Effect of Chemical Fertilizers on Soil Compaction and Degradation

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Abstract

Soil compaction adversely affects nearly all physical, chemical and biological properties of the soil. In this research, effects of fertilizers that resulted in soil degradation and compaction were studied. Soil penetration resistance was measured by electronic penetrologger in 12 wheat fields at depth 0-30 cm (each farm is a treatment with 3 replications), and the randomized complete block design was applied. Having applied a variance analysis, the mean values of data were compared using Duncan's multiple range tests. Results indicated that bulk density changed from 1.34 to 1.80 Mg.m^{-3}, as well as, penetration resistance from 0.89 to 3.54 MPa in noncompacted and highly compacted soils, respectively. According to the results, soil compaction decreased permeability by 81.4 %, available water by 34 % and yields by 40 %. Therefore, usage of fertilizers more than the recommended amounts causes formation, accumulation and concentration of mineral salts of fertilizers which leads to compaction layer and soil degradation in the long-term. High compaction decreases porosity and aeration while increasing bulk density and soil penetration resistance. Furthermore, root development and plant growth will be limited by reducing water and nutrient uptake which decreases yields.

Key words: bulk density; compaction; degradation; penetration resistance; permeability.

Introduction

Soil compaction is an important component of land degradation syndrome and is a significant challenge facing advanced agriculture that adversely affects nearly all soil properties: physical, chemical and biological (Weisskopf, *et al*., 2010). When soil is compacted, its structure alters by crushing aggregate units, reducing the size of pore spaces between the soil particles, reduction in soil volume and total porosity that leads to increase in soil bulk density and penetration resistance. Soil compaction refers to the formation of dense layers of well filled that occurs on cultivated layer, even more, the compressive forces are applied to compressible soil from wheels (Hamza and Anderson, 2005). Compaction is caused by the use of heavy machinery, reduction in use of organic fertilizer, frequent use of chemical fertilizers and plowing at the same depth for many years (Mari *et al*., 2008). One of the principal causes of compaction is over use of fertilizers (usage of fertilizers more than the recommended amount) for long periods and intensive cropping. Soil compaction causes problems including excessive soil strength, limiting root growth, poor aeration, poor drainage, runoff, erosion and soil degradations (Batey, 2009). These changes lead to reduction in permeability, hydraulic conductivity and groundwater recharge (Blanco, *et al*., 2002). Excessive soil compaction impedes root growth and this can decrease the plants uptake ability of nutrients and water. If the bulk density increases from 1.3 to 1.4 Mg.m^{-3} in some sort of soil with loamy texture, infiltration rate and aeration will reduce (Osunbitan *et al*., 2005). Compaction reduces root growth, as well as, the yield by more than 80 % (Rannik, 2009). When the soil bulk density increases, nitrification decreases by 50 % and plant absorbs less nitrogen, phosphorus and zinc from soil (Barzegar *et al*., 2006). Reduction of biological activity due to compaction is a great concern (Beylich *et al*., 2010). Organic matter is the most important factor in soil structure stability. Soil that has high organic matter contents and thrives with soil organisms is more resistant to compactions and can recuperate much better from slight compaction damage (Dexter, 2008; Celik *et al*., 2010). This research aims to study the effects of over use of fertilizers more than the recommended amounts that cause compaction and soil degradation in long term.

Materials and Methods

The soil studied in this research had been planted with wheat for over 50 years. This research was carried out on 12 wheat farms (each plot is a treatment) in Pakdasht regions, station (35º37′ N, 35º37′ E; 1005 m above sea level) located 35 km southeast of Tehran. Average annual precipitation at this site is 210 mm. The research procedure was as follows:

