Crack formation in a Mediterranean rainfed Vertisol: Effects of tillage and crop rotation

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ABSTRACT

The frequency, size and development rate of Vertisols cracks influence the water, solute and heat dynamics and hence on the crop productivity. The aim of this study was to evaluate the effect of the tillage system and crop rotation on the behaviour of cracks and soil compaction in a long-term experiment that was initiated in 1986 on a Mediterranean rainfed Vertisol in southern Spain. The treatments studied were conventional tillage (CT) vs. no-tillage (NT) for five crop rotations: wheat (*Triticum aestivum* L.) - chickpea (*Cicer arietinum* L.), wheat - sunflower (*Helianthus annuus* L.), wheat - faba bean (*Vicia faba* L.), wheat - bare fallow and continuous wheat. The following parameters were measured: penetration resistance, water content at harvest, and perimeter, depth and width of crack. Soil compaction was greater in NT compared to CT in the top 10 cm of soil, with the opposite occurring between 10 and 40 cm. The surface area and volume of cracks was significantly greater in CT than in NT. The perimeter of the cracks was greater in wheat monoculture plots but with smaller crack width and depth in relation to the other studied biannual rotations. The water content at harvest recorded in the first 30 cm of soil was negatively correlated with the depth of cracks. The characterization of the cracks in Vertisols is very important for estimating losses or recharging the water in the soil profile as well as for evaluating its compaction and stability.

Keywords: penetration resistance; water content; crack width; crack depth; crack perimeter, tillage, crop rotation

INTRODUCTION

Many studies indicate that existing cracks destroy soil integrity, diminish soil strength, and weaken its sliding ability; on the other hand, cracks provide a favourable pass for water seepage and evaporation (Shi et al., 2014). Soil crack patterns are closely related to soil properties such as swelling clay and soil organic carbon (Zhang et al., 2016). The frequency, size and development rate of cracks influence the water, solute and heat dynamics of the soil and hence influence crop productivity and the potential for ground water pollution (Bandyopadhyay et al., 2003). The cracks can also improve the air regime (Choudhary, 2015).

A large number of factors influencing soil-cracking behaviour have been studied, including temperature, wetting-drying cycles, layer thickness, soil types (Tang et al., 2010), mineral composition, soil moisture (Kishné et al., 2012) and tillage practices (Bandyopadhyay et al., 2003). Cracks are also influenced by the type of crops grown, as plant roots are known to affect cracking patterns by anchoring the soil mass and influencing soil shrinkage (Fox, 1964; Mitchell, 1991; Mitchell and Van Genuchten, 1992).

Vertisols are also well known for developing wide and deep cracking patterns, which greatly influence water flow (Novak et al., 2000) and can adversely affect crop production under rainfed conditions (Gargiulo et al., 2015). Typical cracks of Vertisols have a direct relationship with the grade and size distribution of the clods that form on its surface when it is tilled, so that the pattern of cracking affects soil tillage (Ahmad and Mermut, 1997). Soil cracks provide an opportunity for water recharge; otherwise, due to the low permeability of these soils, it would be slower (Gardner and Coughlan, 1982; Bouma, 1984; Mitchell and Van Genuchten, 1992). Conversely, cracks extend the contact surface between the ground and the air inside the profile, thereby potentially increasing water loss by evaporation (Adams and Hanks, 1964; Ritchie and Adams, 1974).

Many researchers have tried to improve the description of soil cracks through image analysis (Hallaire, 1984; Perrier et al., 1995; Velde, 1999; Vogel et al., 2005). However, quantification of soil cracks is still a challenge because of their irregular patterns. Peng et al. (2006) introduced digital image analysis to non-destructively and continuously measure soil cracks. Liu et al. (2008) illustrated the procedures of image processing for quantifying crack patterns and proposed some parameters, including crack area density, crack width, fractal dimension, and the connectivity index.

There is little information about how certain agricultural practices can alter the physical properties of a Vertisol in Mediterranean conditions. Therefore, the objectives of this study conducted in a Vertisol under Mediterranean rainfed conditions was i) to evaluate the effect of tillage systems and crop rotation on the behaviour of cracks and soil compaction, ii) to determine the relationships between the different crack parameters and the water content and iii) to evaluate digital photography as an alternative method to characterize the cracks.

