($P > 0.005$) (unpublished data).

In soils with finer texture, like PAR, interaggreagate pores are more continuous across a much larger distance than the intraagregate pores, and thus when the leaching rate exceeds the conductivity of the smaller pores, the interaggregate pores are activated, increasing the dispersivity (Vanderborght and Vereecken, 2007). In the PAR CT system, the amount of mesopores and intraagragate pores may increase because of the turning of the soil. Nevertheless the connectivity of the bigger pores is disrupted (Roseberg and McCoy, 1992). The total porosity measured in the columns (Table 2) shows that there was no significant difference between NT and CT samples of the same soil. However, in a study performed in the same PAR long-term field trial, Sasal et al. (2006) measured macroporosity (>300 μm) and found that it was significantly higher in CT samples. Nevertheless, the measured infiltration rates were not different between NT and CT. A possible explanation is that macroporosity reduction may be compensated by more effective biopores for water movement. Another hypothesis, is that the great residue contribution of the previous crops (wheat/soybean-corn), promotes the activity of organisms and roots, forming a stable and more connected macropore system (Sasal et al., 2006). Other studies (Shipitalo et al., 2000; Vervoort et al., 2001; Besson et al., 2011) have also shown that intense plowing can disrupt and destroy the continuity of biopores. It is clear that soil structure and horizon morphology have a major effect on solute transport, such that strongly developed structures result in more pronounced non-equilibrium transport than weaker structures (Anderson and Bouma, 1977; Bouma and Wösten, 1979).

Dispersivity values in the studied columns ranged from 0.50 to 2.61 cm (Table 4), and are within the order of values found in other column transport studies (Ersahin et al., 2002; Montoya et al., 2006; Bedmar et al., 2008). Statistical analysis showed that there was an interaction between soil and tillage. The λ was higher in PAR-NT columns compared to the values found for MAN-NT and PER-NT ($P > 0.05$). Fine textured soils tend to be more dispersive than coarse textured soils, as it was reported in another study (Perfect et al., 2002) were a positive correlation was found between λ and the air-entry value. This is in agreement with our results since PAR is the soil with the highest clay content. In PAR soil NT samples had significantly higher λ values than CT samples. Since λ increases as the width of the pore-size distribution increases (Vervoort et al., 1999; Perfect et al., 2002), the smaller values found in CT samples could be due to a narrow pore size distribution, as a result of the soil disturbance caused by plowing. The MAN and PER columns did not differ in the estimated λ between treatments. This result can be attributed to similarities in pore space and aggregate size distribution. The impact of tillage practice over the soil structure was only evidenced in PAR soil. High effective dispersivity has been associated to clayey soils, in which it has also been demonstrated that strong preferential flow was the predominant mechanism for water and solute transport (Shaw et al., 2000). Probably in the less fine-textured soils, inter-aggregate porosity does not account for much difference between conventional or conservational tillage practices.

The parameter β represents the fraction of mobile water content and can be reduced from Eq. (4) to $\beta = \theta_m/\theta$, when assumed

Table 4
Estimated transport parameters for each soil from bromide BTC data with the non equilibrium CDE model.

	CDE_{neq}									
Soil	v (cm h^{-1})		D (cm^2 h^{-1})		β		ω		λ (cm)	
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
MAN	1.12	1.05	1.33 aA*	0.51 bA	0.67	0.73	874.25	788.66	1.18 aA	0.50 bA
PAR	1.11	1.72	1.68 aB	4.40 aA	0.47	0.57	667.00	976.76	1.48 aB	2.61 aA
PER	1.07	1.07	1.00 aA	1.36 bA	0.77	0.55	989.00	967.77	0.88 aA	1.27 bA

v: pore water velocity; D: hydrodynamic dispersion coefficient, β: dimensionless mobile water portioning coefficient; ω dimensionless mass transfer coefficient between mobile and immobile regions.

* Different lower case letters indicate differences between soils, different upper case letters indicate differences between different tillage from same soil ($P < 0.05$).

that $R = 1$. No differences were found in β and ω between soils and tillage practices, probably due the high variation in the estimated parameters between replicates. For all soils β values were higher than 0.47. It can be assumed that low values of β indicate preferential flow. For example, Ersahin et al. (2002) reported $\beta = 0.30$ values for transport under saturated conditions, and attributed this large immobile water content to the high saturated pore water velocity caused by macropores. On the other hand, in some cases it is difficult to attach a physical meaning to β and ω due to poor definition of the estimated parameters (Comegna et al., 2001). In the latter case, they found values that ranged from 0.00 to 1.00 in sandy and clayey sandy undisturbed soil columns.

4. Conclusions

In this study we analyzed the long-term impact of NT and CT on solute transport within three different soils. Bromide displacement studies were conducted using undisturbed soil samples from long-term-field trials with a history of over 16 years of NT and CT practices. The estimated transport parameters v and D were positively correlated to soil clay content in NT samples. Such correlation was not observed for CT. This result suggests that clay content in soils under conservation tillage favors the transport of solutes as it increases v and D.