Farms with different levels of soil compaction were randomly selected. After taking soil samples from each farm (2 m × 1 m × 0.3 m), the necessary analysis was performed in soil laboratory using routine methods. The experiment was a randomized complete block design with 3 replications. N-P-K fertilizers were applied in the seedbed at average rates of 405 kg N ha^{-1} (urea), 203 kg P_2O_5 ha^{-1} (triple phosphate) and 120 kg K_2O (Potassium sulfate) sulfate ha^{-1}. The average amounts of recommended fertilizers were 178 kg N ha^{-1}, 85 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1} (Azadegan and Amiri, 2010). Bulk density was determined from undisturbed soil samples and was measured by the core method. Soil moisture content and penetration resistance were measured at the same time. In order to determine the soil moisture content, undisturbed soil samples were taken from each plot using a steel cylinder of 100 cm^{-3} volume at depths of 0-15 and 15-30 cm. Soil gravimetric moisture content was calculated from the weight difference between wet and oven-dried samples (24 h at 105 ºC). The volumetric moisture content was calculated by dividing the gravimetric moisture content by the soil volume of 100 cm^3. Soil optimum moisture was determined via standard proctor test (ASTM). Soil water permeability was measured using double rings and aggregate stability was determined by measuring the mean weight diameter (M.W.D) of soil aggregates in a sieve under running water. Soil bulk density (ρ_b) was determined via volumetric cylinder method and particle density was measured using a Pycnometer. In order to calculate soil porosity, the relationship between bulk density and particle density was used. Available water equals the difference between the water content at field capacity (FC) and permanent wilting point (PWP) which was measured by the use of a pressure membrane apparatus. Wheat net water requirement was determined using regional meteorological data and Crop-wat software.

Soil penetration resistance was determined by a hand-pushed electronic cone penetrometer (Eijkelkamp penetrologger, 06.15.SA) following ASAE standard procedures, using a cone with 2 cm^2 base area, 60º included angle, speed of 3 $cm.s^{-1}$, 80 cm driving shaft; readings were recorded at 10 mm intervals. The measurements were performed at 10 points in each plot. In order to minimize the effect of compaction caused by agricultural machinery traffic in each plot, the soil from the middle cultivation rows (between the tractor tracks) was used for sampling and testing. The penetration resistance of 10 different points in each plot was randomly measured at depths of zero to 30 cm (at distance is 5-10 m each of point). The average penetration resistance of those 10 points represented the compaction status of the soil in each plot. Values of the average penetration resistance of 12 treatments (each plot was considered as one treatment) were compared. In order to compare the average values of penetration resistance, the normality of the data was tested. Grain yield of each plot was measured after harvest. Variance analysis of data was done based on the randomized complete block design and mean comparison was done using Duncan's multiple range test ($P \leq 0.05$). The soil compaction status was studied and conclusions were made based on the results.

Results and Discussion

The experiment showed that the studied soil contained 36 % clay, 33 % silt and 31 % sand at the depth zero-30 cm. Soil texture was loam-silt loam with 1-2 % slope. The soil had a pH of 7.48-7.70, ECe of 1.15-2.20 ds.m-1 and particle density 2.60-2.62 $Mg.m^{-3}$. Soil bulk density and penetration resistance were used to characterize the compaction and soil degradations.

The result of soil analysis of physical properties (**Table 1**) shows bulk density of 1.34-1.80 Mg m^{3-} and the mean aggregate diameter (M.W.D) changes from 1.43 to 0.28 mm. The aggregates diameter in non-compacted soil (plot, P_2) is 5 times greater than the highly compacted soil (plot, P_4). The macro-aggregates are disintegrated into micro-aggregates that decrease the size and proportion. The total pore volume and porosity is decreased 17.4 % which slows down water and air movement in the soil. Previous studies revealed that the number of small pores decreases, and so does the amount of plant-available oxygen. As a result, as soil density increases, total porosity decreases up to 17 % in the severe compaction. The soil with aggregates about 5mm in diameter, has relatively low volume of inaccessible water for the highest crop yield (Jung, *et al*., 2008; Kaufmann *et al*., 2005; Stawinski *et al*., 2010) and reduction in nutrient uptake (Kuht and Reintam, 2004). These adverse effects may be due to restriction in root depth, where roots in compact soil are confined to macro pores and the rate at which they can extract water and nutrients from the soil between the macro pores may be considerably slowed.

