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Review

Soil compaction in cropping systems
A review of the nature, causes and possible solutions

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Abstract

Soil compaction is one of the major problems facing modern agriculture. Overuse of machinery, intensive cropping, short crop rotations, intensive grazing and inappropriate soil management leads to compaction. Soil compaction occurs in a wide range of soils and climates. It is exacerbated by low soil organic matter content and use of tillage or grazing at high soil moisture content. Soil compaction increases soil strength and decreases soil physical fertility through decreasing storage and supply of water and nutrients, which leads to additional fertiliser requirement and increasing production cost. A detrimental sequence then occurs of reduced plant growth leading to lower inputs of fresh organic matter to the soil, reduced nutrient recycling and mineralisation, reduced activities of micro-organisms, and increased wear and tear on cultivation machinery. This paper reviews the work related to soil compaction, concentrating on research that has been published in the last 15 years. We discuss the nature and causes of soil compaction and the possible solutions suggested in the literature. Several approaches have been suggested to address the soil compaction problem, which should be applied according to the soil, environment and farming system.

The following practical techniques have emerged on how to avoid, delay or prevent soil compaction: (a) reducing pressure on soil either by decreasing axle load and/or increasing the contact area of wheels with the soil; (b) working soil and allowing grazing at optimal soil moisture; (c) reducing the number of passes by farm machinery and the intensity and frequency of grazing; (d) confining traffic to certain areas of the field (controlled traffic); (e) increasing soil organic matter through retention of crop and pasture residues; (f) removing soil compaction by deep ripping in the presence of an aggregating agent; (g) crop rotations that include plants with deep, strong taproots; (h) maintenance of an appropriate base saturation ratio and complete nutrition to meet crop requirements to help the soil/crop system to resist harmful external stresses.

Keywords: Soil compaction; Deep ripping; Axle load; Gypsum; controlled traffic; No-tillage; Animal grazing; Plant roots

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Contents

1. Introduction

Intensive farming of crops and animals has spread all over the world and involves shorter crop rotations and heavier machinery that lead to an increase in soil compaction (Poesse, 1992). The extent of compacted soil is estimated worldwide at 68 million hectares of land from vehicular traffic alone (Flowers and Lal, 1998). Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe (Akker and Canarache, 2001) and about 30% (about 4 million ha) of the wheat belt in Western Australia (Carder and Grasby, 1986). Similar problems related to soil compaction have been reported in almost every continent (Hamza and Anderson, 2003 (Australia); Aliev, 2001 (Azerbaijan); Ohtomo and Tan, 2001 (Japan); Bondarev and Kuznetsova, 1999 (Russia); Tardieu, 1994 (France); Suhayda et al., 1997 (China); Mwendera and Saleem, 1997 (Ethiopia); Russell et al., 2001 (New Zealand)).

Although farming systems have improved significantly to cope with the new pressures associated with intensive agriculture, the structure of many otherwise healthy soils has deteriorated to the extent that crop yields have been reduced. Soil compaction is 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" (Soil Science Society of America, 1996) and is related to soil aggregates because it alters the spatial arrangement, size and shape of clods and aggregates and consequently the pore spaces both inside and between these units (Defossez and Richard, 2002).

The nature and extent of this degradation, which can be exaggerated by the lack of organic matter, has been recognised worldwide. Compaction also affects the mineralization of soil organic carbon and nitrogen (Neve and Hofman, 2000) as well as the concentration of carbon dioxide in the soil (Conlin and Driessche, 2000).

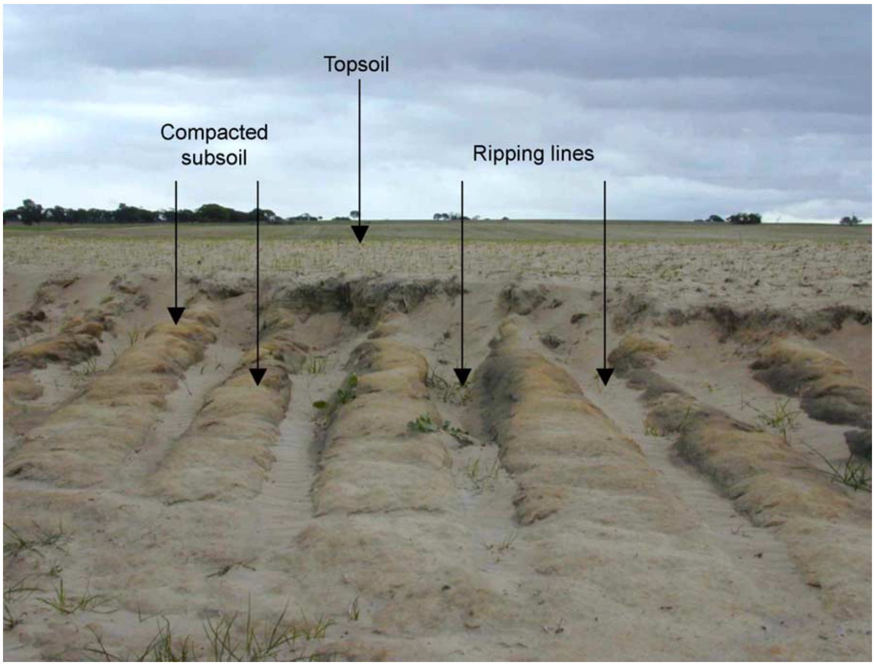

Fig. 1. Soil erosion showing compacted sandy duplex subsoil from Western Australia. The soil had been ripped before erosion to 45 cm (courtesy of Chris Gazey, Department of Agriculture, Western Australia).

Although compaction is regarded as the most serious environmental problem caused by conventional agriculture (McGarry, 2001), it is the most difficult type of degradation to locate and rationalize, principally as it may show no evident marks on the soil surface (Fig. 1). Unlike erosion and salting that give strong surface evidence of the presence of land degradation, degradation of soil structure requires physical monitoring and examination before it is uncovered and its extent, nature and cause resolved. The hidden nature of soil structural degradation (SSD) leads to specific problems such as poor crop growth or water infiltration that may be blamed on other causes. In addition, SSD is often blamed for poor crop performance when it is actually not present. Farmers rarely link their land management practices to the causes of SSD and remain unaware that many deep-ripping exercises worsen SSD (McGarry and Sharp, 2001). Because subsoil compaction is very persistent and possibilities of natural or artificial loosening have been disappointing, it has been acknowledged by the European Union (EU) as a serious form of soil degradation (Akker and Canarache, 2001).

The effects of soil compaction on crops and soil properties are complex (Batey, 1990) and since the state of compactness is an important soil structural attribute, there is a need to find a parameter for its characterization, such as relative bulk density, that gives directly comparable values for all soils (Håkansson and Lipiec, 2000). Since soil bulk density is the mass of dry soil per unit volume, then the relationship between soil compaction and its capacity to store and transport water or air is obvious. For this reason the dry soil bulk density is the most frequently used parameter to characterise the state of soil compactness (Panayiotopoulos et al., 1994). However, in swelling/shrinking soils the bulk density should be determined at standardised moisture contents, to prevent problems caused by water content variations (Håkansson and Lipiec, 2000).

Soil strength is also used as a measure of soil compaction because it reflects soil resistance to root penetration (Taylor, 1971; Mason et al., 1988; Panayiotopoulos et al., 1994; Hamza and Anderson, 2001, 2003). Soil water infiltration rate also can be used to monitor soil compaction status, especially of the topsoil. Water infiltrates uncompacted soils that have well-aggregated soil particles much faster than massive, structure-less soils (Hamza and Anderson, 2002a, 2003).

Interestingly a slight degree of topsoil compaction may prove beneficial for some soil types (Bouwman and Arts, 2000) indicating that there is an optimum level of compaction for crop growth. The concept of optimum level of compaction is important, especially in controlled traffic system where any external source of compaction is avoided because it might cause a sub-optimal level of compaction and yield depressions. Also if compaction is confined to the sub-surface only, roots may grow more laterally or coil upward toward the less compacted layers with no significant decrease in yield (Rosolem and Takahashi, 1998).

This review concentrates mainly, though not exclusively, on crop/livestock systems in the rainfed areas. It mainly considers research published in the period since the major reviews on soil compaction by Soane et al. (1982); Soane (1990); and Soane and Van Ouwerkerk (1994).

2. Factors effecting soil compaction

In modern agriculture, farm animals and machines cause most of the soil compaction. Working the soil at the wrong soil water content exacerbates the compaction process. Accordingly, the influence of soil water content and compaction induced by farm animals and machines will be reviewed here.

