

Soil compaction impact and modelling. A review

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Abstract Compaction of agricultural soils is a concern for many agricultural soil scientists and farmers since soil compaction, due to heavy field traffic, has resulted in yield reduction of most agronomic crops throughout the world. Soil compaction is a physical form of soil degradation that alters soil structure, limits water and air infiltration, and reduces root penetration in the soil. Consequences of soil compaction are still underestimated. A complete understanding of processes involved in soil compaction is necessary to meet the future global challenge of food security. We review here the advances in understanding, quantification, and prediction of the effects of soil compaction. We found the following major points: (1) When a soil is exposed to a vehicular traffic load, soil water contents, soil texture and structure, and soil organic matter are the three main factors which determine the degree of compactness in that soil. (2) Soil compaction has direct effects on soil physical properties such as bulk density, strength, and porosity; therefore, these parameters can be used to quantify the soil compactness. (3) Modified soil physical properties due to soil compaction can alter elements mobility and change nitrogen and carbon cycles in favour of more emissions of greenhouse gases under wet conditions. (4) Severe soil compaction induces root deformation, stunted shoot growth, late germination, low germination rate, and high mortality rate. (5) Soil compaction decreases soil biodiversity by decreasing microbial biomass, enzymatic activity, soil fauna, and ground flora. (6) Boussinesq equations and finite element method models, that predict the effects of the soil compaction, are restricted to elastic domain and do not

consider existence of preferential paths of stress propagation and localization of deformation in compacted soils. (7) Recent advances in physics of granular media and soil mechanics relevant to soil compaction should be used to progress in modelling soil compaction.

Keywords Soil compaction · Soil disturbance · Soil stress · Modelling · Soil degradation

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1 Introduction

Performance of soil on a particular land plays a vital role in the development and survival of civilizations as soil ensures the provision of food and further essential goods for humans (Hillel 2009). But the soil is a nonrenewable resource with potentially rapid degradation rates and extremely slow formation and regeneration processes (Van-Camp et al. 2004). So, the sustainable use of soils is the only solution to deal with the global issues like food security, demands of energy and water, climate change, and biodiversity (Lal 2009; Jones et al. 2009).

Soil degradation is as old as agriculture itself; its impact on human food production and the environment is becoming more serious than ever before because of its extent and intensity (Durán Zuazo and Rodríguez Pleguezuelo 2008).

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Effects of soil degradation are not only on the livelihoods of rural dwellers but it also poses a potential threat to global food supplies over the long term (Scherr and Yadav 1996). Land degradation will remain an important global issue for the twenty first century because of its adverse impact on agronomic productivity, the environment, and its effect on food security and the quality of life (Eswaran et al. 2001). The soil compaction is the physical form of soil degradation that changes the soil structure and influences the soil productivity (Mueller et al. 2010). Unlike salinity, water logging or the soil erosion that can be remarked from the soil surface, the soil compaction causes a hidden degradation of the soil structure that is difficult to locate and rationalize (McGarry and Sharp 2003).

Increased demands for the food and shelter have resulted in mechanization of forests and farms in almost all the developed countries as well as in many developing countries. Mechanized operations involved in intensive cropping and in forest silvi-culture can, directly or indirectly, lead to the soil compaction as shown in Fig. 1 (Ishaq et al. 2001; Silva et al. 2008). About 68 million ha of the soils worldwide are estimated to be affected by the soil compaction from the vehicular traffic. The soil compaction is responsible for the soil degradation in Europe (33 million ha), Africa (18 million ha), Asia (10 million ha), Australia (4 million ha), and some areas of North America (Flowers and Lal 1998; Hamza and Anderson 2003).

The soil compaction can be defined as “the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby, increasing the bulk density” (SSSA 1996). So, the soil compaction involves the changes in physical properties of the soil (bulk density and soil porosity) and these modified physical parameters of the soil are determinants of the influence of the soil compaction on chemical properties of the soil, soil fauna, and diversity and plant growth (Fig. 2).

The soil compaction in cultivated lands affects mostly the upper layer of soil (top soil compaction) but it is also



Fig. 1 Ruts formation after the passage of vehicular traffic on soil; an example of compacted soil

observed at certain depth (subsoil compaction). Except a few cases where a slight degree of top soil compaction can be beneficial for some type of soils especially sandy soils (Bouwman and Arts 2000), in most cases, it has negative effects on the soil. The subsoil compaction is a serious problem because it is expensive and difficult to alleviate and it has been acknowledged as a serious form of the soil degradation by the European Union (Jones et al. 2003). About 38% reduction in grain yield of wheat crop is reported when the subsoil compaction was carried out at 0.15 m depth to a bulk density of 1.93 Mg/m³ (Ishaq et al. 2001). The soil compaction in forests, due to mechanized operations, can be severe but shows more spatial variability than in agricultural lands due to less systemic mechanized operations and presence of stumps and heavy roots in the soil.

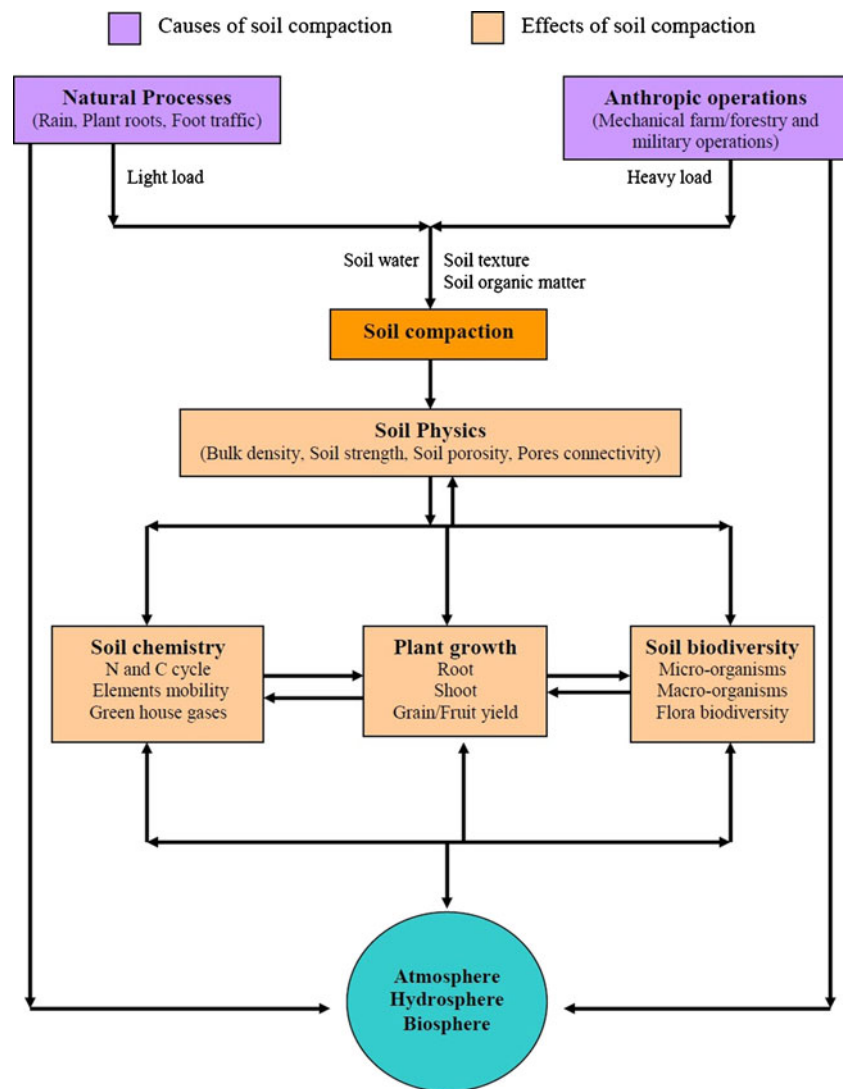
A number of reviews already exist on the soil compaction, but they have been written many years back and are focused on specific aspects such as physical aspects of the soil compaction (Horn et al. 1995; Soane et al. 1982), the influence of organic matter on the soil compaction (Soane 1990), modelling the soil compaction (Lipiec and Hatano 2003; O’Sullivan and Simota 1995), and the soil compaction by grazing animals (Drewry 2006).

