Chilean J. Agric. Anim. Sci., ex Agro-Ciencia (2024) 40(3): 639-651.
https://doi.org/10.29393/ CHJAAS40-55CLAS40055

ISSN 0719-3890 online

CHANGES IN LEAST LIMITING WATER RANGE UNDER DIFFERENT TILLAGE SYSTEMS AND TRAFFIC INTENSITIES IN A SUBHUMID PAMPEAN REGION

Adrián G. Vallejos[1a*], Julio O. Iglesias[1b], Juan A. Galantini[1c,2], and Silvia Imhoff[3,4]

[1a] Departamento de Agronomía, Universidad Nacional del Sur, San Andrés 800, CP 8000 Bahía Blanca, Argentina
https://orcid.org/0000-0003-3761-7568
[1b] Departamento de Agronomía, Universidad Nacional del Sur, San Andrés 800, CP 8000 Bahía Blanca, Argentina
https://orcid.org/0000-0003-2474-4592
[1c] Departamento de Agronomía, Universidad Nacional del Sur, San Andrés 800, (8000) Bahía Blanca, Argentina
https://orcid.org/0000-0002-4536-8605
[2] Comisión de Investigaciones Científicas (CIC). CERZOS. Bahía Blanca, Argentina
[3] Facultad de Ciencias Agrarias, Universidad Nacional del Litoral (UNL), Bv. Pellegrini 2750 CPA 3000, Esperanza, Argentina
https://orcid.org/0000-0001-7330-9728
[4] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
* Corresponding author: avallejo@criba.edu.ar

ABSTRACT

Soil management practices can disrupt soil structure, affecting productivity through changes in water and oxygen availability, and mechanical impedance. These variables can be affected by machinery traffic depending on the management practice used. This research aimed to quantify changes in the least limiting water range (LLWR) in the surface soil layer under varying traffic intensities in both no-till (NT) and conventional tillage (CT) systems. The treatments applied to each system were: control without any traffic (0P), one tractor pass (1P), and five tractor passes (5P). To determine the LLWR and available water (AW), the following variables were measured: soil bulk density (BD), soil water retention curve (SWRC) and soil penetration resistance (SRP). Transit treatments gave different LLWR results depending on tillage system. The changes in AW were less sensitive than the LLWR values. The only treatment that did not reach the critical bulk density (BDc), where the LLWR is zero, was the 0P treatment. Both the NT and CT 1P treatments reached the same BDc of 1.39 m^3 m^{-3}. However, in the 5P treatment, the **BDc was 1.33 m^3 m^{-3}** for CT and 1.41 m^3 **m^{-3}** for NT, respectively. **The LLWR showed a different response of its structural condition to the tillage system and traffic intensity in both tillage systems. These results provide evidence of a greater risk of soil degradation under CT than under NT management. Regardless of soil management and machinery traffic treatments, soil penetration resistance was the attribute that had more influence on the LLWR.**

Keywords: Traffic, Tillage systems, Available water, Soil physical quality.

Received: September 23, 2024 Accepted: November 30, 2024

INTRODUCTION

The international trend to reduce crop management costs has led farm machine manufacturers to increase the working capacity with larger machines (Antille et al., 2019), which has enhanced the risk of soil structure degradation caused by compaction. This degradation reduces soil porosity and increases soil bulk density (BD). However, BD provides little information about the underlying soil environment that affects root and plant growth, since the range of changes in BD with texture (Keller and Hakansson 2010).

Reduced porosity leads to the reorganization of soil aggregates, a change in pore size distribution, increased tortuosity, and connectivity between them, thus affecting gas diffusion, water percolation and mechanical impedance or SRP, and consequently compaction restricts plant root growth (Chen et al., 2014; Fernandez et al., 2017; de Lima et al., 2020).

Soil management practices can also alter soil structure, affecting productivity. According to Reichert et al. (2016), traffic on tilled soil reduces total porosity and soil macroporosity, while it increases BD and soil degree-of-compactness (DC), especially in the upper layer of tilled soils, which are often unstructured and have low bearing capacity. In no-tillage systems (NT), over time, the absence of tillage mitigates these harmful effects by increasing microporosity and organic carbon, leading to greater water infiltration and retention in the upper layer. However, increases in BD and DC were observed at deeper levels. Therefore, quantifying and understanding the impact of management practices on soil physical properties are essential for developing sustainable agricultural systems. Letey (1985) considered water availability, oxygen diffusion, temperature, and SRP as the main soil physical properties influencing plant emergence, root growth and crop production.

Keller et al. (2015) reported that soil compaction affects and alters the distribution and connectivity of soil pore size, thereby altering water retention, hydraulic conductivity, filled air space, and gas transport through convection and diffusion.

Matric water potential is one of the main parameters related to plant growth. It refers to the energy required by the roots to extract water from the soil, i.e., for different soils, the available water (AW) may be different for the same matric water potential (Letey, 1985). AW is the amount of water between field capacity (FC; -0.01 MPa) and the wilting point (WP; -1.5 MPa). Since soil properties are dynamic (i.e., they change according to management) and can be positively or negatively related to each other, the range of AW depends on soil structure. Soil bulk density (BD) influences crop production, with quadratic responses generally been observed with increasing soil BD (Keller and Hakansson 2010). Carter (1990) has determined critical values for wheat production. However, soil BD is related to the SRP and oxygen diffusion, due to variation in the pore size distribution.

Increases in water content fill the pore spaces, lowering the oxygen concentration necessary for root metabolism. Generally, it is accepted that 10% of unoccupied pore space is the limit (da Silva et al., 1994).

Soil penetration resistance, which is largely influenced by soil moisture, is the main soil property regulating root elongation and water accessibility (Colombini, 2018). Soil penetration resistance (SPR) influences root growth and is typically linked to a critical value where root growth starts to decrease. In this sense, da Silva et al. (1994) proposed a threshold value of 2.0 MPa.

Appropriate indicators to evaluate physical quality of soils should include properties that affect plant root growth, such as temperature, water and oxygen availability, and properties that indicate the presence/absence of imposed mechanical constraints by the soil matrix (Imhoff et al., 2016).

Letey (1985) proposed to integrate three properties into a single parameter, and to delimit a range in which roots develop without water limitation, which he called the non-limiting water range (NLWR), later quantified by da Silva et al. (1994) and denominated as the least limiting water range (LLWR). This range defines the water content where there is no water limitation due to decrease in soil aeration and increase in SRP for root growth. Therefore, the probability of crops experiencing restrictive conditions due to water shortage is reduced (da Luz et al., 2022).

The upper limiting range of the LLWR (high water content) is the lowest value between the volumetric water content at 10% air-filled porosity (AFP) and the volumetric water content at FC (-0.33 MPa). The lower limiting range is the highest value between the volumetric water content at WP (-1.50 MPa and the volumetric water content at which the SRP is limiting for root growth. According to Keller et al. (2015), the LLWR concept is appropriate for assessing limiting factors for root growth because soil water retention curve (SWRC) and SRP are functions of BD. Therefore, LLWR is also influenced by BD, and thus LLWR is affected by soil compaction.

