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Soil compaction variation during corn growing season under conservation tillage

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ABSTRACT

Area cultivated using conservation tillage methods has recently increased in Iran and soil compaction increment is one of the most challenging issues in this new technology. In addition to the soil compaction status at the end of growing season, soil compaction variation during the growing season is also important because of its potential effect on the crop growth and yield. Therefore, soil compaction variation during the corn growing season under different tillage methods and its effect on the crop yield was investigated in this study. The research was conducted in the form of a split plot experimental design with nine treatments and six replications. Main plots were tillage methods including: (1) conventional tillage method (CT); (2) reduced tillage (RT); and (3) zero tillage or direct drilling (ZT). Soil depth ranges of 0–0.10, 0.10–0.20, and 0.20–0.30 m were considered as sub plots. Soil bulk density (BD) and soil cone index (CI) were measured during corn growth season (eight measurements for bulk density and five measurements for cone index) as indices of soil compaction. Corn silage yield, thousand kernels weight, and grain yield were also determined in this research. Collected data were analyzed using SAS statistics software and Duncan's multiple range tests were used to compare the treatments means. Results indicated that tillage methods and soil depth had a significant effect on the soil bulk density so that the maximum soil bulk density was obtained from ZT method and soil depth range of 0.10–0.20 m. The difference between soil bulk densities in different tillage methods was statistically significant from the beginning of growth season to two month after the first irrigation (sixth measurement); while, this difference was not significant from the sixth measurement to the end of growth season. Soil cone index was also significantly affected by tillage methods and soil depth in such a way that ZT method and 0.20–0.30 m soil depth range had the maximum cone index. Although, the difference between tillage methods for corn yield and yield components was not statistically different, ZT method decreased corn thousand kernels weight, silage yield, and grain yield compared to the CT method for 11.1, 2.4, and 18.2%, respectively.

1. Introduction

Conservation tillage is a tillage method in which at least 30% of soil surface remains covered by crop residues. Soil compaction enhancement in this rapidly growing technology is one of the most challenging issues in Iran as well as in the world. Soil compaction is affected by tillage methods and degree of soil disturbance during tillage operations. Soil compaction is normally evaluated by measuring soil bulk density and cone index. Soil bulk density and cone index are also used to predict the depth of soil hardpan (Mehari et al., 2005). However, the amount of soil bulk density and cone index may be close together in different tillage methods at the end of growing season, variation trend of these parameters under different tillage methods cannot be identical during the crop growing season because of difference in soil disturbance intensity in different tillage operations. Therefore, investigating on soil bulk density and cone index variation under different tillage operations during the crop growing season enables researchers to have more accurate judgment and interpretation regarding crop yield under different tillage methods. However, no research work was found in the literature regarding soil compaction variation during growing season, results of some studies conducted on effect of tillage methods on the soil compaction is reported here. There are some contradictory results of research work conducted on the effect of conservation tillage on the soil bulk density and cone index. Results of some studies show that conservation tillage methods

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(zero and reduced tillage) increase the soil bulk density and cone index compared to the conventional tillage (Afzalinia et al., 2012; Fabrizzi et al., 2005; Liu et al., 2005; Taser and Metinoglu, 2005). There are also some research results showing no significant effect of conservation tillage on the soil bulk density and cone index (Afzalinia et al., 2011; Logsdon and Karlen, 2004; Rasouli et al., 2012; Touchton et al., 1984). Soil bulk density and cone index are also affected by soil depth. Results of a research work in a Rhodic Ferrasol in Parana, Brazil revealed that soil bulk density had the highest value at the soil depth range of 0.20–0.30 m in a zero tillage system (Cavalieri et al., 2009). According to the results of a study conducted in Argentina, no-till increased soil resistance compared to the conventional tillage and soil resistance increment was greater in the shallow layers compared to the deep layers (Ferreras et al., 2000). Results of a research performed in Kimberly, Idaho showed that soil bulk density was 16–18% greater in disk and no-till treatments compared to paratill in the soil depth range of 0.15–0.20 mm (Aase et al., 2001). Results of this study also indicated that there was a linear relationship between soil bulk density and soil cone index. Objective of this study was to determine the effect of conservation tillage and soil depth on the soil compaction indicators such as bulk density and cone index, crop yield, and some yield components.