Some reviewed articles have also discussed the soil compaction on the basis of a specific land use, mainly crop systems (Hamza and Anderson 2005; Soane and Van Ouwkerk 1995) and rarely forest systems (Greacen and Sands 1980). The most recent review by Batey (2009) focused only on practical soil management issues. In addition to the previous aspects by including the recent studies, this review also considers the effects of the soil compaction on biogeochemical processes and biodiversity, both at macro- and microscales. Furthermore, existing models for the soil compaction are critically discussed and new directions for modelling the effects of the soil compaction on the soil are being proposed

1.1 Description of the phenomenon

The soil compaction involves a microscopic rearrangement and bringing of the solid particles closer to one another and consequently an increase in the bulk density of the soil (Panayiotopoulos et al. 1994). But the degree of compactness is a quantitative parameter and defined as “the ratio of the actual bulk density to the reference bulk density obtained by uniaxial compression of wet soil (sufficiently for drainage) at static pressure of 200 kPa” (Håkansson 1990; Lipiec and Hatano 2003). The soil compaction is accompanied by the removal of the soil air, changes in the soil structure, and macroscopic increase in the soil strength (Taylor 1971). The phenomenon of the soil compaction can be explained in the classical elasto-plastic conception of stress–strain phenomena by considering the soil as a material that reacts elastically up to a certain limit of stress; beyond that limit, any incremental

Fig. 2 Causes of soil compaction and their effects on soil physical properties with ultimate direct effects on soil chemistry, plant growth and soil biodiversity while indirect effects on exchanges of matter with external compartments



stress results in the plastic deformation (Horn 1988). This stress threshold for a given soil, under given climatic conditions, depends on soil texture, degree of aggregation, and matric potential (Horn et al. 1995). The soil compaction, depending on the soil structure, influences soil physical, chemical, and biological processes (Gupta et al. 1989; Fig. 2).

Susceptibility of the soils to compaction varies with the soil texture. For example, the silt loam soils with low colloid contents are more susceptible than medium or fine textured loamy and clayey soils at low water contents while the sandy soils are slightly susceptible to the soil compaction (Horn et al. 1995). In an experiment, Smith et al. (1997) selected 35 types of soils from timber growing areas covering a wide range of the soil textures (clay contents from 8% to 66%) and organic carbon contents (from 0.26% to 5.77%). A vertical stress was applied on the soils by applying pressure of 0, 100, 200, 400, 600, 1,000, and 1,400 kPa at different water contents and then bulk density was measured. Thus, a relationship among pressure applied (P), water content (W), and

bulk density of the soil (D) was established. When a loam-Typic Haplaquept soil was subjected to varied pressures and moisture contents, it behaved totally differently from a loamy sand–Aquic Ustipsamment soil (Fig. 3). The former one was resistant to the compaction when dried and susceptible to compaction when moist to wet while the latter showed only small increases in compaction at incremental load and the moisture contents. Different behaviour in both types of soil is attributed to higher bulk densities of loamy sand soils when they are very dry due to the particles rearrangement with changing water contents (Smith et al. 1997).

Increases in the soil organic matter may reduce compatibility by increasing resistance to deformation and/or by increasing elasticity (rebound effects; Soane 1990). High organic carbon contents can even reduce the compactibility of soil at high moisture levels in clay and silty clay soils (Smith et al. 1997).

The soil compaction process is highly influenced by the soil water content (Hamza and Anderson 2005; Horn et al. 1995; Mosaddeghi et al. 2000). It affects the penetration

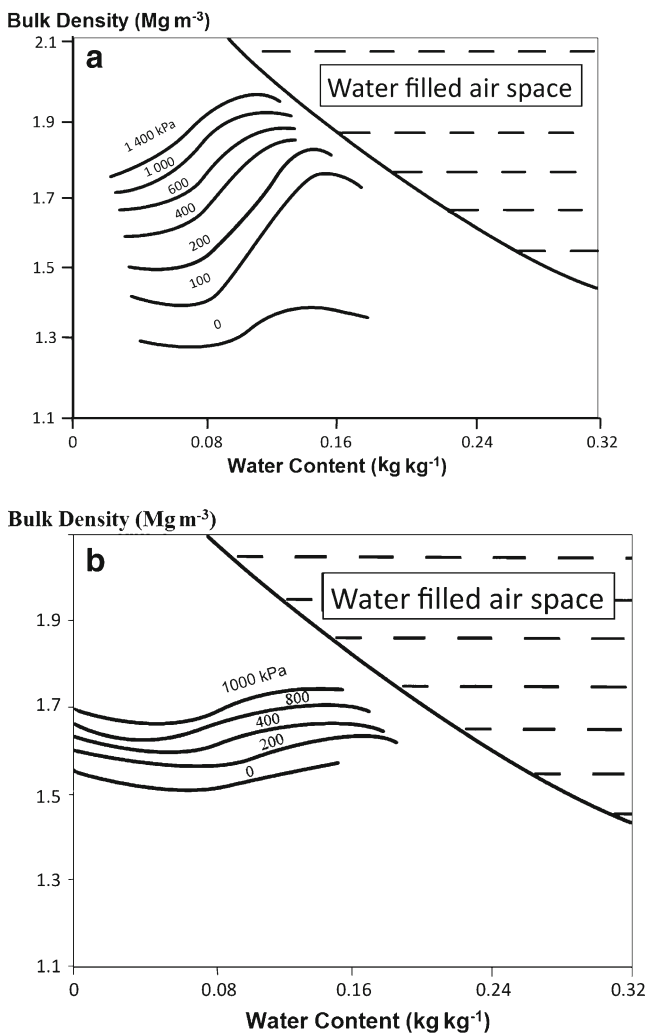


Fig. 3 Contradictory behaviour of two soils with different textures at varied applied pressure and moisture contents. **a** Loam-Typic Haplaquept, **b** loamy sand-Aquic Ustipsamment. From Smith et al. (1997)

resistance and load support capacity or maximum permissible ground pressure on the soil (Medvedev and Cybulko 1995). Vulnerability of a soil to compaction at the given soil moisture and energy level depends also on its clay content and mineralogical characteristics (Smith et al. 1997; Wakindiki and Ben-Hur 2002). Generally, a soil with very low moisture content is less vulnerable to compaction than a soil with high moisture content (Gysi et al. 1999). But when the moisture content is so high that all the soil pores are filled with water, the soil becomes less compressible (Smith et al. 1997). Using the bulk density as the soil compaction indicator, Ishaq et al. (2001) showed as to vulnerability of the soil to compaction increases with increasing water contents up to a limit after which it decreases with the increasing water contents (Fig. 4). They carried out a laboratory experiment on the sandy clay loam soil and found that the soil was compacted to its maximum at a soil moisture content of 120 g/kg. Similar results were reported in another experiment when a vertical

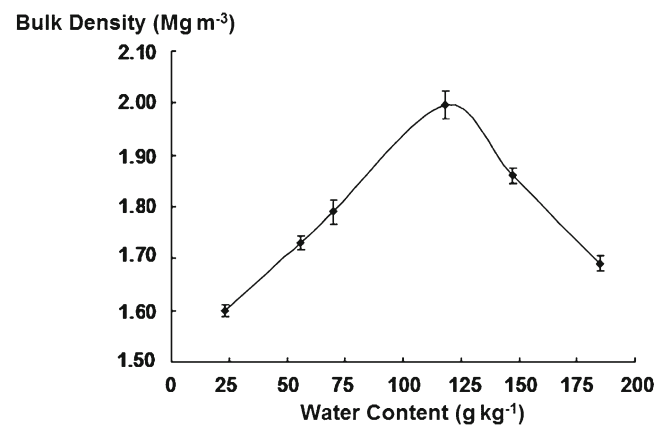


Fig. 4 Relationship between soil water content and bulk density for maximum soil compaction. The error bars represent the standard deviation of mean values. From Ishaq et al. (2001)

pressure was applied on 35 soils of different textures (Smith et al. 1997).

Knowledge of water contents in relation to the soil compaction for a particular soil can be helpful in scheduling the routine mechanical operations on that soil (Batey 2009; Ohu et al. 1989). The soil compaction can also be influenced by the state of energy of water, i.e., water potential, either matric or osmotic potential (Charpentier and Bourrié 1997). In nonsaturated conditions, the suction can influence compaction and the effect of the suction must be separated from the effect of the applied pressure (Cui et al. 2010). So, the soil water contents, soil texture and structure, and soil organic matter are the three main factors among others which determine the degree of compactness after the soil is being exposed to vehicular traffic load.

2 Causes of the soil compaction

Compaction can be a natural phenomenon (Fabiola et al. 2003) caused by freezing and drying or an artificial phenomenon caused by the mechanical operations (Greene and Stuart 1985). Conventional agricultural practices can also degrade the soil by the soil compaction (Quiroga et al. 1999).