2.1. *Influence of soil water content on soil compaction*

Soil water content is the most important factor influencing soil compaction processes (Soane and Van Ouwerkerk, 1994). At all compaction levels, the penetration resistance increases with decreasing soil water potential (Lipiec et al., 2002). In other words, increasing soil moisture content causes a reduction in the load support capacity of the soil (Kondo and Dias Junior, 1999) thus decreasing the permissible ground pressure (Medvedev and Cybulko, 1995). Knowing the changes in soil compaction with changes in water content helps to schedule farm trafficking and cultivation operations at the appropriate moisture content (Ohu et al., 1989). Soil deformation increases with moisture content and the number of passes (Bakker and Davis, 1995) and timing of tillage in relation to soil water moisture content and soil texture (Håkansson and Lipiec, 2000). Accordingly it is important to till the soil at the right soil moisture if compaction is to be minimised. Gysi et al. (1999) reported that moist soil responded at a depth of 12–17 cm to a ground contact pressure of 160 kPa with an increase in bulk density and consolidation pressure, as well as with a decrease in air permeability and macro-porosity. With ground contact pressure of 130 kPa, however, only slight changes of the soil structure were detected at a depth of 32–37 and 52–57 cm and the measurements did not indicate any compaction.

In soils with low moisture however, ‘simplified’ tillage had no influence on soil density to 30 cm depth (Weber et al., 2000). Soil compaction and soil moisture are only significant when comparing soils of the same depth because considerable variation between depths in the same profile, and between profiles, makes it difficult to compare results (Quiroga et al., 1999). For any compaction energy level it is thus necessary to define the moisture content of the soil corresponding to the liquid, plastic and solid limits (Quiroga et al., 1999). These limits are dependent on the clay content and its mineralogical characteristics. Soil moisture lower than PL is desirable for cultivation (Spoor and Godwin, 1978) and the most appropriate soil moisture content is 0.95 PL (Allmaras et al., 1969). At high soil moisture, the difference in soil resistance between compacted soil (with traffic) and un-compacted soil (no traffic) is low and usually smaller than the value that limits root growth (>2 MPa). However, as soils get drier, soil compaction in the topsoil becomes observable (Silva et al., 2000a). Data reported by Medvedev and Cybulko (1995) indicate that at low soil water content, even maximum loads, did not deform the soil more than 2 cm in depth while at higher soil water content the value of the permissible load (the load which causes no significant soil compaction) was appreciably lower (Table 1). This means that the maximum permissible ground pressure of agricultural vehicles to permit satisfactory crop production decreases with decreasing soil bulk density and increasing soil moisture. For a given external load, soil compaction increases

Table 1
Permissible strength potential (SP) and ground pressure (PGP) as a function of topsoil water content and bulk density (after Medvedev and Cybulko, 1995)

Water content (kg/kg)	Bulk density (Mg/m^3)	SP (kPa)	PGP (kPa)
0.28–0.30	1.1	50	22
	1.2	97	45
	1.3	131	63
0.24–0.25	1.1	88	45
	1.2	109	52
	1.3	143	68
0.18–0.20	1.1	98	56
	1.2	122	64
	1.3	174	88
0.12–0.14	1.1	219	130
	1.2	290	179
	1.3	364	226

with increasing moisture. When traffic frequency decreases, the compaction factor diminishes and this decrease is more gradual in a wet soil than in a dry one. However, increasing soil compaction with increasing soil moisture is valid up to a certain value called the optimum moisture content, above which increasing soil moisture content results in decreases in compaction under a given load as the soil becomes increasingly plastic and incompressible.

2.2. Mechanized farm operations and soil compaction

Trafficking by wheeled farm machines is common in most agricultural operations even in zero tillage systems (Tullberg, 1990). Tilling, harvesting and spreading of chemicals or fertilisers are the common operations in most farms. Most, if not all these operations are performed by heavy, wheeled machines. Soil compaction by wheels is characterised by a decrease in soil porosity localised in the zone beneath the wheel and rut formation at the soil surface.

The degree of compaction depends on the following: soil mechanical strength, which is influenced by intrinsic soil properties such as texture and soil organic matter contents (Larson et al., 1980; Hettiaratchi, 1987); structure of the tilled layer at wheeling (Horn et al., 1994) and its water status (Guérif, 1984); and loading, which depends on axle load, tyre dimensions and velocity, as well as soil-tyre interaction (Lebert et al., 1998).

It has been estimated that over 30% of ground area is trafficked by the tyres of heavy machinery even in genuine zero tillage systems (one pass at sowing) (Tullberg, 1990). Under minimum tillage (2–3 passes) the percentage is likely to exceed 60% and in conventional tillage (multiple passes) it would exceed 100% during one cropping cycle (Soane et al., 1982). Tillage and traffic using heavy machines can also induce subsoil compaction in different soil types and climatic conditions in cropped systems (Raper et al., 1998; Mosaddeghi et al., 2000). The depth of the compaction varies widely from 10 to 60 cm (Flowers and Lal, 1998) but it is more obvious on topsoil (around 10 cm). However, cone index (penetrometer reading) increments of between 16 and 76% can occur in the first 40 cm of the surface layer, and bulk density can also increase but increases were limited to a 15 cm depth in a study by Balbuena et al. (2000). However, in a grassland situation differences between heavy and light loads in the shallower depth range (topsoil) were not found (Jorajuria and Draghi, 2000).

The long-term effect of reduced tillage on soil strength properties was studied by Wiermann et al. (2000) on a silty loam soil in Germany (Table 2). The repeated deep impact of tillage tools in conventionally treated plots (CT) resulted in a permanent destruction of newly formed soil aggregates.

This led to a relatively weak soil structure of the tilled horizons as dynamic loads as low as 2.5 t induced structural degradation. In the conservation tillage (CS) plots, in contrast, a single wheeling event with 2.5 t was compensated by a robust aggregate system and did not lead to structural degradation. Thus higher soil strength due to the robust aggregate system was provided by reduced tillage. Increasing wheel loads and repeated passes resulted in increasing structural degradation of the subsoil in both tillage systems.

The effects of traditional tillage, minimum tillage, and no-tillage on soil water, soil organic matter and soil compaction were investigated by Benito et al. (1999). They found that the no-tillage treatment conserved much more soil water than traditional tillage and minimum tillage treatments, especially in dry years. Soil compaction was less in traditional tillage, but there was more compaction in the subsoil

Table 2
Normal stress (NS), shear stress (SS) and their ratio at 10 cm depth of silty loam soil in conventional (CT) and conservation (CS) tillage wheeled by dynamic loads of 2.5 Mg and 5 Mg (after Wiermann et al., 2000)

Wheeling	2 × 2.5 Mg wheel load			2 × 5 Mg wheel load		
	NS (kPa)	SS (kPa)	NS/SS	NS (kPa)	SS (kPa)	NS/SS
CT						
1[a]	58	117	2.02	149	231	1.55
2[a]	99	191	1.93	159	257	1.61
CS						
1[a]	94	74	0.79	105	76	0.72
2[a]	178	146	0.82	153	132	0.86

[a] Number of passes.

after harvesting, thus resulting in less soil compaction than in the no-tillage treatment. The level of soil organic matter increased after minimum tillage and no-tillage treatments. However, some workers prefer minimum or conventional tillage over no-tillage, saying that it may provide more favorable soil physical conditions for the growth of the crop when compared to no-tillage (Tormena et al., 2002) and that the critical values beyond which root penetration is severely restricted (>2 MPa) were mainly observed for the no-tillage system (Silva et al., 2000a).

On any surface where wheels are operated tillage is required to return the soil to low impedance for root exploration and to a conductive state for water infiltration (Carter et al., 1991). If farm operations are performed when soil is dry to very dry, soil compaction could be minimised significantly. Random traffic can severely compact the soil, reduce infiltration, and increase energy consumption (Li HongWen et al., 2000). However, tillage is required under any surface where wheels are operated to return the soil to low impedance for root exploration and to a conductive state for water infiltration. Soil managed with no traffic or tillage during seedbed preparation is stable, with lower soil impedance and higher water infiltration than soil in tilled and trafficked plots. Adoption of these findings will also reduce unit production costs (Carter et al., 1991).

2.2.1. Axle load as a source of soil compaction

The differences between force and pressure when dealing with compaction caused by farm animals or machines should be clearly distinguished. Axle load is the weight of the farm animal or machine in kg or kN, which is a unit of force, while ground contact pressure is the axle load divided by the surface area of contact between the animal or machine and soil. This is measured in kPa, which is a unit of pressure. The ground contact pressure is what causes soil compaction.