2. Materials and methods

This research was conducted in a farm in Fars province, Iran with the soil specifications shown in Table 1. The research was performed in the form of a split plot experimental design with the base of randomized complete block design with two factors (tillage methods and soil depth) and six replications. Tillage methods (TM) as main plots were including: (1) conventional tillage method (CT); (2) reduced tillage (RT); and (3) zero tillage (ZT), and subplots were soil depth (SD) ranges of 0–0.10 (SD_1), 0.10–0.20 (SD_2), and 0.20–0.30 m (SD_3). In the conventional tillage method, primary tillage was performed using a moldboard plow and secondary tillage operation was done using a disk harrow and land leveler. Seed bed was prepared in the reduced tillage method using a tine and disk cultivator which was able to complete the primary and secondary tillage operations simultaneously. Corn seed was directly planted using Bertini pneumatic direct planter (Rosario, Santa Fe, Argentina) without any seed bed preparation in the zero tillage method. Corn (*Zea mays* L.) variety used in this research was 704 single cross at the seed rate of 25 kg ha^{-1} with the row space of 0.75 m in the 20 m $\times$ 6 m plots. Experimental plots were irrigated using sprinkle irrigation for all treatments. Tillage treatments were applied to the farm for two years (2009–2011) in irrigated corn–wheat rotation and soil bulk density and soil cone index (CI) were measured during corn growing season in 2011 (from July to October) according to Table 2. Corn silage yield, thousand kernels weight, and grain yield was also determined at the end of corn growing season in this research. Collected data were analyzed using SAS statistics software (SAS Institute, Cary, NC) and Duncan's multiple range tests were used to compare the treatments means. Soil bulk density was measured in the soil depth ranges of 0–0.10, 0.10–0.20, and 0.20–0.30 m using core samplers from three different locations of each plot and drying samples at 105 °C for 24 h in the oven. The following equation was used to calculate the soil bulk density:

$$BD = \frac{W_d}{V} \quad (1)$$

where BD is soil bulk density (g cm^{-3}), W_d is sample dry weight (g), and V is sample total volume (cm^3).

Soil cone index was measured using a cone soil penetrometer (Eijkelkamp 6.15) up to the soil depth of 0.30 m with 0.10 m depth interval at the moisture content of 22% w.b. Average cone index of 10 penetrations at each soil depth range was considered as the soil cone index of each plot in corresponding soil depth. Corn yield and yield components were also determined by taking samples from the experimental plots at the end of corn growing season.

Table 1
Soil specifications of the farm.

pH	EC	Silt (%)	Clay (%)	Sand (%)	Soil texture
8.4	0.79	54.73	40.94	4.33	Silty clay loam

3. Results and discussion

Results of soil bulk density data analysis indicated that difference between tillage methods was significant ($P < 0.01$) from the growth season beginning (BD_1) to corn sixth irrigation time (BD_5) or fifth measurement stage (Table 3). After fifth measurement or sixth irrigation time (from BD_6 to BD_8) no significant difference was observed between tillage methods from the soil bulk density point of view. Since soil disturbance level in tillage methods is different and it takes time for the soil to reach its undisturbed status (its situation before disturbance), significant difference between soil bulk densities in different tillage methods until fifth measurement is expected. It takes about two month for the soil bulk density in CT and RT methods to get close to its undisturbed status; therefore, there is no significant difference between tillage methods for the soil bulk density from the sixth measurement (BD_6) to the end of growing season (BD_8). There was also statistically significant difference ($P < 0.01$) between soil depths for the soil bulk density from the beginning to the end of corn growing season (Table 3). Interaction between tillage methods and soil depth showed a significant effect on the soil bulk density only for two measurements at the beginning of the growing season (BD_1 and BD_2).

Results of means comparison of soil bulk density in different tillage methods during corn growing season showed that there was a significant difference between soil bulk density of ZT method and those of CT and RT methods from the first measurement (BD_1) to the fifth one (BD_5) so that ZT had the highest soil bulk density and CT had the lowest one (Table 4). There was no significant difference between tillage methods for soil bulk density from sixth measurement (BD6) to the end of corn growing season (BD_8); however, ZT had a greater bulk density compared to the CT and RT methods. Means comparison of average soil bulk density of whole growing season (average of eight measurements) also revealed that ZT had the highest soil bulk density which was significantly different from those of CT and RT methods (Table 4). The higher soil bulk density in zero tillage compared to the conventional tillage method was also reported by Liu et al. (2005), Taser and Metinoglu (2005), Fabrizzi et al. (2005), and Afzalinia et al. (2012). Results of this study indicated that soil disturbance effect on the soil bulk density and soil compaction resists for two months during corn growing season and after that there is no significant difference between CT with high soil disturbance and ZT with zero soil disturbance.