In modern agriculture, most of the field operations from sowing to harvesting are done mechanically by using heavy wheeled machines which can compact the soil at every passage (Williamson and Neilsen 2000). The soil compaction by a machine, in general, depends on the soil strength and loading of machine (Alakukku et al. 2003). The soil strength is influenced by the organic matter, water content, soil structure, and texture while the loading is expressed by axle load, number of tyres, tyre dimensions, tyre velocity, and soil tyre interaction (Kirby et al. 1997; Sakai et al. 2008). Axle load should not be confused with axle pressure as axle load is weight of machine

(kilogram) while pressure is the axle load per unit surface area (kilopascal) and in the soil compaction; the term pressure is used to express the disturbance on a soil. Increasing the pressure on the soil increases the chances of the soil compaction (Gysi et al. 1999). Increasing the frequency of passages of machines over a soil increases its dry bulk density and cone index resulting in the top soil compaction and unsuitable physical soil conditions for seed emergence (Botta et al. 2006; Sakai et al. 2008). However, a major portion of the total soil compaction is caused by the first passage (Bakker and Davis 1995; Silva et al. 2008) or early passages (Sakai et al. 2008) of the machine and 10 passes can affect the soil up to 50 cm depth (Hamza and Anderson 2005).

Animal trampling can cause the soil compaction and can degrade the soil structure (Silva et al. 2003). The soil compaction caused by grazing animals through hoof action is likely to be more widespread within the paddocks as compared to the soil compaction caused by mechanical implements which is limited under the tracks (Drewry 2006; Sigua and Coleman 2009). Physical deterioration by grazing animals depends on the trampling intensity, soil moisture, plant cover, land slope, and land use type. Animal caused the soil compaction could range from 5 to 20 cm and might affect the soil bulk density, hydraulic conductivity, macropore volume, and penetration resistance of the soil (Hamza and Anderson 2005; Sigua and Coleman 2009). Effects of the grazing animals on the soil physical properties (Drewry et al. 2008), and soil nitrogen and carbon have been discussed in detail in literature (Bhandral et al. 2007; Piñeiro et al. 2010).

In contrast to the cultivated lands, harvesting operations in forest cause more soil compaction because of: (1) the use of heavy machinery for harvesting; (2) felling, pushing, pulling, and lifting of logs; (3) during transport of logs that exert a combined pressure on the soil; (4) no tillage operations in forests to loosen the soil. In the forests, harvesting operation causes different types of the soil disturbances and probability of the soil compaction is directly related to harvesting system and harvesting density (Sowa and Kulak 2008). Mostly severe soil compaction is caused when thinning and clear felling operations are carried out with machines and these operations can compact the soil up to the depth of 60 cm leaving the effects for more than 3 years (Greacen and Sands 1980). A simple logging operation in the forests can damage 20–30% of the forest land up to the depth of 30 cm (Herbauts et al. 1996). The use of light weight multifunctioning machines can reduce the passages and ultimately the degradation of the soil (Radford et al. 2000).

In the urban areas, urban parks and recreational sites receive large number of visitors and with increasing urban population, visitors' pressure on these sites is increasing day by day (Frick et al. 2007). Trampling effects of the visitors on the soil and vegetation have been reported by many authors (Jim 1987; Sarah and Zhevelev 2007) and these effects are long term in some cases (Kissling et al. 2009). Increasing visitors' pressure

results in the soil compaction, increased bulk densities, decreased soil porosity and decreased organic matter contents (Marion and Cole 1996; Sarah and Zhevelev 2007).

Military operations or military training exercises in the past have also resulted in severe soil compactions in some places (Silveira et al. 2010) and increased bulk density of the soils up to 2.12 Mg/m³ has been reported due to military operations (Webb 2002).

Natural causes (tree roots, precipitation, seasonal cycles, etc.) of the soil compaction are not as harmful as anthropogenic causes: the soil compaction associated with natural causes is limited in top 5 cm of the soil and the soil compaction due to the trampling and urban pressure on a site can compact the soil up to 20 cm while mechanical operations can compact the soil up to 60 cm. No matter of which origin it is, the soil compaction influences the water dynamics (Schlotzhauer and Price 1999), pesticide diffusion (Alletto et al. 2010; Van den Berg et al. 1999), soil erosion (Kosmas et al. 1997), carbon and nitrogen cycle (De Neve and Hofman 2000), plant growth (Lowery and Schuler 1991), and mechanical operations cost (Soane and Pidgeon 1975); as we shall discuss in the coming sections.

3 Quantifying the effects of the soil compaction

To characterize the soil compaction, physical parameters such as the bulk density and porosity, soil strength, water infiltration rate, and reduction of aeration have been used. Indeed, under natural conditions, due to steady-state aggregation processes, and biological processes, the soil contains a large proportion of macropores. The soil compaction can result in the destruction of inter-aggregate pores, in the reduction of soil hydraulic conductivity and air permeability (Horn et al. 1995). Macropores are relatively more affected during the soil compaction than micropores.

3.1 Bulk density and porosity

Bulk density (dry soil mass per unit volume) is the most frequently used parameter to characterize the soil compaction (Panayiotopoulos et al. 1994), but in swelling/shrinking soil, it is recommendable to determine the bulk density at the standard moisture contents (Håkansson and Lipiec 2000). Typical resistance indicators, used nowadays, are highly precise for the soil density measurements up to the soil depth of 20 cm while for deep stratum, the stress state transducers with six earth pressure gauges that measure three dimensional stresses can be useful (Eguchi and Muro 2007). The bulk density is difficult to measure in gravelly soils (Webb 2002). For an accurate measurement of the effects of the soil compaction on all types of the soil, the soil bulk density alone is not adequate but other soil properties such as the soil strength, soil aeration, and soil moisture should also be measured (Lipiec and Hatano 2003).

In an experiment on a clayey oxisol, Silva et al. (2008) analyzed the effects of the intensity of traffic on the soil compaction. They removed the 7-year-old Eucalyptus stand manually with chainsaw and soil was compacted with forest tractor, weighing 11,900 kg and loaded with 12 m³ wood, by driving along same track zero, two, four, and eight times. They found that the first two passes of forwarder caused maximum increase in the bulk density and maximum decrease in infiltration rate. In other experiments, 30% increase in bulk density was observed after mechanical clearing of the forests (Weert 1974) and 20% increase in the bulk density was found after tree length skidding in pine hardwood stands (Dickerson 1976).

Decrease in the soil porosity has been widely reported in the cultivated crops and forests after mechanical operations (Dickerson 1976; Silva et al. 2008). Herbauts et al. (1996) showed that a logging operation, in the loamy and acidic soils with an illuvial and frequently mottled argillic B horizon, has increased the bulk densities and decreased the total porosity of the soils up to 30 cm depth at two different sites, Terrest and Tumuli (Table 1). It is reported that an increase in contact pressure of 100 kPa caused a decrease of 5.7% in the soil porosity at 10–15 cm depth after 24 passes in the sandy humus rich forest soil (Sakai et al. 2008).

3.2 Soil strength

The soil strength (resistance to penetration) is also widely used for the soil compaction measurement (Bouwman and Arts 2000;

Horn and Rostek 2000; Taylor 1971). The soil strength increases with increasing bulk density while it decreases with decreasing soil moisture content. One should be careful when measuring penetration resistance because it varies between the seasons due to different moisture contents (Bouwman and Arts 2000).

The soil strength is measured by a penetrometer (Usowicz and Lipiec 2009) and, furthermore, cone penetrometer is widely employed (Yu and Mitchell 1998) to measure the soil strength in terms of cone resistance (megapascals). The cone resistance also serves as an indicator of the root penetration and root growth capabilities (Materechera and Mloza-Banda 1997). Sinnett et al. (2008) reported that a soil having a cone resistance larger than 3 MPa caused a major hindrance for the root penetration of four tree species (Japanese larch, Italian alder, birch, and Corsican pine) in the sandy loam soils as shown in Fig. 5; nearly all roots (90.7%) were present in the soil with a cone resistance class less than 3 MPa.