LLWR could be used to study the effect of compaction caused by agricultural machinery (single pass with a heavy machine versus multiple passes with lighter machinery) and controlled traffic versus random traffic (Keller et al., 2015).

In semi-arid and sub-humid regions, where water is the main limiting factor for yield, the LLWR may be used as a soil quality parameter to evaluate different management practices (Haghighi Fashi et al., 2017; de Moura et al., 2021) and the impact of machinery traffic on the soil physical properties.

Based on the concepts discussed, the following hypotheses were put forward: i) the LLWR values are higher in no-till than in conventional tillage due to its higher BD; ii) the SRP is the variable that has the most influence on LLWR; iii) the greatest reduction in LLWR is obtained with the first tractor pass, independently of the tillage system; and iv) LLWR is more sensitive than AW to traffic effects on the soil that affect soil water availability for the crop. Therefore, the objectives of this study were to quantify changes in LLWR under two tillage systems with different traffic intensities.

MATERIAL AND METHODS

Study site

The trial was carried out in a rural establishment "Hogar Funke" (38°07′06″ S - 62°02′17″ W), near the town of Tornquist, Buenos Aires province (Argentina), with two tillage systems used since 1986, on level contours without any slope: no-till (NT) and conventional tillage (CT).

A split plot design with 3 repetitions was used, with the tillage system (no-till and conventional tillage) as the main factor, and treatments 0P (control sample without traffic), 1P (one tractor pass) and 5P (five tractor passes) as the second factor.

The tillage systems used in the experiment were:

CT, was based on two chisel and two disk harrow operations to mix the residues with the soil: one in the early summer fallow at 18 cm in depth and another before sowing at 10 cm.

NT was characterized by the absence of tillage with over 30% residues covering the soil surface. In this system, a direct seed drill (John Deere 750 drill, John Deere Argentina S.A.) was used to sow directly into the standing residues of the previous crop. Glyphosate herbicide (2 L ha^{-1}) was applied for weed control.

The plots were fertilized with 10 kg P ha^{-1} $year^{-1}$ as diammonium-phosphate (18-46-0) at sowing in both tillage systems (Martinez et al., 2017). The complete crop sequence over the last 25 years was: M-W-S-W-S-W-SoB-M-B-M-W-M-W-B-S-W-W-S-B-S-W-M (grazing)-W (no harvest due to severe drought)- W and W, where: M, maize (*Zea mays* L.); W, wheat (*Triticum aestivum* L.); S, sunflower (*Helianthus annuus* L.); B, barley (*Hordeum vulgare* L.); and So, sorghum (*Sorghum bicolor* L. Moench).

It is an interesting example for observing the long-term effects of the tillage systems on the behavior of some soil physical properties, due to the site characteristics, the time elapsed and the tillage system applied. The soil was a Typic Argiudoll, with loamy texture in the topsoil (horizon A) (0-19 cm) and clay loam in the Bw horizon (19-37 cm); the horizon sequence was Ap, Ad, Bw, BC, C, and Ck and the soil depth was 84 cm.

The tillage systems were separated by a contour line. Three plots of 15 m by 20 m were demarcated on each side of the contour line, and the different traffic treatments were applied parallel to the contour line in both systems (0P, 1P, and 5P).

Sampling and soil physical analysis

Undisturbed soil samples were obtained after sowing wheat in 2019. The 0P treatments, without traffic, were positioned to avoid the previously identified tractor tracks. In each experimental unit, samples for the 0P treatment were collected, while samples for the 1P and 5P treatments were taken from the center of the tracks after the tractor had passed.

Traffic treatments in each tillage system were carried out with a simple traction, John Deere 4930 tractor, with a total weight of 9.53 Mg, equipped with 24.5- 32 rear tires (inflated at a pressure of 1.24 bars), and 1100- 16 front tires (inflated at a pressure of 2.21 bars).

For the sampling of all treatments, 30 undisturbed samples per plot were taken using steel cylinders (5 cm in diameter and 5 cm in height) from the 3 to 8 cm depth. The first two centimeters were not considered due to the variability caused by residues (SD), and depths below 10 cm were excluded due to the variability introduced by disc harrow tillage, which ranged between 10 and 18 cm over different years. Samples were wrapped until processing. Once appropriately prepared, they were saturated gradually in a glass humidifier for 24 h. The water retention was determined at different pressures (4, 8, 10, 33, 50, 100, 300, 500, 700 and 1500 kPa) in sand boxes and ceramic plates. The soil water retention curve (SWRC), soil bulk density and water content for each pressure were also determined (Klute, 1986).

The SRP was measured at each matrix pressure. Using a manual cone micropenetrometer with a semi-angle of 30º, a 3.74 mm basal diameter and a 10.99 mm^2 basal area. (Bradford 1986). The SRP values were achieved by introducing the micropenetrometer cone into the center of each cylinder. The measures were taken at intervals of 1 cm, discarding the first and last centimeters where measurements tend to be erratic. After evaluation, the sample was dried at 105°C to determine water content and bulk density (BD), and was subsequently discarded.

LLWR determination

The LLWR was determined as the difference between the upper and lower limits of the water content in which the physical parameters considered occur (da Silva et al., 1994). The lower limit is the highest value of moisture content either by resistance, SRP of 2 MPa, or by matric potential, WP = 1500 kPa. The upper limit is the lowest value of the moisture content considering the FC value or the AFP of 10%.

The SWRC curve was estimated using the model proposed by Leão et al. (2005).

$$\theta = \exp\,(a + b\ BD) * (\psi^{c} \qquad (1)$$

Where *a, b* and *f* are constants, θ is the volumetric water content (m^3m^{-3}).

Volumetric water content at field capacity (θFC) and wilting point (θWP) were determined by matric pressure (ψ) and bulk density, according to equation (1), using 33 and 1500 kPa.

The SRP curve was adjusted using the equation proposed by Busscher (1990).

$$SRP=d * q^{e} * BD^{f} \qquad (2)$$

To calculate θ SRP at 2 MPa, equation (3) was used, which was obtained from equation (2):

$$\theta SRP=2.0/(d*(BD^{e}))^{1/f} \qquad (3)$$

Where *d, e* and *f* are constants, θ is the volumetric water content (m^3m^{-3}).

Available water was obtained from the mean of the differences between the θFC and θWP values, resulting from equation (1). The value where the LLWR= 0 is called the critical soil bulk density (BDc), which occurs at the intersection between the upper and lower limits of the LLWR, where LLWR=0 (Imhoff et al., 2001). BDc is a parameter of soil degradation, which indicates a highly restrictive root growth (Guedes Filho et al., 2013).