Means comparison of soil bulk density at different soil depth ranges revealed that soil bulk density increased with increasing soil depth range from 0–0.10 m to 0.10–0.20 m then decreased when soil depth range increased from 0.10–0.20 m to 0.20–0.30 m during entire corn growing season (Table 5). Therefore, soil depth range of 0.10–0.20 m had the highest soil bulk density during the corn growing season which was significantly different from the soil bulk density of 0–0.10 and 0.20–0.30 m. This was probably because

Table 2
Soil bulk density and cone index measurement during corn growing season in 2011.

Bulk density	Date of measurement	Cone index	Date of measurement
First measurement (BD_1) after first irrigation	July 16th	First measurement (CI_1) after first irrigation	July 16th
Second measurement (BD_2) after second irrigation	July 22nd	Second measurement (CI_2) after third irrigation	August 2nd
Third measurement (BD_3) after forth irrigation	August 14th	Third measurement (CI_3) after forth irrigation	August 14th
Forth measurement (BD_4) after fifth irrigation	August 24th	Forth measurement (CI_4) after fifth irrigation	August 24th
Fifth measurement (BD_5) after sixth irrigation	September 2nd	Fifth measurement (CI_5) eleventh irrigation	October 12th
Sixth measurement (BD_6) after eighth irrigation	September 14th		
Seventh measurement (BD_7) tenth irrigation	October 1st		
Eighth measurement (BD_8) after eleventh irrigation	October 12th		

Table 3
Variance analysis of soil bulk density data during corn growing season. Data shown in this table are *F* values.

Variation sources	BD_1	BD_2	BD_3	BD_4	BD_5	BD_6	BD_7	BD_8
TM	29.18^{**}	54.56^{**}	24.22^{**}	68.71^{**}	27.25^{**}	2.18^{ns}	2.18^{ns}	9.08^{ns}
SD	38.18^{**}	33.01^{**}	22.22^{**}	33.69^{**}	15.62^{**}	3.58^{*}	17.11^{**}	48.51^{**}
TM × SD	6.47^{**}	3.03^{**}	1.56^{ns}	2.03^{ns}	0.31^{ns}	0.37^{ns}	1.33^{ns}	0.86^{ns}

TM, tillage methods; SD, soil depths; ^{ns}, not significant.
* Significant at $p < 0.05$.
** Significant at $p < 0.01$.

of concentration of the pressure applied to the soil by agricultural machinery traffics at the soil depth range of 0.10–0.20 m. Cavalieri et al. (2009) also reported that soil bulk density increased with increasing soil depth from 0 to 0.30 m and then decreased; however, they did not measure the soil bulk density for the soil depth of 0.10–0.20 m. Unlike to the results of present study, the highest soil bulk density was reported for the soil depth of 0.20–0.30 m by Cavalieri et al. (2009). This discrepancy was probably due to not measuring bulk density for the soil depth of 0.10–0.20 m by these researchers and difference in soil nature. There was no significant difference between soil depth ranges of 0–0.10 m and 0.20–0.30 m from the average soil bulk density (average of eight measurements) point of view; however, significant difference was observed between soil bulk densities of these depth ranges in some measurements during the corn growing season (BD_3, BD_4, BD_7, and BD_8). The minimum soil bulk density was related to the soil depth range of 0–0.10 m because of intensive soil disturbance of this soil depth in the conventional and reduced tillage methods.

Effect of interaction between tillage methods and soil depth on the soil bulk density during corn growing season is presented in Table 6. According to this table, the maximum soil bulk densities during the growth season were related to the soil depth range of 0.10–0.20 m with zero tillage operation. This was because of not disturbing soil in the ZT method and likely concentration of pressure exerted to the soil by the agricultural machinery traffics at the soil depth of 0.10–0.20 m. The minimum soil bulk densities during the growth season belonged to conventional tillage method at the soil depth ranges of 0–0.10 m and 0.20–0.30 m. The low soil bulk densities at the soil depth of 0–0.10 m tilled by conventional tillage method was due to intensive soil disturbance of soil surface layers in conventional tillage operation.