To achieve higher yield of crops, it is essential to provide the optimum level of nutrients requirement. In Pakdasht regions, farmers applied usually N, P and K fertilizers in the seedbed at rates of 405 kg N ha^{-1}, 203 kg P_2O_5 ha^{-1} and 120 kg K_2O ha^{-1} for wheat in each year. But fertilizers were applied at average rates of 227 kg N ha^{-1}, 118 kg P_2O_5 ha^{-1} and 70 kg K_2O ha^{-1} more than the recommended amounts. However, there were no significant increases in yields. Results showed that calcium carbonate content increased from 12.24 % in non-compacted soil to 24.8 % in highly compacted soil (increased by 100 %). The calcium carbonate concentrated and accumulated into sub soils with little solubility, which created a compressed layer that slows down the water movement in the soil (Jung, *et al*., 2008). Phosphorus and excessive calcium in soil form insoluble calcium phosphate which reduces phosphorus absorption. Compaction affects phosphorus uptake strongly because the phosphorus is very immobile in soil and the rate of residual phosphorus fertilizers in soils is 75-80 % (Tisdale, *et al*., 1993). Compaction also reduces penetration and growth of the roots because phosphorus uptake is inhibited in compacted soil. Therefore, extensive root systems are necessary to enable phosphorus uptake (Oussible, *et al*., 1992). Potassium uptake is affected the same way as phosphorus. The rate of residual potassium fertilizer is 30-40 % in the soils and gradually forms carbonate Potassium (Kaufmann, *et al*., 2010). Also, nitrification capacity decreases by 50 % while the rate of residual nitrogen fertilizers is 30-35 % in the soils. The results show a reduction in absorption efficiency of fertilizers, as well as, annual increase in fixation and concentration of insoluble forms of nitrogen, phosphorus and potassium in soils. This effect leads to reduced uptake of nutrients in return (Mari, *et al*., 2008). Overuse of fertilizers in each year for monoculture crop causes formation and concentration of mineral salts of fertilizers leading to compaction layer and soil degradation in the long-term. These results in increase of physical properties of the soil, such as, bulk density, penetration resistance and soil compaction which in return decreases plants-absorbable nutrients, crop yield and increases the production cost. In some soils dissolution of salts due to irrigation causes dispersion of soil particles. Once aggregates are dispersed, fine clay particles leach into soil pores and block them. These fine and structure-less substances cover the soil surface which hinders water penetration and forms a hard and impermeable layer (Stawinski, *et al*., 2011).

In this study, 20-40 ton.ha-1 of cow manure was used in non-compacted soil, and nothing in compacted soil. Organic carbon was 0.58-1.17 %, C/N decreased from 19.5 in non-compacted soil to 8.28 in highly compacted soil (42.5 % reduction). Insufficient use of animal manure causes organic matter deficiency in soil that contributes to its compaction decelerates the organic carbon mineralization. This consequently disrupts the biotic activities of the soil which decreases the absorbable nutrients, stunts plant growth and limits the yield. With this loss of organic fertilizer, soil aggregate stability reduces. Total number of bacteria and enzymatic activity in soil under soybean decreased in

Table 1 Results of the soil physical analysis in Pakdasht County (0-35cm depth)

Plot	Clay (%)	ρ_b ($Mg.m^{-3}$)	M.W.D (mm)	Porosity (%)	Permeability ($mm.h^{-1}$)	Available Water (%)
P_1	33	1.62	0.53	37.6	37	19
P_2	32	1.34	1.43	48.2	71	24
P_3	33	1.40	1.37	46.5	64	23
P_4	35	1.79	0.30	30.8	12	16
P_5	35	1.78	0.29	31.5	25	17
P_6	30	1.46	1.32	43.9	59	22
P_7	36	1.55	1.25	41.3	48	21
P_8	30	1.56	1.20	40.4	42	21
P_9	35	1.68	0.32	35.5	33	18
P_{10}	36	1.75	0.28	31.7	19	16
P_{11}	34	1.80	0.28	31.0	15	16
P_{12}	33	1.51	1.25	42.6	53	22

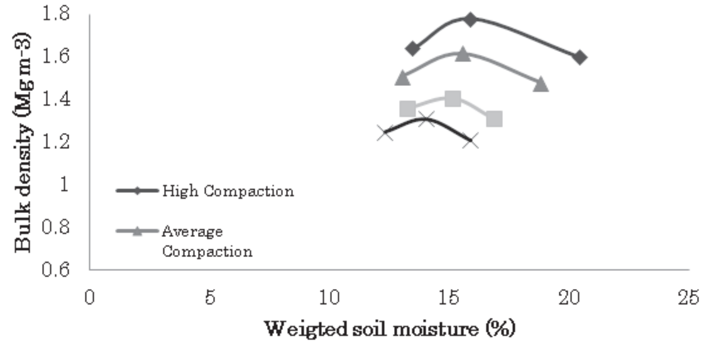

Fig. 1 Soil moisture versus soil bulk density

strongly compacted soil (Beylich, *et al*., 2010; Siczek and Frac, 2012). To optimize organic matter input in the soil for maximum productivity, one should reduce losses of organic matter by preventing the soil erosion (Bandyopadhyay, *et al*., 2011). Structural stability of topsoil with greater organic matter content was considered as enhanced resistance to compaction. Organic matter decomposition is slower in compacted soils, and less biological activity occurs because the size and number of macro pores in the soil, aeration and microbial activity are reduced. Soil with high organic matter content that thrives with soil organisms is resistant to compaction and can better recuperate from degradation.