Data analysis

Data in all tables were presented as the mean in each treatment. Differences in results affected by the treatments, as well as the interaction between them, were evaluated by analysis of variance (ANOVA), while treatment means were compared by the Fisher's test, using a significance level of $\alpha \leq 5\%$. The LLWR was calculated using a simplified excel® algorithm (Leão and da Silva, 2004). To fit the θ and SRP curves, a nonlinear regression model was used. Statistical analysis was carried out with INFOSTAT software (Di Rienzo et al., 2019).

RESULTS AND DISCUSSION

Soil physical properties in each treatment and system

As a result of the statistical analysis, an interaction was found between the tillage system and the different traffic treatments for the variables BD and SRP. Therefore, these variables were analyzed within each system for each tractor pass treatment.

Values of CT for SRP and BD were lower than those of NT (Table 1) due to the tillage carried out at the soil depth studied (details can be found in Iglesias et al., 2021). However, compaction levels were equal after five tractor passes. For CT, the SRP increased significantly at each tractor pass, with the 1P value increased by 100%, whereas the SRP increased by 211% at 5P. In contrast, for NT, the SRP increase was lower, at 107 and 119% for 1P and 5P, respectively. For BD in CT, the increment was significantly higher with each treatment, by 8 and 15% for 1P and 5P, respectively. In the NT system, the increase in BD in NT 5P was only 7% compared to NT 0P. Differences in compaction from traffic in the tillage systems were the result of tillage causing a disturbance in the soil structure. The soil in NT showed higher BD (Table 1) and higher soil organic matter (Duval et al., 2020) than in CT, which could help to resist traffic compaction; for this reason, only significant changes were detected at the 5P. Soil BD increase leads to an increase in the friction forces between the soil particles, decreasing movement between them and their ability to become deformed, increasing the bearing capacity.

Model coefficients analysis

Model coefficients used for equations (1) and (2), utilized for the estimation of (1) and (2) θ and θSRP (Table 2).

The results obtained indicate a negative relationship between θ coefficient *a,* and a positive relationship with coefficient *b*, but an increase in coefficient *a* and a decrease in coefficient *b* were observed with traffic, i.e., traffic decreased θ, and thus it can be inferred that these coefficients are related to soil porosity.

Both *a* and *b* coefficients were affected by traffic in the CT and NT tillage systems (Table 2). Coefficient *a* presented a higher value of θ at the lowest matric potential (0-10 kPa) in the 0P

Table 1. Means, standard error of the mean and range of the variables studied under different traffic intensities and tillage systems.

System	Treatment	Variable	Mean	Se	Min	Max
CT	0P	SRP	0.73 a	0.581	0.04	2.63
	1P	(MPa)	1.42 b	1.057	0.18	5.11
	5P		2.21 c	1.672	0.21	7.52
	0P	BD	1.16 a	0.124	0.94	1.40
	1P	(Mg m^{-3})	1.24 b	0.061	1.10	1.41
	5P		1.32 c	0.071	1.21	1.49
	0P	θ	0.33 b	0.071	0.19	0.51
	1P	(m^3 m^{-3})	0.26 a	0.065	0.16	0.42
	5P		0.25 a	0.059	0.16	0.39
NT	0P	SRP	1.03 a	0.529	0.11	3.10
	1P	(MPa)	2.14 b	1.660	0.20	7.03
	5P		2.26 b	1.651	0.44	8.77
	0P	BD	1.23 a	0.125	0.94	1.46
	1P	(Mg m^{-3})	1.22 a	0.120	0.94	1.39
	5P		1.31 b	0.076	1.13	1.41
	0P	θ	0.32 b	0.0569	0.2051	0.5021
	1P	(m^3 m^{-3})	0.25 a	0.0600	0.1590	0.4420
	5P		0.25+- a	0.0500	0.1574	0.3788

Studied tillage systems, CT (conventional-tillage) and NT (no-till). Treatments 0P, 1P and 5P: number of tractor passes, SRP (soil mechanical resistance), BD (soil bulk density), θ (volumetric water content), Se (standard error of the mean). Different letters indicate significant differences ($P< 0.05$) between treatments in each tillage systems.

Table 2. Adjustment coefficient of the function θ=exp (*a*+*bBD) ψ^c.**

Treatment	Coefficient	Value	RMSE	t	P>t	r^2
CT0P	*a*	-1.33	0.10	-13.90	<0.0001	0.80
	b	-0.14	0.08	-1.79	<0.0770	0.80
	c	-0.11	0.01	-17.88	<0.0001	0.80
CT1P	*a*	-0.71	0.21	-3.35	0.0012	0.85
	b	-0.83	0.17	-4.83	<0.0001	0.85
	c	-0.13	0.01	-21.73	<0.0001	0.85
CT5P	*a*	-0.19	0.17	-1.14	0.2566	0.88
	b	-1.17	0.13	-9.20	<0.0001	0.88
	c	-0.11	4.8*10-3	-23.55	<0.0001	0.88
NT0P	*a*	-1.49	0.09	-15.87	<0.0001	0.78
	b	0.05	0.07	0.074	0.4596	0.78
	c	-0.09	0.01	-15.34	<0.0001	0.78
NT1P	*a*	-0.68	0.09	-7.69	<0.0001	0.96
	b	-0.79	0.07	-12.15	<0.0001	0.96
	c	-0.11	0.01	-20.82	<0.0001	0.96
NT5P	*a*	-0.65	0.12	-5.47	<0.0001	0.86
	b	-0.79	0.09	-8.89	<0.0001	0.86
	c	-0.10	4.3*10-3	-22.52	<0.0001	0.86

Treatments CT 0P, CT 1P, CT 5P; NT 0P, NT 1P NT 5P: (CT, conventional tillage; NT, no tillage), (0P, 1P and 5P: number of tractor passes). Root- mean- square error (RMSE), Coefficient of determination (r^2). a, b, c coefficients, θ (volumetric water content), BD (soil bulk density), ψ (matric pressure).

treatments. As the traffic increased, the values of coefficient *a* were higher, but θ values decreased (Fig. 1a). Coefficient *b* was higher in the treatments without traffic than in the traffic treatments in all comparisons, which is why they presented higher water content than the traffic treatments throughout the retention curve (Fig. 1a,b).

Traffic decreased θ across the entire SWRC range (Fig. 1), these values would indicate that coefficient *a* would be more influenced by drainage macropores and pores generated by tillage (0 to 33KPa), with the volume of these pores decreasing when traffic was applied, leading to a decrease in θ. On the other hand, coefficient *b* would be related to pores within the 33 to 700 KPa range (storage pores), which would decrease in volume upon the application of traffic treatments, reducing θ values as the matrix potential increases (Fig. 1).

In the range of 33 to 700 KPa, the pores corresponding to this matrix potential would be filled with water, meaning that the SWRC would be influenced by coefficient *b*, showing a higher value of θ in 0P NT compared to 0P CT (Fig. 1b).

