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The effects of tillage, cover crop and cropping systems on confined compression behavior of a sandy loam soil

Hossein Bayat[1†], Zeinab Zangeneh[2], Ladan Heydari[3], and Javad Hamzei[4]

[1,2 and 3] *Associate Professor, MSc and PhD Students Department of Soil Science, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran*
[4] *Associate Professor, Department of Agronomy and Plant Breeding, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran*

†*Corresponding Author Email: h.bayat@basu.ac.ir*

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ABSTRACT

The confined compression curve (CCC) of soil and its parameters reflect the impact of management operations such as tillage, cover crops, and intercropping on the physical and mechanical properties of the soil. No research has investigated the simultaneous effect of these three factors on the CCC. Therefore, the effects of two different tillage systems, moldboard plowing (MP, conventional tillage) and chisel plowing (CP, reduced tillage), combined with cover crop (CC) and without cover crop (NC) (i.e., planting *Lathyrus sativus* as/without cover crop) and three cropping systems (summer squash (*Cucurbita pepo*), green bean (*Phaseolus vulgaris*), and their intercropping) were investigated on soil compaction characteristics. Next, the CCC of the soil was measured, and its parameters were derived. In MP-CC treatment compared to MP-NC, the compression index (0.43) decreased and pre-compression stress increased by 19%. The low organic matter in NC-summer squash treatment reduced the swelling index (soil mechanical resilience) compared to other treatments in the ranges of 4.76-33%. Besides, MP increased the loading swelling index compared to CP by 33%. Overall, the best management was the application of the CP-CC under intercropping of summer squash with green beans because it reduced the soil compaction. Moreover, CP improved the soil's physical-mechanical properties.

Keywords: Chisel plowing; Compression curve; Lathyrus; Moldboard plowing; Pre-compression stress; Swelling index.

1. Introduction

Soil compaction has become a critical problem due to the increased use of heavy machines (Shaheb et al., 2021) in the field and less variation in cropping culture. Soil compaction negatively affects soil properties, deteriorates soil productivity, and reduces soil porosity and the rate of water infiltration into the soil (Keller et al., 2019). Also, soil compaction causes the early saturation of the soil surface due to less water permeability. In addition, it may result in soil erosion, reduce the soil's water and air retention, and lower root growth and crop yield (McKenzie and Rapoport, 2010).

The soil compression characteristic is a fundamental soil mechanical property that describes the effect of normal stress on soil volumetric parameters. Soil's confined compression curve (CCC) or soil stress-strain curve expresses the relationship between the logarithm of stress applied against the void ratio or bulk density in a semi-logarithmic scale (Keller et al., 2011a). The soil compression curve has two distinct parts, namely the swelling line (SL) and the virgin compression line (VCL). Soil behavior in the SL is elastic, and soil deformation is reversible. However, new studies (Mousavi et al., 2022) show that even in SL, a fully elastic behavior can be assumed for soils. However, in the VCL, this behavior is plastic and soil deformation is irreversible (Koolen and Kuipers, 1983). CCC can be used to compute three important characteristics of soil compression, including swelling index (C_s), pre-compression stress (P_c), and compression index (C_c) (Keller and Arvidsson, 2007). The compression index indicates soil compressibility or resistance to deformation (Kuan et al., 2007), and the swelling index indicates soil elasticity (Kuan et al., 2007). The soil is not elastic and permanently deforms due to its plastic nature during loading (Johnson and Bailey, 2002). Pre-compression stress as an indicator of the history of stresses has been applied to the soil and shows the bearing capacity of the soil against the applied stresses (Imhoff et al., 2004) or soil compression strength (Horn et al., 1995). The soil behaves elastically if the applied stress does not exceed the pre-compression stress (Keller et al., 2011b). However, small cumulative plastic deformation may occur even if the applied stress is less than P_c (Mousavi et al., 2022).

The appropriate choice of soil management is very important in sustainable agriculture and reducing the soil compaction risk. Selecting different types of tillage such as conventional tillage (MP) and reduced tillage (e.g., no-tillage) is a part of such management. Soil compaction, water content, and crop yields can be affected by tillage

Table 1. The measured physical and chemical properties for 5-10 cm depth of the studied soil

Variable	Value	Reference
Sand (%)	63.88	(Gee and Bauder, 1986)
Silt (%)	21.09	(Gee and Bauder, 1986)
Clay (%)	15.03	(Gee and Bauder, 1986)
Gravel (%)	0.06	(Kemper and Rosenau, 1986)
MWD (mm)	1.80	(Kemper and Rosenau, 1986)
pH	8.40	(Bruce and Rayment, 1982)
EC (dS m^{-1})	0.20	(Rhoades et al., 1992)
CEC ($cmol_c$ kg^{-1} soil)	14.00	(Metson, 1961)
$CaCO_3$ (%)	6.80	(Hazelton and Murphy, 2007)
OC	0.8	(Walkley A and Black, 1934)

practice (Biberdzic et al., 2020). Overall, the compaction in conventional tillage is significantly more than that in the reduced tillage due to the weak soil structure in conventional tillage. Also, long-term zero-tillage improves the soil structure by increasing macro-porosity (Galdos et al., 2019), aggregate stability, and organic matter content (Haghighi et al., 2010). Fernández-Ugalde et al., (2009) showed that no-tillage significantly increased the micropores and mesopores compared to conventional tillage. Tullberg (2007) states that traffic control can reduce the problem of soil compaction by using tires that apply less stress on the ground and controlling the agricultural machinery traffic (Chamen, 2015). The cover crop is a species cultivated to provide a layer of plant residues on the soil surface to suppress weeds (Ghorbani et al., 2009). Cover crops increase root activity and soil organic matter (Villamil et al., 2006) and thus affect soil compaction (Sleighter et al., 2015), compressibility, elasticity (Braida et al., 2006), soil quality (Sleighter et al., 2015), and crop production (Zotarelli et al., 2007). The use of cover crops has been reported in several studies based on their effects on soil's physical, chemical, or biological properties (Adetunji et al., 2020; Saleem et al., 2020).

