Agricultural traffic management systems and soil health

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Abstract

This chapter examines the relationship between agricultural traffic and soil compaction. It begins by reviewing research on how agricultural traffic affects soil compaction as well as ways of measuring soil compaction and its effects. It then discusses a range of potential techniques to avoid soil compaction. These include controlled traffic farming, low ground pressure tyre systems as well as tracks and gantry systems. The chapter also discusses the relationship between different tillage practices and soil compaction. It includes a case study based on research conducted by the authors.

Key words: Soil compaction; bulk density; penetration resistance; porosity; infiltration

Contents:

1 Introduction

Since 1950, the annual increase in the global human population has varied from a peak of 1.98% in 1960 to a current rate of 1.20%. The global population is currently around 7.8 billion and is projected to reach 9.9 billion by 2050, an increase of more than 27% (UN population data, 2021: www.worldometer.info). In addition, dietary requirements are also rapidly changing particularly in developing nations (Ray et al., 2013; Godfray and Garnett, 2014). This dramatic, long-term increase in population and demand for food has prompted an equally dramatic increase in food production, made possible by developments such as advances in high-yielding varieties, the development and use of a new range of fertilisers and pesticides, and major advances in technology to allow crop planting, management, and harvesting to occur on a much larger scale. From 1960 to 2014, e.g. UK wheat production increased 240%, barley 196%, and oats 226% (Ritchie and Roser, 2019) (Fig. 1).

The continued improvement in the sophistication and size of farm machinery to support this growth in agricultural output has resulted in larger, more efficient farms with less labour but much greater productivity (Cavallo et al., 2014). However, increases in agricultural machinery power and capability have also been accompanied by steadily increasing machinery weight. The size and weight of farm machinery has increased significantly in the last 50 years. Chamen et al. (2006) reported that, since 1966, the average weight of farm vehicles has approximately tripled while the average wheel load has increased six times. Schjønning et al. (2015) reported that the average mass of fully loaded agricultural equipment increased by a factor of 6, from 4.3 Mg in 1958 to an average of about 25 Mg in 2009. It has been estimated that average wheel loads of tractors increased from about 1.5 Mg in 1960 to 4 Mg in 2000; wheel loads of combine harvesters increased from 1.5 Mg in 1958 to almost 9 Mg by 2009 (Keller et al., 2019).

One consequence of increasing machinery weight is its link to the problem of soil compaction. Soil compaction has been identified as a factor in stagnating yields more recently observed in wheat and other crops (Knight et al., 2012). Soil compaction has been 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 bulk density' (SSSA, 2008). Soil compaction occurs when the application of a load or stress provided by a vehicle on the soil surface at a given depth exceeds the soil strength (Sohne, 1958). The process of densification results in a wide range of changes to a range of soil characteristics such as porosity, permeability, and strength (Soane and van Ouwerkerk, 1994). Compaction disrupts soil structure and in turn soil biology. Morales et al. (2015) suggested that changes in soil moisture and nutrient availability resulting from soil compaction can influence microbial diversity and consequently the ecosystem services delivered by soil, including carbon (C) sequestration. Kaczorowska-Dolowy (2022) also reported a significant negative effect of soil compaction on Collembola population and soil fauna feeding activity. Soil compaction can also accelerate wind and water soil erosion (Houšková and Montanarella, 2008) and has been linked to problems such as surface run-off and resulting pollution of surface water (Soane and van Ouwerkerk, 1994; Bagarello et al., 2004; Kroulik et al., 2009).

Soil compaction has also been linked to lower crop yields by a number of researchers (Raghavan et al., 1979; Horn et al., 2003; Hula et al., 2009; Chamen 2011), which in turn has been identified as a factor in stagnating yields more recently observed in wheat and other crops (Knight et al., 2012). Yield reduction on trafficked soils has been related to restricted root growth and poorer access to water and nutrients as a result of increased bulk density (BD) and soil strength, and reduced pore size (Kaspar et al., 2001; McHugh et al., 2009; Nawaz et al., 2013; Ngo-Cong et al., 2021). As an example, soil compaction has been associated with changes in root structure, leading to shorter, thicker roots with, potentially, less overall surface area for water and nutrient uptake (Hettiaratchi, 1990; Materechera et al., 1991; Głąb, 2008; Chen et al., 2014; Kaczorowska-Dolowy et al., 2019).

Soil compaction is also seen as a factor in overall soil degradation which is estimated to affect over 30% of arable land in Europe (Oldeman et al., 1998; Keller et al., 2019). This leads to a conclusion that soil compaction has a detrimental effect on 'soil health', a term that integrates soil physical, chemical, and biological properties. Soil health refers to the general quality of the soil resource and embraces both the provision for agricultural crop production and the provision of other ecosystem services (Kibblewhite et al., 2008). Doran (2002) defined soil health as 'the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health'. Improved soil health is vital for resilience and adaptability which in turn is essential for future production, particularly in the face of climate change (Andriuzzi, 2015; Congreves et al., 2015).

This chapter examines the following aspects of agricultural traffic and soil compaction. It begins by reviewing research on how agricultural traffic affects soil compaction as well as ways of measuring soil compaction and its effects. It then discusses a range of potential techniques to avoid/reduce soil compaction. These include controlled traffic farming (CTF), low ground pressure tyre systems as well as tracks and gantry systems. The chapter also discusses the relationship between different tillage practices and soil compaction. It includes a case study based on research conducted by the authors.

2 How agricultural traffic affects soil compaction

It is important to distinguish between compaction of natural origin (e.g. hardsetting and glacial overburden) from compaction induced by agricultural traffic and trampling by grazing animals (Chartres et al., 1990; Raper and Kirby, 2006; Botta et al., 2020). Soil compaction caused by farm traffic has been related to three main factors (Raper et al., 1995; Soane and van Ouwerkerk, 1994):

1. wheel load;
2. tyre inflation pressure;
3. contact area.