In PAR (>35% clay), soil management had an important effect on structure, and therefore on solute and water transport. For this soil, the magnitude of solute dispersion was higher in the NT samples than in CT. Effects of tillage on solute transport were not substantial in the silty loam soils (MAN and PER), even when no-tillage management had been applied for over 30 years. In the studied silty clay loam soil, structure was well preserved under conservation tillage, and this could lead to an increase in the risk of leaching of solutes or chemical substances.

The results presented in this work are relevant as only few studies have analyzed the effect of long term tillage practices on solute transport in different soils.

Acknowledgements

Elena Okada holds a scholarship from CONICET. This work is part of E. Okadás doctoral studies at Fac. De Cs. Exactas y Naturales, Universidad Nacional de Mar del Plata. Funding was provided by INTA (PNSUELO 1134044) and Fondo Para la Investigación Cientifica y Tecnológica (PICT 448). Authors would like to thank Mr. M. Dosanto for assistance in the laboratory.

References

Akhtar, M.S., Stüben, D., Norra, S., Memon, M., 2011. Soil structure and flow rate-controlled molybdate arsenate and chromium (III) transport through field columns. Geoderma 161, 1262–2137.

Anderson, J.L., Bouma, J., 1977. Water movement through pedal soils: I saturated flow. Soil Sci. Soc. Am. J. 41, 413–418.

Bedmar, F., Costa, J.L., Giménez, D., 2008. Column tracer studies in surface and subsurface horizons of two typic argiudolls. Soil Sci. 173, 237–247.

Besson, A., Javaux, M., Bielders, C.L., Vanclooster, M., 2011. Impact of tillage on solute transport in a loamy soil from leaching experiments. Soil Till. Res. 112, 47–57.

Bouma, J., Wösten, J.H.M., 1979. Flow patterns during extended saturated flow in two undisturbed swelling clay soils with different macrostructures. Soil Sci. Soc. Am. J. 43, 16–22.

Bromly, M., Hinz, C., Aylmore, L.A.G., 2007. Relation of dispersivity to properties of homogeneous saturated repacked soil columns. Eur. J. Soil Sci. 58, 293–301.

Brusseau, M.L., Rao, P.S.C., 1990. Modelling solute transport in structured soils: a review. Geoderma 46, 155–192.

Castro Filho, C., Lourenco, A., Guimaraes, M. de F., Fonseca, I.C.B., 2002. Aggregate stability under different soil management systems in a red latosol in the state of Parana Brazil. Soil Till. Res. 65, 45–51.

Comegna, V., Coppola, A., Sommella, A., 2001. Effectiveness of equilibrium and physical non-equilibrium approaches for interpreting solute transport through undisturbed soil columns. J. Contam. Hydrol. 50, 121–138.

Costa, J.L., Prunty, L., 2006. Solute transport in fine sandy loam soil under different flow rates. Agric. Water Manage. 83, 111–118.

Cullum, R.F., 2009. Macropore flow estimations under no-till and till systems. Catena 78, 87–91.

de Jonge, L.W., Moldrup, P., Schjønning, P., 2009. Soil infrastructure interfaces & translocation processes in inner space (Soil-it-is): towards a road map for the constraints and crossroads of soil architecture and biophysical processes. Hydrol. Earth Syst. Sci. 13, 1485–1502.

Ersahin, S., Papendick, R.I., Smith, J.L., Keller, C.K., Manoranjan, V.S., 2002. Macropore transport of bromide as influenced by soil structure differences. Geoderma 108, 207–223.

Gao, G., Zhan, H., Feng, S., Huang, G., Mao, X., 2009. Comparison of alternative models for simulating anomalous solute transport in a large heterogeneous soil column. J. Hydrol. 377, 391–404.

Glaesner, N., Kjaergaard, C., Rubaek, G.H., Magid, J., 2011. Interactions between soil texture and placement of dairy slurry application: I flow characteristics and leaching of nonreactive components. J. Environ. Qual. 40, 337–343.

INTA (Instituto Nacional de Tecnología Agropecuaria), 1972. Carta de suelos de la República Argentina. Hoja Pergamino, 3360-32, pp. 106.

INTA (Instituto Nacional de Tecnología Agropecuaria), 1987. Carta de Suelos de la República Argentina, Hoja Oncativo, 3163-22, pp. 82.

INTA (Instituto Nacional de Tecnología Agropecuaria), 1998. Carta de Suelos de la República Argentina. Hoja Paraná, 17, pp. 114.

Jarvis, N.J., 2007. A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. Eur. J. Soil. Sci. 54, 523–546.

Jaynes, D.B., Ahmed, S.I., Kung, K.-J.S., Kanwar, R.S., 2001. Temporal dynamics of preferential flow to a subsurface drain. Soil Sci. Soc. Am. J. 65, 1368–1376.