Intercropping is one of the components of sustainable agriculture that increases soil organic matter soil conservation, improves the efficiency of using resources, and reduces the growth of weeds (Mazaheri, 2008). This activity also reduces soil compaction compared with single-cultivation of crops through the extensive root system, impacts organic matter, and creates stable aggregates. In intercropping, several crops are cultivated simultaneously (Sullivan et al., 2003).

The CCC and its parameters reflect the impact of management operations such as tillage, cover crops, and intercropping on the soil. However, the simultaneous effect of these three factors on the CCC has not yet been studied in any research. Therefore, the present study aims to investigate the effect of the combination of tillage practices and winter cover crop (Lathyrus) on organic matter and soil compaction in an intercropping system to understand the effects of agricultural management on the soil.

2. Materials and Methods

2.1. Location and site of the study

This experiment was carried out in the seasonal years of 2011 to 2014 at the research farm of the Faculty of Agriculture of Bu-Ali Sina University, located in the Dastjerd village 37 km from Hamedan City, Iran. The study site is located at 48°31′ E, 35°1′N with a height of 1690 meters above sea level. The mean annual rainfall is 266 mm y^{-1}, and the mean annual temperature is 12.75℃ (varying from -9℃ to 35℃) by averaging two years (https://www.worldweatheronline.com/bahar-weather/hamadan/ir.aspx).

Some of the studied soil properties before applying treatments are reported in Table 1. The examined soil has a sandy loam texture and is coarse-textured soil (Gee and Bauder, 1986).

2.2. Experimental design and sampling procedure

During the three years preceding the experiment (2011-2013), corn was grown on the study farm. Then, it was simultaneously subjected to tillage and cover crop treatments, the same as in the fourth year (i.e., 2014). In the fourth year, the effects of tillage systems, cover crop, and cropping systems interaction on CCC were examined by designing the experiment as a factorial split-plot (randomized complete blocks with three replications) in Hamedan, Iran. There were 36 plots of 6 m × 5 m dimensions. Combination of two types of tillage systems as the first factor (moldboard plow (MP, conventional tillage) and chisel plow (CP, reduced tillage)) and two types of cover crops as the second factor (one with Lathyrus as the cover crop, CC; and one without any cover crop, NC) were designed as the main plots (four plots). Also, three types of cropping systems, as the third

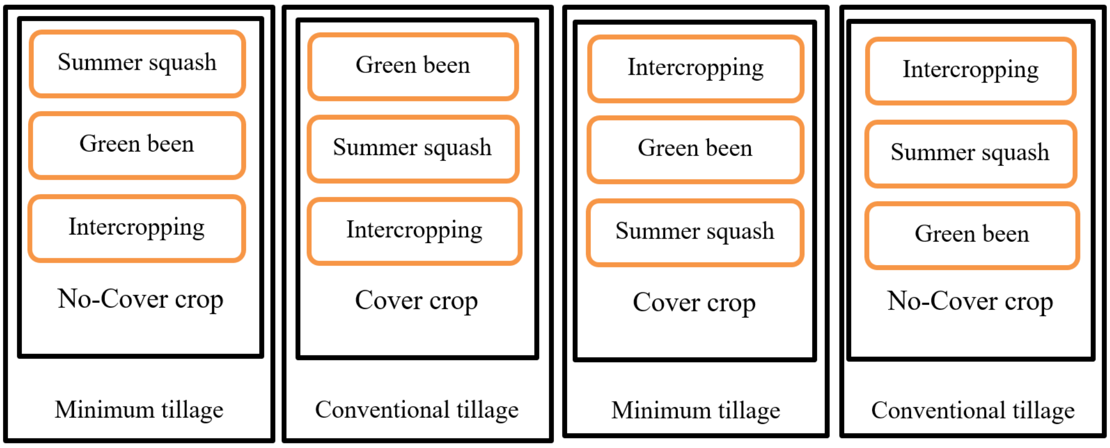

Fig. 1. A diagram of factorial split-plot based on randomized complete blocks applied in this study for the first replicate; tillage systems and cover crop factors were applied for all four years. But, the factor of the cropping system was applied along with two other factors only in the fourth year.

factor (summer squash, green bean, and additive intercropping of 50% green bean with summer squash), were designed as subplots (12 sub-plots) (Fig. 1). Since these treatments had three replications, there were 36 plots in this study.

A moldboard plow (MP) with a maximum depth of 30 cm was used in conventional tillage. On the other hand, in reduced tillage, a chisel plow (CP) with a depth of less than 10 cm was used without any previous tillage in both tillage systems. The cover crop was cultivated on March 6, 2014. Before the cover crop reached the full harvesting stage, it was cut from the soil surface, and depending on the tillage treatment, all cover crop (or plant residue) remained on the soil surface (in reduced tillage) or mixed with soil (in conventional tillage) on May 26, 2014. Summer squash, green bean, and intercropped crops were simultaneously cultivated on June 2 of 2014 (in the fourth year) instead of corn (in the first three years). In other words, tillage systems and cover crop factors were applied for all four years. The cropping systems factor was applied along with two other factors only in the fourth year.

