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Soil compactibility as affected by soil moisture content and farmyard manure in central Iran

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Abstract

Soil compactibility which basically depends on soil texture, organic matter and soil water content during farm machinery trafficking are major factors affecting soil conservation. In a field experiment, cattle farmyard manure was applied to a silty clay loam soil (fine-loamy, mixed, thermic Typic Haplargids, USDA; Calcaric Cambisols, FAO) in Isfahan, Iran. Three rates, 0, 50, 100 Mg ha^{-1} (on oven dry basis) of farmyard manure, were incorporated into the topsoil. After 5 months, a two-wheel drive tractor (48.5 kW) was passed over the plots once (P1) or twice (P2) at soil moisture contents associated with the plastic limit (PL), 0.8PL, and 0.6PL. A randomized complete block design with four replicates with treatments nested (split-block) into the blocks was used. Bulk density (BD), cone index (CI) and soil sinkage were measured as indices of soil compactibility and trafficability. Applying 50 and 100 Mg ha^{-1} of manure significantly counteracted the effects of load and wetness on BD and CI. There was a significant difference between the effects of 50 and 100 Mg ha^{-1} of manure on BD, but not on CI. Manure application also reduced the subsoil compaction. Double passes of the tractor (P2) significantly increased compaction. There was a limitation for trafficability for no-manure treatment even at 0.6PL, whereas this limit was reached at 0.8PL for the 50 Mg ha^{-1} treatment. Results from this study demonstrate that manure application at a rate of 50 Mg ha^{-1} reduced soil compactibility and increased soil moisture trafficability range. Thus, increasing soil organic matter could bring about an appropriate solution for sustainable soil management in the region.

Keywords: Bulk density; Compactibility; Cone index; Farmyard manure; Sinkage; Trafficability

1. Introduction

Soil compactibility is defined as the quantitative behavior of soil under particular pressure (Soane and van Owerkerk, 1994). Soil compactibility depends on soil type, soil moisture content, organic matter (OM), particle size distribution, plastic behavior of clay, clay mineralogy and the number of passes and contact pressures of vehicles (Soane et al., 1981a).

Soil moisture content is the most important factor in the compaction process (Soane and van Owerkerk, 1994) and soil compactibility (Dicky et al., 1985), but farmers usually cannot easily control soil moisture during farm machinery trafficking. Knowing the change in soil compactibility with water content changes helps one to schedule farm trafficking and

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cultivation operations at the proper moisture content (Ohu et al., 1989). Spoor and Godwin (1978) stated that a soil moisture content lower than plastic limit (PL) is desirable for cultivation and Allmaras et al. (1969) suggested that the most appropriate soil moisture content is 0.9PL. Nevertheless, the type of soil is the most important factor in this regard.

Soil structural improvement by incorporation of organic manure into soil can partially help to prevent soil degradation (Thomas et al., 1996). OM reduces soil compactibility by increasing its stability and by retaining a greater amount of moisture for soil to rebound against compaction (Paul, 1974). Soane (1990) proposed six possible mechanisms by which OM influences the ability of soil to resist compactive loads. These mechanisms act through increasing: (i) bond between particles, (ii) elasticity, (iii) dilution effect, (iv) filament effect, (v) electrical charge change, and (vi) effect on friction. OM also increases soil consistency limits and consequently increases the range of soil moisture for optimum trafficability and workability (Baver et al., 1972). Applying manure at the rates of 0, 40 and 80 Mg ha^{-1} annually for 3 years, and concluded that a traffic load of 250 KPa contact pressure caused the cone index to be much lower in manure treatments than in the no-manure treatment (Soane, 1990). Tillage practices in a 20-year old pasture resulted in a lower bulk density and a higher saturated hydraulic conductivity compared to similar land under continuous cultivation (Ellies, 1986). This was due to the higher OM and the more stable structure in the pasture soil.

Different results have been reported regarding the role of OM on soil compactibility. Soane (1990) indicated that the effect of OM on compactibility was likely to be greater at low levels of stress and high moisture contents, whereas Zhang et al. (1997), using the Proctor test, reported that peat application caused a greater effect at a level lower than the critical moisture content (CMC) in cohesive soils, whereas the greatest effect was at the CMC in sandy soils. Therefore, it is necessary to determine the conditions for which one type of OM will have the optimum effect on soil compactibility, and the extent to which it can reduce soil compactibility (Soane, 1990; Ekwue and Stone, 1997; Zhang et al., 1997). This could help to select the best conditions for agricultural practices (Ekwue and Stone, 1997).