Other relevant factors include soil consistency (mainly influenced by soil water content, which influences soil strength and bearing capacity) and the characteristics of the traffic itself (e.g. number of passes, speed) (Soane et al., 1980). This section examines each of these three main factors.

Sohne (1958) reported that higher wheel loads cause stresses reaching progressively greater depths below the soil surface as loads increase (Fig. 2). At the same time, the pressure reaches greater depths with increasing soil moisture content. Soil compaction due to wheel traffic has been found to deteriorate soil structure both in topsoil and deeper in the soil profile (Domżał et al., 1991). Increased loads have thus been shown to increase compaction both in the surface layer and in the subsoil (Kroulik et al., 2009). Obour et al. (2017) found that four-wheel passes by a tractor-trailer combination with a wheel load of 8 Mg on a sandy loam soil had a significant effect on soil structural properties down to 0.65 m. However, he found that 3 Mg wheel load and five-wheel passes did not affect soil structure, highlighting the importance of load as a factor in soil compaction.

Increased tyre inflation pressure increases contact pressure as a result of reduced contact area defined as the area in contact between the tyre and the soil. Raper et al. (1995) reported that rut depth increased with an increasing tyre inflation pressure, confirming the relationship between inflation pressure and vertical impact on the soil profile. Antille et al. (2013), based on the work of Ansorge and Godwin (2007, 2008), investigated three different sizes of combine harvester tyres at three inflation pressures; they reported higher soil BD under higher inflation pressure tyres with a smaller contact area. Spoor et al. (2003) related contact pressure P_c with load and tyre contact area:

$$P_c = \frac{W}{A}$$

where W is the wheel load and A is contact area.

This equation does not, however, account for tyre carcass stiffness or tyre inflation pressure, thus underestimating actual pressure. Misiewicz et al. (2016) accounted for these factors as follows:

$$P_c = P_i + P_{cs}$$

where P_c is calculated contact pressure, P_i is tyre inflation pressure, and P_{cs} is tyre carcass stiffness.

A third variable affecting compaction is contact area. As presented in the equation by Spoor et al. (2003) the greater the contact area, the lower the contact pressure for a given load. The increase of the contact area can be obtained by mounting additional tyres (Alakukku et al., 2003), reducing tyre inflation pressure (Antille et al., 2013), the use of larger tyres (increased tyre width and/or diameter) (Koolen and Kuipers, 2012), or use of tracks (Ansorge and Godwin, 2007).

The total area of a field over which the compaction is applied is determined by the intensity of farming traffic (Kroulik et al., 2009), which, in turn, depends on crop and agronomic practices (Botta et al., 2022). The trafficked area of a field, that is the area covered by wheels each time a crop is produced, can be as high as 90% (Soane et al., 1980) in conventional (grain) farming systems and up to 120–150% in horticulture and root crop systems, but it can be significantly reduced (e.g. to less than 20%) with CTF (Antille et al., 2016 a, 2019 a,b; Tullberg et al., 2010)

Figure 3a illustrates the intensity of traffic on a 1-hectare field resulting from conventional (random) traffic (RTF) with a mouldboard ploughing tillage system during one season of cereal production (Kroulik et al., 2009). This leads to 86% of the field being subjected to at least one wheel pass every growing year (Fig. 3b). Traffic intensity is in part determined by different cultivation techniques and increases with more intensive tillage practices. Reducing tillage intensity leads to a decrease in the trafficked area as a consequence of the lower number of field operations required to prepare the seed bed. The use of shallow tillage and zero tillage reduces the total wheeled area to around 65% and 43%, respectively, as shown in Figs. 4 and 5 (Kroulik et al., 2009).

3 Measuring soil compaction and its effects

Soil compaction occurs when soil particles are brought together, thus reducing the soil pore space and pore size distribution (Berissso et al., 2012). Heavily compacted soils contain few large pores, less total pore volume and, consequently, have greater density. One way, therefore, to measure compaction is by measuring soil BD. Given higher density and disrupted pore structure, water flows and transmission within the soil is retarded or impeded (Ngo-Cong et al., 2021). A compacted soil thus has a reduced rate of both water infiltration and internal drainage. For similar reasons, gas exchange between the soil and atmosphere is also reduced, potentially reducing soil aeration.

Soil compaction has been linked to increased soil BD (Millington, 2019; Shaheb, 2019; Smith, 2017; Lipiec et al., 2003; Evans, 1996), though increases in soil BD are not linear with degree of compaction. As a result, the first pass of a vehicle has the greatest effect on soil compaction (Inns and Kilgour, 1978; Antille et al., 2013; Stranks, 2006). Ahmadi and Ghaur (2015) reported that an increase in the number of passes (from 0 to 4) increased soil BD by 13% and had detrimental effects on root growth. In silt and silt loam soils, Logsdon and Karlen (2004) found that the threshold of soil BD at which roots experience restrictions to growth is at 1.55 Mg m^{-3} whereas, for sandy and sandy loam soils, this critical threshold is increased to 1.6 Mg m^{-3} (Huber et al., 2008).

As well as increased soil density, compaction also increases soil strength which can be measured by penetration resistance (PR). Domżał et al. (1991) observed soil compaction as characterised by increased PR, shear resistance, increased cohesion, and crushing strength of soil aggregates. In their research on cotton, Taylor and Gardner (1963) concluded that the most critical factor for root penetration in the sandy soils of the Southern Great Plains of the United States was soil strength rather than soil BD. They concluded that PR greater than 2.96 MPa is a limiting value for root penetration, regardless of whether soil strength is caused by a decrease in soil moisture or by an increase in BD (though other research has suggested different values, depending on factors such as plant species (Bengough, 2006) and soil texture. Arvidsson et al. (2001) reported a significant increase of PR after 2–4 years of traffic in comparison to undisturbed soil. Increased strength as measured by PR means plant roots must exert greater force to penetrate the compacted layer.