After harvesting the plants, undisturbed soil samples (5.2 cm in diameter and 4.5 cm in height) were taken from a depth of 5-10 cm using 36 steel cylinders (36 plots containing three replications, one sample per each experimental plot).

The wet sieving was used to determine the aggregates' mean weight diameter (MWD) (Kemper and Rosenau, 1986). Soil organic matter (OM) was measured with the oxidation method (Walkley and Black, 1934). Also, bulk density (BD) and porosity were determined using the standard core method (Grossman, 2002). Finally, moisture was calculated at matric suctions of 30 and 400 kPa using a pressure plate apparatus.

2.3. Soil's CCC

In this test, the soil core samples were compressed within a rigid cylinder by moving a piston. In the meantime, the stress on the soil sample and the volume change of the soil was recorded continuously by the uniaxial system (California Bearing Ratio; CBR). Undisturbed samples, equilibrated in the pressure plates at the matric suction of 400 kPa, were used for this test. The reason for using these samples is that moisture content at this matric suction is often suitable for tillage operations. The load was applied to the sample by a CBR piston at a 1 mm/min loading rate. This test was conducted in two stages: loading and unloading. In the loading step, 100 readings with intervals of 0.01 mm (at each interval, stress on the soil sample was increased by 10 kPa) were performed. On the other hand, 33 readings with intervals of 0.03 mm were done at the unloading stage. The maximum applied stress was 1000 kPa.

The void ratio was calculated using the following formula:

$$\frac{\Delta H}{H} = \frac{\Delta e}{1 + e_0} \qquad e = e_0 - \Delta e \qquad [1]$$

where H (mm) and e_0 (cm^3cm^{-3}) are the initial height and void ratio, respectively. Also, Δe (cm^3cm^{-3}) and ΔH (mm) are variations of the void ratio and sample height, respectively.

2.3.1. Fitting the Gompertz model to the soil's CCC

The soil's confined compression loading phase data were fitted by the Gompertz model (Gompertz, 1825) using the SPSS software, as follows (Eq. 4):

$$e = a + c\exp\{-\exp[b(\log\sigma - m)]\} \qquad [2]$$

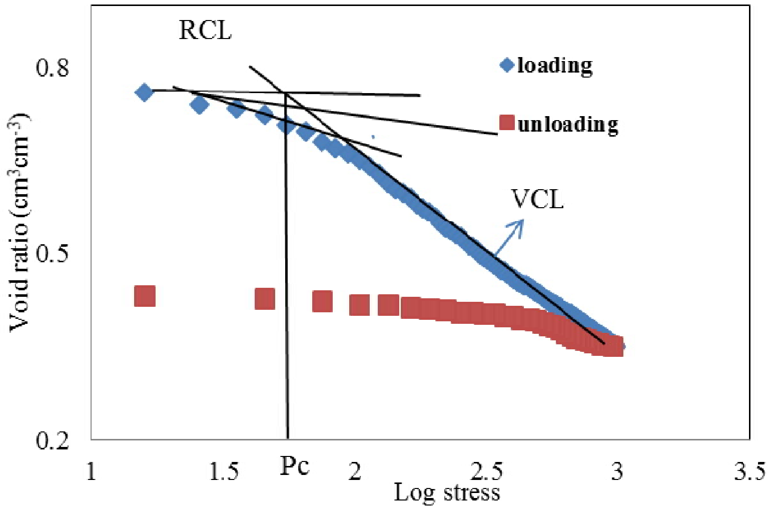

Fig. 2. Soil compaction curve where the void ratio is plotted versus stress; Pc, RCL, and VCL represent pre-compression stress, re-compression line, and virgin compression line, respectively.

$$Cc = \frac{bc}{\exp(1)} \quad [3]$$

$$Cs_{loading-25kPa} = \frac{e_0 - e_{25kPa}}{\log(25kPa)} \quad [4]$$

$$Cs_{unloading-800kPa} = \frac{e_{final} - e_{800kPa}}{\log(800kPa)} \quad [5]$$

where $Cs_{loading\text{-}25kPa}$ is a measure of the swelling index in the 0-25 kPa stress range of the loading stage of the CCC, $Cs_{unloading\text{-}800kPa}$ is a measure of the swelling index in the 0-800 kPa stress range of the unloading stage of the CCC, e is the void ratio, σ is the stress value (kPa), and *a*, *b*, *c*, and *m* are the parameters of the Gompertz model. The graphical method proposed by Casagrande (1936) was used to calculate the pre-compression stress (Fig. 2).

2.4. Statistical Analysis

The normality of the errors was assessed using the Kolmogorov-Smirnov. To have a normal error distribution, variables with non-normal error distribution were transformed by log x, ln x, $x^{0.5}$, 1/x, $1/x^{0.5}$, etc. (where x is the original variable). Analysis of variance (ANOVA) and comparison of means were performed on the variables using SAS.9.1 software.