There is little information on soil compaction and its major sources in Iran, particularity in the central regions (Eghbal et al., 1996). Arid soils in central Iran are intensively tilled, low in OM level and consequently have a weak structural stability. Hajabbasi and Hemmat (2000) reported that in a clay loam arid soil, application of a no-till system resulted in an increase in soil OM and thus larger aggregates. However, the initial heavy soil texture and low initial OM of the soil obligates OM maintenance and using proper tillage implements. Crust formation is also a major problem on many soils of cultivated land in the arid parts of this region. In a research on the soil of this study, Eghbal et al. (1996) reported that formation of crust after the first irrigation reduced seedling emergence by 50%. The surface horizon with a higher silt content was more susceptible to physical deterioration and crust formation. Higher exchangeable sodium together with physical deterioration of surface structure due to a long period of mechanized cultivation on this soil had created a suitable condition for crust formation and soil compaction. Farmers in the region rely on chemical fertilizers to maintain crop yields, and give little attention to maintaining soil OM. However, sources of animal manure and compost and other organic fertilizers are available in the region. There is little research concerning effects of organic amendments on soil physical properties and compactibility. Adding sewage sludge, compost, and cow manure at rates of 50 and 100 Mg ha^{-1} to the soil of this study resulted in an increase in mean weight diameter, available water content, saturated hydraulic conductivity, and infiltration and a decrease on bulk density (Bahremand and Afyuni, 1999).

The objectives of this study were: (i) to determine the effects on soil compactibility of farmyard manure at different soil moisture contents according to the consistency limits of the soil; (ii) to identify trafficable moisture content at different manure treatments; (iii) to measure the effects of repeated passes of tractor on soil compaction at the above-mentioned conditions.

2. Materials and methods

2.1. Study site

The study site (32°32′N; 51°23′E) was at the Isfahan University of Technology Research Station farm at Isfahan (central Iran), which is at 1630 m a.s.l., with an arid climate. The mean annual precipitation and temperature are 140 mm and 14.5°C, respectively. The soil (fine-loamy, mixed, thermic Typic Haplargids, USDA system; Calcaric Cambisols, FAO system) (Lakzian, 1989) is formed on alluvial sediments of the Zayandeh Roud river initially low in OM, and with a history of intensive conventional cultivation and cropping of cereals, hay, and silage corn (*Zea mays* L.) rotation.

2.2. Experiments

The experiment was a randomized complete block design with four replications in which the treatments were nested (split-block) into the blocks. Manure and moisture treatments were taken as the major factors (main plots) and the number of passes as the minor factor (sub-plots) on an unplanted soil (prior to the experiment, the land was followed for 3 years). Plot dimensions were 15×6 m^2.

Farmyard manure (from cow waste, 1 year stored in open air, and dry bulk density of 0.3 Mg m^{-3}) was added at the rates (on oven dry basis) of 0 (M0), 50 (M1) and 100 Mg ha^{-1} (M2). The manure was incorporated to a depth of 20 cm with a heavy disk plough. The M1 treatment was near the commercial rate used in the region. After the farmyard manure application, plots were irrigated every 10 days for 5 months (July–November) to allow soil settlement and partial decomposition of farmyard manure. The above-mentioned period of irrigation is as used in farms of the region. Then, a two-wheel drive Universal tractor (model U-650; 48.5 kW) (conventional vehicle in Iran) was used to compact the soil. The rear tyres of the tractor were 14-0-18 in. cross-ply tyres. The static weights on front and rear axles were 1197 and 2193 kg, and when a moldboard plough was attached at the highest position of the three-point hitch, the static weights were 995 and 2695 kg, respectively. The inflation pressure of front and rear tyres was fixed at 228 and 105 kPa, respectively, as suggested by the tractor manufacturer. The tractor was passed over the plots at a soil moisture content of PL, 0.8PL, and 0.6PL, either once (P1) or twice (P2). In the region, the farmers usually apply more than one pass to cultivate the soil, thus a double pass treatment was chosen to simulate commercial conditions. Coverage of wheel tracked soil was about 10%. The tractor was operated without any draught load at the speed of 4.5 km h^{-1} and a moldboard plough was mounted at the highest position of three-point hitch to simulate weight transfer (Soane et al., 1981b; Wood et al., 1991).