3.3 Water infiltration rate

Soil water infiltration rate can also be used to monitor the soil compaction status because the soil compaction reduces the total porosity of the soil (Silva et al. 2008), and mainly the number of macropores, water infiltrates faster in uncompacted soil than in a massively compacted soil of the same type (Hamza and Anderson 2003). These are not directly related to the changes in porosity but rather to the changes in both the number of macro-pores and in the connectivity between

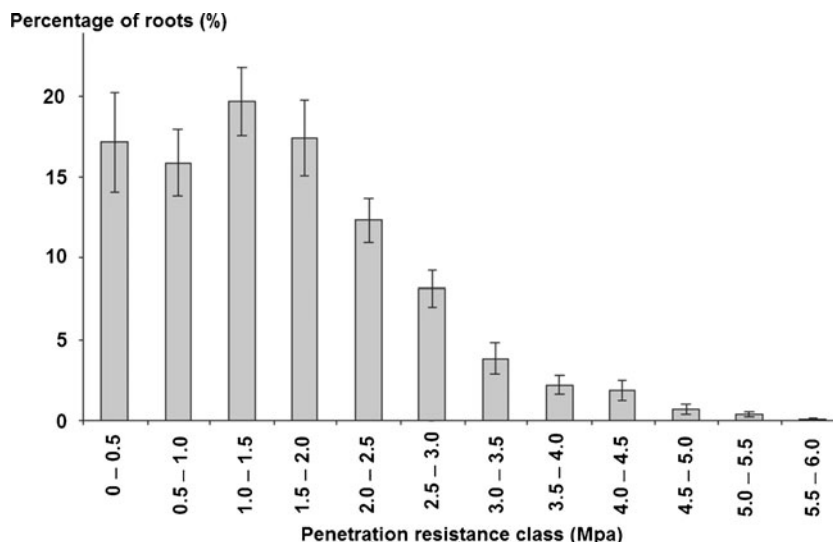
Table 1 Bulk density and total porosity of eluvial and illuvial horizons in the beech stands studied (undisturbed vs. rutted soils)

Horizon	Depth (cm)	Bulk density (kg dm ⁻³) Core method	Total porosity (%)
Terrest n=10			
Undisturbed soil			
<i>E</i>	10–30	1.37±0.08	48.4±3.1
<i>B_t</i>	30–50	1.66±0.04	37.3±1.6
Rutted soil			
<i>E_g</i>	10–30	1.54±0.10	41.8±3.6
<i>B_{tg}</i>	30–50	1.58±0.08	40.2±3.2
Tumuli n=30			
Undisturbed soil			
<i>E</i>	10–30	1.31±0.10	50.6±3.8
<i>B_t</i>	30–50	1.54±0.06	42.1±3.8
Rutted soil			
<i>E_g</i>	10–30	1.62±0.07	38.9±2.8
<i>B_{tg}</i>	30–50	1.54±0.05	41.8±1.8
Bulk density (core method)			
Unpaired <i>t</i> test		Terrest	Tumuli
<i>E</i> vs. <i>E_g</i>		-4.363***	-13.607***
<i>B_t</i> vs. <i>B_{tg}</i>		2.584*	NS

Mean values at two different sites (Terrest site, *n*=10; Tumuli site, *n*=30) are given with standard deviations. From Herbauts et al. (1996)

P*<0.05, *P*<0.01, ****P*<0.001

Fig. 5 Mean percentage of roots in each penetration resistance class using the penetrometer; 90.7% of roots are present in penetration resistance class less than 3 Mpa. From Sinnett et al. (2008)



macropores (see below). Such changes in tortuosity can influence the soil electrical conductivity (Seladji et al. 2010).

3.4 Reduction of aeration

Reduced soil aeration can be an indication of the soil compaction and soil aeration can be quantified by different parameters such as the air filled porosity, oxygen diffusion rate (ODR), redox potential, and air permeability (Cannell 1977). Air permeability varies largely according to the soil physical properties for the same level of compaction while the measurement of ODR by electrode needs a lot of care. Redox potential measurements can be a good tool to characterize the compacted soils as these measurements can be carried out in situ for the long periods, but this method is only applicable to the very wet soils (close to or at saturation; Feder et al. 2005; Lipiec and Hatano 2003; Nawaz 2010).

Among different methods discussed, the soil bulk density and the soil strength are more commonly employed to quantify the soil compaction but the use of other indicators like water infiltration rate, ODR, redox potential, etc. in combination with them can largely increase our understandings and results precisions. Now sensors have also been developed to detect the location and depth of the hard pans in the real time that are equipped with four horizontal operating penetrometers for on-the-go sensing and mapping of the location and intensity of hard pan (Loghavi and Khadem 2006). Sensor systems to measure the soil compaction have already been reviewed (Hemmat and Adamchuk 2008).

4 Effects of compaction on the soil chemical properties and biogeochemical cycles

4.1 Reductive conditions

Modified soil physical properties due to the soil compaction such as the reduced water infiltration rate and reduced soil

air permeability also influence the soil chemical properties. The soil compaction causes decrease in oxygen diffusion (Renault and Stengel 1994) and can lead to anoxic conditions in compacted soils if consumption of oxygen is faster than diffusion (Schnurr-Putz et al. 2006). At the same time, due to the reduced water infiltration rate, the soil compaction can result in the surface water logging in the wheel ruts covered areas during the wet seasons that can influence all the pedological processes, especially iron geochemistry (Munch and Ottow 1983).

Surface water logging and absence of oxygen, in compacted soils; result in the lowering of redox potentials of soil solution, formation of reduced forms of iron (Fe^{2+} ; Ponnampertuma 1985), increased dissolution of iron hydroxides and increase in organically complexed iron forms. Presence of iron minerals such as lepidocrocite that indicates hydromorphy can be observed in compacted soils by naked eye due to orange colours of mottles but detection of these iron minerals by X-ray diffraction (XRD) is not evident (Herbauts et al. 1996). In one experiment, Herbauts et al. (1996) reported higher concentrations of easily reducible iron Fe^{2+} in the above 30 cm of the soils after a logging operation in a forest land (Fig. 6). Exchangeable Fe^{2+} was extracted from a freshly sampled soil with a hydroxylamine/potassium chloride solution and determined colorimetrically using orthophenanthroline. They directly correlated the presence of 15–30% of free iron in the form of easily reducible form Fe^{2+} with the water logging as the result of the soil compaction. Selective extraction techniques using citrate–bicarbonate and citrate–bicarbonate–dithionite showed that the soil compaction under forest resulted in an increase of readily extractable Fe oxides after only 2 years, before mineralogical transformations were detectable by XRD (Nawaz 2010).

4.2 Carbon and nitrogen cycles

The soil compaction affects concentration of carbon dioxide (Conlin and Van den Driessche 2000) and mineralization of

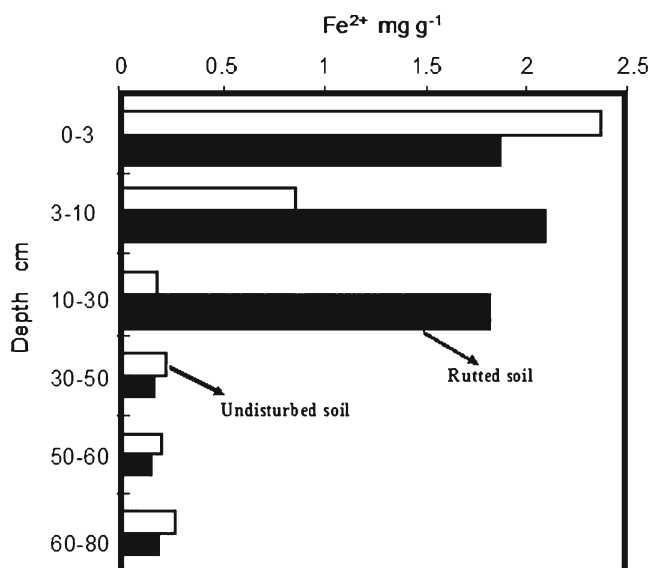


Fig. 6 Profile distribution of easily reducible iron (KCl-NH₂OH-extractable Fe²⁺) in undisturbed (*transparent rectangles*) and rutted soil (*dark black rectangles*). From Herbauts et al. (1996)

the soil organic carbon and nitrogen in the soil (De Neve and Hofman 2000). In a laboratory experiment, when silt loam (acid forest soil) was compacted artificially to a bulk density of 1.5 from 1.1 Mg/m³, a significant reduction in the carbon mineralization and net nitrification rates was observed after 9 months (Tan and Chang 2007). The soil compaction, directly, results in the lower efflux of CO₂ from compacted soils (Silveira et al. 2010) but, indirectly, due to increase of machinery use to plough the compacted soil, can lead to more consumption of the fuel and ultimately more emission of CO₂ (Voorhees and Hendrick 1977).

Denitrification increases with the soil compaction (Arah and Smith 1989) that results in the increased emission of N₂O to the atmosphere (Douglas and Crawford 1993). These emissions can be much larger in the cultivated fields if N fertilizer is applied in wet conditions (Clayton et al. 1994). In fact, in the soils, N₂O is produced by both the nitrification (aerobic soil conditions) and denitrification (anaerobic soil conditions) and sometimes the nitrification and denitrification can occur simultaneously in the same soil aggregate (Davidson et al. 1986). As the soil compaction results in the increase of water contents, so, it can increase strongly denitrification processes in the soil (Maag and Vinther 1996). Soane and Van Ouwerkerk (1995) have reported that the soil compaction can cause an increase in the denitrification rate and emissions of N₂O about 400–500%. But, in compacted soils, there is a possibility of decrease of N₂O transport to atmosphere and decreased reduction of N₂O to N₂ gas, a harmless gas, depending upon the residence time of N₂O in the soil and soil conditions (Soane and Van Ouwerkerk 1995).