Apart from soil BD and PR, another characteristic of the physical condition of soil is porosity which is defined as the fraction of the total soil volume that is taken up by the pore space, i.e. a measurement of the amount of space available to water or other fluids (Nimmo, 2013). Changes in pore size distribution resulting from compaction can be inferred from water retention curves, obtained when saturated soil samples are drained (Dexter and Bird, 2001). However, this method does not identify the complex changes to soil pore structure resulting from different stresses due to compaction (Peth et al., 2010). Another method to analyse pore structure is 2-D image analysis of thin slices of undisturbed soil samples as used by Pagliai et al. (2003). Dried samples are impregnated by polyester resin, sliced into thin sections and then analysed with software such as Image Pro-plus. However, this method of porosity analysis is time-consuming, costly, and requires specialist training (Lipiec and Hatano, 2003). To overcome these limitations, a number of scientists have investigated X-ray computer tomography (CT) to quantify pore size and its distribution in soil (Udawatta and Anderson, 2008; Rab et al., 2014; Beckers et al., 2014; Millington et al., 2017; Shaheb, 2019; Kaczorowska-Dolowy, 2022).

Kim et al. (2010) used X-ray CT to investigate the effect of compaction on a silty loam soil in Missouri (USA) and found that porosity in compacted soil was reduced by 64% in comparison to uncompacted soil, while the number of pores decreased by 71%. The same authors also reported an 8% increase in BD. Kim et al. (2010), Czyz (2004), and Berisso et al. (2012) found that soil compaction reduces the number of larger pores and thus affects total porosity. Shaheb (2019) reported almost two-fold higher macro porosity in untrafficked soil in comparison to trafficked soil, which agrees with observations made by Antille et al. (2016b) and Ebrahimi et al. (2022) based on model-derived data. Millington et al. (2016) found that reduced pore size from soil compaction results in anaerobic conditions, reducing plant establishment and root dry mass of winter barley in compacted areas. Millington et al. (2017) also reported that soil compaction resulting from farm traffic results in reduced porosity, confirming the findings of Soane and van Ouwerkerk (1994) who suggested that farm traffic results in homogenisation of pore systems. The size and distribution of pores within soil is essential for the transport of air, water, and nutrients necessary for the growing plant (Eden et al., 2011). Reduced porosity increases waterlogging and anaerobic conditions, leading to denitrification and a resulting reduction in root growth (Rab et al., 2014), thus reducing crop yield (Czyz, 2004).

The rate at which water enters the soil from the surface to the profile is known as infiltration (Parr and Betrand, 1960). The higher the infiltration rate, the less susceptible the soil is to surface runoff and erosion, particularly when soil is saturated (Barthes and Roose, 2002). Bagarello et al. (2004) argue that 'the hydraulic conductivity (K_{fs}) of saturated soil is one of the most important soil properties controlling water infiltration and surface runoff'. The value of K_{fs} is governed by cracks, root holes as well as by aggregate stability (Kirkham, 2014). It is also dependent on soil structure and texture (Bagarello et al., 2004), as well as on organic matter content and populations of earthworms which build the vertical holes facilitating water movement down the soil profile (Unger, 1996).

Field traffic has been suggested as having a detrimental effect on soil saturated hydraulic conductivity. Ankeny et al. (1995) reported that wheel traffic reduced ponded infiltration rates regardless of tillage system (chisel plough or no-till) by 33–64%, depending on location. Chyba (2012) concluded that the first pass of traffic is responsible for the greatest decrease in surface water infiltration rate (by approximately 82%). Silburn and Glanville (2002) found that rates of water infiltration were 29% higher on untrafficked soils when compared to trafficked soil. Chamen (2011) also reported a 400% difference in infiltration rates on untrafficked compared to trafficked soil. Arvidsson (2001) found that heavy traffic affected saturated hydraulic conductivity at 0.3 and 0.5 m depth.

In addition to soil physical properties, some soil biology attributes have been investigated to assess the effects of farming practices on soil health. Smith (2016) investigated the effects of traffic and tillage systems on earthworm density and found that zero tillage was associated with significantly increased earthworm numbers than deep tillage (250 mm) and shallow tillage (100 mm) measured over the winter period. No significant effects were found for alternative traffic systems. Morales et al. (2015) suggested that changes in soil moisture and nutrient availability resulting from soil compaction can influence microbial diversity and in turn ecosystem services delivered by soil. Rodgers et al. (2018) reported that field traffic significantly decreased Collembola abundance compared to untrafficked soils with highly significant differences in the spring. Thompson et al. (2020) in a study of the effects of wheeled traffic on soil microbial communities in grassland found that direct wheeled traffic had no significant effect on the abundance, diversity, or community structure of either the bacterial or archaeal communities (primitive, single-celled procaryote organisms). In contrast, traffic wheeling increased fungal communities in the loamy soil in comparison to unwheeled soil.

Various measures of soil properties have been used to assess the effects of farm traffic and resulting soil compaction and its consequences on crop growth and yield. Most research supports the view that heavy levels of traffic have a negative effect on crop growth and yields. Chamen (2011) reported a 16% decrease in winter wheat yield under heavily trafficked soil in comparison to untrafficked soil. Dickson and Ritchie (1996) reported that winter wheat, winter barley, and oilseed rape yields increased by 19% in uncompacted soil when compared to soil subject to compaction from farm traffic. In Australia, Li et al. (2007) found that, without traffic, winter wheat yields increased by 9% in comparison to soil exposed to one pass of a tractor. Demmel et al. (2015) also observed higher wheat and rye yields from untrafficked compared to trafficked zones in a study in Germany.