3. Results and Discussion

3.1. Effect of different treatments on organic materials mean weight diameter of aggregates, bulk density, porosity, and the soil moisture content

The ANOVA results showed the significant interaction of the cover crop and cropping systems on soil organic carbon (Table 2). But, the effect of tillage × cover crop × cropping systems on MWD was not significant. The main effect of cover crop and cropping systems and interactions of tillage × cover crop and tillage × cropping systems on the bulk density and porosity were significant at $P < 0.01$ or $P < 0.05$ (Table 2). The main effect of cover crop and tillage × cover crop on soil moisture at the matric suctions of 30 and 400 kPa were significant at $P < 0.01$ (Table 2).

3.1.1. Organic materials

Duncan's comparison of means test showed that in the two-way interaction effect of the cover crop-cropping system, CC intercropping increased soil organic carbon significantly compared to other treatments in the ranges of 12.81-29.67% (Fig. 3). However, its difference with Lathyrus-green bean treatment was not statistically significant. This result suggests the positive effect of cover crops and intercropping on soil organic matter. Cover crops (also intercropping) can be used to increase soil organic matter, maintain or increase plant nutrient availability, and improve soil physical properties (Liebman and Davis, 2000). Cover crops increase soil organic matter (Abdalla et al., 2019). Organic matter increased in simultaneous treatment of cover crop and intercropping. The presence of more roots and the secretion of roots in these treatments have probably affected the amount of organic carbon and increased the soil's organic carbon.

3.1.2. Mean weight diameter of aggregates (MWD)

Comparison of means of the three-way interaction of the tillage factor × cover crop × cropping system showed that

Table 2. The ANOVA results of the effect of tillage, cover crop, and cropping system on the mean weight diameter of aggregates (MWD), bulk density (BD), porosity, organic matter (OC), and moisture at the matric suctions of 30 kPa (θ_{30}) and 400 kPa (θ_{400})

Resources change	Df	Mean square					
		OC$^{\pm}$	MWD	BD	Porosity	θ_{30}	θ_{400}
Replication	2	0.0004^{ns}	0.70^{ns}	0.003^{ns}	0.0004^{ns}	0.9703^{ns}	0.6834^{ns}
Tillage	1	0.003^{ns}	0.04^{ns}	0.020^{ns}	0.003^{ns}	0.6025^{ns}	0.4642^{ns}
Cover crop	1	0.04^{ns}	2.78^{ns}	0.088**	0.012**	0.0016**	0.0001**
Tillage × cover crop	1	0.01^{ns}	0.0001^{ns}	0.052*	0.007*	0.0143**	0.0086**
Main error	6	0.025	0.84	0.001	0.001	0. 5863	0. 7370
Cropping system	2	0.03^{ns}	0.11^{ns}	0.039*	0.006*	0.0935^{ns}	0.1213^{ns}
Tillage × cropping system	2	0.02^{ns}	0.79^{ns}	0.034*	0.005*	0.4135^{ns}	0.1891^{ns}
Cover crop × cropping system	2	0.09**	0.76^{ns}	0.016^{ns}	0.002^{ns}	0.1887^{ns}	0.4830^{ns}
Tillage × cover crop × cropping system	2	0.006^{ns}	0.47^{ns}	0.001^{ns}	0.0001^{ns}	0.1267^{ns}	0.5930^{ns}
Subsidiary error	16	0.02	0.50	0.009	0.001	0.00028	0.00024

ns, *, and ** indicate non-significant effect at P < 0.05, significant effect at P < 0.05, and P < 0.01, respectively.

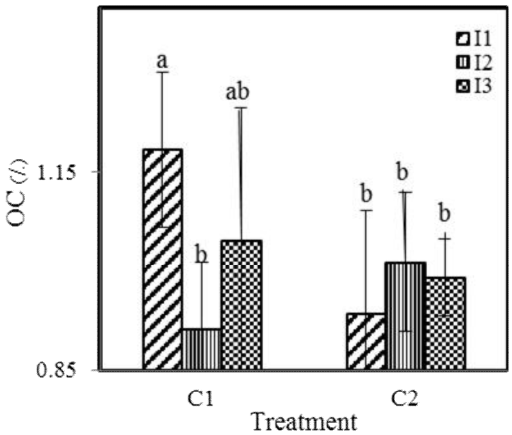

Fig. 3. Interactive effect of cover crop × cropping systems on soil organic carbon. C_1 and C_2 designate Lathyrus cover crop and without cover crop, respectively, while I_1, I_2, and I_3 designate intercropping, summer squash, and green bean, respectively. The vertical line on each column represents the standard deviation. Similar letters at the top of the columns indicate a lack of any difference (P < 0.05) using Duncan's test.

MP-CC intercropping treatment significantly increased MWD compared to other treatments (Fig. 4).

The reason for this increase was increased organic matter due to the Lathyrus cover crop and better and denser intercropping cover. The presence of plants and roots in the soil decreases aggregate breakdown (Carrizo et al., 2015). Similar to this research, Li et al., (2019) also reported that compared to conventional tillage, reduced tillage practices increased MWD. Likewise, Li et al., (2019) reported that reduced tillage practices increased MWD compared to conventional tillage.

3.1.3. Bulk density and porosity

Comparison of means also revealed that compared to other treatments, the MP-CC treatment led to increased bulk density (1.70 gcm^{-3}) (Fig. 5A) and reduced porosity (0.356 cm^{3}cm^{-3}) compared to other treatments (Fig. 5 A). Increasing tillage operations may lead to compaction, reducing the soil porosity and increasing its strength (Celik, 2011).