The trend of soil bulk density variation during corn growing season under different tillage methods showed that at the soil depth of 0–0.10 m, soil bulk density in ZT method was almost constant from BD_1 (first measurement) to BD_4 (forth measurement), and then decreased from BD_4 up to the end of growth season (Fig. 1). It was expected to have almost constant soil bulk density during the growth season in ZT method because of undisturbed soil in this tillage system; therefore, descending trend of this parameter after the forth measurement in ZT treatment was probably due to the presence of corn roots in the soil samples taken for the bulk density measurements. In the case of CT and RT treatments, soil bulk density started from the lower values compared to that of the ZT method (BD_1) due to soil disturbance in these tillage methods, increased up to the sixth measurement (BD_6), and then decreased from the sixth measurement up to the end of growth season (BD_8). Since almost the same level of soil disturbance was applied to the soil depth range of 0–0.10 m in the CT and RT treatments, lines showing the soil bulk density trend for the CT and RT were very close together at the soil depth of 0–0.10 c. In the soil depth of 0–0.10 m, soil bulk density decreased from the sixth measurement (BD_6) up to the end of growing season for all the tillage methods which was not expected. The reason probably was corn root development in the soil in this stage of corn growth and the presence of part of these roots in the taken soil samples. A trend similar to what happened in 0–0.10 m soil layer was also occurred for the soil bulk density variation at the soil depth range of 0.10–0.20 m and 0.20–0.30 m in all the tillage method treatments (Figs. 2 and 3). The main difference between soil bulk density variation in the soil depth ranges of 0–0.10 m and 0.10–0.20 m was the closeness of the line showing soil bulk density variation in RT method to the line showing soil bulk density variation in ZT method in the soil depth range of 0.10–0.20 m compared to the closeness of this line to the line showing soil bulk density variation in CT method at the soil depth range of 0–0.10 m. This was because of less tillage depth in reduced tillage method (about 0.15 m) compared to the conventional tillage (about 0.25 m). Therefore, only about 0.05 m of 0.10–0.20 m soil layer was disturbed and the rest was remained undisturbed in RT tillage method. The most important point shown in Figs. 1–3 is that soil

Table 4
Means comparison of soil bulk density ($Mg\,m^{-3}$) for different tillage methods during corn growing season.

Tillage methods	BD_1	BD_2	BD_3	BD_4	BD_5	BD_6	BD_7	BD_8	Average
CT	1.30b	1.30b	1.27b	1.28b	1.29b	1.33a	1.28a	1.22a	1.28b
RT	1.33b	1.32b	1.28b	1.31b	1.33b	1.35a	1.27a	1.22a	1.31b
ZT	1.39a	1.43a	1.38a	1.41a	1.38a	1.36a	1.30a	1.26a	1.36a

CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; a, b, averages with different letters in each column and group are statistically different at $p < 0.05$.

Table 5
Means comparison of soil bulk density (Mg m^{-3}) for different soil depths during corn growing season.

Soil depths	BD_1	BD_2	BD_3	BD_4	BD_5	BD_6	BD_7	BD_8	Average
SD_1	1.29b	1.29b	1.31b	1.32b	1.31b	1.32b	1.29b	1.24b	1.30b
SD_2	1.41a	1.39a	1.37a	1.39a	1.37a	1.37a	1.32a	1.29a	1.36a
SD_3	1.33b	1.37a	1.26c	1.29c	1.31b	1.34ab	1.23c	1.16c	1.30b

SD_1, soil depth of 0–0.10 m; SD_2, soil depth of 0.10–0.20 m; SD_3, soil depth of 0.20–0.30 m; a, b, c, averages with different letters in each column and group are statistically different at $p < 0.05$.

Table 6
Soil bulk density (Mg m^{-3}) affected by interaction between tillage methods and soil depths during corn growing season.