2.3. Soil measurements

Pre-test composite samples of soil (0–20 cm) were obtained, air-dried and ground to pass a 2 mm sieve for measuring physical properties. Particle size distribution was determined using the hydrometer method (Sheldrick and Wang, 1993). Particle density (PD) was measured using the pycnometer method (Blake and Hartge, 1986). Mean weight diameter (MWD) of aggregates was determined by the method of Van Bavel (1950). Saturated hydraulic conductivity (K_s) was determined by the constant-head method on undisturbed soil cores (8 cm diameter and 7 cm height) (Klute and Dirksen, 1986). OM content was determined using the method of Walkley and Black (1934). Field capacity (FC) was measured using the field method described by Cassel and Nielsen (1986). Atterberg limits (liquid limit (LL) and PL) were determined by the one-point Casagrande method and the 3 mm rod formation technique, respectively (McBride, 1993). The difference between LL and PL is defined as plastic index (PI). The values of some physical properties of the soil are given in Table 1.

Dry bulk density (BD), cone index (CI) and soil sinkage were used as indices of soil compactibility. Bulk density was determined by the core method (5 cm height and 5 cm diameter) (Davies et al., 1973). The undisturbed core samples were taken from center of tyre ruts at 5 cm increments to a depth of 40 cm. Two samples were taken from each plot, and the average value was used for the BD of the corresponding plot. CI was measured using a digital penetrometer (model SP 1000). The soil moisture content at the time of CI measurements was 1.1PL (at 0–20 cm depth) for all the treatments. Penetration measurements were taken in the center of tyre ruts at 2 cm increments to a depth of 40 cm. Ten penetration measurements were taken in each plot and the parallel values at each depth were expressed as an average. An equal number of measurements were taken from the center of the area beneath lugs and between the lugs which result in average highest compaction (Davies

Table 1
Some physical properties of the soil prior to the manure applications

Depth (cm)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Texture[a]	PD[b] (Mg m^{-3})	MWD[c] (mm)
0–20	160	460	370	SiCl	2.62	0.62
20–35	130	480	390	SiCl	2.66	–
35–50	80	460	460	SiC	2.68	–

[a] USDA textural classification.
[b] Particle density.
[c] Mean weight diameter of aggregates.

et al., 1973, 1993; Bedard et al., 1997). Soil sinkage, which is equal to the cumulative movement of soil elements packed under the tyres, was determined by measuring the depth of tyre ruts, at the height of half the tyre ruts from its center to the initial soil surface.

2.4. Statistical analyses

The measurements of non-compacted treatments in the depth of 0–30 cm were averaged. Due to soil sinkage under the tyre for the compacted treatments, similar values were obtained from 0 to 30 cm minus sinkage depth. The reasons for selecting the 30 cm depth as compaction depth were: (1) the highest compaction affected zone (compaction depth) with the most critical condition (at PL moisture level, with no manure added and two passes) was at 30 cm depth, and (2) the most effective zone for many crop roots is also at this depth. According to Cassel (1982) and Adam and Erbach (1995), compaction depth is defined by the depth at which changes in BD or CI between initial and compacted soil (ΔBD or ΔCI) either equals or exceeds 0.05 Mg m^{-3} and 0.1 MPa, respectively.

Bulk density and CI in non-compacted treatments were dependent only on manure treatments, thus comparisons between one (P1) or two (P2) passes and no-pass (P0) were determined using the non-paired Student-*t* test. In fact the data of the no-pass treatment were not entered into the major design. The mean comparisons were determined using the Duncan new multiple range test. All the statistical analyses were undertaken using the SAS package (Helwig and Council, 1982).

3. Results and discussion

The results of pre-test topsoil (0–20 cm) physical properties following manure application is presented in Table 2. Adding manure to the soil decreased PD and BD, but increased K_s, OM, SP, FC, LL, PL and PI significantly.

The effect on BD of different moisture contents at the time of compaction, amount of manure and number of passes were significant ($P<0.01$). However, the effect of moisture content on CI was not significant, both manure application and the number of passes had significant effects on CI ($P<0.05$ and $P<0.01$, respectively). These results agreed with the findings of Al-Adawi and Reeder (1996). The moisture and manure interaction effect (W×M) on BD was significant ($P<0.1$), showing different behaviors of OM on soil compactibility at different moisture levels. Similar trends were observed for the interaction of moisture and passes (W×P) and manure and passes (M×P) which were significant ($P<0.01$ and $P<0.05$, respec-

Table 2
Some topsoil (0–20 cm) physical properties after the manure applications[a]

Manure (Mg ha^{-1})	PD (Mg cm^{-3})	K_s (cm h^{-1})	OM (g kg^{-1})	SP (kg kg^{-1})	FC (kg kg^{-1})	LL (kg kg^{-1})	PL (kg kg^{-1})	PI (kg kg^{-1})
0	2.62a	3.8c	7.3c	0.470b	0.240c	0.333c	0.212b	0.121b
50	2.51b	8.1b	21.5b	0.512a	0.265b	0.379b	0.232a	0.147a
100	2.43c	11.2a	38.6a	0.565a	0.278a	0.401a	0.240a	0.161a

[a] PD: particle density; K_s: hydraulic conductivity; OM: organic matter content; SP: saturation percentage; FC: field capacity; LL: liquid limit; PL: plastic limit; PI: plastic index. Means with the different letter in each column are significantly different at $P<0.05$.