However, Raghavan and McKyes= (1978) found that moderate levels of compaction had less effects on yields. Arvidsson and Håkansson (2014) investigated the effect of traffic-induced compaction on crop yields in an experiment across 13 sites in Sweden. They concluded that, with moderate compaction (one pass with low tyre inflation pressures), wheat showed relative yield increases of up to 12% compared to untrafficked and previously loosened soil. However, a further increase in traffic intensity (to three passes with high tyre inflation pressures) led to bulk densities of 1.40–1.45 Mg m^{-3} which resulted in crop yield decreases of 1–21.3% for winter wheat (T*riticum aestivum*) and horse bean (*Vicia faba*), respectively. Seehusen et al. (2014) studied the effects of load and wheel pass intensities of two different farming vehicle combinations at a total load of 16 Mg and 36 Mg, respectively. They concluded that a single pass at 16 Mg and 36 Mg resulted in a 23% and 28% yield reduction, respectively. The same authors also observed that 10 passes at 36 Mg resulted in total crop loss. Research by Ball and Ritchie (1999) has highlighted that wet conditions play an important role in the effects of soil compaction, decreasing yields by 24% under trafficked compared to untrafficked soil. The impact on yield is greater in drier years, because of the effect of compaction on plant available water: in wet years, the crop is not constrained by water and thus yield is not affected to the same extent than in drier years (Hussein et al., 2021a,b).

4 Techniques to avoid soil compaction: controlled traffic farming

One technique to reduce soil compaction from farm traffic to a very small area of the field is CTF where field operations follow pre-determined traffic lanes and equipment widths and wheel track spacing are matched as far as possible to mimimise trafficked area (Raper, 2005; Tullberg et al., 2007). Confining farming traffic to permanent, pre-selected traffic lanes in a field requires the use of technology such as navigation and auto-steering systems. Use of RTK-GPS (Real Time Kinematic Global Position System) technology provides errors in positional accuracy to less than 20 mm, making it possible to drive farm vehicles on the same permanent traffic lanes every year, leaving the crop zones in between free of traffic and the risk of compaction (Gasso et al., 2013; Bochtis et al., 2010; Raper, 2005). Compacted permanent traffic lanes also improve energy use efficiency (by reducing wheel slip and rolling resistance) and have even made it possible to start work in fields after heavy rainfall at an earlier stage than would be possible if the compacted lanes were not in place (Taylor, 1994; McPhee et al., 1995; Dickson and Ritchie, 1996; Tullberg, 2000; Luhaib et al., 2017).

Bell et al. (2003) have suggested that the greatest benefits of CTF systems are achieved when the width of all track gauges match, that is, when the distance from wheel centre to wheel centre across all equipment is the same. Figure 6 illustrates one preferred ratio for equipment width, called a '3:1 ratio' layout (Australian terminology) or 'ComTrac' system (European terminology). This layout is suitable for equipment less than 12 m wide using a single wheel track (Isbister et al., 2013; Antille et al., 2019b). There is no universal CTF track layout in Europe, given the diverse range of agricultural machinery and road traffic restrictions in different countries. However, as the combine harvester is usually the largest and most expensive piece of equipment, the most popular solution is an 'OutTrac' system where all other machines are adapted or replaced to run on the same track gauge while the combine harvester runs on its own track gauge. Other potential systems are TwinTrac, where a tractor with a narrower gauge straddles adjacent passes of vehicles with a wider gauge (as shown in Fig. 7), and AdTrac, where one track of the wider gauge, i.e. a combine harvester, coincides with the narrower gauge of a tractor (as shown in Fig. 8) (Hargreaves et al., 2016). The uptake of CTF systems has been limited by factors such as technology costs and compatibility of equipment widths (Tullberg et al, 2010; Chamen, 2015). The economics of CTF have been investigated by a number of authors, including Tullberg et al. (2007) and Godwin et al. (2017, 2022).

Compared with conventional (random) traffic farming (RTF), CTF can reduce the trafficked area from up to 85%, in the case of random traffic mouldboard ploughing operations (Kroulik, 2012), to only 10–20% of the total field area using CTF (Antille et al., 2015, 2016a,b; Gasso et al., 2013; Soane and van Ouwerkerk, 1994; Tullberg, 2010;). By reducing the area exposed to farm traffic and thus limiting soil compaction, CTF systems have been seen to improve overall soil health and crop yields (Godwin *at al.*, 2015, 2017). By implementing a CTF system using existing commercially available, unmodified equipment, Galambošová et al. (2017) showed that the field trafficked area could be reduced from 64% to 45% using a 6-m wide CTF system, resulting in 0.5 Mg ha^{-1} increase in crop yields, which they attributed to the overall improvement in the soil physical and mechanical conditions after field traffic was reorganised. Chamen et al. (1992b) reported that CTF increased yields of potatoes, sugar beet, onions, and ryegrass by between 4% and 14%, with improvements in wheat and barley yields varying between -–9% to +21% depending on factors such as soil type and weather conditions. Chamen (2011) reported yield improvements between 7% and 35% using CTF, while Godwin et al. (2015) reported yield increases of 7–10%. Hussein et al. (2021a,b) further showed that cereal yields could be increased by 9–30% in crops grown in CTF systems, compared to non-CTF systems. A detailed long-term study by Harper

Adams University in the UK also found CTF delivered higher crop yields than random traffic using standard tyre pressures (STP) (Kaczorowska-Dolowy et al., 2020; Godwin et al., 2022).

Since compaction affects soil aeration, CTF has been reported to have additional environmental benefits in addition to beneficial effects on crop yields. These include reduction of both powerful greenhouse gases: nitrous oxide fluxes (21–45%) and methane (372–2100%), as well as water runoff (27–42%) from CTF in comparison to random traffic operations (Gasso et al., 2013). In a 3-year Australian study of CTF, Tullberg et al. (2018) found even greater reduction of nitrous oxide (N_2O) emissions from CTF in comparison to those from trafficked soils which were lower by a factor of 2.2. They also reported a decrease of methane emissions from untrafficked soils and concluded that the adoption of CTF might reduce overall soil emissions by 30–50%.