When 1P was applied, θ decreased at the matrix potentials of 0 to 33 KPa (macropores), where the NT treatment exhibited higher θ values than CT (Fig. 1a). At higher matrix potentials (33 to 700 KPa), treatments 1P NT and 5P NT exhibited higher θ values than treatments 1P CT and 5P CT, due to the influence of coefficient *b* (Fig. 1b). The values of *b* were higher in NT treatments with traffic, indicating a better soil structural condition in NT management.

The content of θ showed positive variations with BD only in NT 0P (coefficient *b*) as reported by Betz et al. (1998) and Lima et al. (2015), possibly due to the greater amount of biopores generated by roots and microorganisms, but the relationship was negative in the remaining treatments (Table 2).

No differences due to traffic were observed in coefficient *c* in either tillage system (Table 2). Betz et al. (1998) found a negative effect of the traffic on this coefficient, which affects the matric potential.

In this test, coefficient *c* did not vary because at high matric potentials the volume of undersized pores did not change with the applied traffic and did not influence θ, because compaction generally does not affect the small pore sizes within aggregates.

The *d* coefficient varied between 0.01 and 0.03 showing little variation in the θSRP between treatments, except for NT 0P (Table 3). Therefore, it would have less influence on the SRP value, which would depend more on the other terms in equation (2).

When traffic increased, the coefficient *e* decreased (Table 3) and the SRP increased (Table 1) in all treatments, indicating an inverse relationship between θ and SRP, i.e., there is a greater response to the change in SRP with the variation in θ in the treatments without traffic. Betz et al. (1998) reported that the increase in the SRP variation as a function of θ is due to changes in pore size distribution in no-till soils.

The *e* coefficient decreased from 41.9 and 39.7 % for the CT 1P and CT 5P system, and from 51.6

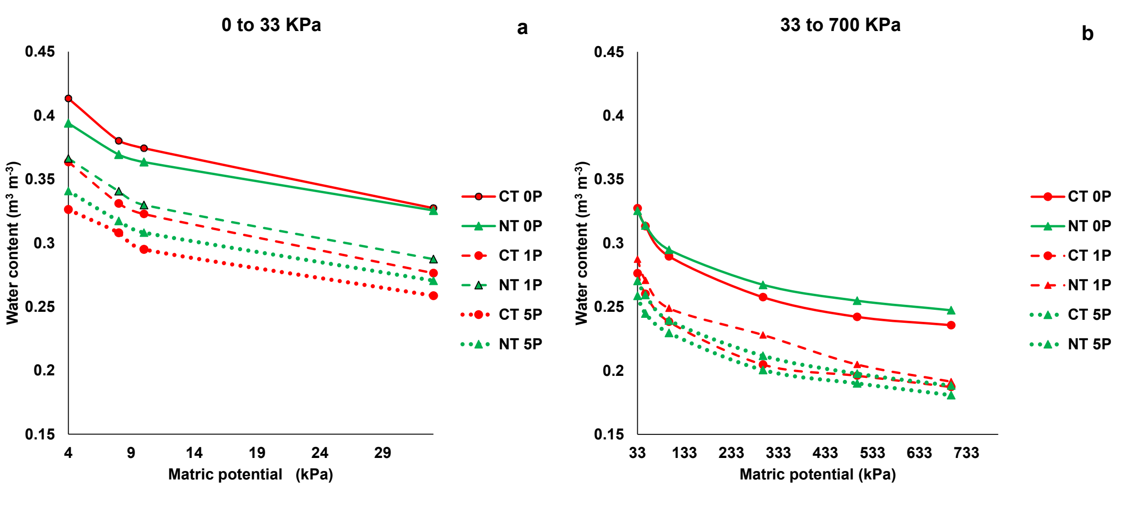

Fig. 1. Predicted soil water content (θ) response to matric potential for tillage systems NT (no till) and CT (conventional tillage). Treatments, without traffic (0P); with one tractor pass (1P); with five tractor passes (5P). a, matric potential 0 to 33 KPa; b, matric potential 33 to 700 KPa. Curve predicted using Eq. (1) with soil bulk density matched to θ.

Table 3. Adjustment coefficient of the function SRP=d * θ^e * BD^f.

Treatment	Coefficient	Value	RMSE	t	P>t	r^2
CT0P	*d*	0.03	0.01	4.81	<0.0001	0.85
	e	-1.74	0.14	-12.83	<0.0001	0.85
	f	6.30	0.32	19.75	<0.0001	0.85
CT1P	*d*	0.02	0.01	2.76	0.0069	0.73
	e	-2.47	0.19	-13.06	<0.0001	0.73
	f	3.41	0.062	5.53	<0.0001	0.73
CT5P	*d*	0.02	0.01	3.07	0.0027	0.83
	e	-2.39	0.17	-13.93	<0.0001	0.83
	f	4.76	0.52	9.23	<0.0001	0.83
NT0P	*d*	0.08	0.02	3.99	<0.0001	0.70
	e	-1.51	0.17	-8.89	<0.0001	0.70
	f	3.90	0.38	10.27	<0.0001	0.70
NT1P	d	0.03	0.01	2.86	0.0054	0.80
	e	-2.29	0.21	-10.94	<0.0001	0.80
	f	3.54	0.54	6.51	<0.0001	0.80
NT5P	d	0.01	0.01	2.65	0.0094	0.48
	e	-2.38	0.19	-12.56	<0.0001	0.48
	f	5.56	0.85	6.52	<0.0001	0.48

Treatments CT 0P, CT 1P, CT 5P; NT 0P, NT 1P NT 5P: (CT, conventional tillage; NT, no tillage), (0P, 1P and 5P: number of tractor passes). Root- mean- square error (RMSE), Coefficient of determination (r^2), d, e, f coefficients, BD (soil bulk density), θ (volumetric water content), SRP (soil resistance to penetration).

to 57.6% for NT 1P and NT 5P, respectively (Table 3). When the soil was transited by machinery the coefficient *e* increased in value; therefore, θ in the treatments without traffic would be less important for predicting SRP than in the traffic treatments.

The positive *f* coefficient confirmed that SRP increased as BD increased. In NT, the *f* coefficient increased by 5P, generating higher SRP values at NT 0P and NT 1P. The *f* coefficient would be determined by soil compaction and the change in pore distribution; as *f* increases, small increases in BD would generate large changes in SRP for the same value of θ. In the CT system, the same behavior is observed in the traffic treatments.

LLWR management systems and traffic effect

The LLWR values obtained in this research were in agreement with those reported in the literature for soils of similar texture (Safadoust et al., 2014; Imhoff et al., 2016; Fernández et al., 2017). These values decreased significantly with tractor passes in both systems. Nevertheless, the LLWR decreased from 1P to 5P in NT and was lower than that in CT. When comparing treatments between systems, LLWR values in NT 0P and NT 1P were lower than in CT 5P (P< 0.05); however, LLWR was higher in NT 5P than in CT 5P (P< 0.05). In the CT system, the decrease in LLWR was 44% and 88% at 1P and 5P, respectively. Conversely, in the NT system, the change was less pronounced, with a reduction of 23% at 1P and 40% at 5P. The NT system exhibited greater resilience, with LLWR reductions being 50% lower than in CT. This indicates a strong negative effect on soil physical quality for plant growth. In the present study, soil SPR was the limiting factor.