Table 3
Mean comparisons of BD (Mg m^{-3}, average of 0–30 cm depth) at different levels of soil moisture at compaction time[a]

Moisture level	P1			P2		
	M0	M1	M2	M0	M1	M2
PL	1.53aA	1.47aB	1.41aC	1.59aA	1.51aB	1.46aC
0.8PL	1.42bA	1.37bB	1.36bB	1.48bA	1.43bB	1.40bB
0.6PL	1.38cA	1.32cB	1.28cC	1.41cA	1.35cB	1.31cC

[a] M0, M1, and M2 represent 0, 50, and 100 Mg m^{-3} rates of manure, respectively. P1 and P2 represent one and two passes of tractor, respectively. PL: plastic limit. Means with the different lower-case letter in each column, and with the different capital letter in each row and each group are significantly different at $P<0.05$.

tively). These are in agreement with reports of Soane et al. (1981a) and Soane (1990).

3.1. Soil moisture and soil compactibility

3.1.1. Effect of soil moisture at compaction time on bulk density

In all manure and tractor pass treatments by increasing soil moisture, BD were significantly increased (Table 3). Since the critical BD value of 1.43 Mg m^{-3} for medium textural soil (Robertson and Erickson, 1978) was reached at PL in all manure treatments, trafficking at PL had a hazardous effect on soil density (Table 3). This indicates that the soil moisture content during the field operations is an important factor influencing compactibility (Soane and van Owerkerk, 1994). Student-*t* values for BD variation at different moisture levels (compared to the initial state, P0) are shown in Table 4. Except for the 0.6PL moisture level, other moisture levels treatment (PL and 0.8PL) had a significant effect on BD. This is probably due to the lubricative effect at the highest moisture content (PL) that causes soil particles to re-orientate and smear giving further increase in BD (Davies et al., 1993).

As the soil moisture content increased, the effectiveness and depth of compaction increased significantly (Fig. 1). Repeated passes (P2) also had an increasing effect on BD. Similar trends were observed for the other manure treatments (M1 and M2). At the PL moisture level, surface soil (0–5 cm) was not confined and could easily flow around the tyre rut, thus resulting in a lower soil surface compactness. However, the soil at the depth immediately under the surface (5–10 cm) was confined, and its BD increased to its maximum value (Fig. 1) (in agreement with Soane et al., 1981a). The shear forces by tyre slip resulted in a lower soil surface compactness, this agrees with the reports of Soane and van Owerkerk (1994).

3.1.2. Effect of soil moisture at compaction time on CI

CI was not significantly affected by soil moisture levels, except in the M0 and P2 treatments, in which increasing soil moisture level caused an increase in compaction (Table 5). Similar trends were observed for the effects of soil moisture levels on CI (compared to the initial state, P0) as well as BD (Table 6). Traffic

Table 4
The Student-*t* values of mean comparisons of BD (average of 0–30 cm depth) at different compaction treatments compared to the no-pass (P0) using non-paired and one-tail Student-*t* test[a]

Moisture level	M0		M1		M2	
	P1	P2	P1	P2	P1	P2
PL	10.5**	10.1**	9.01**	9.97**	7.29**	8.84**
0.8PL	3.04*	9.05**	5.75**	9.65**	5.89**	7.42**
0.6PL	0.36	3.49*	2.06†	3.07*	0.59	1.83

[a] M0, M1, and M2 represent 0, 50, and 100 Mg m^{-3} rates of manure, respectively. P1 and P2 represent one and two passes of tractor, respectively. PL: plastic limit. †, *, and ** represent significant differences at $P<0.1$, $P<0.05$, and $P<0.01$, respectively.