It is reported that emission of N₂O after fertilization is highly dependent on the rainfall (Ball et al. 1999; Fig. 7). In

their experiment, the soil was compacted by increased tractor weight up to a bulk density of 1.40 and 1.39 Mg/m³ at 0–100 and 100–250 mm depths, respectively, as compared to normal bulk densities of 1.21 and 1.26 Mg/m³ at the same depth, respectively. It is clear from Fig. 7 that heavy compaction treatment gave greater response in term of N₂O emission to rainfall than the zero compaction treatment. Bessou et al. (2010) tried to model the emission of N₂O gas after the soil compaction, but their model was not capable of capturing the emission during the cropping cycle.

The soil compaction reduces the available N (Tan et al. 2008) and efficiency of N use by the crops decreases (Douglas and Crawford 1991), which can increase the fertilizer requirements. It is reported that the soil compaction which ultimately increases the water contents and denitrification processes in the soil, likely reduces the emissions of NO_x from the soil (Skiba et al. 1994) but increases the volatilization of ammonia, as compared to uncompacted soils (Soane and Van Ouwerkerk 1995).

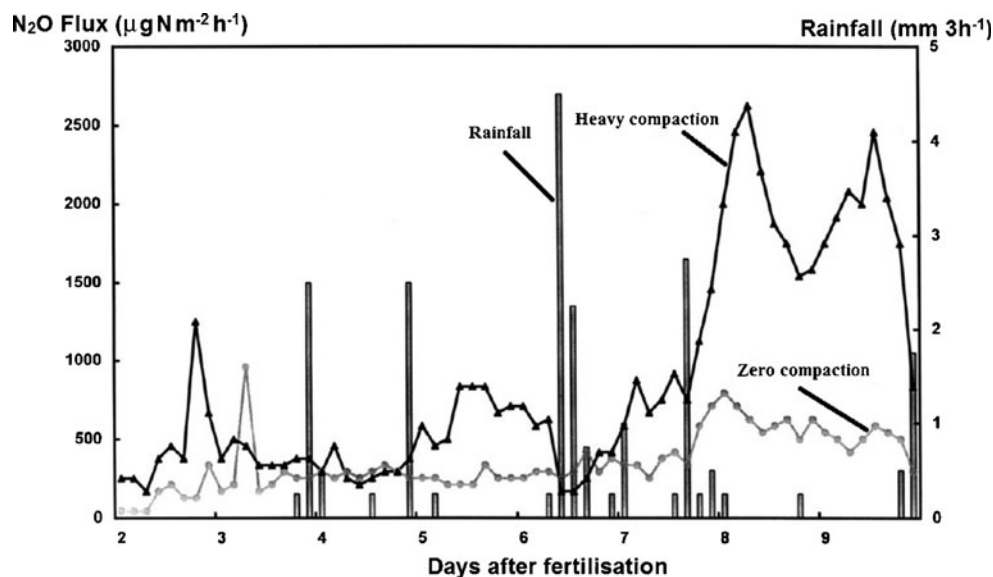
The soil compaction favours the anaerobic soil conditions which can result in the increase in methanogenic (methane producer) bacteria while decrease in the methanotrophic (methane oxidising) bacteria (Yao et al. 1999). The soil compaction will result in the higher production rate of CH₄ than its oxidation or destruction rate and this destruction rate can be reduced up to 58% when well drained soils are compacted (Soane and Van Ouwerkerk 1995).

4.3 Environmental impacts of the soil compaction

Local soil compaction can influence not only the soil but also the local environment (Soane and Van Ouwerkerk 1995). The emissions of greenhouse gases due to the soil compaction (N₂O, CH₄, and CO₂), as discussed in Section 4.2 can enhance the greenhouse effect. The soil compaction results in increased energy costs in the cultivated lands due to the increased fertilizer inputs and greater tillage requirements. However, it can also be responsible for energy savings, in some soils, due to increase in machine efficiency in rolling over compacted soils (O'Sullivan and Simota 1995). Anaerobic conditions in the soil due to the soil compaction can result in reduced decomposition of pesticide and ultimately increased leaching of pesticide in groundwaters and aquifers (Alletto et al. 2010). Similarly, decreased hydraulic conductivities can result in slow downward movement of water and, ultimately, more nitrate contents in ground waters.

If the soil compaction is carried out in steep slopes, this can result in increased runoff and ultimately in increase soil erosion and sediment transport which could be a serious problem for the landscape. Furthermore, increased runoff, in slurry applied fields, can result in the entrance of slurry in surface waters and ultimate threat to the aquatic life as degradation of slurry can reduce the oxygen levels in surface

Fig. 7 Temporal variability of N_2O fluxes and 3-hourly rainfall in heavily compacted soil and uncompact soil under winter barley, shortly after the main spring fertilisation of 110 kgN/ha/year , assessed using the automatic chambers. From Ball et al. (1999)



waters. However, in some soils (sandy soils), the soil compaction increases the soil strength, erodibility, and consequently the soil erosion for the same amount of runoff is reduced. So, modified soil physical properties due to the soil compaction can be beneficial or harmful for the environment depending upon the existing environmental conditions and physical properties of the soil before modification.

5 Effect of the soil compaction on plants

Overall effect of the soil compaction on the plant yield is negative (Ishaq et al. 2001; Saqib et al. 2004a) but it can also result in no effect or yield increase as reviewed by Greacen and Sands (1980). The soil compaction results in the restricted root growth, decreased accessibility of nutrients, and increased loss of the soil nutrients by leaching, runoff, and gaseous losses to atmosphere which can affect plant growth. Effects of the soil compaction on uptake and losses of nutrients have already been reviewed (Lipiec and Stepniowski 1995). If a soil is already suffering from other types of degradation such as the salinity, drastic effects of the soil compaction on the plant growth and crop yield are reported to be doubled (Saqib et al. 2004a).

5.1 Roots

Roots play an important role in the nutrient uptake and plant growth (Marschner 1986). Root penetration ability is adversely affected by the soil compaction due to increased soil strength and decreased number of macropores (Gerard et al. 1982). Soil strength–root relation is well documented and reviewed in literature (Hamza and Anderson 2005; Kirby and Bengough 2002; Masle and Passioura 1987; Taylor et al. 1966; Taylor and Ratliff 1969; Voorhees et al. 1975). Effects of

the soil compaction on roots generally vary with interspecies and for different cultivars of the same species, due to difference in root penetration ability depending on the root physiology and morphology (Materechera et al. 1991; Tardieu 1994).

Generally, compaction results in a decrease in the root length, root penetration, and rooting depth (Glinski and Lipiec 1990; Kristoffersen and Riley 2005). It is reported that the compaction of calcareous loamy soils, having 5% organic matter, with a load of 14.5 Mg resulted in complete failure of the root penetration in the deeper soils ($>20 \text{ cm}$; Bouwman and Arts 2000). The soil compaction can also aggravate a root disease in some species of plants (Fritz et al. 1995). Top soil compaction is a more limiting factor for the root growth than the subsoil compaction (Botta et al. 2006). The effects of the soil compaction on the ion uptake and root growth are more severe in saline soils than in normal soils. Saqib et al. (2004b) found that the compaction of a sandy clay loam soil to a bulk density of 1.65 from 1.21 Mg/m^3 reduced root length density of wheat plants while the presence of salinity (15 dS/m) was more drastic than the soil compaction alone. In the same experiment, they observed greater reductions in K^+ concentrations and the K^+/Na^+ ratio in leaves due to interaction of salinity and compaction.

The roots of some cover crops have shown good penetration ability and less adverse effects of the soil compaction. These crops can be used to alleviate the effects of the soil compaction (Rosolem et al. 2002). Because of larger diameters of roots than soil pores, roots can also increase the bulk density of the soil near the roots during the root penetration (Dexter 1987) and this phenomenon can change the physical, biological, and chemical aspects of the soil near the roots (Glinski and Lipiec 1990). Change in micro- and mesoporosity around roots can also be quantified by scanning electron microscopy (Bruand et al. 1996).

5.2 Shoots

Although rooting system of the plants is badly affected by the soil compaction, this does not always result in reduced shoot growth because it depends on the availability of nutrients in the soil. If a soil is so heavily compacted that it reduces the mobility of the ions in soil and severely restricts the root growth; it can limit the shoot growth. Ishaq et al. (2001) and Silva et al. (2008) observed no effects of the soil compaction on the plant height but reduction in the grain yield was reported by Ishaq et al. (2001).