Regarding the two-way interaction of tillage × cropping systems, the MP × intercropping system reduced bulk density (1.45 gcm^{-3}) (Fig. 5B) and enhanced soil porosity compared to other treatments (0.451 cm^{3}cm^{-3}) (Fig. 5 B). Any tillage system that leaves the plant residue on the soil surface (reduced tillage) will increase soil organic matter and porosity while reducing the soil's bulk density (Arshad et al., 1996). Besides, in this experiment, cover crop and intercropping system with increasing organic matter content, increased soil porosity, and reduced soil bulk density (Fig. 5).

3.1.4. The soil moisture content at the matric suctions of 30 and 400 kPa

The main effect of cover crop and interactions of tillage × cover crop on soil moisture content at the matric suctions of 30 and 400 kPa were significant at P < 0.01 (Table 3). The comparison of means for the effects of different tillage systems and cover crops on the soil moisture content at the matric suction of 30 and 400 kPa

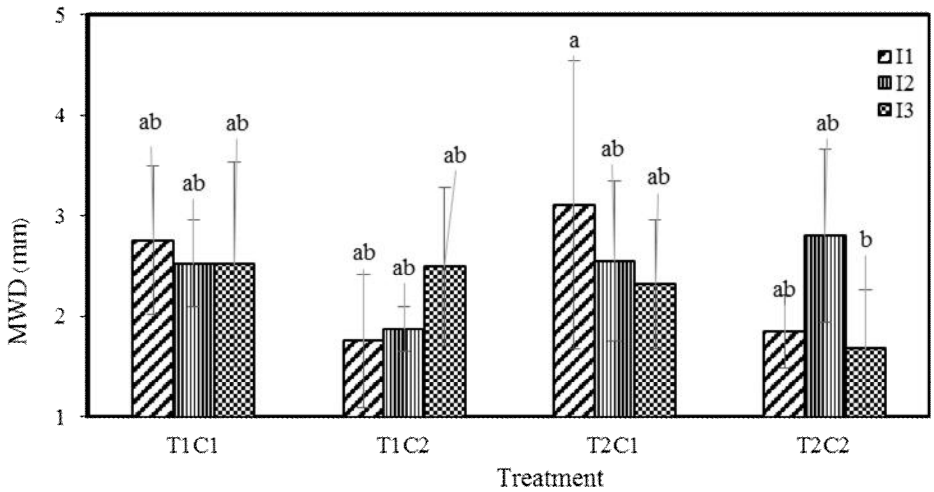

Fig. 4. Comparison of means of the three-way interaction effect of tillage × cover crop × cropping system on the MWD; T1 and T2 indicate the conventional (moldboard) and reduced (chisel) tillage, respectively; C1 and C2 denote the Lathyrus cover crop and control, respectively, and I1, I2, and I3 are intercropping, summer squash, and green been, respectively. TC shows the interaction of tillage × cover crop. The vertical lines on the columns denote the standard deviations. Similar letters at the top of the columns indicate a lack of any difference ($P < 0.05$) using Duncan's test.