MATERIALS AND METHODS

2.1. Site and experimental design

Field experiments were conducted in Cordoba, southern Spain (37º 46’ N and 4º 31’ W, 280 m.a.s.l.) on a Vertisol (Typic Haploxererts) typical of the Mediterranean region (Table 1), where rainfed cultivation is the standard practice. The Vertisol is found on sedimentary plain, on hill slope and piedmont plain. The Vertisol has no gilgai subsurface features. This soil presents swelling clay minerals, mainly vermiculite and montmorillonite. Parent material is very deep Miocene loam. The water table is very deep.

The soil electrical conductivity was 0.44 dS m^{-1}. The study took place within the framework of a long-term experiment that was initiated in 1986, called "Malagon" that began in 1986 and was designed as a randomized complete block with a split-plot arrangement and 3 replications. The main plots tested the effects of the tillage system (no-tillage and conventional tillage); the subplots tested 2-year crop rotations [wheat (*Triticum aestivum* L.) - chickpea (*Cicer arietinum* L.), wheat - faba bean (*Vicia faba* L.), wheat - sunflower (*Helianthus annuus* L.), wheat - bare fallow and continuous wheat]. Each rotation was duplicated in a reverse crop sequence to obtain data for all crops on a yearly basis. The area of each sub subplot was 50 m^2 (10 × 5 m).

2.2. Climatic conditions

A 30-year annual average rainfall in the area was 584 ± 204 mm. Annual rainfall was 702 mm, slightly greater than the average of the study area with a distribution model typical of the Mediterranean region, with abundant rainfall in autumn, scarcer rainfall with more variability in spring and low rainfall and high temperatures in summer (Fig. 1).

2.3. Crop management

The no-tillage (NT) plots were seeded with a no-till seed drill. Weeds were controlled by applying glyphosate (N-[phosphonomethyl] glycine) + MCPA ([4-chloro-2-methylphenoxy] acetic acid) at a rate of 0.5 + 0.5 L active ingredient ha^{-1} before planting. The conventional tillage (CT) treatment included mouldboard ploughing, disk harrowing and/or vibrating tine cultivation to prepare the seedbed. Lopez-Bellido et al. (2007) provided information about the cultivars, planting, and herbicides applied during the growing season. Each year, the wheat plots were supplied with 100 kg N ha^{-1} and 65 kg P ha^{-1}. The fertilizer was incorporated according to standard conventional tillage practices and was applied in bands when drilling in the no-tillage plots.

2.4. Soil Measurements

2.4.1. Penetration Resistance

The penetration resistance was measured in each plot of wheat and during the state of tillering by taking four random measurements using an Eijkelkamp 06.02 penetrograph to a depth of 80 cm. The readings were recorded in MPa at intervals of 15 cm, having the tip of the penetrograph use a base area of 1 cm^2 and an 11.28 mm diameter.

2.4.2. Water content in the soil at harvest

The water content was measured three times in all plots after harvesting wheat to a depth of 0.9 m and at 0.3 m intervals. Measurements were performed with a ThetaProbe ML2x (AT Delta-T Devices, UK) soil moisture sensor.

2.4.3. Manual characterization of soil cracks at harvest

a) Apparent length (m): determined with a flexible tape with a depth of 1-3 cm to avoid inaccuracies that the surface layer of these soils may cause (Dasog et al., 1988).
b) Depth (m): determined with a flexible meter stick (3 mm in diameter and 1.3 m in length). The number of measurements per crack was variable depending on the crack size, but as a rule, a measurement was taken every 30 cm of crack length. When the crack was very short, measurements were made at the ends and in the centre.
c) Width (m): determined with a calliper for inside diameters and at a depth of 1-3 cm for the same reasons as the apparent length. This measurement was made at the same points in which depths were taken following the same cadence.

From these measurements, the crack surface (S) per soil area unit ($m^2\ m^{-2}$) and the volume of crack (V) per unit area ($m^3\ m^{-2}$) was calculated according to the following formulas (Sharma et al., 1995):

$$S = \sum (2\ C\ l), \text{ where } C = [(0.5\ w)^2 + d^2]^{1/2}$$
$$V = \sum (0.5\ w\ d\ l)$$

With "l" as the apparent length of the crack, "w" the crack width and "d" the depth of the crack, assuming that the cross section of the cracks resembles an isosceles triangle.