These results showed the differences in soil structure and response to the traffic treatments in the tillage systems studied, in agreement with the relationship between LLWR and soil structure proposed by da Silva et al. (1994), Benjamin et al. (2014) and Keller et al. (2015).

The change in LLWR with the tillage and traffic treatments demonstrated that the soil structure would have a significant influence on root environment.

In all the tillage systems and treatments, the θSRP boundaries generally showed a steeper slope than θFC and θWP, demonstrating that LLWR has a greater response to soil structure than that indicated by AW.

The useful water content (AW) estimated from equation (1) showed significant differences between CT 5P and the CT 0P and CT 1P treatments, which did not differ from each other in either system (Table 4).

The AW content (Table 4) showed less

Table 4. Means, standard error of the mean and range of the variables LLWR and AW estimated under different traffic intensity and tillage systems.

System	Treatment	Variable	Mean	Se	Min	Max
CT	0P	LLWR	0.1041 c	0.0250	0.0018	0.1158
CT	1P	(m^3 m^{-3})	0.0689 b	0.0266	0.0000	0.1202
CT	5P		0.0238 a	0.0243	0.0000	0.0794
CT	0P	AW	0.1122 b	0.0190	0.1084	0.1158
CT	1P	(m^3 m^{-3})	0.1078 b	0.0053	0.0930	0.1202
CT	5P		0.0884 a	0.0072	0.0072	0.1002
NT	0P	LLWR	0.0846 c	0.0171	0.0181	0.0950
NT	1P	(m^3 m^{-3})	0.0653 b	0.0405	0.0000	0.1199
NT	5P		0.0483 a	0.0312	0.0000	0.0955
NT	0P	AW	0.0947 b	0.0006	0.0934	0.0958
NT	1P	(m^3 m^{-3})	0.0966 b	0.0098	0.1199	0.0843
NT	5P		0.0827 a	0.0051	0.0760	0.0950

Studied tillage systems, CT (conventional-tillage) and NT (no-till). Treatments 0P, 1P and 5P: number of tractor passes, LLWR (Least limited water range), AW (available water), Se (standard error of the mean). Different letters indicate significant differences ($P< 0.05$) between treatment in each tillage systems.

variation with traffic than the LLWR, making it less sensitive for detecting changes in the soil structure. In contrast, the LLWR reductions, observed in Fig. 2 and Table 4, showed more differences with traffic intensity. These results suggest that the AW values estimated from θFC and θWP would overestimate water availability for plants. For this reason, LLWR would be a more sensitive indicator than water for detecting alterations in soil physical quality when BD increases, being in agreement with Li et al. (2020).

The water content limits θFC, θWP, θAFP and qSRP, based on soil bulk density take part in LLWR, in both tillage systems and the three traffic treatments (Fig. 2 a, b, c, d, e, f).

The equations (1) θ, (3) θSRP and the parameters of Table 2 and Table 3 were used for the calculation of LLWR. In this experiment, of the four LLWR critical limits, only three were the limiting, depending on the tillage system and traffic treatment. In all cases, θFC was the upper limit, in agreement with the results found by Fernández et al. (2017). The lower limits were θWP and θSRP, in all treatments, except for CT 5P, where the lower limit was θSRP (Fig. 2f).

BD variation had no impact on water content in θFC and θWP in the treatments without traffic (Fig. 2 a, b), which agrees with the results obtained by Fernández et al. (2017) for Petrocalcic Paleustol with a loam to loamy sand texture. The θFC was not reduced with increasing BD because the soils were already settled in both tillage systems. It is important to note that the absence of tillage in NT did not decrease θFC in comparison with CT (Fig. 2a and 2b).

When the treatments to which traffic was applied were analyzed, these critical limits (θFC and θWP) increased the negative slope (coefficient *b* Table 2) with BD, tending to be parallel to each other in each treatment (Fig. 2 c, d, e, f), being in agreement with the data provided by da Silva (1994). According to de Lima et al. (2020), this effect is caused by the reduction in pore size due to traffic, which increases the suction pressure required by roots to absorb water and nutrients. Increasing BD coincided with a decrease in θAFP in all treatments. The θAFP did not replace θFC as the LLWR upper limit, probably due to the soil texture (Safadoust et al., 2014; Fernández et al., 2017), whereas θSRP decreased LLWR in all treatments. These results agree with those obtained by Betz et al. (1998), and Fernández et al. (2017).

In CT, the LLWR lower limits were different for each treatment, being θWP for CT 0P and CT 1P (Fig. 2 a, d); whereas the lower limit was θSRP for CT 5P. Specifically, 37% of the CT 0P samples decreased the LLWR by the lower limit θSRP when the BD was over 1.26 Mg m^{-3} (Fig. 2 b), whereas for CT 1P the percentage ascended to 72% with a BD over 1.10 Mg m^{-3} (Fig. 2 d).

Under soil drying conditions, soil resistance is the critical limit that most often reduces the LLWR. In the present study, the number of samples where the critical limit of LLWR is reduced by θRP and where BD begins the restriction would indicate a reduction in the structural quality of the soil.