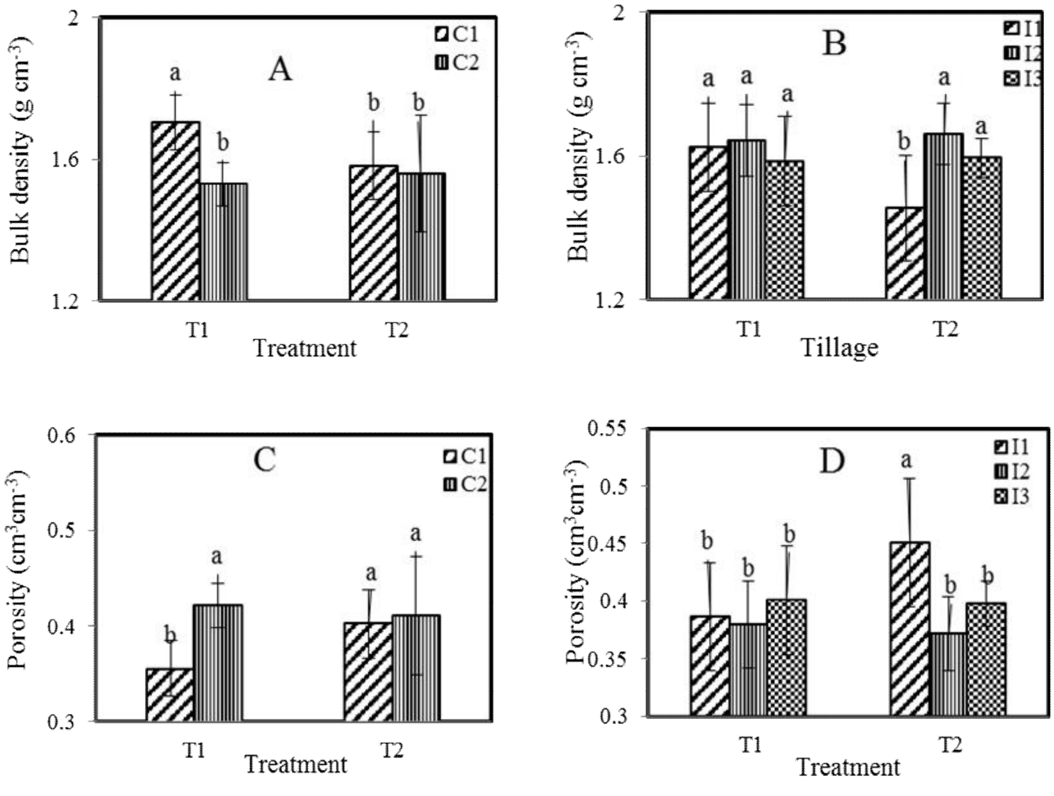

Fig. 5. Interactive effect of (A) tillage and cover crop and (B) tillage and cropping systems on bulk density (A, B) and soil porosity (C, D); T_1 and T_2 represent conventional (moldboard), and minimum (chisel) tillage, respectively; C_1 and C_2 designate Lathyrus cover crop and control treatments, respectively; I_1, I_2, and I_3 designate intercropping, summer squash, and green bean, respectively. TC and TI denote the interactive effect of tillage × cover crop and tillage × cropping systems treatments, respectively. The vertical line on each column represents the standard deviation. Similar letters at the top of the columns indicate a lack of any significant difference ($P < 0.05$) using Duncan's test.

Table 3. The ANOVA results of the effect of tillage, cover crop, and cropping system on the CCC parameters

Resources change	Df	Mean square			
		P_c (kPa)	$Cs_{loading}$	$Cs_{unloading}$	Cc
Replication	2	785 ^{ns}	0.00001 ^{ns}	0.00001 ^{ns}	0.001 ^{ns}
Tillage	1	4926*	0.00004*	0.000003 ^{ns}	0.040**
Cover crop	1	4822*	0.00003 ^{ns}	0.00002 ^{ns}	0.140**
Tillage × cover crop	1	3514*	0.00001 ^{ns}	0.00002 ^{ns}	0.013 ^{ns}
Main error	6	624	0.000006	0.00001	0.004
Cropping system	2	3689 ^{ns}	0.000002 ^{ns}	0.00003 ^{ns}	0.007 ^{ns}
Tillage × cropping system	2	711 ^{ns}	0.00002 ^{ns}	0.00004 ^{ns}	0.006 ^{ns}
Cover crop × cropping system	2	1819 ^{ns}	0.000004 ^{ns}	0.00004 ^{ns}	0.003 ^{ns}
Tillage × cover crop × cropping system	2	2064 ^{ns}	0.00001 ^{ns}	0.00005*	0.019*
Subsidiary error	16	3957	0.00001	0.00002	0.004

s; * and ** indicate a non-significant effect at $P < 0.05$, a significant effect at $P < 0.05$, and a significant effect at $P < 0.01$, respectively.
±, OC, organic carbon; P_c, pre-compression stress; $Cs_{loading}$, loading swelling index; $Cs_{unloading}$, unloading swelling index; Cc, compression index; Df, degree of freedom

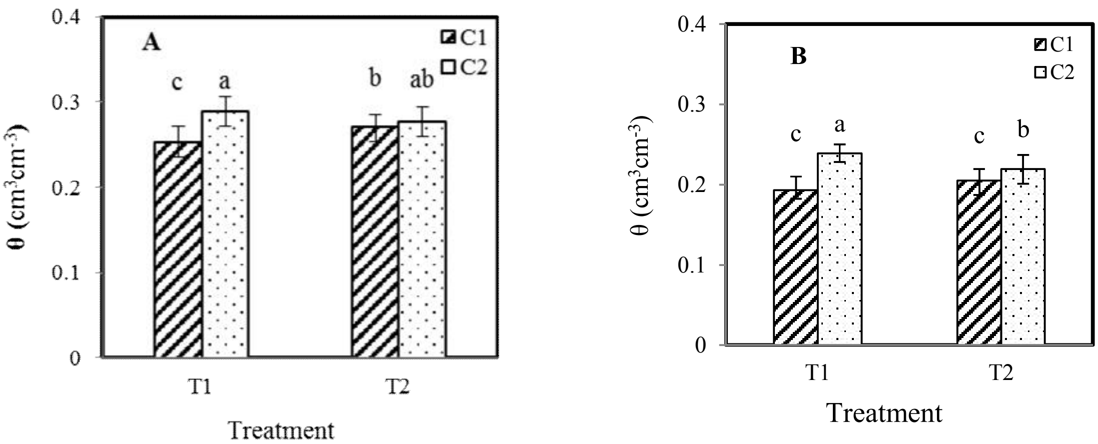

Fig. 6. Interactive effect of tillage × cover crop on soil moisture (θ) at the matric suctions of 30 (A) and 400 kPa (B). T_1 and T_2 represent conventional (moldboard), and minimum (chisel) tillage systems, respectively. Also, C_1 and C_2 designate Lathyrus cover crop and control, respectively. The vertical line on each column represents the standard deviation. Similar letters at the top of the columns indicate no difference ($P < 0.05$) using Duncan's test.

showed that the CT × CC decreased soil moisture content at 30 kPa compared to other treatments (Fig. 6).

Also, in both tillage systems, the cover crop decreased soil moisture content (Figs. 6A and 6B). At low suctions (30 kPa), soil moisture is controlled by soil structure and coarse porosity (Hillel, 1982). Many researchers reported the excellence of the no-till system in storing moisture compared to moldboard plow. By increasing the organic matter content in the soil, aggregation gets larger and more (Beare et al., 1994). Then, moisture drainage increased due to increasing macro-aggregates and macro-porosity and reduced soil moisture at these suctions.