Most of the soil compaction in intensive agriculture is caused by external load on soil from farm machinery or livestock. This causes considerable damage to the structure of the tilled soil and the subsoil, and consequently to crop production, soil workability and the environment (Defossez and Richard, 2002). The over-compacted soils are generally found along the wheel tracks and on the turning strips at field edges (Cyganow and Kloczkow, 2001) with the effects more marked on topsoil (Balbuena et al., 2000). There is evidence that topsoil compaction is related to ground pressure while subsoil compaction is related to total axle load independently of ground pressure (Botta et al., 1999). Severe structural degradation caused by agricultural machinery restricts or impedes plant growth and thus should be limited to layers that can be structurally reclaimed and re-moulded with reasonable effort by tillage (Gysi et al., 2000). Almost all models of tractors and machines generate pressures above the limits recommended as maximum to avoid soil compaction (Hetz, 2001). It is suggested that the most effective means of protecting soil from structure degradation by the action of agricultural machines is to use units that carry out several operations simultaneously (Aliev, 2001). This will lead to a significant reduction in the number of wheel passes. Radford et al. (2000) determined the changes in various soil properties immediately after the applica-

Table 3
The number of soil pores per unit area of three size classes as calculated from disc permeameter data

Depth (m)	No. of pores per m^2	
	Uncompacted	Compacted
0.74–1.0 mm diameter		
0	92.9	49.2
0.1	55.7	20.9
1.0–1.5 mm diameter		
0	33.5	17.3
0.1	25.4	6.25
1.5–3.0 mm diameter		
0	5.42	1.29
0.1	5.38	0.68

The soil is a black cracking clay (after Radford et al., 2000).

tion of a known compaction load (10 and 2 Mg load on the front and rear axles, respectively) to a wet Vertisol and found that compaction was mostly restricted to the top 20 cm of the soil where it decreases the number of pores per unit area in each of the three size ranges at both zero (soil surface) and 10 cm depth (Table 3).

Soil type also influences soil compaction. Ellies Sch et al. (2000) reported that in soil with coarse texture, the dominant penetration of stress was in the vertical direction, while in soil with a finer texture stress propagation was multidirectional. However, they suggested that in soil with a good structure (aggregated soil) compaction due to axle load was not as deep. The effects of axle loads on soil compaction have been researched by many workers all over the world in the last decade (Werner and Mauersberger, 1995; Alakukku, 1996; Ricardo Smith and Achim Ellies, 1998; Ridge, 2002).

2.2.2. *Effects of wheels and tyres on soil compaction*

Wheel load, tyre type and inflation pressure increase soil bulk density (Horn et al., 2001) and play an important role in soil compaction. Almost all tyres significantly increase soil compaction in the wheel track, while only some of them increase soil compaction near the track. At greater distances from the wheel track, a general reduction in soil compaction occurs, especially in the subsoil (Blaszkiewicz, 1998). Soil compaction due to wheeling has been shown to result in higher bulk density values in contrast to soil shearing, which either maintained or increased the pore volume (Horn et al., 2001). Many workers have reported that operating with low-pressure tyres can significantly decrease soil compaction and increase crop yield (Boguzas and Håkansson, 2001; Ridge, 2002) while high tyre inflation pressure increases soil compaction (Soane et al., 1982). On the other hand, tyre ground pressure values vary significantly between different machines with trailers, slurry tankers and combine harvesters exerting the highest ground pressures (Pagliai and Jones, 2002). However, ground pressures exerted by tyres are strongly reduced by a sand layer at the surface and it has been suggested that it is better to use a non-homogeneous load distribution for predicting soil compaction under tyres of agricultural machinery (Gysi et al., 2001). It also has been suggested that floatation tyres appeared to be the preferred option with respect to several key parameters (fuel consumption, drawbar draught, wheel rut depth, dry bulk density) under particular soil and loading conditions (McBride et al., 2000). Reduced ground contact pressure systems in which vehicles, machines and implements are fitted with tracks or larger than standard tyres with low inflation pressures (such as radial tyres) are suggested to increase tractive efficiency and reduce tyre/soil contact pressure and, thereby, the potential for compaction (Douglas, 1994; Correa et al., 1997; Hetz, 2001). Febo and Planeta (2000) reported that wider wheels fitted with radial tyres to reduce soil compaction are generally preferred to those with metal tracks and diagonal-ply tyres which usually destroy the structure of arable layers more than radial tyres. They also suggested that tractors with rubber tracks led to greater compaction of the topsoil but the more damaging compaction of the subsoil was less.

The influences of wheel and tracked machines on soil compaction were compared by Jansson and Johansson (1998) who reported that although the wheeled machine caused deeper ruts than the tracked one, alterations caused by the two machines to the measured soil parameters (dry bulk density, penetration resistance, intrinsic air permeability, saturated hydraulic conductivity, porosity and pore-size distribution) were similar, except in the uppermost 5–10 cm. The wheeled machine caused a decrease in bulk density, whereas the tracked machine caused an increase, despite its lower ground pressure. Tyre pressure also influences wheel load such that heavier loads can be used with low tyre pressures before deformation occurs (Werner and Mauersberger, 1995). Overall, in considering the benefits of decreasing ground pressure and increasing ground contact area it is important to recognise that the total area of the field trafficked by such wheels is greater than is the case with narrow wheels using high pressure. This can mean that there is actually more compaction of the topsoil over a whole field with low ground pressure in the tyres than with high ground pressure but the damage to the soil is likely to be greater with the narrower tyres at higher pressures.

Wheel slip also influences degree of soil compaction. For example, Maziero et al. (1997) reported that slip influenced degree of soil compaction to a depth of 5 cm and a 30% level of slip produced significant differences in degree of soil compaction. Although there was an increasing compaction effect from 19.2 to 31.9% slip, no significant differences were observed among the cone index values for the 10–20% slip. However, improving traction characteristics with the use of radial tyres can reduce wheel slip and increase forward speed significantly (Correa et al., 1997).

2.2.3. Number of passes

Intensity of trafficking (number of passes) plays an important role in soil compaction because deformations can increase with the number of passes (Bakker and Davis, 1995). Experimental findings have shown that all soil parameters become less favorable after the passage of a tractor (Chygarev and Lodyata, 2000) and that a number of passes on the same tramlines of a light tractor, can do as much or even greater damage than a heavier tractor with fewer passes. The critical number of passes was ten, beyond which advantages from the use of a light tractor were lost (Jorajuria and Draghi, 2000). However, the first pass of a wheel is known to cause a major portion of the total soil compaction (Bakker and Davis, 1995). Subsoil compaction may be induced by repeated traffic with low axle load and the effects can persist for a very long time (Balbuena et al., 2000). Wheeled traffic from machinery with axle load in excess of 9 Mg can cause increases in bulk density and penetrometer resistance in subsoil at a depth >30 cm below the surface. These changes in physical properties can lead to long-term yield suppression. In highly weathered soils, compaction may not increase the strength but may reduce the porosity, thus restricting water supply to the root surface (Rengasamy, 2000). Alakukku (1996) reported that in both clay (Vertic Cambisol) and organic soil (Mollic Gleysol), the penetrometer resistance was 22–26% greater, the soil water contents were lower, and the soil structure more massive, in plots compacted with four passes than in the control plots. These data were supported by Seker and Isildar (2000) who reported that the number of tractor passes increased soil bulk density and compaction, and decreased total porosity, void ratio, air porosity and drainage porosity. These findings were also supported by Balbuena et al. (2000) who reported that 10 passes significantly affected soil properties of the surface layer to 50 cm depth compared to the 1-pass and no-traffic control treatments. The negative effect of the number of passes on soil compaction is illustrated by Table 4 (Mosaddeghi et al., 2000) which shows that increasing the number of passes counterbalanced the effect of manure in ameliorating soil compaction.

