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Degree of seedbed compaction and response of spinach (*Spinacia oleracea* L.) under different traffic treatments

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Abstract: Soil compaction has negative impacts on plant productivity. Degradation of soil structure as a result of soil compaction can inhibit the development of plant roots and make it difficult for plants to take up water and nutrients. This can negatively affect plant growth and productivity. Compaction restricts plant root growth by increasing mechanical resistance, reducing oxygen uptake, and thus reducing crop yields as it inhibits plant development. In this study, the effects of soil compaction due to machinery traffic on the physical structure of soil, morphological characteristics and yield of spinach were investigated in Tokat, where vegetable farming is intensively practised. In the study, four different tractor traffic treatments [C – zero tractor traffic (control), T1 – 1 tractor traffic, T3 – 3 tractor traffic, T5 – 5 tractor traffic] were used. As traffic increased, the penetration resistance, bulk density, and porosity increased, and the lowest volume weight was obtained from the control treatment. Plant weight losses in T1, T3 and T5 treatments compared to the control treatment were 1.92%, 31.09% and 64.64%, respectively. The yield value, which was 62.0 t/ha in the C treatment, was determined to be 31.8 t/ha in the T5 treatment, representing a 48.70% decrease. The proper use of modern agricultural machinery plays an important role in preventing soil compaction and increasing plant productivity.

Keywords: penetration resistance; spinach marketable yield; spinach root diameter; tractor traffic

Spinach (*Spinacia oleracea* L.) is one of the essential vegetables in terms of its nutritional value (Kalkan 2019). Thanks to its relatively easy cultivation and short vegetation period, it is suitable for second crop cultivation and is also one of the ideal vegetables for crop rotation (Abak et al. 1992). World spinach production was 33.12 million t on 937 829 ha in 2022. Türkiye is one of the essential spinach-producing countries in the world and ranks third after China (30.65 million t on 731.94 thousand ha) and the USA (382.36 million t on 24.40 thousand ha) with 230.07 thousand t on 15.36 thousand ha (FAO 2022). Tokat province has an important potential for spinach cultivation due to its ecological structure. In 2022, 6 123 t of spinach were produced on 360 ha in Tokat. It provides 2.66% of Türkiye's spinach production (TURKSTAT 2022).

Soil tillage, the first step in crop production, is one of the most critical operations performed each season and aims to physically optimise the soil for the crop to be grown, including seedbed preparation, water-soil conservation and weed control (Battikhi, Suleiman 1999). Soil compaction (SC) has been a major problem in agricultural lands since

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the late 19th century, when heavy and large agricultural machinery became popular in crop production (Soane, van Ouwerkerk 1994). The degree of compaction (DC) varies depending on soil texture, moisture content (MC), axle load, tyre size, tyre inflation pressure, slippage, the number of repeated machine passes and forward speed (Soane 1970; Oni, Adeoti 1986; Ngunjiri, Siemens 1995).

Repeated passage of tractors and other equipment for seedbed preparation, sowing, harvesting and crop protection results in significant SC (Gupta, Allmaras 1987). SC is greater when the soil is moist and/or when high-pressure tyres are used with heavy equipment (Botta et al. 2004; Hamza, Anderson 2005). The main parameters obtained from the Proctor test are the maximum bulk density of the soil (BD_{max}), critical moisture content (CMC) and degree of soil compaction (DC). Soil BD_{max} can be used as a reference value to estimate the relative SC (Carter 1990; Beutler et al. 2005). BD_{max} is reached at a certain critical water content.

SC increases mechanical resistance (Unger, Kaspar 1994), reduces oxygen uptake of plant roots (Czyż 2004), restricts plant root growth and inhibits plant development (Cook et al. 1996) and causes yield reduction (Vrindts et al. 2005). Munsuz (1985) states that roots cannot pass through pores with diameters smaller than the root diameter, and that solid grains must be displaced to enlarge the pores through which the roots can pass while growing in the compacted layer, and during this process, they exert a pressure to overcome the mechanical resistance of the soil. SC is one of the most important factors that can lead to soil degradation, endangering the future productivity, efficiency, and sustainability of soils (Aksakal 2004). Orzolek (1991) reported that SC caused 87% yield reduction in watermelon, 65% in pepper and 44% in tomato. Wolfe et al. (1995) reported that the marketable yields of cabbage, beans, cucumbers and sweet corn decreased by 73%, 49%, 41% and 34%, respectively, in compacted soil.

Although there are many studies in the literature on the effect of SC on plant production, there is no study on the effect of SC caused by machine traffic on plant development and yield in the transition climate zone where spinach is produced. In this study, the effects of SC due to machine traffic on the physical structure of the soil and the morphological characteristics and yield of spinach were investigated in Tokat, where vegetable farming is intensive.