3.2. The soil's CCC parameters

The ANOVA results showed that the main effect of the tillage factor was significant on the compression index ($P < 0.01$), loading swelling index ($P < 0.05$), and pre-compression stress ($P < 0.05$). The main effect of the cover crop factor was significant on the compression index ($P < 0.01$) and pre-compression stress ($P < 0.05$). Moreover, the two-way interaction effect of tillage factor × covers crop was significant on pre-compression stress ($P < 0.05$), and the three-way interaction effect of tillage factor × cover crop × cropping system was significant ($P < 0.05$) on the compression index and unloading swelling index (Table 3).

3.2.1. Pre-compression (P_c) stress

Comparison of means of the two-way interaction of tillage × cover crop showed that MP-CC treatment significantly increased the pre-compression stress compared to other treatments (Fig. 7A). Also, at the matric suction of 400 kPa, pre-compression stress was increased by Lathyrus cover crop in conventional tillage.
In conventional tillage, more severe soil disintegration causes plant residue to decompose and results in faster loss of organic matter.

A decrease in soil moisture content and the decomposition of plants due to disturbance with conventional tillage increased the pre-compaction stress of the soil. Lima et al., (2015) attributed the pre-compression stress to the bulk density. Thus, soil water potential strongly affects the mechanical properties of soil (Horn et al., 1998).

An increase in organic matter causes an increase in soil moisture retention and, thus, an increase in soil compaction. Larson and Pierce (1994) stated that soil compressibility depends on the soil moisture content. As soil moisture increases, soil compaction increases due to tractor traffic such that the soil will have the highest compaction at a critical moisture content.

In contrast, the absence of cover crops and possibly lower moisture content brought the particles closer, resulting in increased resistance to soil compaction. Therefore, the cover crop affects the soil compaction by increasing the organic matter and affecting the moisture content.

The pre-compression stress is higher in finer aggregates than in coarser aggregates because of their higher strength (Keller et al., 2011b). Therefore, in this study, CP reduced Pc by affecting soil organic matter, creating macro-aggregates in soil (Figs. 3 and 4), and increasing total porosity. In the treatments with fewer bonding agents (organic matter and roots) and weak structure, the fine aggregates increase, which is less stable and less porous, resulting in higher density. As a result, these micro-aggregates were unstable and crushed under the compaction. However, due to less porosity, lower volume reduction and lower soil deformation occurred (Fig 7-A).

3.2.2. Compression index (Cc)

The comparison of means for the three-way interaction of tillage factor × cover crop × cropping system showed that the MP-CC-green bean treatment significantly reduced compression index compared with other treatments. However, this reduction was not significant compared with two treatments of MP -CC-intercropping and MP-CC-summer squash (Fig. 7B). The lower organic matter content in the MP-CC-green bean treatment reduced porosity (Fig. 5) and void ratio, increased bulk density (Fig. 5), and decreased the compression index. Conventional tillage often reduces carbon by destroying aggregates and rapid decomposition of organic matter. Consequently, with the increase in fine aggregates, the space of pores has become smaller and more compact, thereby reducing soil compaction.

Also, MP-NC- intercropping treatment increased Cc compared to other treatments. However, the increase was not statistically significant compared to the CP-NC-green bean and MP-NC-summer squash treatments (Fig. 7B). In addition, conventional tillage and CC significantly reduced the compression index by increasing soil mechanical strength (Salih et al., 1998) and organic matter, respectively. Deep tillage breaks the plow pan and other compressed layers in the soil profile. Besides, cover crops improve soil structure and volumetric properties (porosity and bulk density) of soil (Higashi et al., 2014). The cover crop could be a main source of organic matter. Adding organic matter to the soil reduces the compressibility due to increased soil resistance to compression and increased soil elasticity (Braida et al., 2006). Also, the decrease in the compression index due to the application of cover crops is due to the increase in the bonding of soil particles and reducing the soil deformation against external stresses (Aksakal et al., 2016). Soil compaction capacity increases due to reducing the amount of organic matter (Howard et al., 1981).

In this research, reduced tillage with less manipulation and stability of aggregates and maintaining plant residues on the soil surface might increase soil moisture retention. Also, intercropping increased soil pores might increase soil compaction. Moreover, the presence of high root density increased the void ratio and, thus, increased compaction .

3.2.3. Swelling index (Cs)

In the three-way interaction, reduced tillage-no cover crop-intercropping treatment significantly increased the unloading swelling index compared to other treatments; however, this increase was not significant compared with the MP-NC-green bean treatment (Fig. 7C). The lower organic matter content in the NC-summer squash treatment (Fig. 3) reduced the unloading swelling index compared to other treatments. In this regard, Zhang et al., (2005) and Kuan (2007) reported less resistance to compaction in soil with high OC but better recovery from compaction. Therefore, a higher void ratio in reduced tillage has probably increased this index. A positive correlation between the swelling index with the void ratio and organic matter was reported by Keller et al., (2011). Therefore, intercropping may increase the swelling index by increasing organic matter.