2.3. Trampling and soil compaction

Treading by grazing animals can have a significant adverse effect on soil properties and plant growth, particularly under wet soil conditions. It may also affect water and nutrient movement over and through soil (Di et al., 2001). Soil compaction due to animal trampling is one of the factors responsible for the degradation of the physical quality of soils (Imhoff et al., 2000; Silva et al., 2000b) and mainly influences soil parameters such as soil structure (Ferrero and Lipiec, 2000). The intensification of dairy farming has also been found to have a deleterious effect on soil quality, particularly in terms of compaction by trampling, which results in losses of production, pasture quality and hydraulic conductivity (Mitchell and Berry, 2001). One of the most important soil properties vulnerable to animal trampling is penetration resistance, which is highly sensitive to animal trampling. Scholz and Hennings (1995) linked the critical values of penetration resistance for grazing to the depth of water table and weight of animal. They reported that the limits of penetration resistance without any trampling damage to the grass were 600 and 800 kPa, depending on the weight of cattle (300–500 kg per head). They also found that with homogeneous conditions of soil and vegetation, the

Table 4
Compaction depth[a] (cm) at different moistures, manure and pass levels (after Mosaddeghi et al., 2000)

Treatment	Rate of manure					
	One pass			Two pass		
	0 Mg/m^3	50 Mg/m^3	100 Mg/m^3	0 Mg/m^3	50 Mg/m^3	100 Mg/m^3
ΔBDт 0.05 Mg/m^3						
Plastic limit (PL)	25aA	25aA	22aA	35aA	25aB	25aB
0.8PL	17bA	20aA	22aA	23bA	24aA	24aA
0.6PL	0cA	0bA	0bA	13cA	0bB	0bB
ΔCIт 0.1 MPa						
Plastic limit (PL)	32aA	22aB	28aB	34aA	27aB	27aB
0.8PL	24bA	0bC	28aA	34aA	26aB	24aB
0.6PL	0cA	0bA	0bA	20bA	15bB	0bC

[a]Compaction depth is defined by the depth at which changes in BD or CI between initial and compacted soil (ΔBD or ΔCI) either equals or exceeds 0.05 Mg/m^3 and 0.1 MPa respectively. means with the different lower-case letter in each column, and with the different capital letter in each row and each group are significantly different at $p < 0.05$.

critical value of penetration resistance (800 kPa) corresponded to a groundwater level of 30 cm below the soil surface. With heterogeneous soil and vegetation, the critical value (600 kPa) was, in wet periods, at a groundwater level of 20–60 cm and in dry periods was at 0–30 cm, depending on the dominant plant species. Mapfumo et al. (1999) reported that surface (0–2.5 cm) bulk density and penetration resistance was significantly greater under heavily grazed than under medium and lightly grazed meadow. Trampling can also significantly influence soil saturation capacity and root ratio (Gokbulak, 1998) and reduces soil water infiltration (Vahhabi et al., 2001; Mwendera and Saleem, 1997). Soil compaction induced by trampling is affected by the following: (a) trampling intensity (Mwendera and Saleem, 1997; Donkor et al., 2002); (b) soil moisture (Aliev et al., 1999); (c) plant cover (Terashima et al., 1999); (d) slope (Ferrero and Lipiec, 2000) and (e) land use type (Gokbulak, 1998).

2.3.1. Critical depth of trampling-induced compaction

The depth of trampling-induced soil compaction varies depending on animal weight and soil moisture and could range from 5 to 20 cm. Ferrero and Lipiec (2000) reported that most compaction effects were limited to the surface and intermediate depths (to a depth of 20 cm). Vzzotto et al. (2000) reported that animal trampling increased soil density at the first 5 cm soil depth and Terashima et al. (1999) reported that trampling affected soil properties to a depth of 20 cm, with the greatest effect in the top 5 cm. Usman (1994) suggested that trampling produced dense zones, which reduced water infiltration at a depth of 7.5 cm. The depth of this dense zone is very close to the depth of the hardpan detected by other researchers (Mulholland and Fullen, 1991; Ferrero, 1994).

2.3.2. Trampling intensity

Mwendera and Saleem (1997) compared different grazing intensities (animal-unit-month per hectare, AUM/ha) and found that heavy (3 AUM/ha) to very heavy (4 AUM/ha) grazing pressure significantly increased surface runoff and soil loss and reduced infiltration, compared to light (0.6 AUM/ha) or moderate grazing (1.8 AUM/ha). However, fine-textured soils were more susceptible to trampling effects than coarse-textured soils. These results are somewhat different from the results reported by Donkor et al. (2002) who showed that the same degree of soil compaction can be achieved by smaller numbers of animals grazing for a longer period or a large number of animals grazing for a short period. They compared the effects of high intensity, short-duration grazing (SDG, 4.16 AUM/ha) with moderate intensity, continuous grazing (CG, 2.08 AUM/ha) and concluded that grazing for short periods did not show any advantage over continuous grazing in improving soil physical characteristics and herbage. Different grazing techniques, such as traditional set-stocking (where sheep were grazed continuously for 17 weeks), controlled grazing (where sheep were temporarily removed from the enclosure when the topsoil was close to its plastic limit), and no grazing (where the pasture was mown to simulate grazing without trampling), were compared on a sandy clay loam (red duplex soil, Alfisol) growing a medic (*Medicago polymorpha*) pasture (Proffitt et al., 1995). At the end of the grazing period, all soil structural attributes measured showed that topsoil structure under the controlled grazing practice was not only superior to that under the traditional set-stocking practice, but similar to that in the no grazing treatment.

3. Solutions to soil compaction problems

Since soil compaction mainly decreases soil porosity (or increases soil bulk density), then increasing soil porosity (or decreasing bulk density) is a clear way of reducing or eliminating soil compaction. Managing soil compaction, especially in arid and semi-arid regions, can be achieved through appropriate application of some or all of the following techniques: (a) addition of organic matter; (b) controlled traffic; (c) mechanical loosening such as deep ripping; (d) selecting a rotation which includes crops and pasture plants with strong tap roots able to penetrate and break down compacted soils.

Improved land management techniques are vital in ensuring that soil physical conditions are not compromised and that practices which increase the organic content, reduce tillage and sustain utilization of agricultural land are encouraged (Mitchell and Berry, 2001).

3.1. Compaction and soil organic matter

Organic matter retains soil water thus helping soil to rebound against compaction. Maintaining an adequate amount of organic matter in the soil stabilizes soil structure and makes it more resistant to degradation (Cochrane and Aylmore, 1994; Thomas et al., 1996), and decreases bulk density and soil strength (Sparovek et al., 1999; Carter, 2002). The following mechanisms have been identified as the most common means by which organic matter influences soil structure and compactibility: (a) binding soil mineral particles (Theng and Oades, 1982; Zhang, 1994); (b) reduction of aggregate wettability (Zhang and Hartge, 1992); and (c) influencing the mechanical strength of soil aggregates, which is the measure of coherence of inter-particle bonds (Quirk and Panabokke, 1962). However, some workers have not found such positive correlation (Dexter et al., 1984) and others have reported different behaviour for different types of organic matter (Ekwue, 1990). Still others have reported different behaviour for the same type of organic mater at different soil conditions (Soane, 1990). These differences seem to be related to the type of organic matter, C/N ratio and the degree of resistance to decomposition as well as to soil type and environmental conditions such as moisture and temperature. The type of organic matter is also important. Readily oxidisable soil organic matter seems to be more relevant than total organic matter in determining mechanical behaviour of the soil (Ball et al., 2000). On the other hand, the less humified the organic matter, the greater is its effect in increasing aggregate porosity and hence the greater the decrease in aggregate tensile strength (Zhang, 1994). Since organic materials possess lower bulk density and greater porosity than that of mineral soils (Martin and Stephens, 2001), mixing them with soil would improve soil bulk density and porosity (Zhang, 1994). Addition of organic matter to topsoil through incorporation of plant residues or manure application has been widely studied by many researchers (Soane, 1990; Ohu et al., 1994; Hamza and Anderson, 2002a, 2003). However, using organic matter to improve subsoil compaction is less common. The reason behind this is technical and economical. To inject organic matter into the rooting zone, the soil must be ripped to at least 20–30 cm, and this usually involves high cost. The availability of a delivery system to place organic matter at the desired depth is another problem that must be overcome. However, there have been a few successful attempts that have succeeded in achieving both processes in one machine (Khalilian et al., 2002).

While plant residues are a common source of organic matter in soil, animal manure is also used extensively by farmers to reduce soil compaction and improve soil fertility. The elasticity of manure prevents the transmission of the stresses toward the subsoil in the lower depths (Soane, 1990) thus acting as a buffer to decrease the impact of farm machinery on subsoil. Mosaddeghi et al. (2000) showed that incorporating 50 and 100 t ha^{-1} of cattle manure significantly counteracted the effects of load (one and 2 passes of 48.5 kW tractor) and wetness (0.06 plastic limit (PL) and 0.08 PL) on bulk density and soil strength of a silty clay loam topsoil.

Green or brown manuring as a source of organic matter may not be an economically viable option in a high yielding environment (Fettell, 2000) but it is a beneficial practice in improving soil physical properties in compacted soils. Reddy (1991) observed a decrease of 0.02 Mg m^{-3} in bulk density and 11.8 kPa in soil strength of a sandy loam soil due to the application of 10 t ha^{-1} of green leaf manure, while infiltration rate increased by 0.4 cm h^{-1}. However, plant species and the method of incorporation influence the efficiency of the process. The most important difference in plant species is their C:N ratio, which is related to the rate of decomposition by bacteria. In dry areas the process of adding organic matter to clay soils is probably counterbalanced by losses from the existing organic matter pool in the soil. Injecting organic matter into the subsoil may prove a better alternative to stubble retention in tackling the soil compaction problem in dry environments where surface applied materials may be partially lost due to the harsh environment.