Tillage method	Soil depth (cm)	BD_1	BD_2	BD_3	BD_4	BD_5	BD_6	BD_7	BD_8	Average
CT	SD_1	1.23	1.24	1.29	1.26	1.27	1.30	1.28	1.23	1.26
RT	SD_1	1.28	1.22	1.26	1.30	1.31	1.32	1.25	1.22	1.27
ZT	SD_1	1.37	1.40	1.38	1.41	1.36	1.35	1.32	1.29	1.36
CT	SD_2	1.35	1.33	1.30	1.31	1.34	1.34	1.31	1.28	1.32
RT	SD_2	1.40	1.39	1.36	1.37	1.37	1.38	1.31	1.27	1.37
ZT	SD_2	1.41	1.46	1.44	1.48	1.41	1.38	1.34	1.31	1.40
CT	SD_3	1.33	1.32	1.23	1.26	1.27	1.34	1.23	1.14	1.26
RT	SD_3	1.25	1.35	1.23	1.25	1.31	1.33	1.24	1.16	1.29
ZT	SD_3	1.40	1.44	1.31	1.35	1.36	1.36	1.23	1.18	1.33

CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; SD_1, soil depth of 0–0.10 m; SD_2, soil depth of 0.10–0.20 m; SD_3, soil depth of 0.20–0.30 m.

has almost identical bulk density under different tillage methods at the end of growing season in all the soil depth ranges; however, the difference between soil bulk density in different tillage methods is statistically significant from the first measurement (beginning of growing season) to the sixth one. Therefore, results of this research proved that in order to have a precise judgment about soil bulk density difference in different tillage methods, it is necessary to measure this parameter during the crop growth season rather than at the end of growing season.

Variance analysis of cone index data revealed that difference between tillage methods was statistically significant ($P < 0.01$) from the soil cone index point of view during the corn growth season (Table 7). Soil cone index was also affected by soil depth and interaction between tillage methods and soil depths at the confidence level of 99% in this research.

Results of treatments means comparison for soil cone index showed that there was a significant difference ($P < 0.01$) between CT method and conservation tillage treatments (RT and ZT) from the first measurement right after corn planting to the end of corn growth season; while, the difference between RT and ZT was not significant (Table 8). Zero tillage had the highest soil cone index and conventional tillage had the lowest soil cone index in all the measurement stages during corn growth season because of intact soil in ZT compared to the tilled soil in CT method. Increasing soil cone index in ZT method compared to the CT has been already reported in the literature (Ferreras et al., 2000; Liu et al., 2005; Taser and Metinoglu, 2005; Fabrizzi et al., 2005). The maximum average soil cone index during corn growth season also belonged to the ZT method which was significantly different from that of CT method. Although zero tillage method had the maximum amount of soil cone index, the cone index obtained from this tillage method was lower than the critical soil cone index for agricultural crops (about 2 MPa).

Results also showed that soil cone index increased with increasing soil depth so that the maximum soil cone index was obtained from the soil depth range of 0.20–0.30 m and the minimum value of cone index was related to the soil depth range of 0–0.10 m for all the measurement stages during corn growth season (Table 9). In addition to significant difference between soil cone indices in SD_1 and SD_2, the difference between SD_1 and SD_3, and SD_2 and SD_3 was also significant from the soil cone index point of view. Means comparison of interaction between tillage methods and soil depth also indicated that the maximum soil cone index was measured at the soil depth range of 0.20–0.30 m under reduced tillage operation and the minimum cone index was obtained from the conventional tillage operation at the soil depth

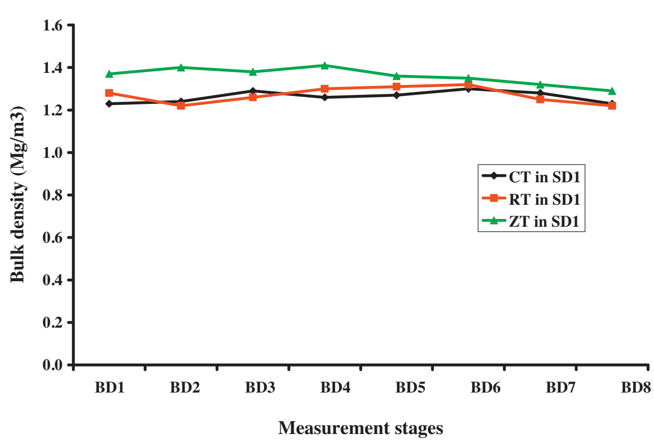

Fig. 1. Soil bulk density variation in different tillage methods during corn growing season at the soil depth range of 0–0.10 m. CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; and SD_1, soil depth range of 0–0.10 m.