MATERIAL AND METHODS

This study was conducted in a loam (medium, mixed, mesic Ustic Fluvents) with 0–1% slope, located at the experimental station of the Agricultural Applications and Research Center, Tokat Gaziosmanpasa University, Türkiye (Figure 1). The experimental area was located at 40°20'03.44"N and at 36°28'36.01"E. The elevation of the study area is 588 m above sea level, and the average annual precipitation is between 381.7 mm and 586.2 mm. The average maximum and minimum temperature values for summer months are 30.3 °C and 14.6 °C, and for winter months are 8.8 °C and –0.4 °C, respectively (MGM 2022). The texture and some chemical properties of the soils of the experimental area are given in Table 1.

Experimental design and cultural operation. The experiment was conducted with three replications according to the randomised block trial design. In the study, four different tractor traffic [C – zero tractor traffic (control), T1 – 1 tractor traffic, T3 – 3 tractor traffic, T5 – 5 tractor traffic] were applied. Each plot was prepared as a length of 12.5 m

Figure 1. Study area

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Table 1. Texture and chemical properties of experimental soil

Depth (cm)	Sand (%)	Clay (%)	Loam (%)	Texture class	EC (dS/m)	pH	Lime (%)	N (%)	P (kg/ha)	K (kg/ha)	OM (%)
0–10	32.0	20.5	47.5	loam	0.67	7.9	11.9	0.38	356.6	1 126.0	2.9
10–20	32.0	20.6	47.5	loam	2.15	7.8	11.9	0.52	704.6	1 711.7	2.2

EC – electrical conductivity; N – available nitrogen; P – available phosphorus; K – available potassium; OM – organic matter

and a width of 5 m, and a space of 2 m was left between the plots. Before traffic applications, all plots were cultivated with a mouldboard plough, and seedbed preparation was done using a combination of a cultivator and rotary harrow. After tillage, traffic applications were carried out at an average tractor speed of 5.5 km/h according to the experimental design. A 4WD New Holland TD 75D tractor with 75 HP and a weight of 3 600 kg was used in soil tillage and traffic applications. The inflation pressure of the tractor front tyres (size 11.2–24) and rear tyres (size 16.9–30) is 2.07 bar and 1.52 bar, respectively.

After traffic applications, seeds were sown so that one of the planting rows was in the wheel track. In sowing, 20 cm was applied between the rows and 5 cm within the rows. Seeds were sown in 1.5 cm deep scratches on the compacted soil surface. 'Şahmeran' spinach variety [*Spinacia oleracea* L. cv. 'Sahmeran' (Pop Vriend Seeds, The Netherlands)] was used as plant material.

The experiment was conducted in the second crop period in 2022. Before tillage, 20 t/ha of barnyard manure was applied. Seeds were sown on August 16th and harvested on October 6th. Herbicide was applied for post-emergence weed control (100 g/L cycloxydim), and manual weed control was also carried out 20 days after seed sowing. Plants were irrigated with a mini spring irrigation system. Irrigation intervals were adjusted according to soil MC. During harvesting, the plants were removed with the help of a belt together with the soil in the root zone and washed under water to remove soil particles from the roots.

Sampling and measurement of soil properties. Soil MC, penetration resistance (PD), and bulk density (BD) were determined immediately after traffic application and at harvest to determine SC caused by tractor traffic. All sampling and measurements were made from wheel tracks in three repetitions in each plot. In order to determine BD and soil MC, 72 undisturbed soil samples (12 plots × 3 replicates × 2 depths) were taken from 0–10 cm and 10–20 cm depths using cylinders of 0.05 m diameter and 0.05 m height. After the samples were taken, they were weighed and then dried in an oven (Nukleon, Türkiye) at 105 °C until their weights stabilised (Vepraskas, Wagger 1989). BD and MC were determined using the wet and dry weights of the soil samples (Baver et al. 1972; Demiralay 1993). Soil PD measurement was made using a penetrometer (Penetrograph, Eijkelkamp, The Netherlands) that can measure at a maximum of 5 MPa and a depth of 80 cm. By averaging the data obtained, the average PD value was obtained for depths of 0–10 cm and 10–20 cm. Additionally, porosity (P) values were determined using equation (1):

$$P = 1 - (BD/Pd) \quad (1)$$

where: BD – bulk density (g/cm^3); Pd – soil particle density (2.65 g/cm^3).