3.2. Controlled traffic

Controlled traffic is a system that could help to maintain a zone more favourable for plant growth by restricting soil compaction to the traffic lanes (Braunack et al., 1995) thus providing a firmed, traffic lane and a loose rooting zone (Kayombo and Lal, 1993). Controlled traffic also offers the possibility for long-term management of traffic-induced soil compaction (Taylor, 1992), avoids machinery-induced soil compaction and allows optimization of soil conditions for both crops and tyres (Taylor, 1989). However, before controlled traffic is implemented the soil must be loosened to remove any compacted layers. Under a controlled traffic, zero-till system, soil water infiltration rate is similar to that of virgin soil (Li YuXia et al., 2001). However, if the soil is worked by a medium sized tractor, infiltration rate could be reduced to that of long-term cropped soil. This suggests that wheel traffic, rather than tillage and cropping, might be the major factor governing infiltration. It also means that exclusion of wheel traffic under a controlled traffic farming system, combined with conservation tillage, provides a way to enhance the sustainability of cropping and improved infiltration, increases plant-available water, and reduces soil erosion caused by runoff.

Controlled traffic slows down the effect of re-compaction on tilled soil (Busscher et al., 2002), significantly increases soil water infiltration (Li YuXia et al., 2001), decreases wheel slip (Li YuXia et al., 2001), minimises losses of nitrogen by reducing the emission of N_2O (Ball et al., 1999), improves soil structure, increases soil moisture, reduces run-off, and makes field operations more timely and precise (Li Hong Wen et al., 2000). Other studies have shown that controlled traffic with direct drilling provided marked improvements in timeliness of farm operations, allowing earlier planting opportunities in all types of season (McPhee et al., 1995). Further, under controlled traffic, when surface seal is not a problem, tillage will not be necessary to obtain adequate infiltration rates except in the wheel paths (Meek et al., 1992). The wheel tracks in a controlled traffic system may occupy 20% of the land, but the losses in this area can be compensated by higher yield (Li Hong Wen et al., 2000). Despite the many advantages reported by researchers for controlled traffic, some researchers are still critical of the concept arguing that no marked benefit in soil properties or plant yield resulted from controlled traffic (Braunack et al., 1995).

Raper et al. (1998) compared the effect of controlled traffic (total absence of traffic) on soil compaction with trafficked areas (Table 5) and the subsequent effect on crop root penetration on sandy loam (Typic Hapludult). Their results showed that soil that was initially completely disrupted to a depth of 51 cm was re-consolidated by traffic into a soil condition similar to one that had never received a sub-soiling treatment. They also found that traffic decreased the total soil volume estimated for root growth (Fig. 2) using a 2 MPa limiting cone index value, but not the maximum rooting depth beneath the row, when an annual in-row sub-soiling practice was used. The findings of Raper et al. (1998) were confirmed by Bulinski and Niemczyk (2001) who

Table 5
Soil measurements in the row and cotton yield (after Raper et al., 1998)

Treatment	Surface bulk density (Mg/m^3)	Surface moisture content (%)	Depth to hardpan (m)	Hardpan bulk density (Mg/m^3)	Hardpan moisture content (%)	Yield (t/ha)
No traffic						
TSP	1.4	15.8	0.4	1.6	16.8	0.98
HTP	1.4	16.6	0.3	1.6	17.3	1.02
TP	1.4	15.9	0.2	1.7	16.3	1.07
SP	1.3	19.9	0.4	1.6	20.2	1.07
Traffic						
TSP	1.5	14.3	0.4	1.6	15.7	0.89
HTP	1.5	16.8	0.2	1.6	16.5	0.88
TP	1.6	15.1	0.2	1.7	14.6	0.91
SP	1.4	17.8	0.4	1.6	20.0	1.10
LSD	0.1	2.7	0.1	0.1	2.8	0.09

TSP = surface tillage + subsoiling + planting, HTP = Hardpan disturbance + surface tillage + planting, TP = surface tillage + planting, SP = Subsoiling + surface tillage.

reported that the volumetric density of soil sampled from the traffic lanes in a controlled traffic system was higher by 15–39% as compared with the area under crop. The porosity of the wheel-compacted soil decreased by 8%, mainly in pores of diameter >12 cm, the capillary pore volume decreased by 5.8%, and soil compaction increased by 39–272% compared to the cropped areas outside the traffic lanes. Similar results were also reported by Wanink et al. (1990) and Panayiotopoulos et al. (1994) who found that controlled traffic resulted in better root growth and lower resistance to penetration.

The long-term effects of controlled wheel traffic on soil properties have also been investigated by Liebig et al. (1993) who found that on a silty clay loam (Typic Argiudoll) soil strength in the trafficked inter-row was 56% greater than the non-trafficked inter-row and 104% greater than the row. These results were supported by Alakukku (1998) who compared compacted (by three passes of high axle load traffic) and un-compacted (no traffic) silt and clay loam soils and reported that soil penetrometer resistance was greater in compacted than control plots in the 35–49 cm layer of a clay loam and the 25–35 cm layer of a silt soil. The subsoil structure was also more massive and homogeneous in compacted than in control plots.

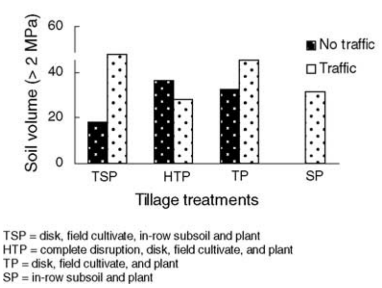

Fig. 2. Effect of tillage and traffic treatment on the proportion of soil volume beneath row and wheel tracks with cone index greater than 2 MPa (after Raper et al., 1998).

Ridge (2002) provided an overview of recent trends in harvesting systems and harvest-transporters, which reduce soil compaction through controlled traffic and management of chopper harvesting such as sugarcane (*Saccharum officinarum* L.) harvest which has continued to expand in Brazil, Argentina, Louisiana (USA), Mauritius and several African countries. He suggested that soil compaction during harvesting in all mechanized sugarcane producing countries can be reduced by controlled traffic or otherwise by limiting axle loads and capacity of individual trailers, use of high-floatation tyres or tracks, and using weight transfer principles to give even loading of axles. Controlled traffic, though it greatly reduces soil compaction, may not eliminate it completely. Kirchhof et al. (2000) reported that hydraulic conductivity underneath permanent tracks in a controlled traffic system had spread laterally into the subsoil.

The effect of traffic-induced soil compaction within conventional traffic, reduced ground pressure

Table 6
Total crop yields for winter barley (*Hordeum* spp.), winter oats (*Avena* spp.), suger beet (*Beta* spp.), potatoes (*Solanum* spp.), onions (*Allium* spp.) and ryegrass (*Lolium* spp.) as a percentage of the conventional or control treatment for some crops in Europe (after Chamen et al., 1992)

Crop	Country	H				R				Z			
		IT	CS	CL	NT	IT	CS	CL	NT	IT	CS	CL	NT
Winter barley	Scotland	100			95					106			95
Winter barley	Germany	100	93	95						98	91	91	
Winter wheat	England		100		99		104		101		93		94
Winter wheat	England		94	100							110	121	
Winter wheat	Germany	100	96	94						94	93	91	
Winter wheat	Netherlands	100				101				97			
Winter oats	England		100	100							100	91	
Sugar beet	Germany	100		104						107	112	108	
Sugar beet	Netherlands	100	104			104				108			
Potatoes	Scotland	100								118			
Potatoes	Netherlands	100				104				111			
Onions	Netherlands	100				106				110			
Ryegrass	Scotland				100				115				116

H, conventional practices for each country; R, reduced ground pressure; Z, zero traffic on the cropped area; IT, intensive tillage to 0.2–0.25 m depth; CS, conservation tillage without topsoil loosening; CL, conservation tillage with periodic topsoil loosening; NT, no tillage.

and zero traffic treatments, and different tillage techniques on the yield of a range of crops in different European countries was reviewed by Chamen et al. (1992) (Table 6). They concluded that conventional high pressure field vehicle systems damage soil structure and increase cultivation inputs compared with reduced pressure or zero traffic systems. This conclusion was confirmed by Dickson and Ritchie (1993) who compared the response of winter barley (*Hordeum* spp.) and spring barley to zero and reduced ground pressure traffic systems and to a conventional traffic system. They reported that yields of winter and spring barley over three seasons were significantly greater for the zero traffic system than for the reduced ground pressure and conventional traffic systems.