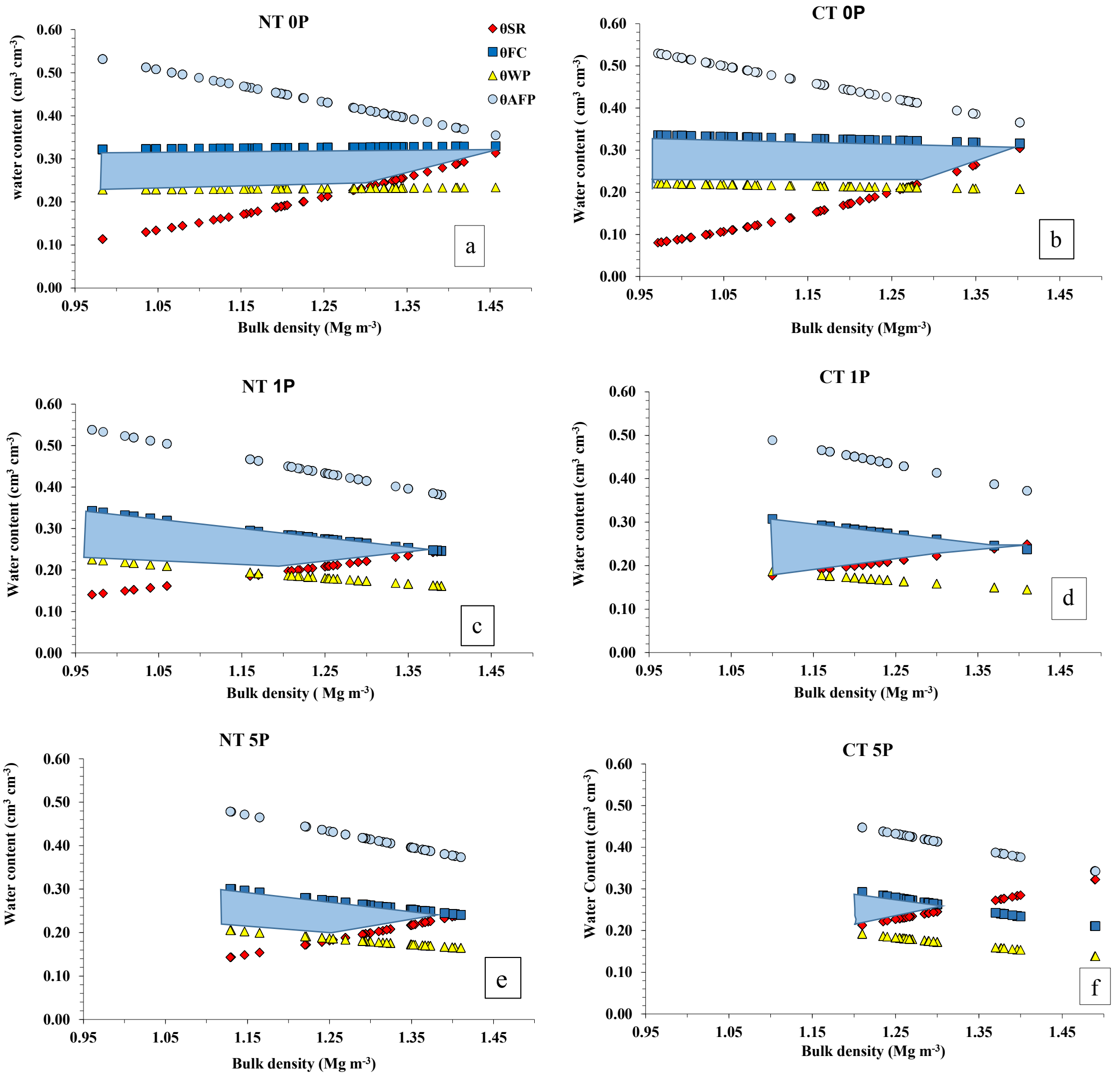

Fig. 2. Water content variation with soil bulk density at critical levels of field capacity (θFC) of -0.033 MPa, at wilting point (θWP) of -1.5 MPa, at air-filled porosity (θAFP) of 10%, and at soil resistance to penetration (θSRP) of 2 MPa. Shaded area represents the least limiting water range (LLWR), for tillage systems and traffic treatments. NT (no-till) and CT (conventional tillage); without traffic (0P); with one tractor pass (1P); with five tractor passes (5P).

In CT 5P, none of the samples exhibited θWP as the lower limit for LLWR. Among the samples, 46% displayed LLWR restrictions at a BD of 1.21 Mg m^{-3} (Fig. 2f), while the remaining samples exceeded the upper limit (θFC) at a BD of 1.32 Mg m^{-3}, equivalent to the BDc, where LLWR=0. This suggests that the physical conditions were highly inhibitory to root growth. The 42% of the NT 0P samples presented LLWR limitations at a BD of 1.28 Mg m^{-3} (Fig. 2 a). This value ascended to 87% at a BD of 1.17 Mg m^{-3} for NT 1P (Fig. 2 c), and to 83% at a BD of 1.25 Mg m^{-3} for NT 5P (Fig. 2e).

The impact of traffic on NT was lower than in CT, since the BD at which θSRP was the LLWR lower limit was lower in the CT treatments. In addition, no samples were found with a BD greater than BDc, i.e., when traffic increases in the NT system, the water availability near the root is less affected than in CT.

The BDc, where LLWR equals zero (Fig. 2 a, b), was never reached by any treatment without traffic, which coincides with the findings of Fernández et al. (2017) in a soil with similar texture. Extrapolating θSRP and θFC, the common point was at a BDc of 1.40 and 1.47 Mg m^{-3} for CT 0P and NT 0P, whereas all treatments with traffic reached BDc. For CT, BDc decreased while traffic increased (1.37-1.33 Mg m^{-3} for CT 1P and CT 5P). Nevertheless, BDc was higher in NT than in CT both for NT 1P and NT 5P (1.39-1.41 Mg m^{-3}). These results show that the CT system is more sensitive to traffic due to lower stability than the NT system, coinciding with the results obtained by Iglesias et al. (2017). The BDc values showed a greater BD range in which roots can obtain water in NT rather than in CT. This suggests that NT would improve soil structure in the long term by avoiding soil deformation and reduction of pore space due to traffic.

Least limiting water range as a function of bulk density/ functional relation between LLWR and bulk density

Root growth in tillage systems with traffic will be restricted depending on the magnitude of the θ change in LLWR, and the relationship between volumetric water and BD (Betz et al., 1998).

The horizontal range of the curves shows favorable conditions for root development (Fig. 3). In addition, the higher the BD range, the better the soil structural conditions. From the BD value where θSRP begins to restrict the LLWR, the lower the negative slope of the curve, the greater the range of BD and the better the structural conditions of the soil.

A wide range of LLWR and BD suggests favorable conditions for root development, while a narrow range of LLWR and BD indicates a restrictive environment for roots.

For tillage systems without traffic, the LLWR was not affected by an increase in BD up to 1.26 Mg m^{-3} for CT 0P, and 1.30 Mg m^{-3} for NT 0P (Fig. 3), after which the LLWR decreased in both systems. This indicates that the unrestricted LLWR range by the θSRP was higher in NT, and thus the water and nutrient uptake environment for plants would be more favorable.

Up to BD 1.30 Mg m^{-3}, the LLWR values were higher in CT0P, and then it decrease with BD showed a steeper slope than for NT 0P (Fig. 3). The behavior of LLWR can be explained by the changes induced by tillage systems in the BD and soil structure, which according to Tavanti et al. (2019) cause changes in total porosity and its distribution. As a consequence, AW, AFP and resistance to root penetration could also show changes, in many cases associated with soil organic matter losses (da Silva and Kay 1997).