The standard Proctor test (ASTM 1982) was performed to determine the $BD_{max.}$ Approximately 24 kg of soil samples taken from the experimental plots at 0–10 cm and 10–20 cm depths and sieved through a 4 mm sieve were divided into sub-samples weighing 3 kg, and seven different MC were obtained. Each of the sub-samples with different MC was compacted in three layers by dropping a hammer weighing 2.5 kg 25 times from a height of 30.5 cm within the Proctor mould (944 cm^3). Then, each compressed sub-sample was dried in an oven (Nukleon, Türkiye) at 105 °C and its gravimetric MC and BD (g/cm^3) were determined. The prediction equation was obtained using the relationship between MC and BD values. Equation (2) expressed the DC caused by tractor traffic in the experimental plots (Tapela 2001).

$$DC = (BD/BD_P) \times 100 \quad (2)$$

where: DC – degree of compaction (%); BD – bulk density measured in the trial area (g/cm^3); BD_P – Proctor bulk density (g/cm^3) determined in the moisture content at the time of BD measurement in the experimental area.

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Morphological observations. The effects of the treatments on plant growth, yield and morphological characteristics of spinach were measured on 30 plants in each plot. Plant weight, plant height, number of leaves, root length, number of roots, root weight, yield and marketable yield were determined. After the plants were harvested, they were cleaned by washing them in tap water, kept in the shade at room temperature until the washing moisture was removed, and then measurements and observations were made.

Plant weight was determined by cutting the cleaned plants from the root collar, removing the roots, and weighing the above-ground parts on a 0.01 g precision balance. Plant height was measured from the above-ground parts of the plants to the leaf tip during the harvest period. The number of leaves is counted by counting the leaves that have completed their development in marketable plants during the harvest period. Root weight was determined by weighing the roots separated from the above-ground parts on a 0.01 g precision balance. Root length was determined by measuring the roots prepared for determining the root weight from the root collar to the root tip with a ruler. The root number was determined by counting the primary lateral roots formed on the main root of the plants during the harvest period. Root diameter was determined by measuring the diameter of the roots of the plants removed from the soil during the harvest period, 1 cm below the root collar, with a digital calliper.

The yield was determined by removing the roots of all plants harvested from each plot during the harvest period and weighing them on a 0.01 g precision balance, which was calculated as a ha yield. Marketable yield was calculated by weighing the remaining part of the plants after the leaves with no market value were separated from the plants, together with the petioles.

The percentage of emerged seedlings was determined by counting the plants that emerged in 3 strips of 1 m length randomly in each plot, and the percentage of emerged seedlings was determined by proportioning the number of emerged plants to the number of sown seeds (Bilbro, Wanjura 1982).

Data analysis. The normality test was applied to the dataset created for each parameter, and it was determined whether the dataset showed a normal distribution or not. Normally distributed data sets were subjected to analysis of variance and a Duncan multiple comparison test (P < 0.05). Statistical analyses were performed using the SPSS version 10.0.9 software (SPSS Inc., IL, USA).

RESULTS AND DISCUSSION

Soil properties. Average soil MC, BD, P, PD, and DC were determined for 0–10 and 10–20 cm depths after traffic treatments and at harvest time to determine the effect of traffic treatments, as shown in Tables 2 and 3.

Table 2. Effect of traffic treatments on some physical properties of the soil after treatment

Depth	Treatments	SMC (%v/v)	BD (g/cm^3)	P (%)	PD (MPa)	DC (%)
0–10 cm	C	23.39 ± 2.61^b	1.19 ± 0.06^c	55.21 ± 2.42^a	0.37 ± 0.12^c	73.33 ± 1.32^c
	T1	28.87 ± 4.58^a	1.32 ± 0.07^b	50.08 ± 2.68^b	1.10 ± 0.36^b	82.59 ± 1.50^b
	T3	29.20 ± 2.50^a	1.43 ± 0.06^a	46.15 ± 2.15^c	1.66 ± 0.27^a	87.78 ± 1.43^a
	T5	29.67 ± 3.52^a	1.44 ± 0.08^a	45.63 ± 3.08^c	1.87 ± 0.14^a	88.82 ± 1.84^a
	significance	**	**	**	**	**
10–20 cm	C	29.26 ± 3.24	1.34 ± 0.11^b	49.55 ± 4.17^a	0.95 ± 0.32	81.42 ± 1.27^b
	T1	31.05 ± 1.05	1.46 ± 0.05^a	45.03 ± 2.00^b	1.13 ± 0.17	87.16 ± 1.23^a
	T3	30.50 ± 1.67	1.49 ± 0.08^a	43.73 ± 2.96^b	1.25 ± 0.39	90.33 ± 1.70^a
	T5	31.88 ± 2.30	1.44 ± 0.08^a	45.62 ± 3.03^b	1.05 ± 0.18	86.94 ± 1.67^a
	significance	ns	**	**	ns	**