5.3 Seedling emergence

Seedling emergences are adversely affected by the soil compaction (Dürr and Aubertot 2000). The soil compaction is more detrimental to the seedling growth and survival as compared to established plants and trees. Increase in the bulk density of a dry soil from 1.3 to 1.8 Mg/m³ in a greenhouse experiment resulted in the late emergence of oak seedlings and a mortality rate of 70% (Jordan et al. 2003). In the same experiment, they found that the soil compaction resulted in reduced height of the young seedlings and reduced N recovery. Similar findings were reported by different authors in the pot experiments and field experiments (Corns 1988; Moehring and Rawls 1970; Tworkorski et al. 1983). But the response of seedlings growth to the soil compaction is also subjected to the soil types and plant species because sometimes moderate compaction of sandy soils can be useful to the seedlings growth of woody plant species (Alameda and Villar 2009).

5.4 Nutrients uptake

Generally, the soil compaction reduces the uptake of nutrients due to the damaged roots but it also increases the contact between the roots and soil particles which may lead to the rapid exchange of ions between the soil matrix and roots. The uptake of nutrients transported by diffusion is more affected by compaction than for nutrients transported by mass flow (Arvidsson 1999). The soil compaction can decrease the uptake of phosphorus and potassium in the maize (Dolan et al. 1992) or can increase the uptake of phosphorus in the ryegrass and maize (Shierlaw and Alston 1984) depending on the type of the soil and nature of the soil compaction. Kristoffersen and Riley (2005) subjected three types of soils (loam, clay loam, and silt) to relative degree of compactness (RDC) of 75% (RDC75%) and 90% (RDC90%) of the standard degree of compactness. They observed that heavy soil compaction reduced the P uptake and yield of barley in all three types of the soils (Table 2).

So, the soil compaction negatively affects the root portion of the plants but ultimate effect on the shoot depends on the nutrient availability and uptake by the plants. However,

Table 2 Effects of the relative degree of soil compactness (RDC) on barley shoot yield (gdrymatter/pot) and on P uptake (mgP/pot) in the three soil groups

		Loam	Clay loam	Silt
Shoot yield (g pot ⁻¹)	RDC _{75%}	8.6	5.6	4.8
	RDC _{90%}	7.4	4.8	3.4
	<i>p</i> Value	0.03	0.001	0.006
P uptake (mg pot ⁻¹)	RDC _{75%}	28.9	11.9	8.9
	RDC _{90%}	24.2	10.2	7.0
	<i>p</i> Value	0.005	0.003	0.02

From Kristoffersen and Riley (2005)

severe soil compaction can result in the root deformation, stunted shoot growth, late germination, low germination rate, and high mortality rate. All these impacts of the soil compaction contribute largely in reducing the yield of most agronomic crops in compacted soils.

6 Effect of the soil compaction on soil biodiversity

Modified soil physical parameters determine the effect of the soil compaction on physical and chemical properties of the soils and ultimately on soil biota. The soil compaction can be favourable to soil biodiversity and vice versa depending upon the nature of the soil, climate, and extent of the soil compaction. Beylich et al. (2010) reported the negative influence of the soil compaction on microbial biomass and C mineralization above an effective bulk density of 1.7 Mg/m³.

6.1 Bacterial population

Soil microbial biomass is adversely affected by the soil compaction (Frey et al. 2009; Pupin et al. 2009). The soil compaction resulted in reduced soil aeration of the soil due to 13–36% decrease of air filled porosity which led to the reduction in microbial biomass carbon and microbial biomass nitrogen (Tan and Chang 2007). Tan et al. (2008) also reported the reduction of microbial biomass phosphorus after the soil compaction. Shestak and Busse (2005) reported that the soil strength values ranging 75–3,800 kPa changed the physical properties of the soil but did not affect any biological indicator of the soil (microbial biomass and enzymatic activity).

6.2 Enzymatic activity

Any disturbance or stress to the soil can influence enzymatic activities in the soil (Buck et al. 2000). The soil compaction changes physical and chemical properties of the soil which leads to the reduction of phosphatase, urease, amidase, and

dehydrogenase activities (Dick et al. 1988; Jordan et al. 2003; Pupin et al. 2009; Tan et al. 2008), but sometimes increase in the phosphatase activity is also reported (Buck et al. 2000). Anoxic conditions in the soil induce the changes in the microbial community and favour organisms capable of tolerating these conditions, thus, lower eukaryotic/prokaryotic ratios, more iron and sulphate reducers, and higher methanogens were found in compacted soils than in uncompacted soils (Schnurr-Putz et al. 2006).

6.3 Larger soil fauna

Soil fauna plays an important role in the decomposition and incorporation of organic matter in the soil (Petersen and Luxton 1982). Habitat of the soil fauna is interstitial spaces in the soil. The soil compaction changes the pore size availability and distribution which generally leads to the reduction of the proportion of large pores and affects the movements of nematodes and larger soil fauna. Nematodes, being diverse in food habit (bacterivores, herbivores, and omnivores), play an important role in the soil food web as well as in organic matter decomposition, nutrient decomposition and herbivory (Bouwman and Arts 2000). Heavy soil compaction may not affect the quantity of nematodes in the soil but can influence their distribution. Bouwman and Arts (2000) reported reduction of bacterivore and omnivore nematodes while increase of herbivore nematodes in heavily compacted soils. Earthworms are also reported to be influenced by the soil compaction (Kretzschmar 1991; Radford et al. 2001) and their population decreases with increase in the soil compaction (Chan and Barchia 2007), but they are capable to penetrate a soil with penetration resistance of 3,000 kPa by ingesting the soil particles (Dexter 1978).

6.4 Ground flora

Ground flora is very important in the forest ecosystem in terms of revegetation, productivity, aesthetics, and water and nutrient cycling (Gilliam 2007). Any disturbance to the forest ecosystem and/or soil affects adversely the native ground flora (Zenner et al. 2006; Demir et al. 2008), but some plant species are capable to show healthy habitat and a rapid recovery after extreme degradation of the soil (Demir et al. 2008). Zenner and Berger (2008) reported that the soil compaction resulted in shifting of ground flora from interior forest species to noxious/invasive and disturbed forest species and relative resistance of the initial ground flora to change was found to be linearly related to relative resistance to penetration. The soil compaction influences the soil biodiversity negatively and it results in decrease in the microbial

biomass, enzymatic activity, soil fauna, and ground flora in compacted soils.

7 Modelling

Modelling not only provides a better way to quantify the processes involved in the soil compaction but also helps us to predict the vulnerability of a particular soil to compaction. It (modelling) is useful in the organisation and integration of existing knowledge and identification of gaps in knowledge. It (modelling) is a simulation of all the processes involved in the soil compaction but soil compaction depends on a lot of parameters and considering each parameter is difficult for heterogeneous structures of the soil. Modelling of the effects of the soil compaction on the environment and plant growth are reviewed and discussed in detail in literature (Clausnitzer and Hopmans 1994; Grant 1993; O'Sullivan and Simota 1995). Several attempts have been made to model the effects of mechanical operations on the soil (Blackwell and Soane 1981; Défossez and Richard 2002; Dickson and Ritchie 1993; Raper and Erbach 1990), but most models have limited applications due to a large number of parameters as input or heterogeneous field conditions. Models can also be classified and discussed as mechanistic or empirical, depending on the treatment of underlying mechanisms, and deterministic or stochastic, depending on the treatment of variability (O'Sullivan and Simota 1995).

7.1 Stress–strain models based upon boussinesq equation

Most of the models are based on the stress–strain theory where two problems are addressed:

- The propagation of stress in the soil
- The local relation between stress and strain i.e.; the “constitutive equation”

The propagation of stress in the soil is classically described by some form of the Boussinesq equation (Boussinesq 1885, p. 104), and a constant linear relation between stress and strain is assumed, that is, soil reacts elastically. The form of the Boussinesq equation depends on the limiting condition. For a point load (Fig. 8), it is:

$$\sigma_z = (3P/2\pi r^2) \cos^3\theta \quad (1)$$

where, r is the radial distance from point A to the origin O where the load P is applied, and θ is the angle between OA and the vertical, σ_z is the vertical stress.