5 Techniques to avoid soil compaction: low ground pressure tyre systems

As noted earlier, increased tyre inflation pressure increases contact pressure. A number of studies have therefore investigated the use of low ground pressure tyres as a way to avoid soil compaction (Tijink et al., 1995; Alakukku et al., 2003; Antille et al., 2013; Chamen et al., 2015). A range of improved flexion tyres and very high flexion tyres has been developed for many agricultural machines. These tyres feature uniform load distribution thanks to a wider footprint of the wheel which reduces compaction and, at the same time, improves fuel efficiency and tyre life (Michelin, 2014).

The effects of tyre inflation pressure (in the range of 150–300 kPa) on PR were investigated by Schjønning et al. (2016) who found that a lower tyre pressure (LTP) produced lower stresses in the upper soil profile, resulting in lower PR though, for deeper layers, PR was more correlated with vehicle load. Antille et al. (2013) investigated the effects of a single pass of three sizes of combine harvester tyres at a fixed vertical load of 10.5 Mg; they reported that the least change in soil BD and vertical soil displacement was found when the combine was fitted with a larger tyre size with the lowest safe tyre inflation pressure.

On the other hand, when Millington (2019) and Smith (2017) investigated the effects of tyre pressures in the range of 70–100 kPa on the front axle and 80–90 kPa on the rear axle for LTP and STP, respectively on PR, they found no significant differences between those two tyre pressures systems.

The relationship between low tyres pressures and crop yields is unclear. Shaheb (2019) found that LTP resulted in a 4.6% increase in corn (*Zea mays*) yield (2-year average: 2017 and 2018) in a silty clay loam soil; in the first year of his experiment, there was no difference in yields; however, in the second year, the low inflation pressure tyres brought a noticeable increase in yields compared to tyres with standard inflation pressures. Chamen et al. (1990) investigated the effects of different tyre pressures on winter wheat yields and found no significant effects of low pressures. Kaczorowska-Dolowy et al. (2020) found that the effects of reduced tyre inflation pressures depend on the depth of tillage: deep tilled sandy loam soil (250 mm) benefits most from low inflation pressure tyres, resulting in an average 4% crop yield increase. For zero and shallow tillage, there was no significant effect using different tyre pressures.

6 Techniques to avoid soil compaction: tracks and gantry systems

Another approach to minimise contact pressure is to equip the vehicle with tracks (Bashford and Kocher, 1999). The development of rubber tracked vehicles dates back to 1987 (Cousins et al., 2016). Blunden et al. (1994) studied the effects of a rubber tracked Cat Challenger on earthy sand and found no significant difference in the maximum stress from the rubber tracked vehicle and dual tyres at the depth of 0.3 m. However, deeper in the soil profile (i.e. at 0.4 and 0.5 m), the tyres resulted in significantly higher maximum stress, suggesting that stresses under the tracked vehicle do not extend as deep in the soil profile. Alakukku et al. (2003) also found that the uneven load distribution from tracked vehicles only affected soil surface layers. On the other hand, Bashford et al. (1998) found no significant differences in the effects of tyres and tracks on soil BD in the topsoil and subsoil.

Ansorge and Godwin (2007, 2008) found that wheels caused greater soil deformation than tracks. They also suggested that cone penetrometer resistance is minimal using tracks, though pressure distribution using tracks is not constant. Arvidsson (2014) also found out that stresses were more variable along the length of the track in comparison to wheels, though the highest soil stress was caused by single wheel tyre vehicles.

Another potential solution to the problem of soil compaction has been identified as the development of wide-span gantry systems. These systems rely on a frame mounted on a wide track gauge with equipment attached onto sections that are able to move independently of each other, as shown in Fig. 9. Chamen et al. (1992a) investigated the effects of a partial 12-m-wide gantry system and found that it reduced the trafficked area by 50%, reduced fuel consumption by up to 44% and increased yield by 19% in comparison to conventional systems. Pedersen et al. (2013) found that a 9.6-m prototype gantry system reduced the trafficked area from 21% to just 6%.

7 Tillage practices and soil compaction

Tillage is defined as the mechanical manipulation of soil for crop production. The role of tillage is to provide favourable conditions for good crop establishment, including providing a suitable seedbed, incorporating the residues of previous crops back into the soil and suppressing weeds (Godwin, 2014). Alskaf et al. (2020) reports that conventional tillage (i.e. mouldboard plough) is still practised on 45% of arable land in England.

Primary tillage includes the use of different types of plough (e.g. mouldboard or disk ploughs) to turn over the soil after a crop is harvested in order to prepare a seedbed for the next crop. Subsequent tillage operations to prepare the seedbed are known as secondary tillage. They include the use of tandem or off-set disks, field cultivators, and harrows to break up larger aggregates left from mouldboard ploughing (Morris et al., 2010; Hallett and Bengough, 2013). The purpose of these operations includes improving soil aeration, water infiltration, and facilitating root development (Sommer and Zach, 1992; Hallett and Bengough, 2013).

Deep tillage (operating at depths of 200+ mm) has been related to heavy traffic and consequently increased soil compaction (Kroulik et al., 2009; Foley et al., 2011). As a result of running two tractor wheels in the open furrow during ploughing, a compacted stratum is created in the soil at about 200–350 mm from the surface; subsoiling can alleviate this but again poses a risk of re-compaction from subsequent traffic (Spoor and Voorhees, 1986; Morris et al., 2010). Alakukku (1996) found that the effects of soil compaction below 0.1 m on clay soil can be long-lasting, despite annual ploughing to 0.2 m. Soane et al. (1986) also found significant re-compaction as a result of trafficking of soil that had been deep loosened and then ploughed. Millington et al. (2017) found porosity decreased with depth in deep tilled soils across the analysed soil horizon down to 250 mm. Dal Ferro et al. (2014) also found that tillage had significant effects on macroporosity (enhancing the pore class in the range 54–250 µm) but did not have a significant effect on microporosity in the analysed soil horizon down to 300 mm.