Fig. 1 shows soil moisture content versus soil bulk density. Soil optimum moisture was 13.2 %. Farmers were usually tilling soil at moisture content above the optimum level (15-16 %) which contributes to soil compaction. The compacted soil often has higher soil moisture because soil water is unable to drain away freely and air movement in the soil is restricted. Compaction of soil pushes the soil particles closer together, reduces the pore space and so bulk density increases. That process reduces porosity, permeability and crop yield. A tractor of 75 HP cannot easily till the farm due to its highly compacted soil. Therefore, heavy-duty tractor with more than 75 HP is needed, which results in increasing the cost of production. High penetration resistance and soil compaction are functions of soil moisture content. Each soil type with a certain amount of moisture (optimum moisture content) has optimum penetration resistance, bulk density, compression and compaction. When the soil rewets and expands, the extra soil present in the subsoil will induce compaction (Kaufmann, *et al*., 2010; Jung, *et al*., 2010). If tillage is done under improper moisture conditions, big clods are formed. The wetting of clogged soil pores gradually after irrigation reduces soil porosity and permeability (Weisskopf, *et al*., 2010). The effect of the plowing and machineries traffic on yield can be predicted by measuring of penetration resistance and soil compaction. If soil is dry and firm throughout the profile, there may be no significant effect. If the surface layers are moist and soft lying over dry soil, the upper layers may be strongly compressed. But if the surface layers are dry and firm with moist soil below, the compression may be transmitted downwards to compress the moisture in the more vulnerable soil. Obviously, suitable moisture content, during the cultivation, prevents soil compaction.

Fig. 2 compares the mean values of penetration resistance and soil depth in non-compacted, low compacted, moderate compacted and highly compacted soils. Values of soil bulk density were strongly correlated to soil penetration resistance. Penetration resistance in non- compacted soil at first increased slightly with depth but later changes were insignificant because soil compaction was within the normal range due to stable aggregates and proper soil structure. Penetration resistance changes dramatically from the soil surface to greater depths in highly compacted soil as a result of compaction caused by the disintegration of soil macro-aggregates and formation of micro-aggregates, reduction in the aggregates diameter, total volume of soil pores, porosity percentage, the size and proportion of the voids in it. An increase in soil bulk density and penetration resistance reduces soil permeability, air diffusivity, rate of root development and plant growth (Zhang, *et al*., 2006). As noted, a moderate increase in soil bulk density leads to an increase in the cohesion among particles and better adhesion between particles and root surfaces by facilitating water and nutrient absorption.

Table 2 shows the variance analysis of soil compaction in order to

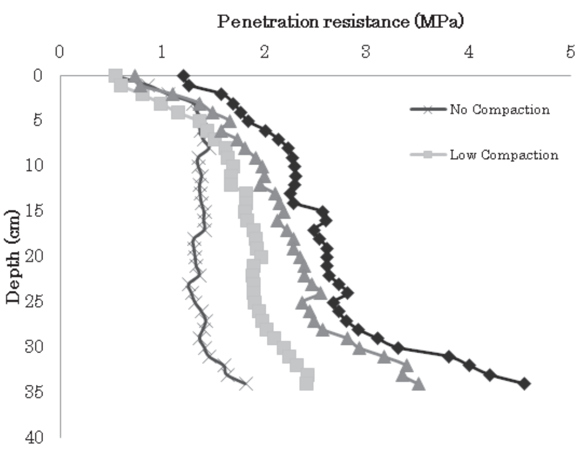

Fig. 2 Comparison the mean of penetration resistance and soil depth

Table 2 Variance analysis of soil compaction to compare 12 farms

Variation Source	df	Ms
Block	58	0.4189**
Treatment	12	6.1008**
Error	509	0.0499
C.V = 7.79 %		