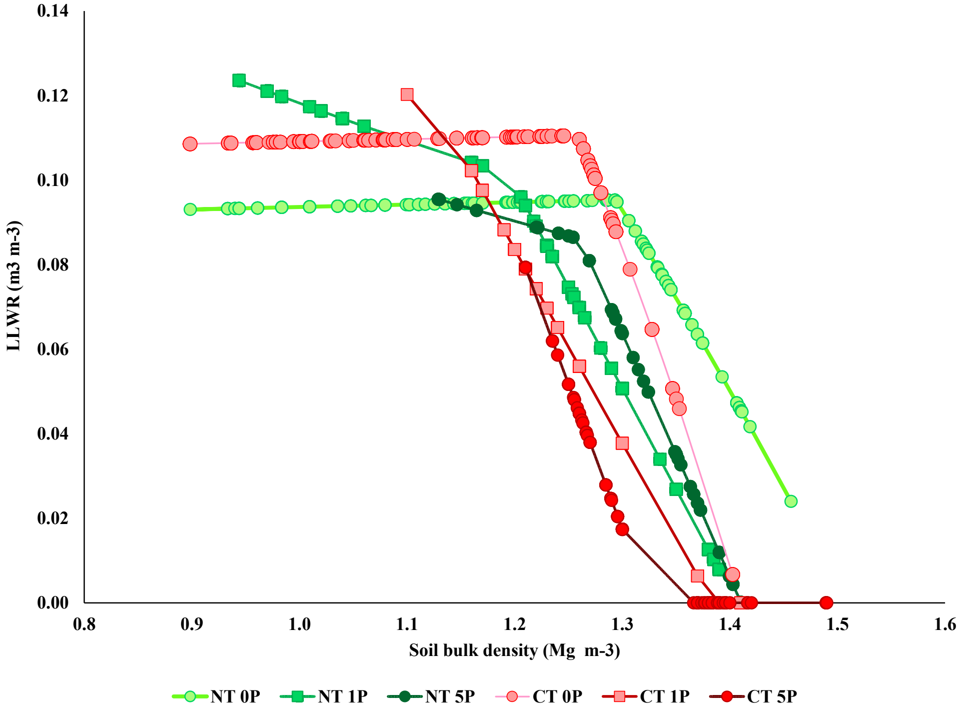

Fig. 3. Optimal water range (LLWR) variation as a function of soil bulk density in NT (no-till) and CT (conventional tillage); a, without traffic (0P); b, with one tractor pass (1P); c, with five tractor passes (5P).

These results suggest that the water content values for root growth in NT 0P were higher than in CT 0P at high densities, which agrees with those of Guedes Filho et al. (2013). Furthermore, the density ranges with LLWR > 0 was higher in NT 0P, clearly showing the better conditions for roots in this treatment, which is in agreement with Betz et al. (1998).

Traffic reduced LLWR in both tillage systems (Table 1). Nevertheless, the response was different; for NT 1P, the slope was negative and smoother until a BD of 1.17 Mg m^{-3}, and then it increased to a value similar to the slope of the CT 1P treatment, which presented a pronounced negative slope throughout the range of the BD studied (Fig. 3).

The range of BD with LLWR >0 was similar for both systems. However, in the NT system, the increase in BD from 0.94 to 1.17 Mg m^{-3} did not practically alter the range of humidity in which the roots grow with minimal restrictions. On the contrary, the minimum BD increase in CT caused a large reduction, exposing the crops to restrictive conditions for their development.

When we analyzed the 5-pass traffic treatments, the range of LLWR values was higher in NT. On the other hand, the range of LLWR>0 in CT 5P corresponds to a lower range of bulk densities than in NT 5P. As observed in Fig. 3, in NT 5P, the lower limit up to BD 1.25 Mg m^{-3} was θWP. On the other hand, the lower limit of LLWR in CT 5P was θSRP for the entire BD range. Therefore, NT 5P showed a greater resistance of the soil to the structure degradation and expressed a more favorable environment for root development.

In all NT treatments, the range of densities with water available to the roots was higher than in CT. The tillage system influenced the traffic effect since the CT 1P density range is equal to the NT 5P density range.

The higher the value of the LLWR and the greater the BD range in which the LLWR > 0, the lower the probability that the crops will suffer restrictive conditions due to lack of water, reduced AFP or high SRP (da Luz et al., 2022). Under these conditions, the period between rains in which crops can grow with minimal restrictions could be longer (da Silva and Kay 2004).

CONCLUSIONS

The tillage systems and traffic intensity produced different responses in the soil structural condition, detected through the least limiting water range (LLWR). In both tillage systems, the highest LLWR was observed in the treatment without traffic. In this treatment, the widest range of bulk density (BD) in which the LLWR>0 was verified.

In all treatments, the soil resistance penetration was the variable that reduced the amplitude of the LLWR.

The available water (AW) content showed less variation with traffic than the LLWR, making it less sensitive for detecting changes in the soil structure.

The range of BD, in which the LLWR>0, was reduced with an increase in traffic intensity, with this reduction being more notable in the conventional tillage (CT) system. The LLWR values were similar in 1P in both tillage systems. In all treatments, the lowest BDc value (LLWR=0) was reached with CT 5P and at a lower BD value than in NT 5P, denoting more severe restrictive conditions for crop root development. These results provide evidence of a greater risk of soil degradation under CT with respect to NT management.

ACKNOWLEDGEMENTS

The authors wish to thank Asociación Argentina de Productores en Siembra Directa (AAPRESID)-Regional Bahía Blanca. We would also like to give special thanks to Hogar Funke, where the sampling was carried out. We also want to thank to engineer Laura Vallejos and Mrs. Rosemary Scoffield for their valuable contribution in the revision of grammar and spelling in this article.

Statements and Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

The authors declare active participation in the bibliographic review by Adrián Vallejos and Julio Iglesias in the development of the methodology: Adrián Vallejos; Julio Iglesias and Juan Galantini; in the discussion of the results: Adrián Vallejos; Julio Iglesias; Juan Galantini and Silvia Imhoff; in review and approval of the final version of the article: Adrián Vallejos; Julio Iglesias; Juan Galantini and Silvia Imhoff.

LITERATURE CITED

Antille, D. L., S. Peets, J. Galambošová, G.F. Botta, V. Rataj, M. Macak, and R.J. Godwin. 2019. Soil compaction and controlled traffic farming in arable and grass cropping systems. Agronomy Research 17(3): 653–682. https://doi.org/10.15159/AR.19.133

Benjamin, J.G., and D.L. Karlen. 2014. LLWR techniques for quantifying potential soil compaction consequences of crop residue removal. Bioenergy Res., 7(2):468-480.

Betz, C.L., R.R. Allmaras, S.M. Copeland, and G.W Randall. 1998. Least limiting water range: traffic and long-term tillage influences in a Webster soil. Soil Sci. Soc. Am. J. 62(5):1384-1393. doi: 10.2136/sssaj1998.03615995006200050034x

Bradford, J.M. 1986. Penetrability, p 463-477.In Klute (ed.) Methods of soil Analysis. Part 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI, USA.

Busscher, W.J. 1990. Adjustment of flat-tipped penetrometer resistance data to a common water content. Trans. ASAE 33(2): 519-0524. doi: 10.13031/2013.31360.