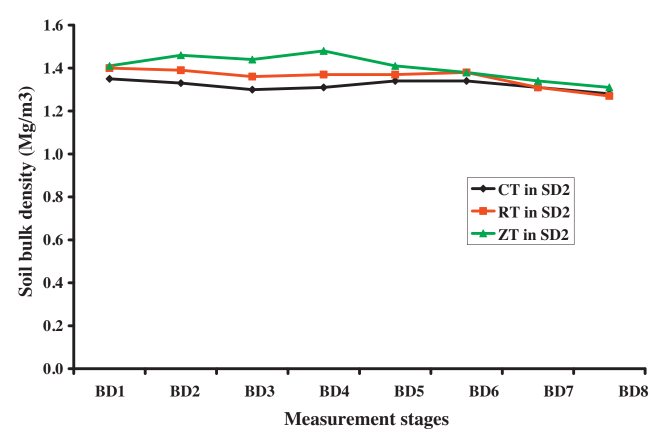

Fig. 2. Soil bulk density variation in different tillage methods during corn growing season at the soil depth range of 0.10–0.20 m. CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; and SD_2, soil depth range of 0.10–0.20 m.

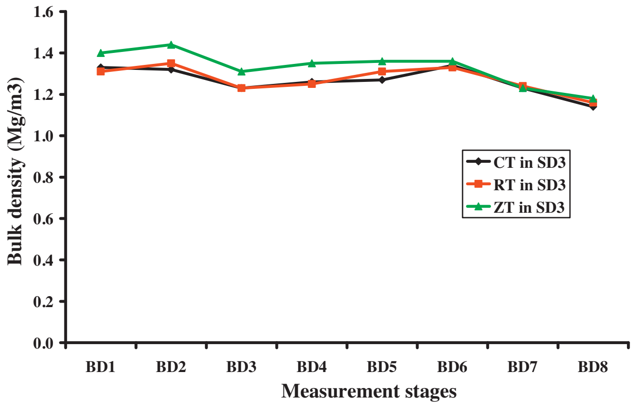

Fig. 3. Soil bulk density variation in different tillage methods during corn growing season at the soil depth range of 0.20–0.30 m. CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; and SD_3, soil depth range of 0.20–0.30 m.

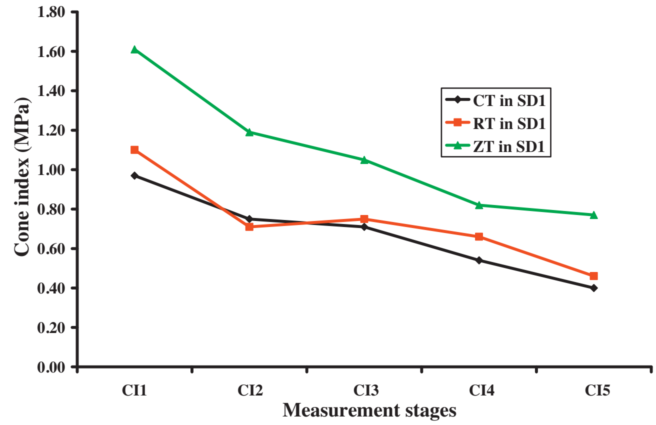

Fig. 4. Soil cone index variation in different tillage methods during corn growing season at the soil depth range of 0–0.10 m. CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; and SD_1, soil depth range of 0–0.10 m.

Table 7
Variance analysis of soil cone index data during corn growing season. Data shown in this table are *F* values.

Variation sources	CI_1	CI_2	CI_3	CI_4	CI_5
TM	54.54**	24.75**	49.81**	28.21**	117.33**
SD	11.85**	35.79**	71.45**	35.62**	71.11**
TM × SD	4.54**	3.28*	7.13**	3.46**	8.85**

TM, tillage methods; SD, soil depths.
* Significant at $p < 0.05$.
** Significant at $p < 0.01$.

Table 8
Means comparison of soil cone index (MPa) of different tillage methods during corn growing season.