In this equation, time is absent, and, therefore, it describes the situation at mechanical equilibrium in static conditions. Moreover, as underlined by Smith et al. (2000), the stress

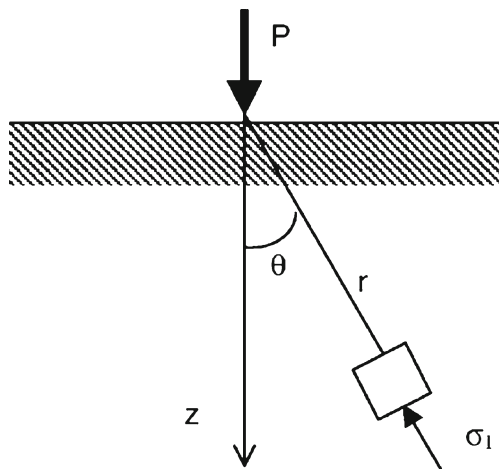


Fig. 8 Stress propagation to a layer parallel to the surface at depth z for a homogeneous isotropic soil, under the assumption of elasticity, in a soil submitted to a point load P exerting a normal stress at the surface. From Défossez and Richard (2002)

distribution is “irrespective of differences in texture, bulk density or water content”. To better describe the stress distribution, the “concentration factor”, ν was introduced by Fröhlich (1934; quoted by Défossez and Richard 2002), so that the equation becomes:

$$\sigma_z = (\nu P / 2 \pi r^2) \cos^{\nu} \theta \quad (2)$$

which means that, when compared to Eq. 1, the geometric coefficient 3 is treated as an adjustable parameter. When the “concentration factor” increases, stress increases at a given point. Söhne (1958; quoted by Défossez and Richard 2002) suggested n values of 4, 5, and 6 for hard, firm and soft soil respectively, and Défossez and Richard (2002) commented as: “The firmness results from empirical combinations of both the bulk density and water status of the soil.” According to Smith et al. (2000), the concentration factor can even obtain values of 6–9, and is influenced by the soil structure: “in well-aggregated soils, the concentration factor values are smaller than in the same but homogenized soils.” They used even values smaller than 3 ($\nu=1$), in simulations, and calculated values from 1.5 to 2.8 for different decreasing laws of the tire load from just below the tire centre to its external limit.

Analytical models based upon Boussinesq equation and on its modifications are largely used as they demand less number of inputs as compared to models based on the finite element method (FEM). The comparison with experiments largely gives variable results, acceptable for homogeneous soils and unreliable for heterogeneous soils due to the presence of clods or a firm soil at depth (Défossez and Richard 2002). In homogeneous soils, they can predict efficiently not only soil stress–strain behaviour but also the propagation of the loading forces within the soil resulting from forces applied at the soil surface from farm vehicles.

A recent analytical model is SoilFlex, easily usable, is based upon a description of the upper boundary condition (load of tyre) as an ellipse or a super ellipse, considering both normal and shear stresses, an analytical solution to compute the stress propagation and a calculation of the soil deformation (Keller et al. 2007; Keller and Lamandé 2010). According to Keller et al. (2007), “A weak point of the analytical solution may be the concentration factor, as it is not a directly measurable soil parameter.”

According to Smith et al. (2000), the concentration factor fitted “can result in inaccurate results if they are used for comparing strength among different soils [...], and it is a machinery-soil dependent parameter, [influenced by] inflation pressure, tires dimensions, lugs and carcass stiffness”. These latter authors concluded that “Boussinesq’s equations, modified by concentration factors and elliptic coordinates failed to predict experimental stress values in a Hapludand.”

In addition, the Boussinesq equation and its classical modifications are restricted to a boundary condition of normal stress while Boussinesq proposed other integrals applicable to tangential forces which due to the linearity of the differential operators can be combined to give general solutions for any external stresses; the solutions are derived from potentials that are: (1) ordinary, $\int (dm/r)$, when displacements are known at the boundary surface; (2) logarithmic $\int \ln(z+r)dm$, when normal stresses are known; (3) logarithmic $\int [-r+z \ln(z+r)]dm$, when stresses at the surface are purely tangential (Boussinesq 1885, p. 201).

The major problem with Boussinesq’s theory is that it is restricted to elastic domain which implies that there is no permanent deformation and no rupture and the solid is supposed to be homogeneous and isotropic. Moreover, it does not represent accurately hydraulic properties of the soil and cannot describe the soil deformation. Furthermore, these methods fail to predict changes at pore-scale level (Or and Ghezzehei 2002).

7.2 Virtual work formulation

A different way of computing the propagation of stress is based upon a local description of the virtual work:

$$\int \delta \underline{\underline{\varepsilon}}^T \underline{\underline{\sigma}} dV = \int \delta \underline{\underline{u}}^T \underline{\underline{p}} dV + \oint \delta \underline{\underline{u}}^T \underline{\underline{t}} dA \quad (3)$$

where, V and A are the volume and the area of the surface of the deformed body, $\underline{\underline{\sigma}}$ and $\underline{\underline{\varepsilon}}$ the tensors of stress and strain, $\delta \underline{\underline{u}}$ is the incremental displacement, $\underline{\underline{p}}$ and $\underline{\underline{t}}$ are respectively the body forces and surface traction, and the superscript T stands for transformed (Défossez and Richard 2002).

Time is equally absent from the equation and it describes static deformation of a soil body. This equation is then linearized which assumes low deformation and numerically

solved, using finite element methods. The corresponding models are referred to as FEM. These models are adequate for modelling the 3D distribution of stress within the soil induced by wheeling and the complex stress–strain behaviour of the soil but due to continuous changes of elastic parameters of the soil, application of FEM models becomes limited (Raper and Erbach 1990).

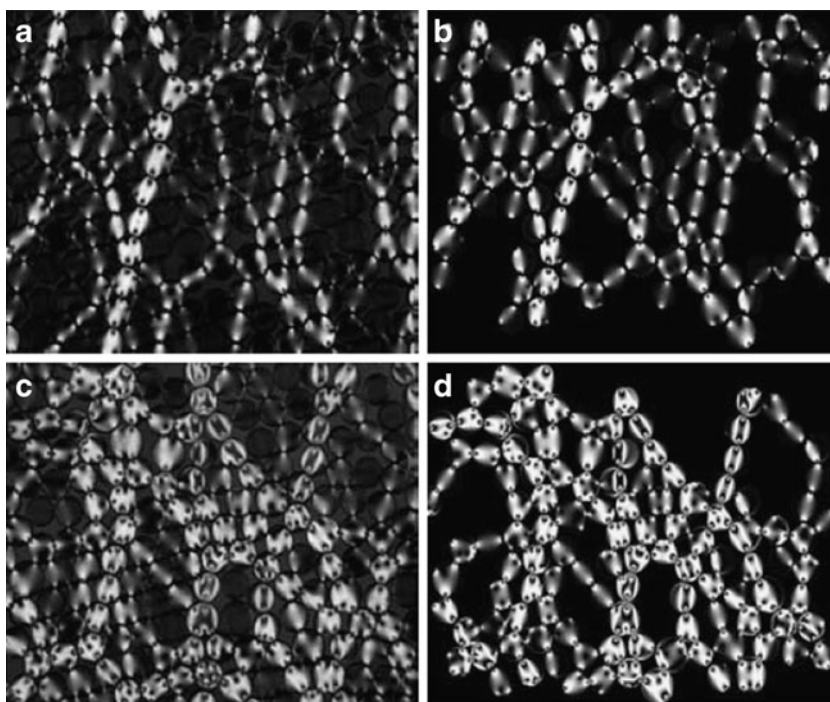
Whether the stress propagation is computed by a pseudo-analytical procedure (Boussinesq and its variants) or by FEM, it fails to account for two evidences: the existence of preferential paths of stress propagation and the localization of deformation (hard pans, plough pans...). These items will be addressed in the following paragraphs.

7.3 Preferential paths of stress propagation

Stresses do not often propagate homogeneously but through preferential paths, isolating bulk volumes that are not under so large stress as it is in the preferential path. This is due to the fact that in soils, there coexist different assemblages due to small differences between the size and shape of the particles. When submitted to a compression, the soil particles or grains will tend to move at first elastically. Soon, some of these grains will be blocked (“jammed”) against each other and normal stresses will be transmitted along chains of preferential propagation. When these chains constitute a continuous path, by a percolation process (Bideau and Hansen 1993; Guyon and Troadec 1994; Roux et al. 1993), they will isolate bulk volumes submitted to smaller stress or even free to move (Fig. 9).

There have been advances in physics of granular media, due to both fundamental interest for physicists as models of much more complex systems and to practical and/or industrial interest: “granular materials are ubiquitous in nature and are the second most manipulated material in industry (the first one is water)” (Richard et al. 2005). One of the main characteristics of granular materials is that their behaviour is intermediate between solids and fluids. Compaction from a loose-packed material can be efficiently obtained by tapping and shearing, and this is more efficient than compression. Granular packings submitted to gentle mechanical taps can reach a stationary configuration which does not depend on the initial conditions (looser packing or denser packing; Ribière et al. 2007). As friction between solid particles oppose to mixing and thermal agitation is entirely negligible with respect to potential energy due to gravitation ($>1 \times 10^{12}$ kT), solid particles can segregate which is well-known in soils, though at first sight, it could be considered as violating the natural tendency for entropy to increase. Those materials are, thus, considered as “a-thermal” and metastable assemblages can persist as long as no perturbation occurs (Jaeger et al. 1996). This metastability of different assemblages explains in a large part soil heterogeneity. Forces in such materials at rest appear to be very heterogeneous, forming chains along which stresses are very intense (Majmudar and Behringer 2005). Those chains isolate volumes which are not under stress forming arches, as is well-known in silos. This behaviour is strongly influenced by the shape and rugosity of particles. When compression proceeds further, deformation can be localized in specific locations.