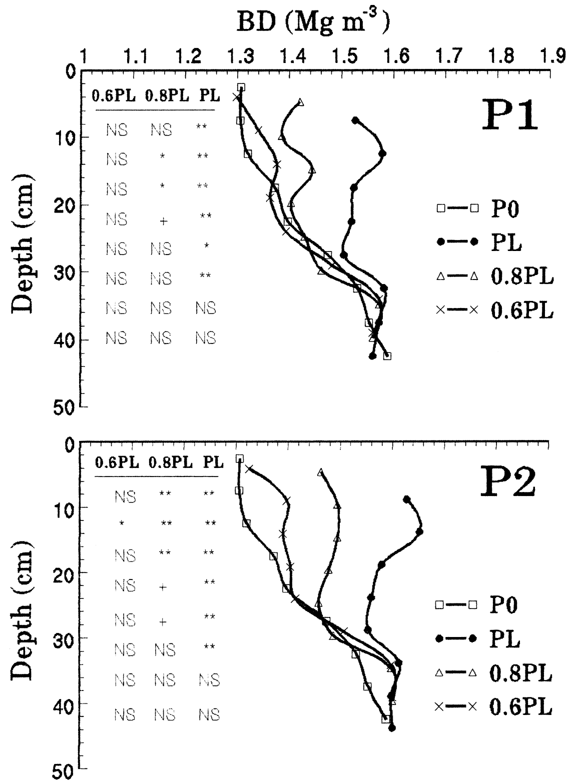

Fig. 1. The effect of different soil moisture contents at no-manure treatment (M0) and one (P1) and two (P2) passes on BD. †, *, and ** represent significant effects of moisture treatments compared to initial state (P0) using non-paired and one-tail Student-*t* test at $P<0.1$, $P<0.05$, and $P<0.01$, respectively. NS: non-significant difference.

at 0.6PL did not cause any significant increase in soil strength.

The effect of soil moisture content on CI in the M0 treatment is shown in Fig. 2. The moisture levels at the time of compaction had a similar effect on CI as was observed for the BD. CI increased with soil moisture content. A similar trend was observed for the other manure treatments. Due to a high cohesion between soil particles and OM, in the M2 treatment, and at the highest moisture level (PL), soil particles close to the rut was not moved around and this resulted in a higher CI (Table 6 and Fig. 2).

At the depth of 28 cm, CI had a significant increase, indicating the existence of a plough pan (Bedard et al., 1997) together with an argillic horizon at this depth as reported by Lakzian (1989).

3.2. Farmyard manure and soil compactibility

3.2.1. Farmyard manure effect on bulk density of compacted soil

Adding manure to the soil significantly decreased BD of compacted soil (Table 3). The highest application rate of manure resulted in a significantly ($P<0.01$) lower BD compared to the M0 or M1 treatments. The Student-*t* analysis in Table 4 indicates a similar observation, particularly at PL with double passes (P2). Bulk density changes (ΔBD) due to compaction were decreased as the amount of manure added to the soil increased. Similar results were reported by other researchers (Soane, 1990).

Comparing BDs of low (M1) and high (M2) manure rates with the M0 treatment before and after compaction indicates the importance of OM in decreasing ΔBD (Fig. 3) and consequently soil compactibility even at high traffic loads (P2) supporting the suggestions of Soane (1990). Adding manure to the soil is also beneficial to seed emergence because it causes a lower soil surface resistance against the emerging seedling (Zhang et al., 1997). The compaction depth

Table 5
Mean comparisons of CI (MPa, average of 0–30 cm depth) at different levels of soil moisture at compaction time[a]

Moisture level	P1			P2		
	M0	M1	M2	M0	M1	M2
PL	0.81aA	0.73aA	0.78aA	1.05aA	0.88aB	0.81aB
0.8PL	0.76aA	0.74aA	0.56aA	0.88aA	0.81aA	0.66aA
0.6PL	0.62aA	0.62aA	0.51aA	0.65aB	0.70aA	0.55aB

[a] M0, M1, and M2 represent 0, 50, and 100 Mg m^{-3} rates of manure, respectively. P1 and P2 represent one and two passes of tractor, respectively. PL: plastic limit. Means with the different lower-case letter in each column, and with the different capital letter in each row and each group are significantly different at $P<0.1$.