C – control; T1 – 1 tractor traffic; T3 – 3 tractor traffic; T5 – 5 tractor traffic; SMC – soil moisture content; BD – bulk density; P – porosity; PD – penetration resistance; DC – degree of compaction

**significance at P < 0.01 level; ns – non-significant

[a,b,c]values with the same letter in the columns indicate no statistical difference ± standard deviation values

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Table 3. Mean comparison results of some physical properties of the experimental area soils during the harvest period

Depth	Treatments	SMC (%v/v)	BD (g/cm^3)	P (%)	PD (MPa)	DC (%)
0–10 cm	C	30.62 ± 3.15	1.39 ± 0.07	47.54 ± 2.82	0.67 ± 0.24^b	86.24 ± 1.62
	T1	28.68 ± 1.84	1.40 ± 0.13	47.00 ± 4.80	1.08 ± 0.17^{ab}	86.56 ± 2.54
	T3	28.64 ± 3.58	1.42 ± 0.16	46.39 ± 6.01	1.42 ± 0.38^a	82.47 ± 1.59
	T5	29.94 ± 4.71	1.43 ± 0.14	45.97 ± 5.31	1.55 ± 0.39^a	88.42 ± 3.12
	significance	ns	ns	ns	*	ns
10–20 cm	C	29.55 ± 3.41	1.44 ± 0.09	45.51 ± 3.31	1.36 ± 0.16	86.73 ± 1.85
	T1	29.70 ± 2.80	1.47 ± 0.17	44.44 ± 6.48	1.66 ± 0.75	85.83 ± 2.74
	T3	30.21 ± 3.74	1.49 ± 0.15	43.59 ± 5.62	1.81 ± 0.67	85.76 ± 1.99
	T5	30.75 ± 4.59	1.46 ± 0.13	44.97 ± 4.93	2.19 ± 0.71	87.93 ± 2.87
	significance	ns	ns	ns	ns	ns

C – control; T1 – 1 tractor traffic; T3 – 3 tractor traffic; T5 – 5 tractor traffic; SMC – soil moisture content; BD – bulk density; P – porosity; PD – penetration resistance; DC – degree of compaction

*significance at $P < 0.05$ level; ns – non-significant

[a,b]values with the same letter in the columns indicate no statistical difference ± standard deviation values

Soil MC increased as the number of SC increased in the 0–10 cm soil depth after the treatment. While the difference between the traffic treatments was not significant, the difference between the traffic treatments and the control treatment was significant at the 0.01 level. The lowest MC was measured in the control treatment. Although the MC of the soil at a depth of 10–20 cm was higher than that of the control in traffic treatments due to SC, the difference between the treatments was not significant (Table 2).

Soil BD increased due to SC at a depth of 0–10 cm. As the number of traffic increased, BD also increased, and the lowest BD was obtained from the control treatment. While the difference between treatments was significant at the 0.01 level, the difference between the T3 and T5 treatments was not significant. Similarly, at a depth of 10–20 cm, while the lowest BD was obtained from the control, the difference between the traffic treatments and the control was found to be significant ($P < 0.01$). However, the difference between traffic treatments was not significant (Table 2). In T1, T3, and T5 traffic treatments, the BD increased by 10.92%, 20.17%, and 21.01% at a depth of 0–10 cm, and by 8.96%, 11.19%, and 7.46% at a depth of 10–20 cm, respectively.

These results showed that traffic treatments were more effective, especially at 0–10 cm soil depth, and that maximum SC occurred in three passes, and BD did not increase significantly after three passes. Şeker and Işıldar (2000) reported that tractor traffic is more effective in SC in the first 15 cm of soil depth, and Wang et al. (2022), the soil BD in the 0–20 cm soil layer of tractor traffic with 1, 3, 5, 7 and 9 passes is 5%, 10.7 %, 21.4%, 22.1%, 22.9% and 3.6%, 7.1%, respectively. They determined that it increased by 17.1%, 22.9%, and 24.8%.

Tractor traffic caused a significant ($P < 0.01$) decrease in soil P. At 0–10 cm soil depth, the P decreased linearly as the number of traffic increased, while at 10–20 cm soil depth, the P difference between traffic treatments and control was found to be significant, but there was no difference between traffic numbers. While soil PD was significantly affected by traffic treatments at the 0–10 cm soil depth ($P < 0.01$), although PD at the 10–20 cm soil depth was higher than in the control treatment, the differences were not significant (Table 2). The increase in PD in T1 and T3 treatments was higher than in the T5 traffic treatment. It is understood that soil PD was not affected much after three passes.