2.4.4. Characterization of soil cracks by digital

Digital images were taken after the removal of waste straw and prior to taking the manual measurements described above to avoid soil disturbance. The images were taken with a Nikon Coolpix 5700 camera. The camera was mounted on a tripod at a height of one meter from the ground where a square frame was used as reference. Figure 2 is an example of digital photography images. To calculate the crack area and perimeter (horizontal projection) from the images taken, CIAS 2.0 (CID, 2002) software was used.

2.5. Statistical analysis

The data for each variable were subjected to analysis of variance (ANOVA) using a randomized complete block design combined with the error term according to McIntosh (1983). The blocks (replications) were considered random effects, while the tillage system, crop rotation and soil depth were considered fixed effects. Means were compared using the Fisher's protected least significant difference (LSD) test at $P < 0.05$. LSDs for the different main effects and interaction comparisons were calculated using appropriate standard error terms according to Gomez and Gomez (1984). The Statistix v. 9.0 (Analytical Software, 2008) package was used for this purpose.

RESULTS

3.2. Soil water content at harvest

The tillage system did not influence the water content at any depth (Fig. 3A).

The water content was significant for the previous crop in the 0-30 and 30-60 cm soil layers and also for the average of the full profile (0-90 cm) (Table 2, Fig. 3B). In these soil layers, the highest water content at harvest was observed in the plots where the previous crop was wheat, showing mean values of 0.27 m^3 m^{-3}, 0.39 m^3 m^{-3} and 0.35 m^3

m^{-3} for 0-30, 30-60 and 0-90 cm (full profile), respectively, without differences in the other rotations (Fig. 3B).

3.3. Soil penetration resistance

The penetration resistance showed significant differences for the tillage system from 0 to 40 cm of depth (Fig. 4A). In the topsoil (0-10 cm), resistance to penetration was greater in NT than in CT. However, from 10 to 40 cm, the opposite occurred, and from that point, there were no differences between the tillage systems (Fig. 4A). The evolution of the values of penetration resistance from the surface to 30 cm under the CT system was very rapid, going from values below 1 MPa to 3.44 MPa. This value was maintained to 40 cm, descending from here very gently to 80 cm of depth, where the resistance had a value of 2.96 MPa (Fig. 4A). The values in the NT show a less pronounced performance at depth, increasing from the surface to 40 cm and then remaining stable to 80 cm (Fig. 4A).

In relation to the previous crop, there are significant differences beginning at a depth of 10 cm. In these layers, the penetration resistance was greater in plots with sunflower as the preceding crop, while the other plots showed no significant differences between them (Fig. 4B).

3.4. Crack parameters from manual measures

There were significant differences in the total perimeter of cracks with respect to the previous crop, being wheat where the perimeter was highest (Table 2, Fig. 5). The crack width was significant compared to the previous crop and to the tillage x previous crop interaction (Table 2). The smallest width was found with wheat as the preceding crop; no differences were found between the others (Fig. 6A). Considering rotations, the crack width was greater in CT than in NT for faba bean and fallow (Fig. 6A). Wheat as the preceding crop had the lowest average crack depth, differing significantly from the rest of the preceding crops, which have values below 0.27 m, corresponding to the value of chickpea as a preceding crop (Fig. 6B). There was a positive linear correlation between crack depth and crack width [crack depth (cm) = 0.72 crack width (cm) + 3.97] (r^2=0.47, n =30, p<0.001).

The crack surface area was greater in CT than in NT (5 m^2 m^{-2} vs. 4 m^2 m^{-2}), as well as crack volume (0.04 m^3 m^{-2} vs. 0.03 m^3 m^{-2}) (Table 3).

There was a negative correlation between the topsoil (0-30 cm) water content at harvest and the depth of cracks [crack depth (cm) = -30.00 water content (m^3 m^{-3}) + 29.68] (r^2=0.24, n =30, p<0.01).

3.5. Crack measurements using digital images

The crack perimeter through digital photography was significant with regard to crop rotation (Table 2), where it was greater with the wheat as the precedent than with faba bean, sunflower or chickpea (Fig. 5). The crack area showed no significant differences in relation to the parameters studied (Table 2).