Tillage methods	CI_1	CI_2	CI_3	CI_4	CI_5	Average
CT	1.04b	0.94b	0.85b	0.69b	0.48c	0.80b
RT	1.48a	1.16ab	1.18a	1.07a	0.78b	1.13a
ZT	1.65a	1.37a	1.25a	1.02a	0.99a	1.27a

CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; a, b, c, averages with different letters in each column and group are statistically different at $p < 0.01$.

range of 0–0.10 m during corn growing season (Table 10). On the other hand, zero tillage method at 0–0.10 m soil depth had the higher cone indices compared to the conventional tillage at the soil depth of 0.20–0.30 m which proved that tillage method had more determinant effect on the soil cone index compared to the soil depth.

Soil cone index variation trend for different tillage methods at the soil depth ranges of 0–0.10 (SD_1), 0.10–0.20 (SD_2), and 0.20–0.30 m (SD_3) are presented in Figs. 4–6, respectively. Unexpectedly, soil cone index showed descending trend from the beginning to the end of corn growing season for all the tillage methods and soil

Table 9
Means comparison of soil cone index (MPa) of different soil depths during corn growing season.

Soil depths	CI_1	CI_2	CI_3	CI_4	CI_5	Average
SD_1	1.23b	0.88c	0.84c	0.67c	0.55c	0.83c
SD_2	1.44a	1.18b	1.09b	0.97b	0.75b	1.09b
SD_3	1.50a	1.41a	1.35a	1.14a	0.94a	1.27a

SD_1, soil depth of 0–0.10 m; SD_2, soil depth of 0.10–0.20 m; SD_3, soil depth of 0.20–0.30 m; a, b, c, averages with different letters in each column and group are statistically different at $p < 0.01$.

depth ranges. The potential reason for this phenomenon can be the effect of corn root development during the corn growing season which can loosen soil and reduce the soil resistance. At the soil depth range of 0–0.10 m (SD_1), the line showing the soil cone index variation trend in the RT treatment is close to the line showing soil cone index variation trend in the CT treatment rather than ZT cone index line because of similar soil disturbance in the CT and RT operation at this soil depth (Fig. 4). In contrast, at the soil depth ranges of 0.10–0.20 m (SD_2) and 0.20–0.30 m (SD_3), the line showing the soil cone index variation trend in the RT treatment is close to the line showing soil cone index variation trend in the ZT treatment instead of being close to CT cone index line (Figs 5 and 6). This was due to the identical undisturbed soil status in ZT and RT operations (the maximum tillage depth in RT was 0.15 m) at the soil depth ranges of 0.10–0.20 m (SD_2) and 0.20–0.30 m (SD_3). Unlike to the soil bulk density variation during corn growing season, difference between tillage methods from the soil cone index point of view was significant for all the soil depth ranges tested from the beginning to the end of corn growing season. Therefore, measuring soil cone index at the end of growth season can present an acceptable judgment about soil cone index difference in various tillage

Table 10
Soil cone index (MPa) affected by interaction between tillage methods and soil depths during corn growing season.

Tillage method	Soil depth (cm)	CI_1	CI_2	CI_3	CI_4	CI_5	Average
CT	SD_1	0.97	0.75	0.71	0.54	0.40	0.67
RT	SD_1	1.10	0.71	0.75	0.66	0.46	0.74
ZT	SD_1	1.61	1.19	1.05	0.82	0.77	1.09
CT	SD_2	1.01	0.96	0.79	0.71	0.46	0.79
RT	SD_2	1.62	1.26	1.21	1.13	0.78	1.20
ZT	SD_2	1.69	1.31	1.26	1.06	1.02	1.27
CT	SD_3	1.15	1.10	1.04	0.98	0.57	0.93
RT	SD_3	1.73	1.49	1.57	1.42	1.10	1.46
ZT	SD_3	1.64	1.63	1.44	1.19	1.16	1.41

CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; SD_1, soil depth of 0–0.10 m; SD_2, soil depth of 0.10–0.20 m; SD_3, soil depth of 0.20–0.30 m.