The effects of conventional tillage on soil BD are variable. Alvarez and Steinbach (2009) in their review of 35 papers, reported higher BD from reduced or zero tillage in comparison to conventional mouldboard ploughing in the upper 0–200 mm. However, the levels of BD and cone PR in the 0–20 cm layer were often below the thresholds which inhibit root development. Franzluebbers et al. (1995) investigated BD down to 200 mm and reported decreased BD shortly after tillage; however, over the growing season, the differences between tilled and no-tilled soil decreased, regardless of the crop (wheat, sorgum, and soya bean). Other studies have found that tillage systems did not significantly affect BD, including Taboada et al. (1998), who did not observe significant differences down to 400 mm of a silty clay soil profile before harvest. Logsdon and Cambardella (2000), who investigated fine loamy soils down to 300 mm in Iowa (USA), reported that none of the observed bulk densities were significantly different between the zero tillage and cultivated fields. Jabro et al. (2016) reported that soil BD of sandy loam in North Dakota (USA) was not significantly influenced by tillage (deep, shallow, and zero) in the 0–40 cm layer in 3 out of 4 years. Similarly, Millington (2019) did not find significant differences in BD measured down to 250 mm soil profile several months after tillage on sandy loam in the West Midlands (UK).

The effects of tillage on macroporosity have been investigated by many researchers but with often contradictory results. Capowiez et al. (2009) reported that mouldboard ploughing leads to a significant decrease in the total number and distribution of pores in comparison to reduced tillage. However, other research suggests higher hydraulic conductivity and macroporosity from conventionally ploughed soils compared to zero-tilled soils (Ferreras et al., 2000; Fabrizzi et al., 2005; Sasal et al., 2006; Villarreal et al., 2020).

There is similar inconsistency in studies on the effects of tillage on water infiltration rates and hydraulic conductivity. Nielsen et al. (2005) reported an increase of infiltration rates under zero-tillage, but Rasmussen (1999) found greater water infiltration in tilled soil. Esser (2017) also found higher infiltration and less runoff under conventional tillage as well as higher soil moisture in the top soil under conventionally tilled soil than under Conservation Agriculture. These conflicting results can be attributed in some cases to temporal variability in soil infiltration rate as suggested by Strudley et al. (2008) who found that infiltration was highest immediately after tillage but decreased with time, whilst water infiltration under zero-tillage can be higher than in tilled soil after the first wetting-drying cycle.

Wuest (2010) found that tillage to depths of 100 and 150 mm preserved up to 0.01 kg kg^{-1} greater water content than zero-tillage or shallow tillage (to 50 mm). However, Oorts et al. (2007) found no significant differences in soil moisture between different tillage systems. Smith (2017) also did not find any significant differences in gravimetric soil moisture between contrasting tillage and traffic treatments. Other studies suggest that soil moisture is higher under zero tillage but with significant variability in results, depending on factors such as soil conditions, depth, crop, and season (Rasmussen, 1999; Fuentes et al., 2003; Alvarez and Steinbach, 2009; Gruber et al., 2011; Slawinski et al., 2012). Wuest (2010) have suggested it is often difficult to discern significant differences between tillage practices.

Because it leaves the soil bare until the next crop is planted, conventional tillage has been linked to greater risk of erosion by wind and water (Lal, 2007; Huggins and Reganold, 2008; Bogunovic et al., 2018). Since nutrients and pesticides from eroded soils may be attached to sediment, the transport of soil particles to surface waters possess a significant pollution risk (Rickson, 2014; Melland et al., 2017). For these and other reasons, reduced tillage (non-inversion tillage) and zero-tillage have been suggested as alternatives to conventional mouldboard ploughing (Gauer et al., 1982; Tullberg et al., 2007; Verhulst et al., 2010; Derpsch et al., 2010, 2014; Warner et al., 2016). Zero-tillage is often combined with other techniques such as continuous soil cover and the use of rotations in what has become known as 'Conservation Agriculture', actively promoted by the FAO as promoting soil health and more sustainable agricultural practices (FAO, 2013). This makes it difficult to distinguish the benefits of zero-tillage on soil properties from other Conservation Agriculture practices which may have a more important impact on soil health or crop yields (Esser, 2017; Bogunovic et al., 2018).

Joergensen and Emmerling (2006) in their review of methods for evaluating human impact on soil microorganisms suggested that soil microorganisms are sensitive to farm management practices. Pelosi et al. (2014) in his study into the effects of three main cultivations types: ploughing (250–300 mm), reduced tillage (80 mm), and zero-tillage on earthworm populations concluded that the tillage intensity did not affect the number of observed species nor abundance though different cultivation techniques did affect some functional traits (e.g. body length, body mass/length ratio, cocoon diameter, vertical distribution). That experiment however contained varied crops across the experimental plots (i.e. sugar beet, wheat, and flax). Crittenden et al. (2015), in a 2-year experiment, found that non-inversion tillage significantly increased total earthworm density by 34% and total earthworm biomass by 15% compared with inversion tillage. The same authors also reported that anecic earthworms particularly suffered from deep tillage which resulted in very low numbers of these organisms. Springtails are also suggested to be sensitive to different soil use practices. The effects of two deep tillage systems on Collembola communities were investigated by Petersen (2002), who reported that in the uppermost 4 cm stratum conventional ploughing reduced their population more than the non-inverting deep tillage while, in the deepest stratum (28–32 cm), the immediate effect was opposite. Hu et al. (2014) reported that the soil microbial biomass is determined by soil organic carbon, which is influenced by plant inputs. However, there are no coherent conclusions on the effects of farming traffic or tillage on microbial populations. Some studies show that tillage negatively affects the size of microbial populations (Sun et al., 2016; Wright et al., 2008), others reported on little effect of tillage on microbial biomass (Calderón et al., 2000; Jackson et al., 2003). Kaiser et al. (2014) suggested that those inconsistencies might derive from different soil physical properties across different studies as well as from varying tillage intensities. Some studies have found changes between microbial taxa but with total biomass unchanged. Campbell et al. (1991), who investigated crop rotation and influence of fertilisers on soil microbial biomass, suggested that fungal communities can benefit from a decrease in bacterial communities and vice versa. In agreement, Sun et al. (2018) found that susceptibility to tillage intensity varied across different microbial communities and reduced tillage had a greater effect on fungal communities while bacterial communities were more affected by mouldboard ploughing.