A correlation was observed between the digitally calculated crack perimeter and the perimeter obtained by manual measurement (Fig. 7A). In addition, there were positive correlations between the crack area measured with digital images and the surface and volume obtained through manual measurements (Fig. 7B, 7C).

DISCUSSION

The tillage system was not significantly associated with the soil water content at harvest. According to Hatfield et al. (2001), conventional tillage can increase water storage by infiltration, but at the same time, it can also increase losses by evaporation, although excessive tillage may reduce infiltration by affecting hydraulic conductivity.

Wheat monoculture was the rotation in which the greatest water content at harvest was observed. This might occur because, according to Lopez-Bellido et al. (2007), the lowest grain yield was obtained with this rotation.

The penetration resistance of the top layer of the profile (0-10 cm) was greater in NT plots. This result coincides with the results of Potter and Chichester (1993) and Cassel et al. (1995) and could be attributed to the fact that the soil structure under this system remains unchanged and therefore facilitates the aggregation of particles (Barzegar et al. 2003) and the formation of a more defined structure, which may induce a greater penetration resistance. From 10 cm of soil to 40 cm, the resistance was greater under CT. This result may indicate the existence of a compacted layer (tillage pan) caused by the passage of the machinery and tools necessary to perform tilling (Huwe, 2003).

In the average crack depth, with respect to the tillage system, no significant differences were found. However, Bandyopadhyay et al. (2003) found the deepest cracks in no-till plots.

Unlike our case, where we find a lower crack depth in wheat monoculture than in other rotations, Dasog and Shashidhara (1993) found no significant differences between wheat, sunflower, chickpea and fallow.

The crack width was greater in the CT system compared to the NT system when the biannual rotation was wheat – faba bean and wheat - fallow. However, Bandyopadhyay et al. (2003) found that NT plots showed greater crack widths than CT plots. Previous authors, as in this study, indicated that depth and width of cracks were significantly and positively correlated. Bandyopadhyay et al. (2003) found wider cracks in NT and therefore deeper cracks because of this relationship. In our case, the width of cracks was not affected by tillage system, so that there were no differences in crack depth.

Wheat monoculture has the highest crack perimeter and the lowest crack depth and width. This could mean that wheat monoculture plots had many small cracks compared to the other treatments.

The crack surface area was greater under CT. This result is reasonable if one considers that a larger crack surface facilitates water loss by evaporation (Ritchie and Adams, 1974) and that the water content of CT plots, while not significantly different, except in wheat rotation, was lower than in NT plots in the first 30 cm of the profile.

Just as with the surface area, the volume of cracks was greater in CT. However, Bandyopadhyay et al. (2003) observed a greater volume under NT. These authors suggest that the root density could be negatively related to the volume of the cracks, as the roots anchored to the soil mass can cause a decrease in the contraction of this type of soil, and therefore, a greater mass is covered at a greater root density. In a study conducted during the same experiment, Muñoz-Romero et al. (2010) observed a greater root density of wheat for most of the growth stages and depths in NT compared to CT.

The existence of a direct correlation between the crack surfaces obtained by both methods shows that the digital photographs can be a fast alternative for the estimation of the crack surface area.

Bandyopadhyay et al. (2003) observed that all crack parameters were negatively correlated with the water content of the topsoil. In our case, there was only this type of relationship between the soil water content in the surface layer and the depth and width of cracks. According to Choudhary (2015), the crack depth and number are dependent upon the soil water status and rainfall received during the stage, with fewer and more superficial cracks if the water content in the soil increases. Thus, as noted by Flowers and Lal (1999), the increase of soil crack area and volume could be due to the decrease of water content, especially in the soil surface layer.

CONCLUSIONS

The soil compaction was greater in NT compared to CT in the surface layer (0-10 cm), which can be attributed to the improving the formation of aggregates produced in NT. The opposite occurred beginning at a depth of 10 cm, indicating the presence of a tillage pan caused by the passage of the machinery in the CT. Soil compaction was greater in the wheat - sunflower rotation, with this latter being a spring-summer cycle crop with drier soil conditions.

Overall, the surface area and volume of the cracks was greater in CT than in NT.