Carter, S.R. 1990. Relative measures of soil soil bulk density to characterize compaction in tillage studies on fine Sandy loams. Can. J. Soil Sci. 70:425-433. doi: 10.4141/cjss90-042

Chen, G., R. Weil, and R. Hill. 2014. Effects of compaction and cover crops on soil least limiting water range and air permeability. Soil Tillage Res. 136:61-69. doi: 10.1016/j.still.2013.09.004

Colombi, T., L.C. Torres, A. Walter, and T. Keller. 2018. Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth–A vicious circle. Science of the Total Environment 626: 1026-1035.

da Luz, F.B., G.A.F. Castioni, C.A. Tormena, R. dos Santos Freitas, J.L.N. Carvalho, and M.R. Cherubin. 2022. Soil tillage and machinery traffic influence soil water availability and air fluxes in sugarcane fields. Soil Tillage Res. 223:105459. doi:10.1016/j.still.2022.105459

da Silva, A.P., B.D. Kay, and E. Perfect. 1994. Characterization of the least limiting water range of soils. Soil Science Society of America Journal 58(6):1775-1781. doi: 10.2136/sssaj1994.03615995005800060028x

da Silva, A.P., and B.D. Kay. 1997. Estimating the least limiting water range of soils from properties and management. Soil Science Society of America Journal 61(3):877-883. doi:10.2136/sssaj1997.03615995006100030023x

da Silva, A.P., and B.D Kay. 2004. Linking process capability analysis and least limiting water range for assessing soil physical quality. Soil Tillage Res. 79(2):167-174. doi:10.1016/j.still.2004.07.005

de Lima, R. P., M. M. Rolim, C Dantas, D. D., A. R. da Silva, and E.A. Mendonça. 2020. Compressive properties and least limiting water range of plough layer and plough pan in sugarcane fields. Soil Use and Management 37(3):533-544. doi: 10.1111/sum.12601

de Moura, M. S., B.M. Silva, P.K. Mota, E. Borghi, A.V. de Resende, S.F. Acuña-Guzman, and N. Curi. 2021. Soil management and diverse crop rotation can mitigate early-stage no-till compaction and improve least limiting water range in a Ferralsol. Agricultural Water Management 243: 106523.

Di Rienzo, J., F. Casanoves, M.G. Balzarini, L González, M. Tablada, y C.W. Robledo. 2019. InfoStat, Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina. Disponible: URL http://www.infostat.com.ar 13/09/2024.

Duval, M. E., J. M. Martinez, and J.A. Galantini. 2020. Assessing soil quality indices based on soil organic carbon fractions in different long-term wheat systems under semiarid conditions. Soil Use and Management 36(1):71-82.

Fernández, R, A. Quiroga, C Lobartini, and E. Noellemeyer. 2017. Determinación del intervalo hídrico óptimo en Ustoles de la región semiárida pampeana. Ciencia del suelo (Argentina) 35(2):215-227.

Guedes Filho, O., H. Blanco-Canqui, and A.P. da Silva. 2013. Least limiting water range of the soil seedbed for long-term tillage and cropping systems in the central Great Plains, USA. Geoderma 207:99-110. doi:10.1016/j.geoderma.2013.05.008

Haghighi Fashi, F., M. Gorji, and F. Sharifi. 2017. Least limiting water range for different soil management practices in dryland farming in Iran. Archives of Agronomy and Soil Science 63(13): 1814-1822.

Iglesias J.O., J.A. Galantini, y A.G. Vallejos. 2017 Estabilidad de agregados de un argiudol del SO bonaerense con diferentes sistemas de labranza. Ci. Suelo (Argentina) 35(2):189-20.

Iglesias, J.O., J.A. Galantini, A. Vallejos, y S. Imhoff. 2021. Intervalo hídrico óptimo en un argiudol del SO de la provincia de Buenos Aires en dos sistemas de labranzas. Ciencia del suelo Argentina 39(2):253-267.

Imhoff, S., A. Da Silva, P Ghiberto, and C. Tormena. 2016. Physical Quality Indicators and Mechanical Behavior of Agricultural Soils of Argentina. PLOS One 11(4):1-21. doi: 10.1371/journal.pone.0153827

Keller, T., and I. Håkansson. 2010. Estimation of reference bulk density from soil particles size distribution and soil organic matter content. Geoderma 154(3-4):398-406.

Keller, T., A.P. Da Silva, C.A. Tormena, N.F.B., Giarola, K. M. V. Cavalieri, M. Stettler, and J. Arvidsson. 2015. SoilFlex-LLWR: linking a soil compaction model with the least limiting water range concept. Soil Use and Management 31(2):321-329.

Klute, A. 1986 Water Retention: Laboratory Methods, p 635-662. In Klute (ed.) Methods of soil Analiysis. Part 1. 2nd. ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI, USA.

Leão, T. P., and A. P. D Silva. 2004. A simplified Excel® algorithm for estimating the least limiting water range of soils. Scientia Agricola 61:649-654.

Leão, T.P., A.P. da Silva, E. Perfect, and C.A. Tormena. 2005. An algorithm for calculating the least limiting water range of soils. Agronomy Journal 97:1210–1215. doi:10.2134/agronj2004.0229

Letey, J. 1985. Relationship between Soil Physical Properties and Crop Production. In: Stewart, B.A. (eds) Advances in Soil Science. Advances in Soil Science 1:277-294. Springer, New York, NY. doi:10.1007/978-1-4612-5046-3_8

Li, S., X. Wu, G. Liang, L. Gao, B Wang, J. Lu, and A. Degré. 2020. Is least limiting water range a useful indicator of the impact of tillage management on maize yield. Soil Tillage Research 199:104602. doi:10.1016/j.still.2020.104602

Lima, C.L., L.A. Suzuki, D.J. Reinert, and J.M. Reichert. 2015 Least limiting water range and degree of compactness of soils under no-tillage. Bioscience Journal 31(4):1071- 1080.

Martínez, J. M., J.A. Galantini, M.E. Duval, and F.M. López. 2017. Tillage effects on labile pools of soil organic nitrogen in a semi-humid climate of Argentina: A long-term field study. Soil Tillage Res. 169:71-80. doi.org/10.1016/j.still.2017.02.001.

Reichert, J. M., V. T. da Rosa, E. S. Vogelmann, D. P. da Rosa, R. Horn, D.J. Reinert... and J.E. Denardin. (2016). Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. Soil and Tillage Research 158:123-136.

Safadoust, A., P. Feizee, A. Mahboubi, B. Gharabaghi, S.R. Mosaddeghi, and B Ahrens. 2014. Least limiting water range as affected by soil texture and cropping system. Agric. Water Manag. 136:34-41. doi:10.1016/j.agwat.2014.01.007

Tavanti, R.F.R., O. da Silva Freddi, V. Marchioro, T.R. Tavanti, F.S. Galindo, F.J. Wruck, and C.C. Breda. 2019 Least limiting water as a soil indicator in an integrated crop-livestock system of the Cerrado, Brazil. Geoderma Regional 19:e00232. doi:10.1016/j.geodrs.2019.e00232