Some researchers have reported an increase in crop yields under zero-tillage compared to mouldboard ploughing (e.g. Lal, 1997; Singh et al., 2016). However, other studies have reported no differences in crop yields between these two tillage systems (e.g. Shipitalo and Edwards, 1998; Logsdon and Karlen, 2004; Alvarez and Steinbach, 2009), while some have found reduced yields under zero-tillage compared to conventional tillage (Clutterbuck and Hodgson, 1984; Rusu, 2005; Rieger et al., 2008; Alvares and Steinbach, 2009; Smith, 2017). A possible reason for this apparent lack of consistency in reported crop yield data from zero-tillage studies is the fact that field traffic management practices are not always reported, which therefore makes interpretation of such data rather cumbersome.

Researchers have suggested zero-till may be more suited to semi-arid regions where it is more effective in water retention (Buschiazzo et al., 1998; De Vita et al., 2007) whereas, in wet conditions, deep tillage can deliver higher crop yields due to better infiltration (Alvarez and Steinbach, 2009). As an example, Godwin (2015) concluded that chalk limestone soils and well-drained loamy soils might provide yields of both autumn and spring cereals under zero-till similar to those from conventionally cultivated crops. On calcareous clays and clayey or loamy soils over clay with improved drainage, only winter cereal crop yields are likely to be similar to those from conventionally cultivated soil, whilst spring crops yields are likely to be lower. The least suitable soils for zero-till (with a substantial risk of lower yields) are sandy soils with low organic matter content, silty soils, wet alluvial soils, and poorly drained clayey soils. Another complication is that the benefits to soil health of a transition from conventional cultivation to Conservation Agriculture may take a number of years to materialise with an initial dip, e.g. in yields followed by longer-term improvements in soil properties, ultimately leading to increased crop yields which equal or exceed yields under conventional tillage (Rhoton, 2000; Chamen, 2011; Jemai et al., 2013; Kaczorowska-Dolowy et al., 2020; Godwin et al., 2022).

8 Case study

The previous sections suggest the effects of traffic on soil compaction vary, though high traffic levels generally have a significant impact on compaction. Compaction leads to higher soil BD, soil strength, a decreased number of pores and lower pore size, as well as poorer infiltration. Research suggests that CTF can play a significant role in reducing compaction and its effects, whilst the benefits of other measures such as LTP systems are less clear. The research on differing types of tillage shows widely varying effects on soil characteristics such as BD, pore number and size, infiltration, and overall moisture levels.

Some of these issues have been the basis of a long-term experiment established at Harper Adams University in the UK (Smith, 2017; Millington, 2019; Kaczorowska-Dolowy, 2022). The experiment was started in 2011 by Smith (2017) on a uniform sandy loam field called Large Marsh within the Harper Adams University campus in the county of Shropshire (52°46'58.0"N 2°25'43.9"W). The aim of the experiment was to examine the effects of three traffic systems:

1. random traffic with standard tyre inflation pressure (STP);
2. random traffic with low tyre inflation pressure (LTP) systems;
3. CTF

These were subject to three tillage depths:

1. deep tillage: 250 mm;
2. shallow tillage: 100 mm;
3. zero tillage .

These different systems were applied across a typical crop rotation for the UK with cereals as main crop, including wheat, barley, and oats with field beans as a break crop. A starting point was the research conducted by Chamen (2011) who suggested that the effects of reduced trafficking on soil properties, yields, and profitability requires systematic investigation. The study examined effects of the different systems on soil properties, crop growth, yield, and farming economics.

The first 5 years of the experiment by Smith (2017) and Millington (2019) focused on the effects of the traffic and tillage systems on soil physical properties related to compaction (BD, PR, moisture, hydraulic conductivity, total porosity, and pore distribution) and crop yields. Initial published results from the study found that yields for all crops across the 5-year rotation were significantly lower using zero tillage than those for deep and shallow tillage, with an average reduction of 1.0 t ha^{-1} (Godwin et al., 2017). Nevertheless, as from the sixth year, no yield penalties have been observed under zero tillage. Moreover, the yield under zero tillage exceeded the yield from deep tillage in year 7 and 8 whereas, in comparison to shallow tillage, it was significantly greater in year 7 (Godwin et al., 2022).

Compared to random traffic using standard tyre inflation pressure, CTF with trafficked areas of 30% and 15% produced 4% and 7% greater yields worth £39 ha^{-1} and £74 ha^{-1}, respectively. The study also investigated the use of LTP of 0.7 bar for both the front and rear types of the tractor, compared to conventional pressures of 1.2 bar in front tyres and 1.5 bar in rear tyres. The beneficial effect of low inflation pressure tyres on crop yields was found for the deep tillage treatment where the crop yields were 3.9% greater than those of the STP systems giving a financial gain of £39 ha^{-1} (Godwin et al., 2022).

Millington (2019) continued the study by focusing on analysing the long-term effects of traffic and tillage on soil physical properties using X-ray tomography. This has confirmed that vehicular traffic decreases soil macro-porosity down to 0–250 mm of the soil profile. Moreover, this effect is enhanced under deep tillage, resulting in a reduction in the ability of soil to support vehicular traffic which leads to significant soil recompaction. Research by Kaczorowska-Dolowy (2022) was focused on the effects of traffic and tillage systems on soil biological properties, including soil fauna feeding activity, soil organic matter, soil microbial carbon, earthworm, and Collembola abundance. She reported that vehicular traffic decreased invertebrate feeding activity (in the 0–80 mm soil horizon), whereas the effect of tillage depended on the year and under zero tillage, it was significantly lower than under both tilled systems in 2019, whereas in 2020 under shallow and zero tillage, the soil fauna feeding activity was significantly greater than under deep tillage. Similarly, the abundance of Collembola in 2019 decreased under compacted soil in comparison to unwheeled area, at the same time Collembola abundance was significantly greater under shallow tillage than zero tillage. Reduced tillage (shallow and zero) increased soil organic matter over deep tillage in the 0–100 mm soil horizon. Earthworms' abundance increased with decreased tillage intensity and so under deep tillage, it was significantly lower than under zero and shallow tillage whereas under zero tillage, it was significantly greater than under shallow tillage (Kaczorowska–Dolowy, 2022).