The crack perimeter was greater in the wheat monoculture plots; however, the cracks were smaller in the width and depth in areas due to the greater degree of ground cover of the cereal throughout the growing season. In the wheat - faba bean and wheat - fallow rotations, the crack widths were greater in CT than in NT.

The water content at harvest recorded in the first 30 cm of soil was negatively correlated with the depth of cracks.

The high significant relationship between the digitally calculated crack perimeter and the manually calculated crack perimeter and the positive relationship between the digitally determined area and the manually evaluated area and volume of cracks suggest that the digital method can be a fast and effective alternative for estimating the dimension of the cracks in a Mediterranean rainfed Vertisol and to indirectly evaluate the water losses and/or storage in the soil profile.

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Table 1. The properties of the Vertisol used in field experiments. Córdoba (Spain)

	Depth[a] (cm)		
	0-30	30-60	60-90
Fine sand (g kg^{-1})	127 (17)	143 (19)	187 (21)
Silt (g kg^{-1})	179 (20)	152 (20)	26 (5)
Clay (g kg^{-1})	694 (35)	705 (37)	787 (39)
Soil-water ratio for pH 1:2.5	7.7 (0.15)	7.6 (0.15)	7.6 (0.1)
Organic matter (g kg^{-1})	10.2 (0.11)	7.4 (0.17)	5.3 (0.2)
Calcium carbonate equivalent (g kg^{-1})	75 (13)	93 (41)	71 (5)
CEC (cmol kg^{-1})	46.5 (3.7)	36.6 (5.4)	30 (6.9)

[a] Standard errors of the means are given in parentheses

Table 2: Significant effect of tillage system, preceding crop and soil depth in soil penetration resistance (SPR), soil water content at harvest (SWC) and different crack parameters.

Source	Manually					Digital photograph		SPR	SWC
	Width	Depth	Perimeter	Area	Volume	Perimeter	Superficial area		
Tillage system (T)	ns	ns	ns	*	*	ns	ns	ns(1)	ns
Preceding crop (P)	*	**	***	ns	ns	**	ns	***(2)	**(4)
T × P	*	*	ns	ns	ns	ns	ns	ns(3)	ns(5)
Depth (D)	–	–	–	–	–	–	–	***	***

(ns: no significant, *,**,***)
(1) only significant differences in 0-10 cm (**), 10-20 cm (*), 20-30 cm (*) and 30-40 cm (*).
(2) no significant differences in 0-10 cm.
(3) only significant differences in 0-10 cm (***).
(4) no significant differences in 60-90 cm.
(5) only significant differences in 0-30 cm (**).

Table 3. Crack surface area and volume measured manuallyas affected by tillage system and preceding crop

treatment	crack surface area *(m^2 m^{-2})*	crack volume *(m^3 m^{-2})*
Tillage system:		
conventional tillage	4.99 ***a******	0.036 ***a***
no tillage	4.01 ***b***	0.025 ***b***
l.s.d. ($p \leq 0.05$)	*0.91*	*0.005*
Preceding crop:		
wheat	4.69 ***a***	0.029 ***a***
fallow	4.45 ***a***	0.030 ***a***
sunflower	4.09 ***a***	0.029 ***a***
chickpea	4.56 ***a***	0.033 ***a***
faba bean	4.69 ***a***	0.034 ***a***
l.s.d. ($p \leq 0.05$)	*1.13*	*0.009*
mean	**4.50**	**0.031**

(*) for each treatment and parameter; different letters show significant differences at $p \leq 0.05$.
Within treatment (years or tillage) means followed by the same letter are not significantly different at P<0.05 according to LSD.