Table 6
The Student-*t* values of mean comparisons of CI (average of 0–30 cm depth) at different compaction treatments compared to the no-pass (P0) using non-paired and one-tail Student-*t* test[a]

Moisture level	M0		M1		M2	
	P1	P2	P1	P2	P1	P2
PL	1.38	2.14[†]	1.43	4.1[**]	4.29[**]	1.98[**]
0.8PL	1.1	2.31[†]	1.32	2.87[*]	0.86	2.94[*]
0.6PL	0.18	0.26	0.29	0.52	−0.126	0.48

[a] M0, M1, and M2 are 0, 50, and 100 Mg m^{-3} rates of manure, respectively. P1 and P2 are one and two passes of tractor, respectively. PL: plastic limit. [†], [*], and [**] represent significant differences at $P<0.1$, $P<0.05$, and $P<0.01$, respectively.

of the M0 treatment with two passes (P2) was about 35 cm, whereas this value for the M1 and M2 treatments were about 25 cm. At the highest moisture level (PL), application manure resulted in a decrease in the subsoil compaction. Ekwue and Stone (1997) reported a higher elasticity and dilution effect of farmyard manure as a reason for reduction in soil compactibility. The elasticity of farmyard manure prevents the

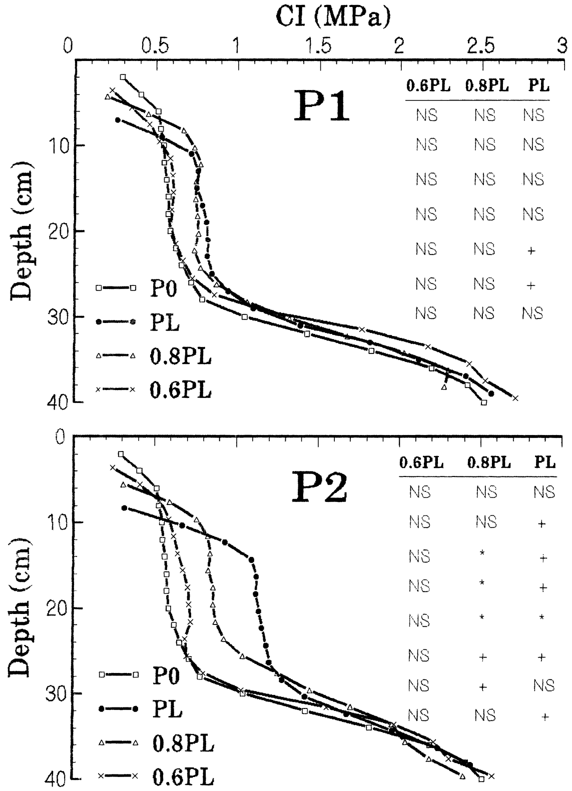

Fig. 2. The effect of different soil moisture contents at no-manure treatment (M0) and one (P1) and two (P2) passes on CI. [†], [*], and [**] represent significant effects of moisture treatments compared to initial state (P0) using non-paired and one-tail Student-*t* test at $P<0.1$, $P<0.05$, and $P<0.01$, respectively. NS: non-significant difference (each two consecutive points were averaged for the test).

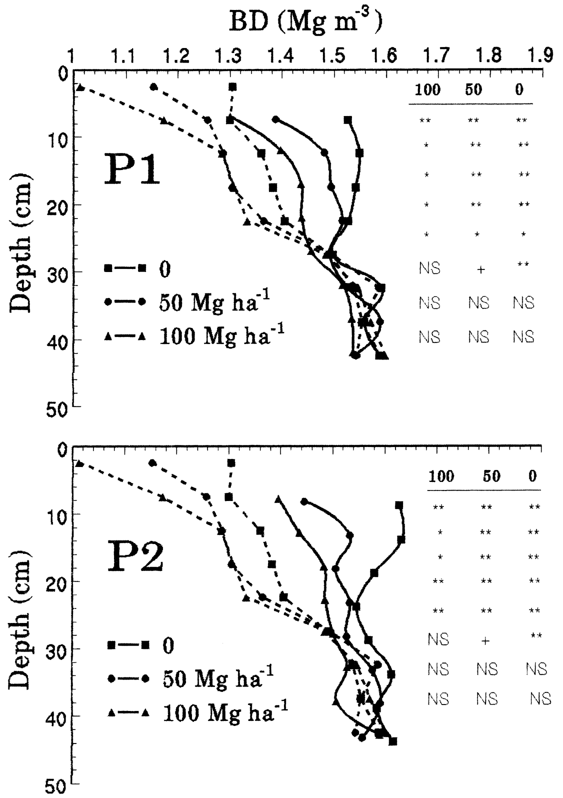

Fig. 3. The effect of manure treatments at PL moisture level and one (P1) and two (P2) passes on BD. [†], [*], and [**] represent significant effects of manure treatments compared to the corresponding initial state, P0 (dashed lines) using non-paired and one-tail Student-*t* test at $P<0.1$, $P<0.05$, and $P<0.01$, respectively. NS: non-significant difference.

transmission of the stresses toward the subsoil in the lower depths (Soane, 1990).