A slight degree of soil compaction may prove beneficial for some soil types. Bouwman and Arts (2000) subjected a loamy sand soil to full-width traffic with widely different loads (0, 4.5, 8.5 and 14.5 t) one to four times per year for a period of 5 years. Interestingly they found that a moderate degree of compaction (equal to a 4.5 t load) gave the highest crop yield but that at higher degrees of compaction roots failed to penetrate into the deeper soil layers (>20 cm depth).

If compaction is confined to the sub-surface only, roots may grow more laterally or coil upward toward the less compacted layers with no significant decrease in yield (Rosolem and Takahashi, 1998). Subsoil compaction may reduce total yield but not all yield components. For example Ishaq et al. (2001a) reported that although subsoil compaction (of a sandy clay loam) resulted in a 38% decrease in grain yield of wheat (*Triticum* spp.), plant height and 1000-grain weight was unaffected.

Controlled traffic has been shown to have lower energy requirements as compared to other tillage techniques (Coates and Thacker, 1990). Williams et al. (1991) also reported that controlled traffic used up to 79% less energy to perform a tillage activity such as disking while Nikolic et al. (2001) estimated the saving in energy as 20–25%. The second best tillage as far as energy is concerned is reduced (minimum) tillage, which has been shown to offer significant energy savings over conventional systems (Coates, 1997). However, these findings were contradicted by Dickson and Ritchie (1993) who reported that there were no effects of traffic system (controlled traffic and conventional traffic systems) on fuel and power use in winter barley and spring oilseed rape (*Brassica* spp.) crops. The energy requirements for different types of tillage are related to tillage depth, soil type, degree of compaction, soil moisture at the time of tilling and to the type of implements used, and these might explain the discrepancies in reported data.

3.3. Soil compaction and deep ripping

Deep ripping or deep cultivation, is an important practice for eliminating soil compaction, destroying hard pans and ameliorating hard setting soils (Jarvis et al., 1986; Whitehead and Nichols, 1992; Hall et al., 1994; Torella et al., 2001; Laker, 2001; Hamza and Anderson, 2002a,b, 2003). It has become a common management technique used to shatter dense subsurface soil horizons that limit percolation of water and penetration of roots (Bateman and Chanasyk, 2001). Interest in loosening dense subsoil to improve plant growth has received sporadic attention around the world over many years (Ellington, 1996). However, with the increasing soil compaction associated with mechanised agriculture and the availability of more powerful tractors and better sub-soilers, ripping can become a beneficial soil management practice.

Henderson (1991) reported that deep ripping of compacted, sandy soil increased dry matter at flowering of all species tested by about 30%, seed yields of field peas (*Pisum* ssp.) and lupins (*Lupinus* spp.) were increased on ripped soils by 64 and 84%, compared to undisturbed soils. Hamza and Anderson (2003) reported that a combination of deep ripping to 40 cm and application of 2.5 t ha^{-1} of gypsum in the absence of nutrient deficiency increased the yield of legumes and wheat significantly on loamy sand and sandy clay loam soils (Table 7). The yield increases reported above may be attributed to reduced soil strength and increased soil water permeability (Clark and Humphreys, 1996; Moffat and Boswell, 1996; Bateman and Chanasyk, 2001).

Deep ripping of compacted soil can also improve soil health and the ability of plants to resist disease. Laker (2001) reported that growth-stunting disease was eradicated completely, and yields of sultanas (*Vitis* spp.) increased substantially by deep cultivation, which eliminated compacted soil layers. Laker (2001) also reported that ripping increased the quality of tobacco (*Nicotiana* spp.), and consequently the unit price and income per hectare, compared with conventional tillage. The same study suggested that in sandy soils, compaction did not interfere with water infiltration into deep soil layers, but prevented roots from reaching and utilizing this water, which led to poor water use efficiency, increased drought hazard under rain fed conditions, and increased irrigation costs. Tennant (1986) reported that the total wheat and lupin root lengths per unit area of soil surface in the profile of a deep loamy sand soil ripped to 35 cm in Western Australia were higher than those on un-ripped soil (Table 8). The direct effect of subsoil compaction on the root and shoot growth of lettuce (*Lactuca sativa*) and broccoli (*Brassica oleracea* var *italica*) was investigated by Montagu et al. (1998). They reported that root growth was restricted by the compact subsoil, only 6–13% of the total root system being present in the compact layer, deep ripping reduced the maximum subsoil strength by 1.2 MPa, and roots of both crops were able to penetrate the compact subsoil approximately half-way through the vegetative growth phase. This finding is consistent with Mason et al. (1988) who reported that ripping the soil improved root form and vertical extension, and with Schmidt et al. (1994) who reported that increasing the depth of soil loosening beneath the sowing depth of wheat increased root density beyond the loosened depth.

Table 7
Response of grain yields (t ha^{-1}) of wheat (*Triticum* spp.), field pea (*Pisum* spp.) and chickpea (*Cicer* spp.) grown on sandy clay loam and loamy sand soils to a combination of deep ripping to 0.4 m and the application of 2.5 t ha^{-1} of gypsum (DRG) from 1997 to 2000. Numbers in brackets refer to the percentage change in yield relative to the control (after Hamza and Anderson, 2003)

	Sandy clay loam	Loamy sand
1997	Wheat (t/ha)	Wheat (t/ha)
Control	2.98	3.28
DRG	3.22 (8)	3.72 (13)
l.s.d.[a]	0.23	0.38
1998	Field pea (t/ha)	Chick pea (t/ha)
Control	1.43	0.97
DRG	1.85 (29)	1.26 (30)
l.s.d.[a]	0.55	0.16
1999	Wheat (t/ha)	Wheat (t/ha)
Control	3.15	2.88
DRG	3.95 (25)	4.01 (39)
l.s.d.[a]	0.43	0.29
2000	Field pea (t/ha)	Field pea (t/ha)
Control	0.93	0.77
DRG	1.07 (15)	0.95 (23)
l.s.d.[a]	0.36	0.21

[a] l.s.d.: $p = 0.05$.

Table 8
Effect of deep ripping on total length of roots per unit area of soil surface (cm/cm^2) of wheat and lupins (after Tennant, 1986)

Day after planting	Control	Wheat deep ripping	Control	Lupin deep ripping
44	24	36	18	20
58	66	72	24	32
72	103	131	33	38
93	127	161	38	42
113	142	183	57	67

One drawback of the loosening operation however, is that the open soil condition left is particularly vulnerable to re-compaction by subsequent machinery traffic and grazing animals (Spoor, 1995). Re-compaction also occurs through repeated precipitation of fine clay and colloids through wetting–drying cycles (Allen and Musick, 2001; Busscher et al., 2002) especially in clayey soils. To prevent re-compaction and help re-forming the structure of ripped soil, a binding or flocculating agent (gypsum or organic matter) is needed. Without such agent compaction can recur (Hamza and Anderson, 2002a, 2003) some time in the first year after ripping (Moffat and Boswell, 1996). Hall et al. (1994) reported that the effect of deep ripping on soil–water relations declines after the first year and yield increases associated with deep ripping did not persist beyond the second year of the experiment, presumably due to re-compaction. Hamza and Anderson (2002a) found that deep ripping alone increased the infiltration rate in the first three years but the effect did not last into the fourth year (Table 9). In fact the effect of ripping on water infiltration began to decline sharply in the second year. It was suggested that the decrease in the infiltration rate with time for the ripped treatments indicates that large soil voids created by ripping filled gradually with fine particles and colloids and the soil became compacted again.

Table 9
Soil water infiltration values (mm/h) from 1997 to 2000 as affected by deep ripping and gypsum treatments (after Hamza and Anderson, 2002a)

Treatment	1997	1998	1999	2000
C	6.2–8.0	6.9–9.2	9.9	10.1
G	19.7	20.8	20.1	19.3
DR	21.0	16.0	15.1	9.8
DRG	23.5	23.6	23.8	23.5
l.s.d. ($p = 0.05$)	1.7	1.1	0.3	0.8

C, control; G, gypsum; DR, deep ripping; NB: values for the control in 1997 and 1998 are given as ranges due to high variability in the readings.