Tractor traffic caused significant ($P < 0.01$) SC compared to control plots at both 0–10 cm and 10–20 cm soil depths. At depths of 0–10 cm, there was a linear increase in the DC as the number of traffic increased. In contrast, at depths of 10–20 cm, although the T5 treatment caused more SC than the control, the DC was lower than that of T1 and T3 traffic (Table 2).

It was determined that there was no statistically significant effect of traffic treatments on the MC, BD and P values measured at both depths at harvest time. However, the PD values were statistically significantly different at the $P < 0.05$ level between the treatments at the superficial depth. When the values

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of soil properties determined immediately after traffic treatments (Table 3) were compared with the values determined at harvest time, it was observed that the main difference occurred in the control plots.

The BD, P, and PD values determined in the control plots at harvest time were higher than the initial values (Table 3). This change generally eliminated the statistical difference between the treatments. Negiş et al. (2016) determined that the PD, which varied between 0.59 MPa and 1.95 MPa at a depth of 0–20 cm before planting, varied between 2.36 MPa and 3.42 MPa during the harvest period, and stated that periodic field traffic caused an increase in PD.

At harvest time, the measured BD, P and PD values for 0–10 cm and 10–20 cm depths were 1.39 g/cm^3 (C) – 1.43 g/cm^3 (T5), 45.97% (T5) – 47.54% (C), 0.67 MPa (C) – 1.55 MPa (T5) and 1.44 g/cm^3 (C) – 1.49 g/cm^3 (T3), 43.59% (T3) – 45.51% (C), 1.36 MPa (C) – 2.19 MPa (T5), respectively (Table 3). It is thought that field activities during the production period stabilised the BD, MC, PD and P values.

It is important to observe the variation of PD with depth in order to determine whether there are compacted layers, such as a tillage pan, which adversely affect plant growth, below the tillage depth and to take necessary precautions. For this purpose, the graphs given in Figure 2 were created. Accordingly, it can be seen that the PD values measured immediately after traffic treatments in the experimental area become similar after 15 cm depth. At harvest time, the PD value increased to a depth of approximately 20 cm, but decreased at a depth of 20–40 cm. When the graph showing the variation of PD with depth at both measurement times was analysed, it was determined that there was no compact layer like the tillage pan (Figure 2).

The BD values obtained in the experiment were generally higher than the accepted limit values for plant root development. Lhotsky et al. (1984) reported the limit BD as 1.45 g/cm^3 in loamy soils. The measured BD values at both measurement times are close to the value of 1.45 g/cm^3, which is considered the limit BD, and are higher, especially at depths of 10–20 cm.

Soil PD is often used as an index for root growth potential; PD > 2 MPa indicates limiting conditions for root elongation (Bengough, Mullins 1990; Murdock et al. 1993; Colombi et al. 2018). At high root PD, root elongation decreases, while root elongation stops when the root growth pressure is equal to or less than the root PD (Bengough, McKenzie 1994). For plant roots to elongate, the pressure they exert must be greater than the soil resistance (Misra et al. 1986). Clark and Barraclough (1999) reported that the axial root growth pressure in monocotyledonous and dicotyledonous species was 0.44 MPa and 0.41 MPa, respectively.

To express the DC caused by traffic treatments, the graph showing the change in MC and BD obtained by the Proctor test and the estimation equation is presented in Figure 3. The CMC and BD_{max} values of the experimental area soils are 19.89 (%w/w) and 1.66 g/cm^3 for the surface depth, and 20.58 (%w/w) and 1.67 g/cm^3 for 10–20 cm depth. Using the esti-