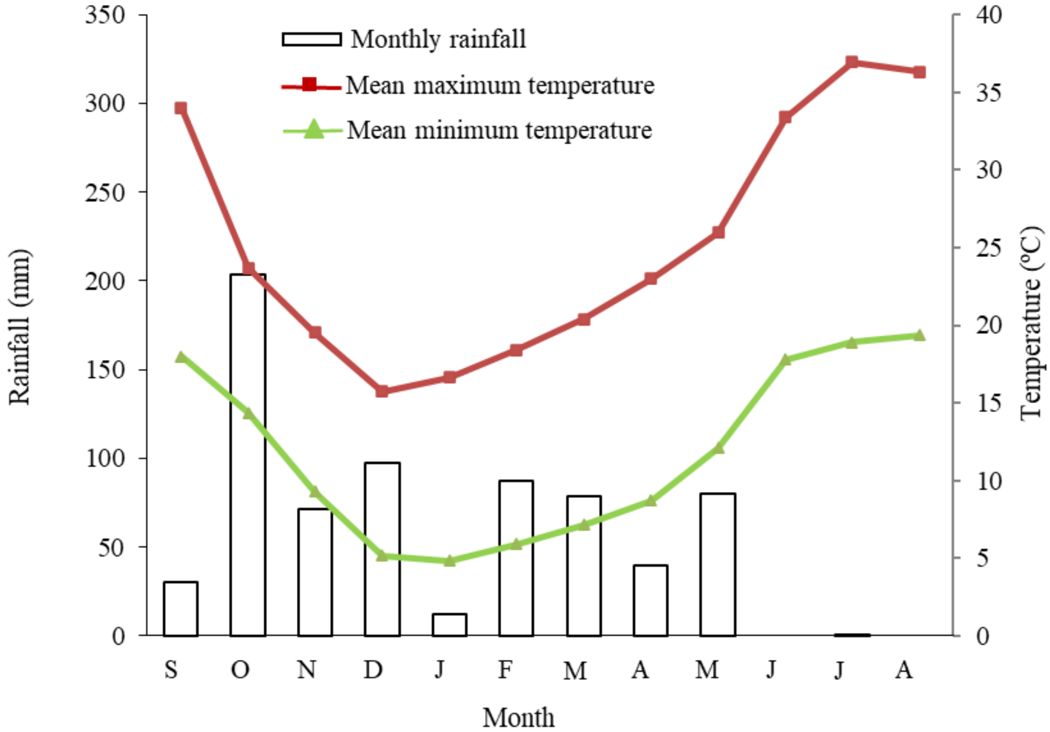

Fig. 1. Monthly and annual rainfall and mean maximum and minimum temperatures over the study period at Cordoba (Spain).

No tillage

Conventional tillage

Fig. 2. Effect of tillage system (A) and preceding crop (B) on the water content in the soil profile (0-90 cm). Horizontal bars in figure 2B represent LSD ($P<0.05$) for the same level of depth. The box indicates the tillage × preceding crop interaction of water content at harvest in the 30 cm of soil depth. Vertical bars in the box represent LSD ($P<0.05$) for the same level of tillage system (a) and for different levels of tillage system (b).