3.2.2. Farmyard manure effect on CI of compacted soil

The effects of different amounts of farmyard manure on CI values of compacted soil are illustrated in Table 5. At PL with two tractor passes, CI was significantly different, comparing M0 and M1. However, CI in M1 and M2 treatments was not significantly different (Table 5 and Fig. 4). The reason for this may be that at high moisture contents, high amounts of FYM can prevent the soil escaping around the tyre rut and therefore increasing compaction.

Fig. 4 shows CI versus depth for the manure treatments at PL. Due to the similarities of the CI values for P0, these data were averaged among the three manure treatments in order to draw Fig. 4. It was observed that in P1, there was no significant difference between manure treatments, however, with P2, FYM gave resistance against additional CI increase (Fig. 4). The CI of the M0 with P2 treatment was nearly twice that of P1. Soane (1990) showed that when manure was added to the soil, a beneficial effect on compactibility was observed after inserting a high or repeated load.

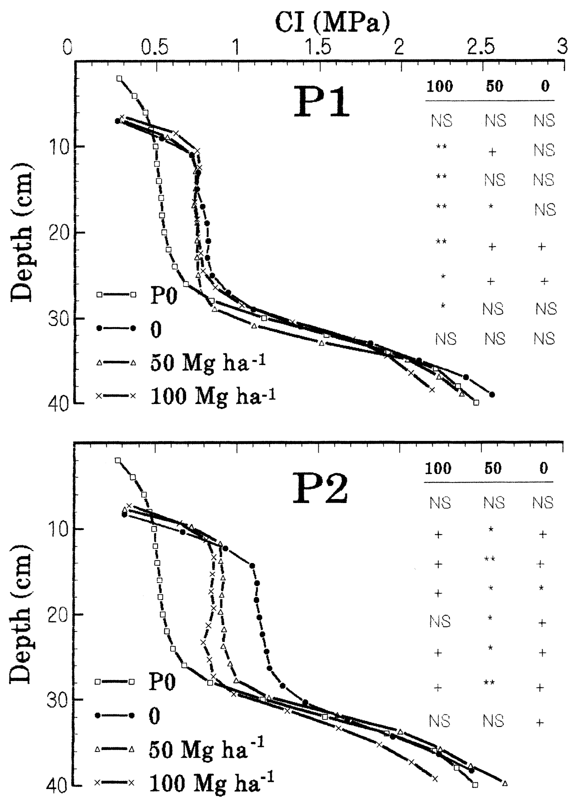

Fig. 4. The effect of manure treatments at PL moisture and one (P1) and two (P2) passes on CI compared to the initial state (P0). † and * represent significant effects of manure treatments compared to initial state (P0) using non-paired and one-tail Student-*t* test at $P<0.1$ and $P<0.05$, respectively. NS: non-significant difference (each two consecutive points were averaged for the test).

3.2.3. Effect of farmyard manure on compaction depth

According to Cassel (1982) and Adam and Erbach (1995), compaction depth is defined by the depth at which changes in BD or CI between initial and compacted soil (ΔBD or ΔCI) either equals or exceeds 0.05 Mg m^{-3} and 0.1 MPa, respectively. Details of compaction depth are shown in Table 7. A decrease in compaction depth was observed with an increase in OM. This decrease was higher with PL and P2 treatments compared to the other treatments. There were no significant differences between M1 and M2 treatments. As the moisture level at compaction time decreased, compaction depth declined significantly. At the 0.6PL moisture level, wheel traffic had a minor effect on BD and CI and compaction depth was negligible.

3.2.4. Effect of farmyard manure on soil sinkage after compaction

Due to a higher elasticity of OM (Soane, 1990) at higher soil moisture, soil sinkage value decreased as soil OM increased, especially on PL with two passes (P2) treatments (Fig. 5). On the other hand, at the moisture levels of 0.8PL and 0.6PL, sinkage increased as the amount of manure increased. Thus, at low moisture contents (0.8PL and 0.6PL), farmyard manure reduced the traction requirement because of the loosening effect of this material (according to suggestions of Soane, 1990; Stone and Ekwue, 1995). However, difference between M1 and M2 treatments were not significant. As the soil moisture level decreased from PL to 0.8PL, sinkage declined significantly. However, further reduction in moisture level did not result in a significant reduction in sinkage, indicating that the change in soil physical attributes during

Table 7
Compaction depths (cm) at different moisture, manure and pass levels[a]