Fig. 9 Preferential paths of stress propagation. From Majmudar and Behringer (2005): comparison of experimental images (a, c) and computed images (b, d). *Top pair* a low-force sheared state. *Bottom pair* a high-stress isotropically compressed state



7.4 Strain localization

There exists a broad evidence that strain is not evenly distributed in soils, rocks, and geomaterials such as concrete. Indeed, strain localization is rather a rule. It is generally associated with plastic deformation and ruptures in solids and is observed to concentrate in narrow zones, called shear bands (Desrues and Chambon 2002). Such localized deformations have been observed in many granular materials, from sand (Desrues and Viggiani 2004) to clays, e.g., by X-ray tomography (Bésuelle et al. 2007; Fig. 10).

The material undergoes a transition from a diffused strain mode to a localized strain mode where strain is strongly spatially concentrated while the material outside this zone behaves approximately as rigid (Bésuelle et al. 2007). In soils, this is the case for example in hard pans. And, at a much larger scale, this is the basic paradigm of plate tectonics. This feature seems, thus, very general. Looking back at Boussinesq Eq. 1, equation structure precludes the existence of a maximum in stress and strain at a specific location as second derivative of this equation is always positive. It is interesting to note that the presence of an inclusion, whether weaker or stronger than the bulk material, dictates the location of the shear band (Desrues and Viggiani 2004). Chambon et al. (1994, 2000) proposed a constitutive model based upon a stress rate/strain rate relationship instead of a stress/strain relationship. It is a continuous model like the aforementioned models which means that the distances considered are much larger than the grain size and is called CLoE, formed on the words *consistency* and *explicit localization*. Failure is accounted for by incorporating explicitly a limit surface in stress space separating admissible states from inaccessible states. The constitutive equation is:

$$\dot{\sigma} = A : \dot{\varepsilon} + b \|\dot{\varepsilon}\| \quad (4)$$

where, σ is the stress rate, $\dot{\varepsilon}$ the strain rate, A is a fourth-rank tensor and “ b ” a second-order tensor; the incremental non-linearity is due to the norm $\|\dot{\varepsilon}\|$; $\dot{\varepsilon}$ is not decomposed into elastic and plastic parts. A and b depend on state variables and

are determined by an interpolation procedure between the responses for axisymmetric triaxial states. The formation of a shear band is treated in model CLoE as a bifurcation problem. The appropriate 16 parameters for a given material are derived from simple axisymmetric triaxial compression and extension tests except out-of-axes shear moduli which are derived from special experimental tests combined with inverse analysis (Desrues and Chambon 2002).

Time is, thus, present in this model and this accounts for the fact that the rate of stress is a parameter of a paramount importance. The discrepancies between laboratory tests and field wheeling experiments have been ascribed to the differences in loading time (Keller and Lamandé 2010). In the soils, the localization of strain in shear bands separated by volumes behaving as more rigid can explain the observation of discrepancies when modelling the soils with clods or with an underlying dense layer at depths less than 0.5 m (Défossez and Richard 2002).

Boussinesq equations and FEM models are restricted to elastic domain and fail to take account of existence of preferential paths of stress propagation and localization of deformation in compacted soils. Modified forms of a constitutive model like CLoE that is based upon a stress rate/strain rate relationship in granular media can be able to decrease discrepancies in modelling the soil compaction when there is localised soil deformation.

8 Remedies to the soil compaction

Natural phenomena involved in the recovery of compacted soils are precipitations, wetting and drying cycles, subsequent soil cracking, freeze–thaw cycles, and bioturbation which includes earthworm burrowing and root penetration and decay (Drewry 2006; Webb 2002). Natural recovery of compacted soil is a very complex and slow process that can take at average from 5 to 18 years depending on the soil type, degree of compaction, and climate (Froehlich et al. 1985).

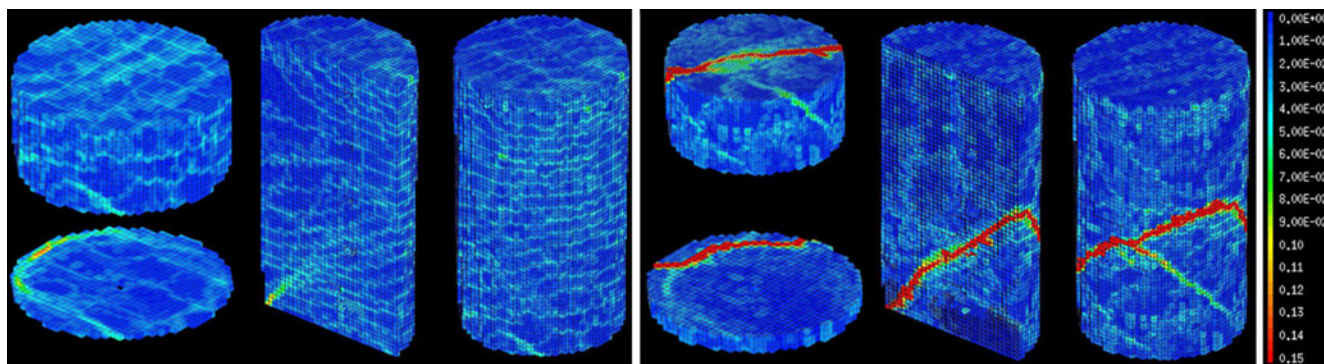


Fig. 10 Strain localization in shear bands. From Bésuelle et al. (2007). *Left* initialization of the shear band. *Right* development of the shear band

Among all the aforementioned factors, the degree of compaction or bulk density is the most important factor to monitor the recovery time of a soil (Heinonen 1977). If the soils are not highly compacted, repetitions of alternative dry and wet periods can reduce the soil compaction in the clay soils but the sandy compacted soils are less affected by these natural restoration cycles. Rapid natural amelioration of physically deteriorated topsoil to about 5 cm is possible but below 15 cm natural rejuvenated process is very slow (Drewry 2006). For example, full recovery time for a heavy compacted soil can range from 100 to 190 years (Webb 2002).

Compaction can be reduced by the natural methods through increase of vegetation and addition of organic matter by preventive measures through controlling traffic and animal load or by mechanical methods by deep ripping (Berg 1975) and disking (Dickerson 1976). Aforementioned solutions have been reviewed in farm systems (Hamza and Anderson 2005). In the forests, any mechanical work to reduce the soil compaction is difficult due to presence of stumps and large roots, so, natural methods are encouraged and employed.

9 Conclusion

Soil productivity is very important for human survival but any form of soil degradation can reduce the soil fertility and ultimately, it lowers the soil productivity. The soil compaction, a physical form of soil degradation, is a worldwide problem that has resulted in the yield reductions of agronomic crops and reduced growth rate of forests. It has attracted scientists' attention for more than a century, both on the practical and theoretical aspects. Experimental studies have shown that the soil compaction results in increase in the soil strength, bulk density, volumetric water contents, and field capacity while decrease in total porosity, soil aeration, water infiltration rate, and saturated hydraulic conductivity. Causes of the soil compaction identified are natural (rainfall, plant roots, foot traffic of man, or animal) or artificial (mechanical operations).

Several models, nowadays, are available to not only assess the soil compaction due to traffic load but also to calculate the negative effects of the soil compaction on different compartments of the soil, plant, and environment. However, until now, there is no unique model for all types of soils and climates. Classical engineers' approach derived from Boussinesq equation by introducing an empirical "concentration factor" fails to account for the experimental results as soon as the soil is heterogeneous; the stress applied exceeds the elasticity limit. Moreover, the assumption of a normal stress is not valid as soon as tangential stresses are present at the boundary limit (soil surface) while more general solutions were given by Boussinesq himself.

Virtual work equation, solved by FEM, is more satisfactory but requires many more parameters. Recent advances in physics

of granular materials are promising but until now restricted to very simple systems. A link between those two approaches is, in principle, possible and is indeed the need of the time. Many recent reviews suggest that the future research should focus more on dynamics of loading and the data acquired could be treated with dynamic models, such as CLoE, relating stress rate and strain rate.

The soil compaction is rapid and easy due to mechanisation, but it takes years to restore a compacted soil. In spite of hundreds of articles appearing during the last 10 years on the soil compaction, there is an urgent need to apply multidisciplinary approach in the soil compaction studies, addressing diverse effects in different soil compartments (Fig. 2). Progress in sensors in both the soil physics and soil chemistry and in data treatment should be of a great help to evaluate the effects of the soil compaction on every compartment of the biogeosphere.

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