Data presented by Busscher et al. (2002) confirms the re-compaction of ripped soil by showing that regressions of cone indices with cumulative rainfall explained 67–91% of the re-compaction, and indicates that water filtering through the soil was causing the re-compaction. However, the re-compaction in their trial was slower than that reported by Hamza and Anderson (2002a), taking place 6 years after tillage, and was also temporarily higher for the 10–20 cm depths when compared with that in the 25–35 cm depths indicating that it was moving down the profile. However, yield can be reduced even by incomplete re-compaction that increases soil strength after a year or less (Busscher et al., 2002). Ripping soil without removing the causes of compaction might not improve yield. Ellis (1990) reported that grain yields showed little response to deep ripping in wheeled treatments even though penetrometer resistance showed a marked decrease, but a significant increase in grain yield occurred where both the compacted layer and wheel traffic were removed. Kayombo and Lal (1993) discussed soil compaction in semi-arid and arid regions suggesting that the alleviation of soil compaction can be achieved by two methods. The first is to use a controlled traffic tillage system to provide a loose, rooting zone and a firmed traffic lane, thereby providing good plant growth and traffic-ability for timely field operations. The second method is to use mechanical loosening techniques such as deep ripping and subsoiling to remove soil compaction. They added that the effect of mechanical loosening tends to be of short duration if the ensuing field traffic is not controlled. Deep ripping may also delay soil salinity by disrupting capillary action that brings water to the surface where evaporation causes salt to accumulate. The potential for soil salinity can also be reduced by improving water penetration and leaching of soils through deep ripping or other cultivation and mulching methods, rather than by improving the subsurface drainage system (Grismer and Bali, 1998). There is also evidence that deep ripping may reduce groundwater recharge (McFarlane and Cox, 1992) and soil erosion (Schillinger and Wilkins, 1997).

Ripping the soil is the most expensive and critical component of removing soil compaction by physical means. However, choosing the right soil moisture (Hamza and Penny, 2002) and the right combination of ripping depth and tine spacing can minimise the cost of ripping. Riethmuller and Jarvis (1986) found a good relationship between unit draft (which is proportional to energy expenditure), tillage depth and tine spacing (Table 10). Ripped soil must be allowed to settle down before seeding, otherwise seeding depth is difficult to control and seeds may be placed below the preset seeding depth.

The cost of ripping the soil can be reduced significantly by using a new generation of soil rippers (Fig. 3) which utilises the concept of shallow leading tines (Spoor and Godwin, 1978; Palmer and Kirby, 1992). This is also expected to significantly reduce the size of clods, which are usually associated with ripping. Tine modifications such as winged shanks and shallow leading tines have been shown to improve the work efficiency (volume of soil loosened per unit

Table 10
The relationship between unit draft, depth of soil ripping and tine spacing for loamy sand soil (after Riethmuller and Jarvis, 1986)

Tine spacing (m)	Depth (m)	Unit draft ($kN\ m^{-1}$)	Regression[a] ($kN\ m^{-1}$)
0.215	0.1	5.18	4.01
	0.2	13.16	11.41
	0.3	21.56	18.81
0.495	0.1	2.31	2.29
	0.2	6.38	6.09
	0.3	11.78	13.49
0.825	0.1	2.23	1.65
	0.2	4.96	4.53
	0.3	10.28	9.32

[a] Regression percentage variance accounted for 87.1.

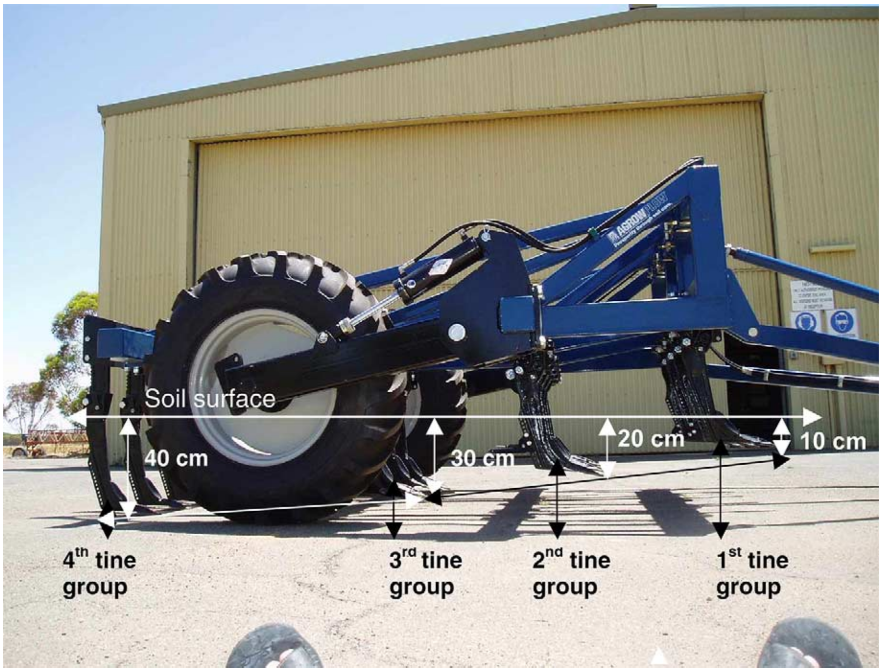

Fig. 3. A new generation ripper (Agrowplow®) applying the shallow leading tine concept where tines are aligned behind each other to rip consecutive soil depths. The first tine rips the first 10 cm of the soil, the second tine rips the next 10 cm, the third and the fourth tines each rip the next 10 cm. The total depth ripped by the four tines is 40 cm.

drawbar pull) of deep ripping and decrease cost (Lacey et al., 2001). A machine that works at several depths, such as a leading tine ripper, can allow for injection of more than one ameliorant behind the tines and at each depth. It will thus be possible to treat almost the whole rooting zone.

3.4. Plant roots and soil compaction

The ability of plant roots to penetrate soil is restricted as soil strength increases (Mason et al., 1988) and ceases entirely at 2.5 kPa (Taylor, 1971). The inability of plant roots to penetrate compacted soil layers is well documented in the literature (Kirkegaard et al., 1992; Venezia et al., 1995; Laker, 2001). Hydrostatic pressure (Turgor) within the elongating region of the root provides the force necessary to push the root cap and meristematic region through the resisting soil. If the hydrostatic pressure is not sufficient to overcome wall resistance and soil impedance, elongation of that particular root tip ceases. Plant roots constitute a major source of soil organic matter when decomposed and while growing are capable of both creating and stabilizing useful structural features (Cochrane and Aylmore, 1994). The effect of roots on soil structure depends on the species grown, soil constitution and environmental factors (Monroe and Kladivko, 1987). The effect is also influenced by soil micro-flora associated with plant roots (Tisdall, 1991). Plants grown in compacted soil have shown a smaller number of lateral roots with less dry matter than plants grown under controlled conditions at both low and high soil water contents (Panayiotopoulos et al., 1994). Roots grown in more compact soil had smaller ratios of fresh to dry mass. Soil compaction can have adverse effects upon plants growing in the soil by: (a) increasing the mechanical impedance to the growth of roots; (b) altering the extent and configuration of the pore space (Taylor and Ashcroft, 1972; Tardieu, 1994); and (c) aggravating root diseases such as common root rot of pea by decreasing drainage and thus providing more favorable soil water conditions for early infection of pea roots (Allmaras et al., 1998).

Diurnal changes in root diameter loosen and break down any compacted soil layer around them. Hamza et al. (2001) using a Computer Assisted Tomography technique, showed that radish (*Raphanus* spp.) and lupin (*Lupinus* spp.) roots exhibit a temporary decrease in diameter after transpiration commences followed by a significant temporary increase. This diurnal fluctuation in diameter destabilises soil and loosens the compaction. Roots of different crop species, as well as of cultivars within species, differ considerably in their ability to penetrate through hard soil layers (Singh and Sainju, 1998). Their response is related to the ability of the root system to overcome the soil strength limitations of compacted soil (Kirkegaard et al., 1992). This was confirmed by Cochrane and Aylmore (1994) who reported that legumes are more effective for stabilizing soil structure than non-legumes, and lupins were the most efficient species (Fig. 4).