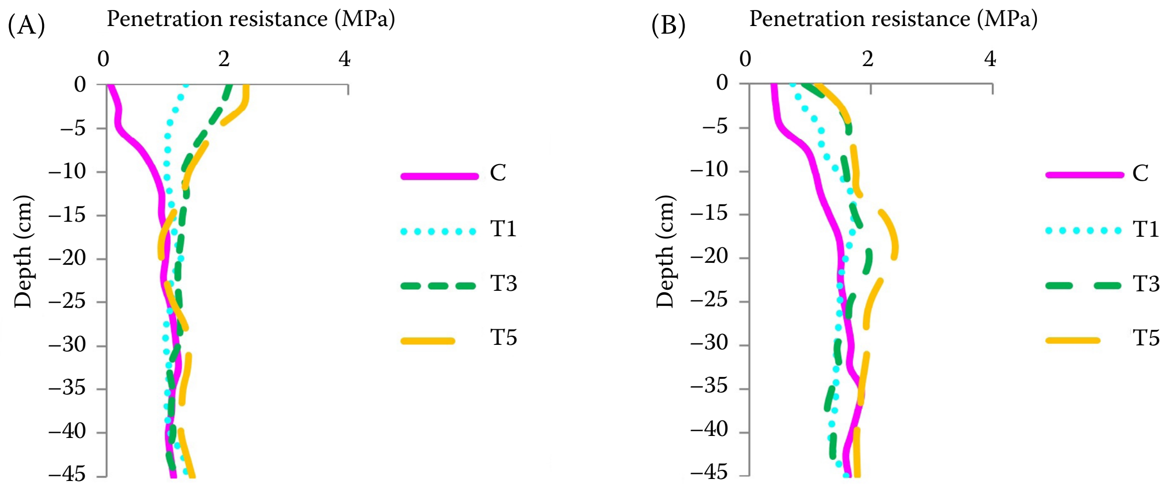

Figure 2. Variation of penetration resistance values with depth measured (A) immediately after traffic treatment and (B) at harvest time

C – control; T1 – 1 tractor traffic; T3 – 3 tractor traffic; T5 – 5 tractor traffic

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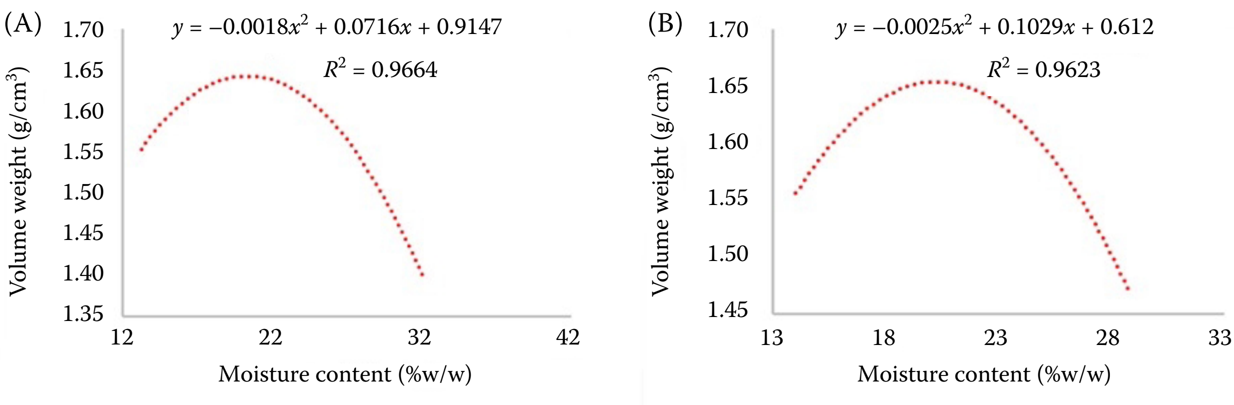

Figure 3. Maximum dry bulk density values of experimental soils for (A) 0–10 cm and (B) 10–20 cm
R^2 – coefficient of determination

mation equations given in Figure 3, SC values were obtained using the BD_P values obtained from the soil MC values when the measurements were made in the experimental area.

The DC after traffic treatments was significant at the $P < 0.01$ level for both depths. There was no significant difference between the T3 and T5 treatments at the surface depth, and between the T1, T3 and T5 treatments at 10–20 cm depth. The highest and lowest DC values were obtained in C (73.33%) and T5 (88.82%) treatments for the 0–10 cm depth, and in the C (81.42%) and T3 (90.33%) treatments for 10–20 cm depth, respectively. During the harvest period, it was observed that traffic treatments had no significant effect on the DC at either depth.

Effect of traffic practices on plant emergence and yield. Although there was no relationship between traffic treatments and plant emergence rates, the effect of treatments on emergence was not significant. The highest emergence rate was obtained from the T3 treatment (64.44%), followed by the T1 (63.11%), control (55.56%) and T5 (52.00%) treatments, respectively (Table 4).

Depending on the number of traffic treatments, yield and marketable yield changed significantly ($P \leq 0.05$). The highest yield and marketable yields were obtained from control plots without traffic treatment, while yield and marketable yield decreased as the number of traffic treatments increased (Table 4). According to traffic treatments, yield decreased by 20.48% (T1), 26.94% (T3) and 48.71% (T5), while marketable yield decreased by 22.96% (T1), 29.22% (T3) and 48.35% (T5), respectively.