Comparison of means of the main effect of the tillage factor showed that MP treatment significantly increased the loading swelling index compared to reduced tillage treatment (Fig. 7D). The conventional tillage system

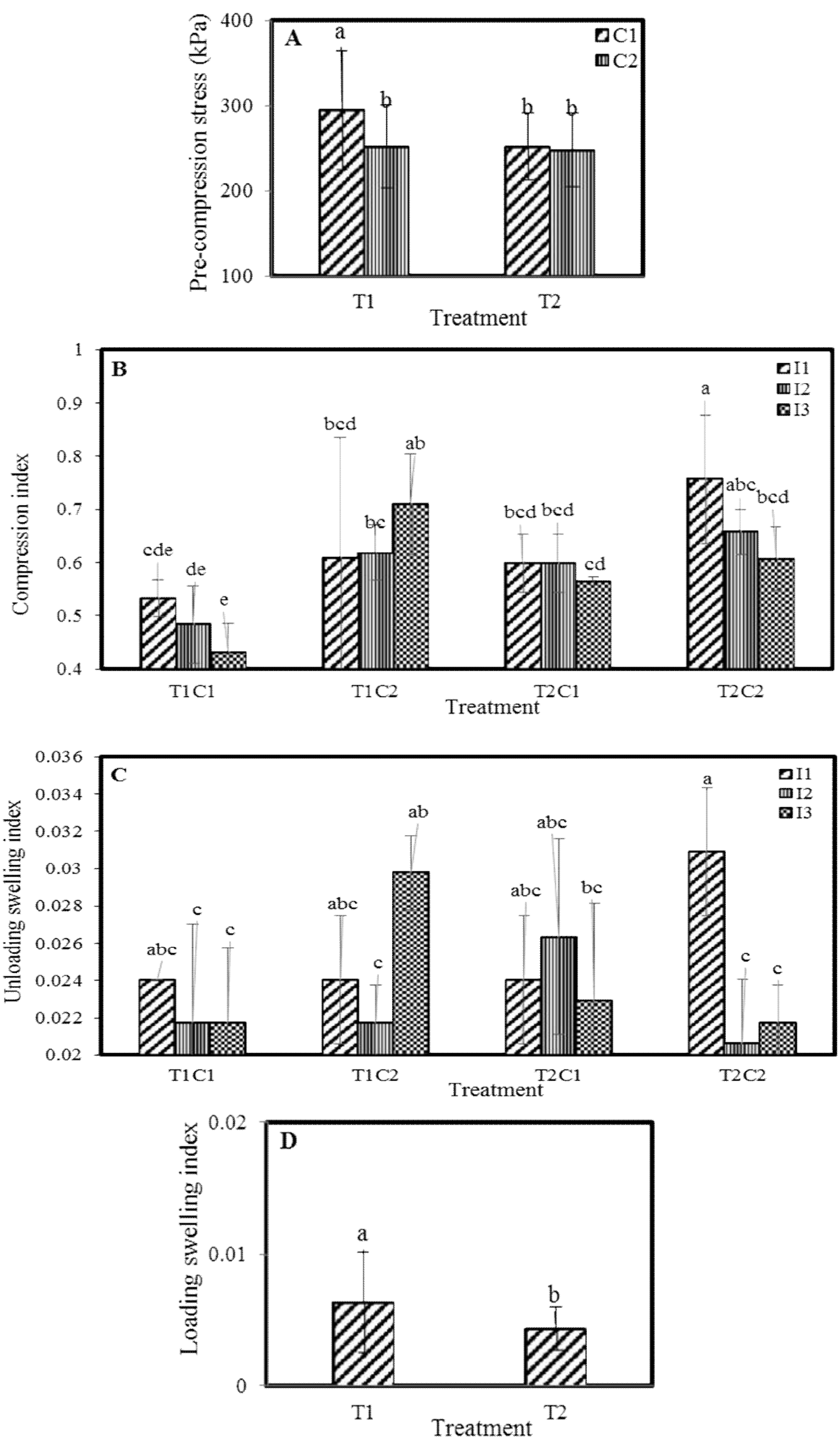

Fig. 7. (A) Comparison of means of the two-way interaction effect of the tillage × cover crop on the pre-compression stress (kPa); Comparison of means of the three-way interaction effect of tillage × cover crop × cropping system on (B) the compression index and (C) the unloading swelling index; (D) Comparison of means of the effect of tillage on the loading swelling index; T1 and T2 indicate the conventional (moldboard) and reduced (chisel) tillage, respectively; C1 and C2 denote the Lathyrus cover crop and control, respectively, and I1, I2, and I3 are intercropping, summer squash, and green been, respectively. Also, TC shows the interaction of tillage × cover crop. The vertical lines on the columns denote the standard deviations. Similar letters at the top of the columns indicate a lack of any difference ($P < 0.05$) using Duncan's test.

reduced soil resistance to a greater depth compared with the reduced tillage system in both stages (before cultivation and maximum growth times) (Shirani et al., 2011). Also, the organic matter increases the elasticity of the soil and thus increases the swelling index. Hence, conventional tillage causes an increase in the swelling index. Conservation tillage increases soil moisture (Singh and Haile, 2007).

4. Conclusion

Among the strategies employed to improve soil structure and reduce soil compaction, reduced tillage using the Lathyrus cover crop under an intercropping system of summer squash and green bean was found as the most important management treatment affecting soil compaction. This method significantly increased organic carbon and improved the soil structure. Therefore, the CP-CC-intercropping system is recommended for this purpose. However, the soil compression index was reduced in MP-CC due to the increased mechanical strength of the soil and the effect of organic matter.

Overall, the study results can be useful in choosing the correct management type, reducing the problems caused by soil compaction, and increasing crop yield. However, further research is needed for this purpose. Since the project was carried out in a short period (4 years), the effect of tillage, cover crop, and cropping system on soil compaction did not show a clear trend in some cases. Hence, an investigation of the simultaneous effect of tillage, cover crop, and cropping system on soil physical-mechanical properties in arid regions in longer periods is suggested.

Conflict of interest

There is no conflict of interest in this study.

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