Treatment	P1			P2		
	M0	M1	M2	M0	M1	M2
ΔBD$\geq$0.05 Mg m^{-3}						
PL	25aA	25aA	22aA	35aA	25aB	25aB
0.8PL	17bA	20aA	22aA	23bA	24aA	24aA
0.6PL	0cA	0bA	0bA	13cA	0bB	0bB
ΔCI$\geq$0.1 MPa						
PL	32aA	22aB	28aB	34aA	27aB	27aB
0.8PL	24bA	0bC	28aA	34aA	26aB	24aB
0.6PL	0cA	0bA	0bA	20bA	15bB	0bC

[a] Compaction depth is defined by the depth at which changes in BD or CI between initial and compacted soil (ΔBD or ΔCI) either equals or exceeds 0.05 Mg m^{-3} and 0.1 MPa, respectively (Cassel, 1982; Adam and Erbach, 1995). M0, M1, and M2 represent 0, 50, and 100 Mg m^{-3} rates of manure, respectively. P1 and P2 represent one and two passes of tractor, respectively. PL: plastic limit. Means with the different lower-case letter in each column, and with the different capital letter in each row and each group are significantly different at $P<0.05$.

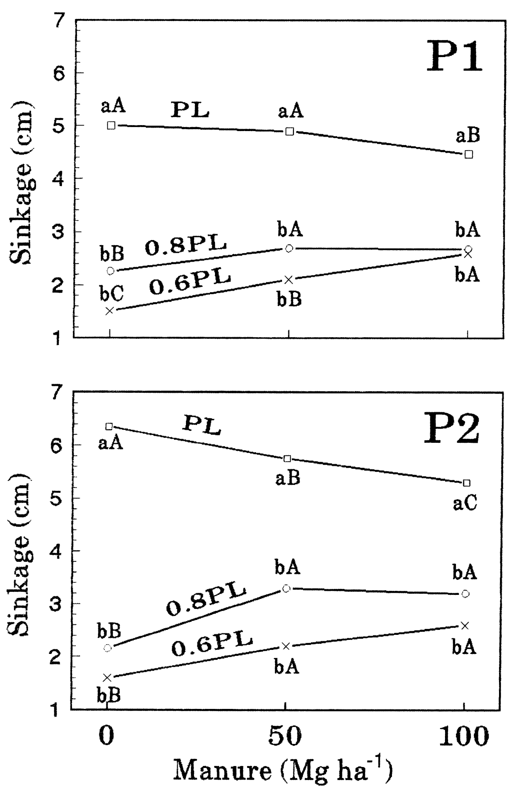

Fig. 5. The effect of manure treatments and moisture levels at one (P1) and two (P2) passes on soil sinkage. Points with the different lower-case letter in each column, and with the different capital letter in each row are significantly different at $P<0.05$.

compaction has a non-linear relationship with soil moisture content (Baver et al., 1972).

4. Summary and conclusions

Soil moisture was a major factor affecting observed soil compaction and trafficability. Vehicle traffic at PL moisture level gave critical increases in BD and CI, significantly. Trafficking at PL caused BD and CI to reach critical values for plant growth (1.43 Mg m^{-3} and 0.8 MPa, respectively). Therefore, traffic at PL has a destructive effect on the structure and quality of soil due to smearing. Lowering the moisture level to 0.8PL reduced this effect significantly.

Applications of manure to the soil counteracted the effect of soil wetness at loading time. Adding manure to the soil not only reduced compactibility and increased soil trafficability but also decreased subsoil compaction. The greatest effect of FYM was obtained at the highest moisture level (PL) and high traffic load (P2). There were significant differences in BD comparing the effect of low (M1) and high (M2) manure application rates at PL with P2 treatment, but had no effect on CI. This indicates that, at high moisture content, high amounts of farmyard manure prevented the soil from escaping around the tyre rut and, therefore, CI did not significantly decrease. Manure application reduced soil sinkage at PL moisture level but increased at low moisture contents (0.8PL and 0.6PL). Generally, manure application had a high suppressive effect on compactibility at high moisture level (PL) with high load (P2).

Repeated tractor passes (P2) increased compaction significantly. This result is in agreement with the study of Håkansson et al. (1988). However, some other literature review did not fully support this result (Soane et al., 1981b; Davies et al., 1993; Soane and van Owerkerk, 1994). This result is probably because soil has a high susceptibility to compaction due to low OM content, silty clay loam texture, and a history of intensive cultivation practices.

In summary, the trafficable moisture content for the soil in this region is about 0.6PL (0.13 kg kg^{-1}). However, application of manure to soil at a rate of nearly 50 Mg ha^{-1} would increase this limiting value to 0.8PL (0.18 kg kg^{-1}). Therefore, manure application could achieve a relatively sustainable soil management and an increase in soil quality.

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