As DC increases, BD increases (Karakaplan 1982; Gomez et al. 2002) and pores, especially the large ones (> 50 µm diameter), decrease (Gupta, Allmaras 1987; Gomez et al. 2002). Germination and shoot emergence, as well as the development of plant roots, are physically inhibited (Ehlers et al. 1983; Unger, Kaspar 1994), resulting in decreases in product yield and quality (Unger, Kaspar 1994; Hakansson, Medvedev 1995). Kruger (1971) reported that resistance to infiltration increases when soil pores larger than 50 µm decrease, and that SC caused by tractor tyres leads to significant yield losses in heavy-textured soils.

Hoffmann (1984) reported that the yield reduction due to SC was between 1% and 26% in sugar beet,

Table 4. Effect of traffic treatments on the percentage of emerged seedlings and yield of spinach

Treatment	Percentage of emerged seedlings (%)	Yield (t/ha)	Marketable yield (t/ha)
C	55.56 ± 19.44	62.0 ± 9.6^{a}	57.47 ± 11.64^{a}
T1	63.11 ± 13.23	49.3 ± 29.3^{ab}	44.27 ± 25.59^{ab}
T3	64.44 ± 15.55	45.3 ± 03.7^{ab}	40.67 ± 2.45^{ab}
T5	52.00 ± 24.08	31.8 ± 13.0^{b}	29.73 ± 12.30^{b}
Significance	ns	*	*

C – control; T1 – 1 tractor traffic; T3 – 3 tractor traffic; T5 – 5 tractor traffic
*significance at $P < 0.05$ level; ns – non-significant
^{a,b}values with the same letter in the columns indicate no statistical difference ± standard deviation values

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up to 45% in winter barley and 15% to 34% in winter wheat. Wolfe et al. (1995) reported that the average reduction in total marketable yield in compacted plots was 73%, 49%, 41%, and 34% for cabbage, beans, cucumbers, and sweet corn, respectively.

Effect of traffic treatments on some morphological characters of spinach. Plant weight varied between 44.29 g and 125.26 g depending on traffic treatments. As the number of traffic treatments increased, plant weight decreased, and the difference between treatments was significant at the $P \leq 0.01$ level. The weight losses in T1, T3 and T5 traffic treatments were 1.92%, 31.09% and 64.64%, respectively, compared to the control treatment (Figure 4). Plant height varied between 39.80 cm and 50.89 cm. Traffic treatments caused a significant decrease in plant height, and the difference between the treatments was found to be significant at the $P \leq 0.01$ level. As the number of traffic increased, plant height continued to shorten (Figure 4). Compared to the control treatment, the decreases in plant height in T1, T3 and T5 traffic treatments were 13.03%, 17.78% and 21.79%, respectively. The number of leaves varied between 20.93 and 25.36 units/plant depending on the treatments, and decreased as the number of traffic increased. The difference between the treatments was significant at the $P \leq 0.05$ level (Figure 4). Compared to the control treatment, the number of leaves decreased by 5.17%, 13.80% and 17.47% in T1, T3 and T5 traffic, respectively.

Traffic practices also limited the growth of spinach roots. Root length varied between 13.43 cm and 22.10 cm, root diameter between 6.87 mm and 10.50 mm, number of lateral roots between 18.24 and 28.71, and root weight between 3.33 g and 5.40 g, depending on the treatments. Root length, root diameter, number of roots and root weight decreased as the number of traffic increased (Figure 5). Compared to the control (C), T1, T3, and T5 traffic treatments decreased root length by 23.17%, 26.88% and 39.23%, root diameter by 7.33%, 24.29% and 34.57%, root number by 16.23%, 32.32% and 36.47%, root weight by 6.11%, 14.81% and 38.33%, respectively.

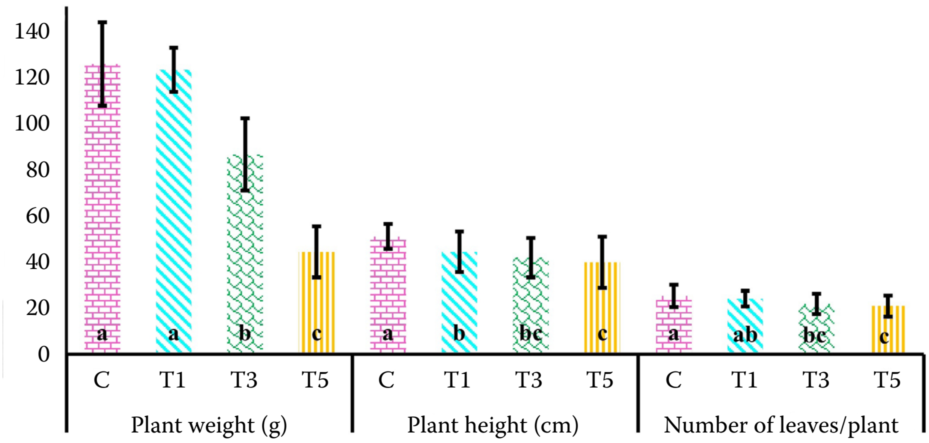

Figure 4. Effect of traffic treatments on plant weight, plant height and number of leaves of spinach