Table 3 Comparison of the mean values of soil compaction in 12 farms using Duncan's multiple tests ($P \leq 0.05$)

Plot	P4	P10	P11	P5	P9	P1
average	3.54a	2.73b	2.72b	2.69b	2.00c	1.67d
Plot	P8	P7	P12	P6	P3	P2
average	1.66de	1.60de	1.48ef	1.41fg	1.34g	0.89h

compare the 12 farms on the basis of randomized complete block design. The results have been significant at ($P \leq 0.01$). **Table 3** shows the comparison of mean soil compaction amounts of 12 farms using Duncan's multiple range test ($P \leq 0.05$). **Table 1** shows that plot P_4 has the penetration resistance 3.54 MPa (highly compacted), while plot P_2 has 0.89 MPa (non-compacted). Soil penetration resistance in highly compacted soil is 14 times greater than non-compacted soil. Penetration resistance is a better indicator of the effects of soil compaction on root growth because results can be interpreted independent of soil texture. In **Table 1**, the average bulk density increases from 1.34 $Mg.m^{-3}$ in non-compacted soil to 1.80 $Mg.m^{-3}$ in highly compacted soil. It can be observed that penetration resistance increases as the bulk density increases; this leads to an increase in soil compaction which adversely affects the indices of porosity and available water. Highly compacted soil constrains root penetration and development, impedes plant growth and reduces the yield. The biggest differences between bulk soil and the rhizosphere occurred in heavily compacted soil, where soil penetration resistance limited root growth (Nosalewicz, 2011). When soil penetration resistance is over 2 MPa (the critical level), root growth in many plants will be restricted and may stop due to soil compaction (Henderson, 2005). Penetration resistance index may individually account for 50 % of the variations in wheat growth and yields (Passioura, 2002; Rannik, 2009). Soil compaction destroys soil structure and leads to a more massive soil structure with fewer natural voids. When penetration resistance changes from 0.4 to 4.2 MPa due to compaction, the lengths of the primary root and lateral roots are reduced by 71 and 31 %, respectively. Consequently, the yield reduces by 20-40 % (Kuht and Reintam, 2004; Jung, *et al.*, 2008). Compaction alters soil structure by increasing soil bulk density, breaking down the soil aggregates, decreasing soil porosity, aeration and infiltration (Weisskopf, *et al.*, 2010).

Fig. 3 shows the relation between soil bulk density and porosity. Porosity was 48.2 % in non-compacted soil and changed to 30.8 % in highly compacted soil (reduced by 17.4 %); the bulk density also increased from 1.34 $Mg.m^{-3}$ normal to 1.80 $Mg.m^{-3}$ in highly compacted soil. Soil high compaction reduces the pores diameter by disintegrating the soil particles; therefore, increases soil strength and decreases porosity. High bulk density and low porosity reduced the pore-spaces due to which roots were incapable to extract soil nutrients. Therefore, reduced nutrient uptake by plant and also inadequate water may impede and even stunt plant growth, resulting in decreased yields. Compaction reduced air-filled porosity considerably and caused more frequent and pronounced conditions of low O_2 concentration in soil air (Bassett, *et al.*, 2005). Soil compaction causes other problems such as poor aeration, limited root growth, excessive runoff, erosion and a degradation of soil structure. This degradation is enforced when tillage is used to break up compacted soils.

Fig. 4 shows the relation between permeability and available water. Permeability reduced from 71 mm/h in non-compacted soil to 12 mm/h in highly compacted soil (81.4 % reduction). The permeability in highly compacted soil is 6 times less than that in non-compacted soil. Consequently, available water is also reduced from 23.5 % in non-compacted soil to 15.5 % in highly compacted soil (34 % reduction). Plant suffers from nutrients deficiency, physiological dryness and water stress. The occurred water stress hinders plant growth and reduces yield. Permeability and available water decreased by 21 and 49 % in moderately and highly compacted soils, respectively. In this study, average wheat yield was 3,500 to 5,800 $kg.ha^{-1}$