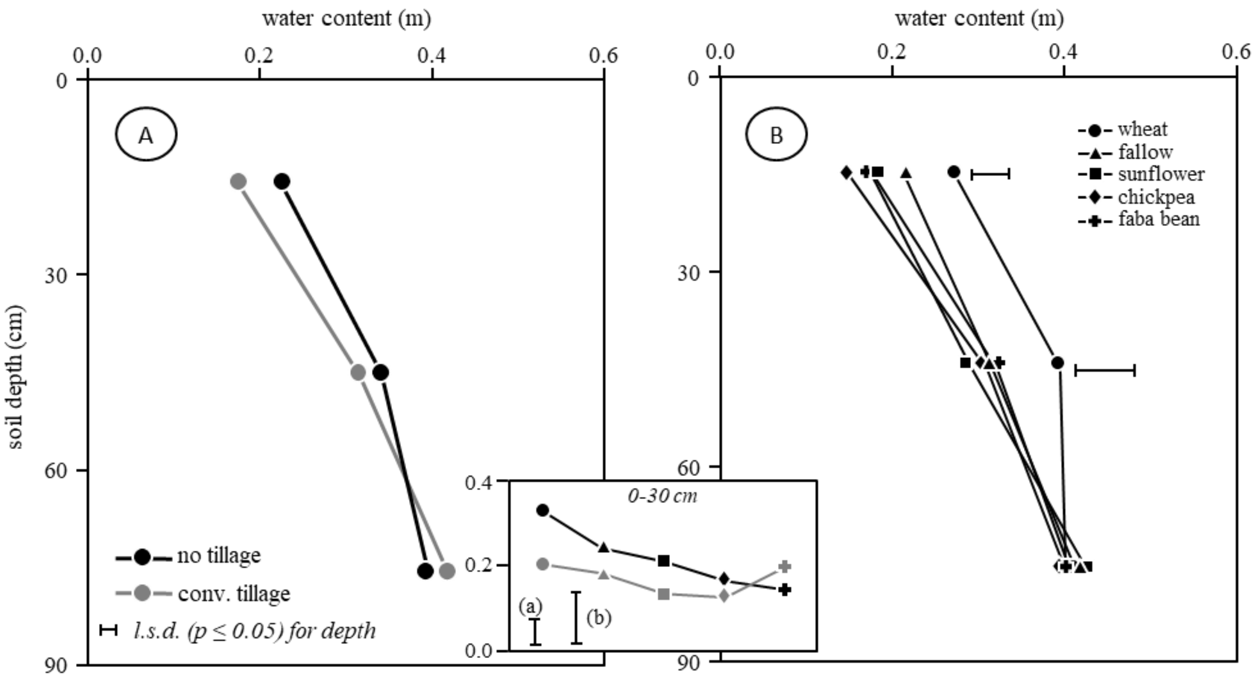

Fig. 3. Effect of tillage system (A) and preceding crop (B) on the penetration resistance of the soil profile (0-90 cm). Horizontal bars in represent LSD (P<0.05) for the same level of depth. The box indicates the tillage × preceding crop interaction of soil strength in the 10 cm of soil depth. Vertical bars in the box represent LSD (P<0.05) for the same level of tillage system (a) and for different levels of tillage system (b).

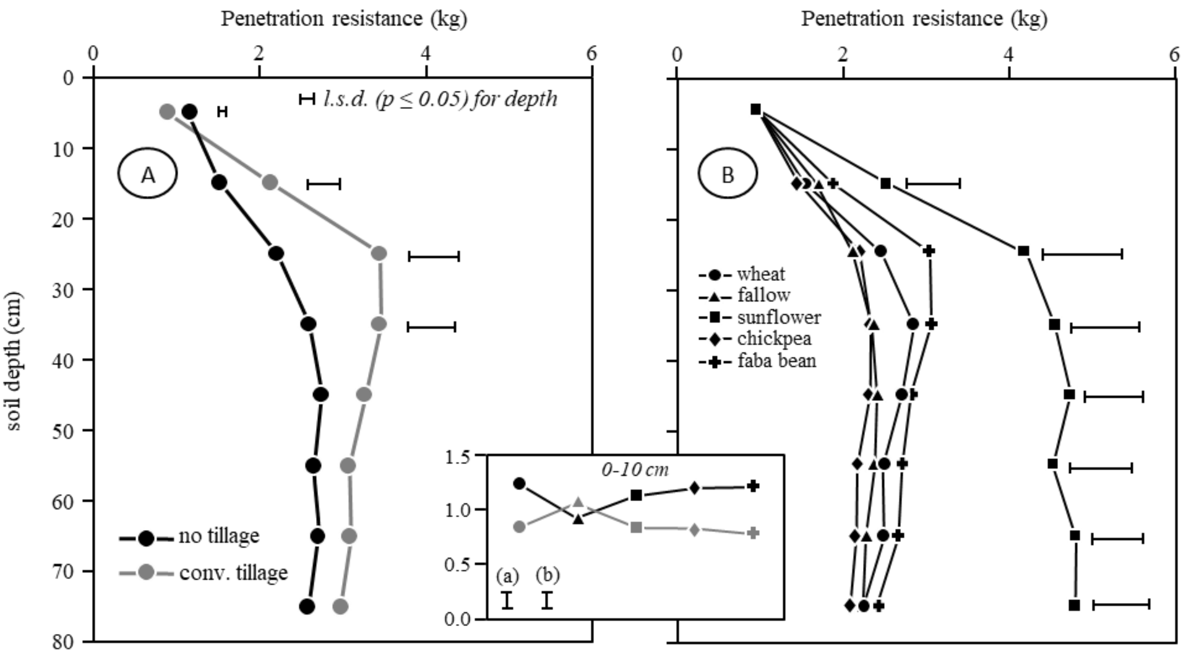

Fig. 4. Effect of preceding crop on crack perimeter measured digitally and manually.