C – control; T1 – 1 tractor traffic; T3 – 3 tractor traffic; T5 – 5 tractor traffic

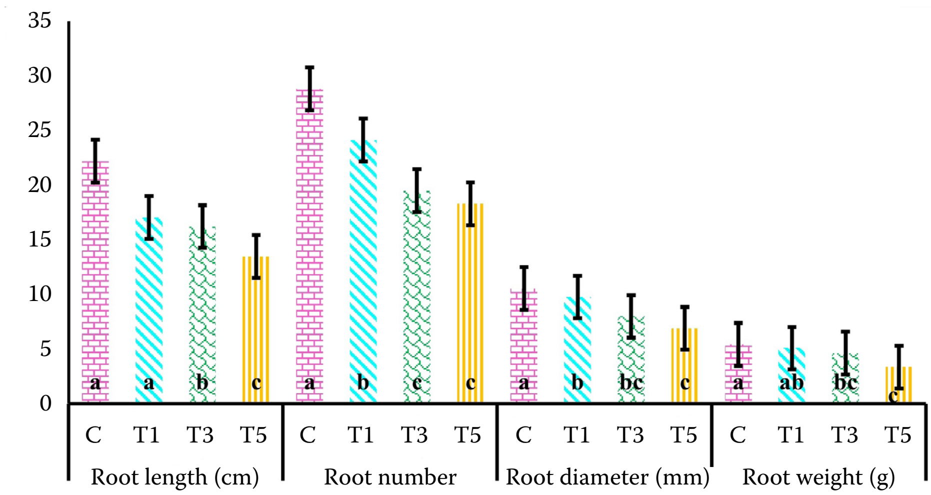

Figure 5. Effect of traffic treatments on root length, root number, root diameter and root weight of spinach

C – control; T1 – 1 tractor traffic; T3 – 3 tractor traffic; T5 – 5 tractor traffic

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SC due to traffic treatment affects many morphological and physiological processes in plants. The growth and development of the above-ground part of the plant depend on the growth and development of the root in the soil (Shah et al. 2017). SC causes roots to become stunted and weakened (Dexter 2004). Shortening of the root length of plants and concentration of roots near the soil surface are the most common problems in SC (Lipiec et al. 1991). According to Rosolem et al. (2002), high PD in compacted soil causes significant regressions in the development of roots and above-ground parts. SC not only limits root development but also causes losses in the above-ground parts (Botta et al. 2002). Chen and Weil (2010) reported that SC, due to wheel traffic, causes a 31% decrease in root dry matter and a 31.25% decrease in biomass in radish.

CONCLUSION

This study aimed to investigate the effects of SC due to field traffic on some soil properties, plant quality parameters and yield in Tokat, where vegetable farming is intense. One of the risks to be encountered with changing climate conditions is drought. SC causes plants to be more sensitive to drought conditions by preventing the roots of plants growing in the soil from going deeper.

At the same time, it causes serious losses in yield by preventing plant root development. The yield value, which was 62.0 t/ha in the C treatment (control), was determined as 31.8 t/ha in the T5 treatment, with a decrease of 48.70%. T1, T3, and T5 traffic treatments caused weight losses of 1.92%, 31.09%, and 64.64%, respectively, compared to the control group, while reducing root length by 23.17%, 26.88%, and 39.23%, root diameter by 7.33%, 24.29%, and 34.57%, root number by 16.23%, 32.32%, and 36.47%, and root weight by 6.11%, 14.81%, and 38.33%, respectively. These results clearly show the effects of traffic density on plant root morphology and weight loss. As traffic density increases from T1 to T5, there is a significant decrease in root length, diameter, number and weight. T5 shows the most significant losses with the highest traffic density. As a result of SC, the number of pores between soil particles that hold water and air decreases. Therefore, it becomes difficult for microorganisms and beneficial soil fauna to survive. This indirectly causes a decrease in the amount of soil organic matter. SC is an issue that cannot be ignored for sustainable production, as it can seriously affect productivity and plant health. Taking measures to prevent or reduce SC will be beneficial in growing healthier plants and increasing productivity. Traffic of tractors or other heavy equipment in agricultural areas should be reduced. Knowing that the problem of SC can be minimised with correct soil management, alternative soil tillage methods should be preferred rather than intensive tillage methods, and field treatments (soil tillage, plant protection, fertiliser application, harvesting, etc.) should not be done when soil moisture is high.

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