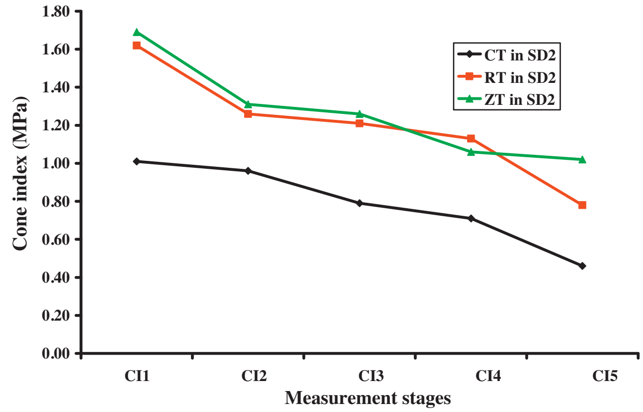

Fig. 5. Soil cone index variation in different tillage methods during corn growing season at the soil depth range of 0.10–0.20 m. CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; and SD_2, soil depth range of 0.10–0.20 m.

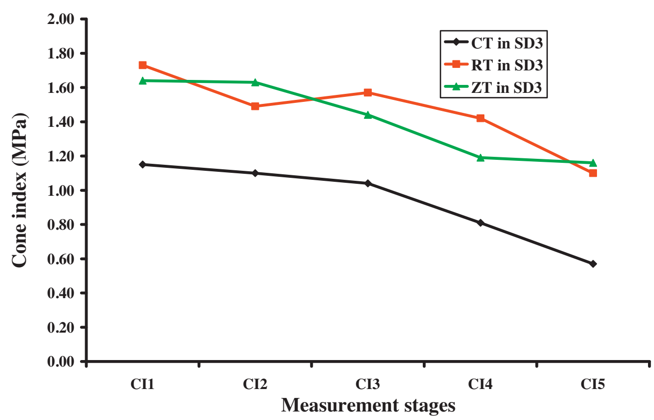

Fig. 6. Soil cone index variation in different tillage methods during corn growing season at the soil depth range of 0.20–0.30 m. CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; and SD_3, soil depth range of 0.20–0.30 m.

Table 11
Variance analysis of corn yield and yield components data during corn growing season. Data shown in this table are *F* values.

Variation sources	Weight of 1000 kernels	Biologic yield	Grain yield
Replication	6.25^{*}	0.70^{ns}	1.15^{ns}
Tillage methods	4.50^{ns}	0.51^{ns}	0.14^{ns}

^{ns}, not significant.
* Significant at $p < 0.05$.

methods; however, cone index measurement during growth season can provide more accurate data.

Data analysis of corn 1000 kernels weight, silage yield, and grain yield revealed that tillage methods had no significant effect on corn yield and yield components (Table 11). Treatments means comparison from the corn yield and yield components point of view indicated that ZT method decreased corn thousand kernels weight, silage yield, and grain yield compared to the CT method for 11.1, 2.4, and 18.2%, respectively; however, this reduction was not statistically significant (Table 12). Results of this study showed that soil compaction increase in the zero tillage method is a potential reason for corn yield and yield components reduction in this tillage method.

Table 12
Means comparison of corn yield and yield components in different tillage methods.

Tillage methods	Weight of 1000 kernels (g)	Silage yield (ton/ha)	Grain yield (kg ha^{-1})
CT	180a	43.21a	6075a
RT	170a	43.28a	5515a
ZT	160a	42.19a	4967a

CT, conventional tillage; RT, reduced tillage; ZT, zero tillage; a, averages with the same letters in each column and group are not statistically different at $p < 0.05$.

4. Conclusions

Results of this research showed that both soil bulk density and cone index increased under zero tillage method compared to the conventional tillage operation due to the lack of soil disturbance in ZT. A significant difference was observed between the tillage methods from the soil cone index point of view from the beginning to the end of corn growth season; whereas, the difference between tillage methods for soil bulk density remained significant until about two months after corn planted. Soil bulk density and cone index were also affected by soil depth throughout the corn growth season; however, the way of soil depth influence on the soil bulk density was different from the effect of this variable on the soil cone index. Both soil bulk density and cone index had a lower amount at the end of growth season compared to the growth season beginning probably due to more corn root development at the end of growth season. Results of this study also proved that measuring soil bulk density and cone index during crop growing season gave more accurate data compared to measuring these parameters at the end of growth season. Among tillage methods tested, zero tillage had the lowest corn silage yield, weight of thousand kernels, and grain yield because of higher soil compaction.

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