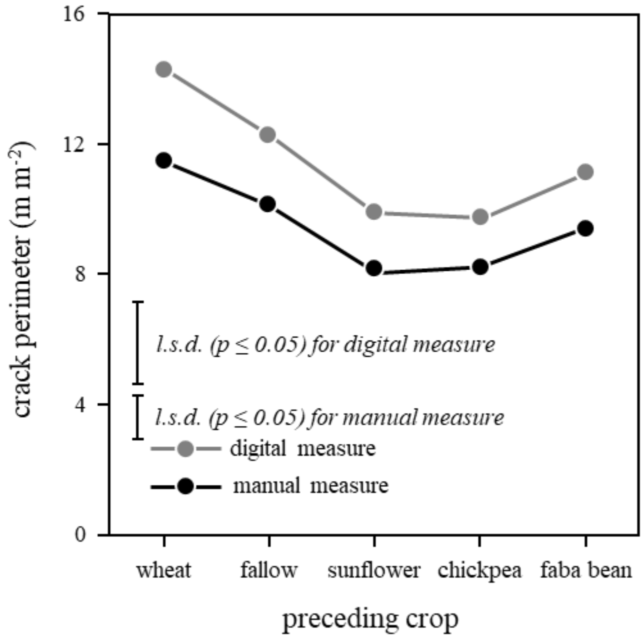

Fig. 5. Effect of tillage system and previous crop on crack width (A) and crack depth (B).

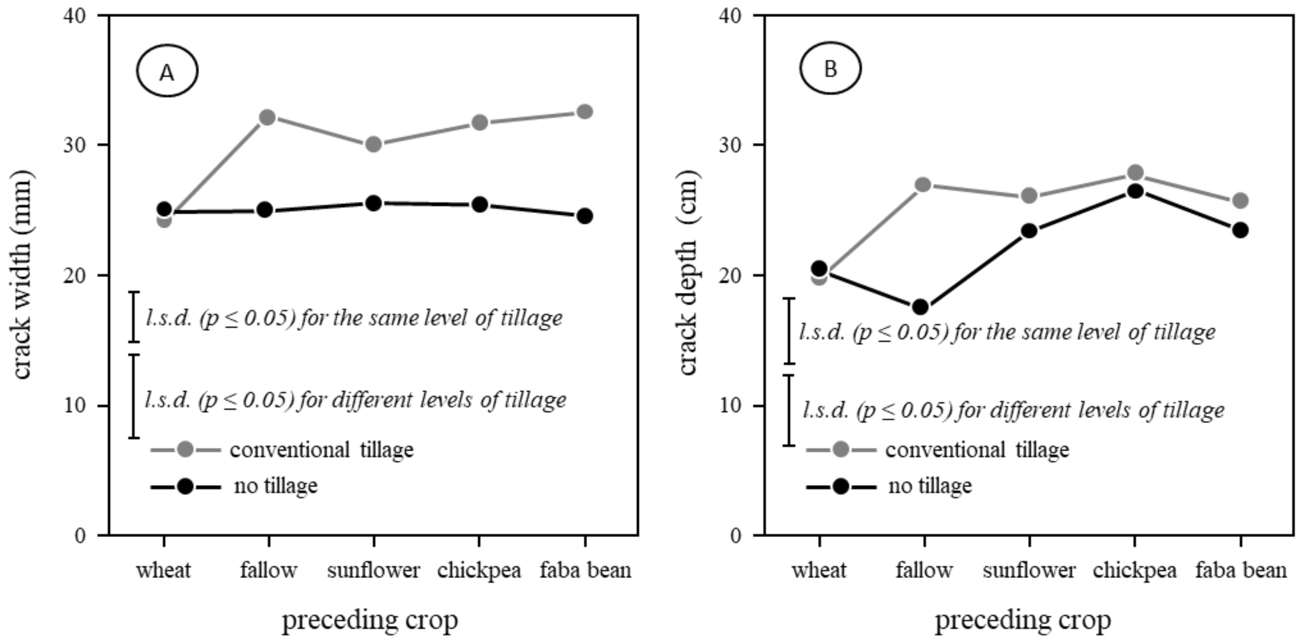

Fig. 6. Relationship between manual and digital crack perimeter (A), manual and digital crack area (B) and crack volume (manual) and area (digital).

Fig . Example of photographs taken in plots of conventional tillage and no tillage.