Kung, K.-J.S., Steenhuis, T.S., Kladivko, E.J., Gish, T.J., Bubenzer, G., Helling, C.S., 2000. Impact of preferential flow on the transport of adsorbing and non-adsorbing tracers. Soil Sci. Soc. Am. J. 64, 1290–1296.

Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil Till. Res. 89, 210–220.

Locke, M.A., Bryson, Ch.T., 1997. Herbicide–soil interaction in reduced tillage and plant residue management systems. Review article. Weed Sci. 45, 307–320.

Mahboubi, A.A., Lal, R., Faussey, N.R., 1993. Twenty-eight years of tillage effects on two soils in Ohio. Soil Sci. Soc. Am. J. 57, 506–512.

Mc Vay, K.A., Budde, J.A., Fabrizzi, K., Mikha, M.M., Rice, C.W., Schlegel, A.J., Peterson, D.E., Sweeney, D.W., Thompson, C., 2006. Management effects on soil physical properties in long-term tillage studies in Kansas. Soil Sci. Soc. Am. J. 70, 434–438.

Montoya, J.C., Costa, J.L., Liedl, R., Bedmar, F., Daniel, P., 2006. Effects of soil type and tillage practice on atrazine transport through intact soil cores. Geoderma 137, 161–173.

Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. Soil Till. Res. 79, 131–143.

Perfect, E., Sukop, M.C., Haszler, G.R., 2002. Prediction of dispersivity for undisturbed soil columns from water retention parameters. Soil Sci. Soc. Am. J. 66, 696–701.

Plante, A.F., McGill, W.B., 2002. Soil aggregate dynamics and the retention of organic matter in laboratory-incubated soil with differing simulated tillage frequencies. Soil Till. Res. 66, 79–92.
Roseberg, R.J., McCoy, E.L., 1992. Tillage and traffic-induced changes in macroporosity and macropore continuity: air permeability assessment. Soil Sci. Soc. Am. J. 56, 1261–1267.
SAS Institute Inc., 1992. SAS/STAT User's Guide Version 9. SAS Institute Inc., Carry, NC, USA.
Sasal, M.C., Andriulo, A.E., Taboada, M.A., 2006. Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinean Pampas. Soil Till. Res. 87, 9–18.
Schwen, A., Bodner, G., Scholl, P., Buchan, G.D., Loiskandl, W., 2011. Temporal dynamics of soil hydraulic properties and the water-conducting porosity under different tillage. Soil Till. Res. 113, 89–98.
Shaw, J.N., West, L.T., Radcliffe, D.E., Bosch, D.D., 2000. Preferential flow and pedotransfer functions for transport properties in sandy Kandiults. Soil Sci. Soc. Am. J. 64, 670–678.
Shipitalo, M.J., Dick, W.A., Edwards, W.M., 2000. Conservation tillage and macropore factors that affect water movement and the fate of chemicals. Soil Till. Res. 53, 167–183.
Shukla, M.K., Ellsworth, T.R., Hudson, R.J., Nielsen, D.R., 2003. Effect of water flux on solute velocity and dispersion. Soil Sci. Soc. Am. J. 67, 449–457.
Sinkevich, M.G., Walter, M.T., Lembo, A.J., Richards, B.K., Peranginangin, N., Aburime, S.A., Steenhuis, T.S., 2005. A GIS-based ground water contamination risk assessment tool for pesticides. Ground Water Monit. Redem. 25 (4), 82–91.
Six, J., Elliott, E.T., Paustian, K., 2000. Soil structure and soil organic matter: II. A normalized stability index and the effect of mineralogy. Soil Sci. Soc. Am. J. 64, 1042–1049.
Soil Conservation Service, 1972. Soil Survey Laboratory. Methods and Procedures for Collecting Soil Samples. Soil Survey Report 1. U.S.D.A., Dept. Agric., WA, USA.
Tabarzad, A., Sepaskhah, A.R., Farnoud, T., 2011. Determination of chemical transport properties for different textures of undisturbed soils. Arch. Acker. Pfl. Boden. 57, 915–930.
Toride, N., Leij, Fj., Van Genuchten, M.Th., 1999. The CXTFIT Code for Estimating Transport Parameters from Laboratory or Field Tracer Experiments, Version 2.1. Research Report No. 137. U.S. Salinity Laboratory, USDA, ARS, Riverside, CA, pp. 119.
Vanderborght, J., Vereecken, H., 2007. Review of dispersivities for transport modeling in soils. Vadose Zone J. 6, 29–52.
Vervoort, R.W., Dabney, S.M., Römkens, M.J.M., 2001. Tillage and row position effects on water and solute infiltration characteristics. Soil Sci. Soc. Am. J. 65, 1227–1234.
Vervoort, R.W., Radcliffe, D.E., West, L.T., 1999. Soil structure development and preferential solute flow. Water Resour. Res. 35, 913–928.
Vogeler, I., Horn, R., Wetzel, H., Krümmelbein, J., 2006. Tillage effects on soil strength and solute transport. Soil Till. Res. 88, 193–204.
Walkley, A., Black, I.A., 1934. An examination of degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 3, 29–37.