Plant species that have the ability to penetrate soils with high strength usually possess a deep tap root system. Incorporating such species in the rotation is desirable to minimize the risks of subsoil compaction (Ishaq et al., 2001b). For example, in soils such as Vertisols with high shrink-swell potential, strong-rooted crops such as safflower (*Carthamus* spp.) could be used for biological soil loosening, through deep soil profile drying (Jayawardane and Chan, 1994). Cochrane and Aylmore (1994) also observed that variations between cultivars of the same species were generally small relative to differences between species

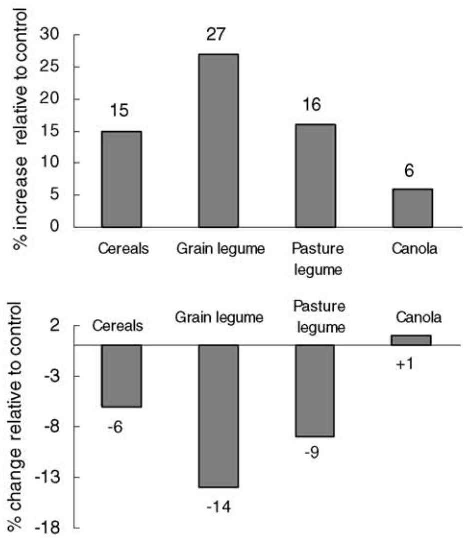

Fig. 4. Effect of plant roots on water stable aggregates (A) and disaggregation (B) averaged over six types of wheat belt soils in Western Australia (after Cochrane and Aylmore, 1994).

and the plant species they used did not have the same ranking for structural efficacy in all soils but depended on initial structural status. They concluded that for particular plant/soil combinations roots may stabilize some soil fractions while destabilizing others. Busscher et al. (2000) also reported that soybean (*Soja* spp.) CV PI 416937 possesses a superior genetic capability over CV Essex to produce more root growth in soils with high penetration resistance. Accordingly they suggested that genetic improvement for root growth in soils with hard layers could potentially reduce dependence on tillage. However, crop management practices, such as tillage, use of heavy farm machinery, and crop rotation can also influence root growth by altering soil physical and morphological properties.

If there is enough topsoil for root growth, roots will concentrate themselves there and increases in density of the subsoil may not result in significant decreases in yield. Rosolem and Takahashi (1998) studied the effects of soil subsurface compaction on root growth and nutrient uptake by soybean grown on sandy loam. They reported that sub-surface compaction led to an increase in root growth in the superficial soil layer with a corresponding quadratic decrease in the compacted layer. There was no effect of subsoil compaction on total root length or surface area, soybean growth or nutrition. Soybean root growth was decreased by 10% when the soil penetrometer resistances was 0.52 MPa (bulk density of 1.45 Mg m^{-3}) and by 50% when the soil penetrometer resistances was 1.45 MPa (bulk density of 1.69 Mg m^{-3}).

3.5. Minimising the effect of trampling

The impact of animal trampling can be reduced if the soil surface is covered with vegetation (Greene et al., 1994). Gifford and Dadkhah (1980) showed that plots with 30% grass cover had the lowest infiltration rates at all levels of trampling, but 50% cover was adequate for maximizing infiltration rates and preventing erosion. Russell et al. (2001) reported that a 2 cm canopy height of the forage species common on a New Zealand hill land pasture, was adequate to minimize the effects of a short-term treading event on soil water infiltration rate and sediment loss. This finding is consistent with that of Silva et al. (2000b) who found that animal trampling had no effect on soil physical properties when pasture biomass of oats (*Avena* spp.) and Italian ryegrass (*Lolium* spp.) were kept at about 1.0 t ha^{-1} dry matter.

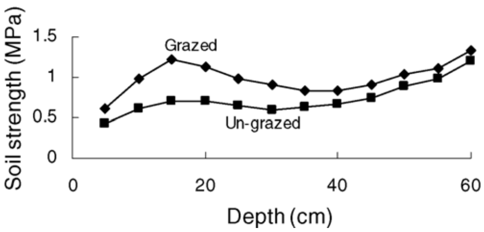

Fig. 5. Average soil strength for grazed and un-grazed sandy soil (after Ballenger, 2001).

Soil moisture is an important factor in determining the degree of compaction upon trampling where the deleterious impact of livestock trampling generally increases as the soil moisture at the time of trampling increases (Warren et al., 1986) and grazing should be strictly prevented on wet soils. However, in swelling soils high in sodium, aggregate size was found to be lower under grazing (from 4.4 to 5.1 mm) than in an excluded area (from 4.7 to 5.4 mm) (Taboada et al., 1999). This reduction in aggregate size was attributable to the mechanical shearing action of trampling at low soil water contents when the structure of the grazed soil became less stable. Grazing effects on soil structural stability were significant only in periods when the soil dried, and it was suggested that stocking rates must be regulated in those dry periods. However, some workers have reported that animal trampling did not show a significant effect on soil physical properties. For example, Roundy et al. (1990) reported that neither light nor heavy trampling strongly affected soil physical properties while Ballenger (2001) concluded that, although the differences in soil bulk density and soil resistance data between grazed and un-grazed sites were statistically significant (Fig. 5), these differences were not large enough to influence plant growth. This was supported by the lack of differences in infiltration between the treatments, and thus the minimal impact of grazing on the soil water relationships.

3.6. Modeling soil compaction

Quantifying the mechanical processes of compaction in agricultural soils can provide the necessary understanding to estimate and predict physical changes, allowing comparison with the maximum variations consistent with minimal damage to the productive potential of soil. Many attempts have been made to model soil compaction caused by farm machinery (McBride et al., 2000; Boguzas and Håkansson, 2001; Defossez and Richard, 2002). Horn et al. (1998) and Gupta and Raper (1994) have described the structure and physical processes associated with most models. However, the difference between simulations and observations becomes more apparent when dealing with heterogeneous structures. Because most of the soil compaction is obtained by wheel traffic treatments (Lipiec et al., 1998) most models require a large number of mechanical parameters and have been evaluated under limited conditions in laboratory bins or in the field with low compaction intensities.

Traditionally, stress–strain relationships that rely on empirical geo-technical engineering practices have been used to study compaction of agricultural soils. However, these approaches failed to address key features of soil structural dynamics required for modelling of hydraulic properties because they were not adequate for a priori prediction of soil structural changes (Hillel, 1998). In addition, they are based on equilibrium state stress-strain relations, while deformation in agricultural soils is often a dynamic process that rarely reaches equilibrium (Or, 1996), especially when transient and rapid loading by agricultural machinery is considered. Furthermore, while these methods can describe the changes in bulk volume, they cannot predict changes at pore-scale which is crucial for flow and transport processes (Or et al., 2002). An alternative approach has been suggested which circumvents some of the limitations by considering pore-scale mechanistic models coupled with intrinsic soil rheological properties and stochastic up-scaling (Ghezzehei and Or, 2001; Leij et al., 2002; Or and Ghezzehei, 2002). These models address soil structural changes induced by internal capillary forces and external steady and transient forces such as passage of a tractor (Or et al., 2002). A model based on Boussinesq Equations has been developed by Defossez and Richard (2002) which includes: (1) propagation of the loading forces within the soil resulting from forces applied at the soil surface from farm vehicles, and (2) modelling soil stress-strain behaviour. The model has been successfully evaluated in field conditions for homogeneous soil under a wide range of soil and water conditions. Another principle (Elasticity Theory) has been used by Ricardo Smith and Achim Ellies (1998) to derive equations describing stress distribution in a semi-infinite and homogeneous medium when a load is applied on its surface. Their model was modified in order to correct the equations for the plastic properties of soil, and an expression for continuous load distribution and different shapes of the tyre-soil interface was obtained by applying the principle of super-position. The authors concluded that simplified procedures of calculation can lead to inaccurate estimates. Nevertheless, we consider that reasonably accurate models that predict soil compaction over a range of conditions can be useful tools to assist the design of systems less damaging to agricultural production.

4. Conclusion

The ever-increasing population of the world necessitates the intensification of farming and cropping systems to cope with the demand for more food. As a result, more and heavier farm machinery and/or animals per land surface area have become common all over the world. This intensification of the farming system has led to soil compaction and deterioration in soil physical fertility particularly in dryland areas. Soil compaction adversely affects soil physical fertility, particularly storage and supply of water and nutrients, through increasing soil bulk density, decreasing porosity, increasing soil strength, decreasing soil water infiltration, and water holding capacity. These adverse effects reduce fertilizer efficiency and crop yield, increase water-logging, runoff and soil erosion with undesirable environmental pollution problems. It is hard to suggest one single agronomic practice as a solution to the soil compaction problem. Rather, a combination of practices is suggested to mitigate or delay the problem. These practices include minimum (and zero) tillage, controlled traffic, combining more than one farm operation simultaneously using the same machine to minimize number of passes, minimizing traffic, minimizing intensity of grazing and number of animals per grazing, maintaining vegetative soil cover, loosening compacted soil by deep ripping accompanied by an aggregating agent such as gypsum to slow down the re-compaction process, and using a rotation which includes deep and strong rooting plants able to penetrate relatively compacted soils. Machines with low axle loads and tyres with high surface contact area should be used to minimize ground pressure.

Increasing soil organic matter through stubble retention, green and brown manure or addition of plant or animal organic matter from external sources is also important in decreasing bulk density of the soil and acting as a buffer preventing or lessening the transmission of compaction to subsoil from external loads acting on the topsoil. Finally, farm operations and grazing must be carried out at the minimal acceptable soil moisture necessary for farm operations. All other farm operations which do not require moisture in the soil should be carried out when soil is dry to very dry.

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