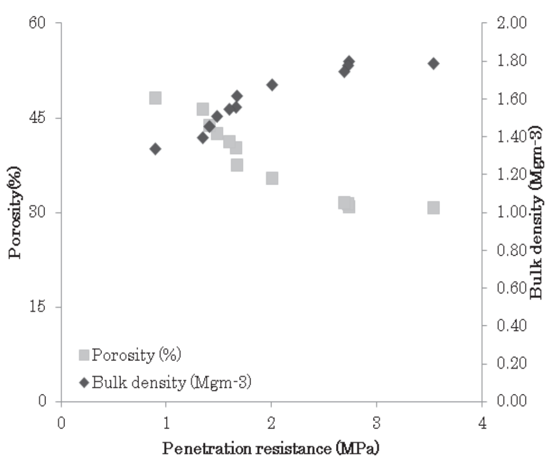

Fig. 3 Relation between the bulk density and soil porosity

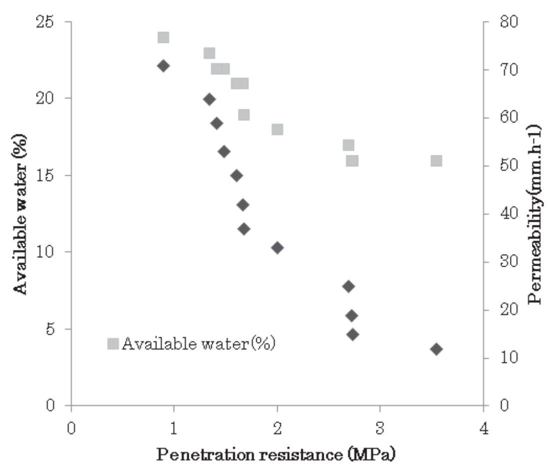

Fig. 4 Relation between permeability and available water

in highly compacted soil and non-compacted soils, respectively. The yield decreases 2,300 kg.ha^{-1} (40 % reduction) due to high compaction (Azadegan and Amiri, 2010). This yield reduction not only reduces the farmer income but also increases the production cost. Reduction of yield components was due to compaction and less supply of necessary nutrients from soil because roots were less proliferated, and were unable to supply the required material, thus the yield decreased. Insufficient water and nutrients absorption, as well as, increasing water stress in plants reduced the yield (Kaufmann, *et al*., 2010). With slow permeability through the clay pan, soils saturate quickly creating a high probability of runoff (about 30 %), clay pan soil reduced yields by 20-47 % (Blanco, *et al*., 2002; Jung, *et al*., 2010)

High soil compaction substantially damages the physical, chemical and biological properties of soil and reduces the yield. In this research, some operations like performing tillage at optimum moisture condition, employing appropriate methods of irrigation, and observing the technical tips of soil and water management have been undertaken in farms P_4, P_3, P_6 and P_{12} under the supervision of an expert, soil compaction had been within the normal range. But in farms P_2, P_5, P_{10} and P_{11} soil is highly compacted because of the farmers' excessive use of fertilizers and not using organic matter. Also, there was mismanagement of the soil and water and not observing crop rotation traditionally. Soil compaction in farms P_1, P_7, P_8 and P_9 had been moderate. High soil compaction decreased absorbability of water and nutrients, increased resistance against root penetration and development, stunted plant growth, decreased available water, reduced soil quality, yields and finally, increased production costs. Soil compaction affects significantly the soil structure, and nutrient uptake in wheat plants (Mari *et al*., 2008).

Soil structure can be improved by adding enough organic matter to soil, reducing usage of chemical fertilizers, observing crop rotation, proper cultivation operation, using modern irrigation methods and applying sub-soiler to shatter the deep compact layers (Azadegan and Amiri, 2010).

Conclusions

Over-use of fertilizers more than the recommended amounts for continuous monoculture cropping caused formation, accumulation of mineral salts of fertilizers that lead to compaction layer, compaction and soil degradation in long-term. Soil degradation affects significantly the soil structure and nutrient uptake.

Results showed that the size and number of macro pores in the soil reduced which lead to increase in soil bulk density and penetration resistance that degraded soil physical properties. Soil bulk density values were strongly correlated with soil penetration resistance.

The plowing is performed moisture content higher than the optimum level. Consequently soil structure is damaged and caused compaction because soil water is unable to drain away freely and air movement in the soil is restricted.

Not using organic fertilizers reduced C/N, organic carbon mineralization, aggregate stability and porosity which consequently disrupted the biotic activities of soil, decreasing the absorbable nutrients.

High soil compaction decreased permeability, drainage, aeration, water availability, absorption of nutrient, plant growth and yield. It can be concluded that the major contributory factors to high soil compaction are caused by the over-use of fertilizers.

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