9 Conclusion

Agricultural intensification has been accompanied by an increase in machinery size and weight, resulting in soil compaction and leading to soil degradation. Compacted soil inhibits root development, nutrient uptake, water movement, and availability leading to yield losses. Remedial actions such as subsoiling are expensive, time-consuming, not always effective at greater depths, and require burning additional fossil fuels. Maintaining the soil in a good (uncompacted) condition is key to improving aspects of soil health such as water infiltration, crop growth, and health as well as ecosystem services such as carbon sequestration. The effects of alternative tillage practices on soil properties and crop growth have been well reported. The effects of alternative traffic management systems generally indicate their benefits for soil health though more research is needed, especially effects on soil biology.

10 Where to look for further information

Further information can be obtained from the following sources:

- Australian Controlled Traffic Farming Association Inc.: http://www.actfa.net/
- Controlled Traffic Farming Europe Ltd.: http://controlledtrafficfarming.com/Home/Default.aspx
- Godwin R. J., 2014. Potential of “No-till” Systems for Arable Farming. The Worshipful Company of Farmers. London, UK. http://cdn.harper-adams.ac.uk/document/project/Potential-of-No-till-Systems-for-Arable-Farming-Report.pdf
- McPhee, J. E., Antille, D. L., Tullberg, J. N., Doyle, R. B., Boersma, M. (2020). Managing soil compaction – a choice of low-mass autonomous vehicles or controlled traffic? Biosystems Engineering 195: 227-241. https://doi.org/10.1016/j.biosystemseng.2020.05.006
- The National Centre for Precision Farming, Harper Adams University: http://www.harper-adams.ac.uk/research/ncpf/
- The Soil and Water Management Centre: http://www.soilandwater.org.uk/
- Traffic and Tillage Research Project, Harper Adams University: http://www.harper.ac.uk/tillage

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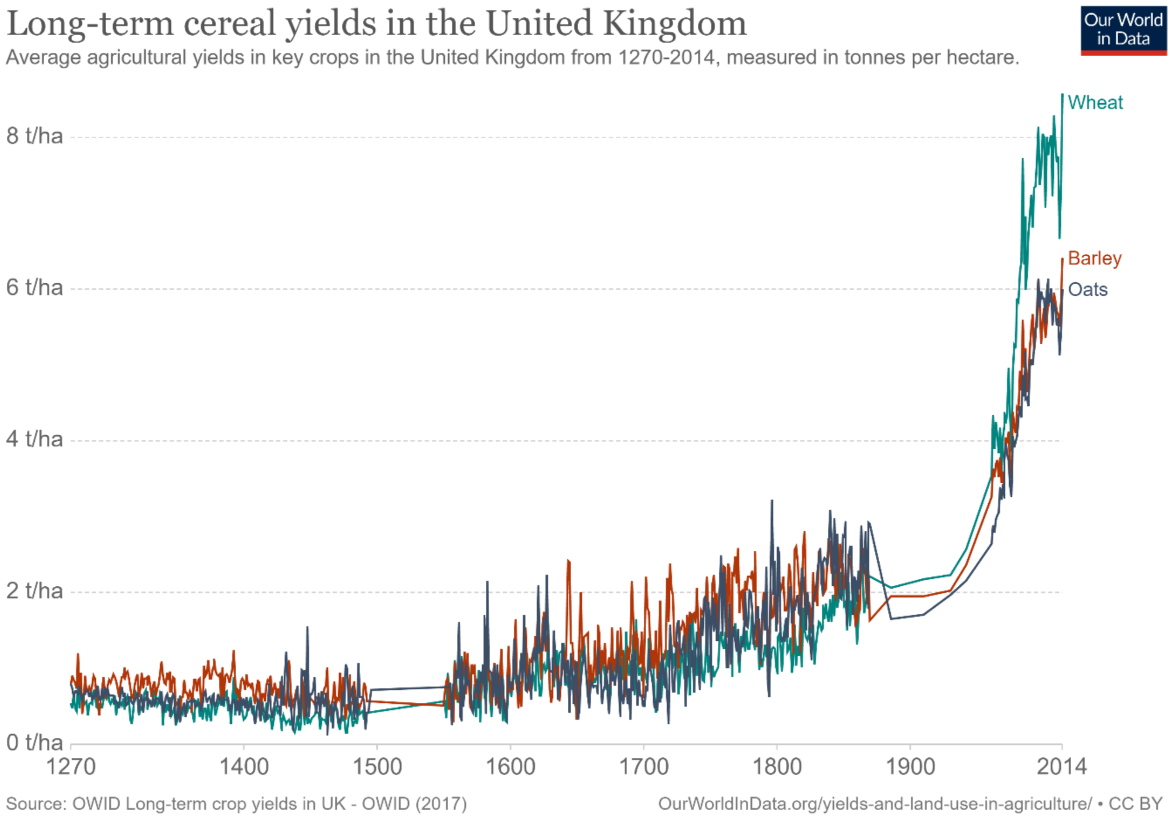
Long-term cereal yields in the United Kingdom

Average agricultural yields in key crops in the United Kingdom from 1270-2014, measured in tonnes per hectare.

Source: OWID Long-term crop yields in UK - OWID (2017)

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Figure 1 Long term cereal yields in the United Kingdom after OWID (2017).

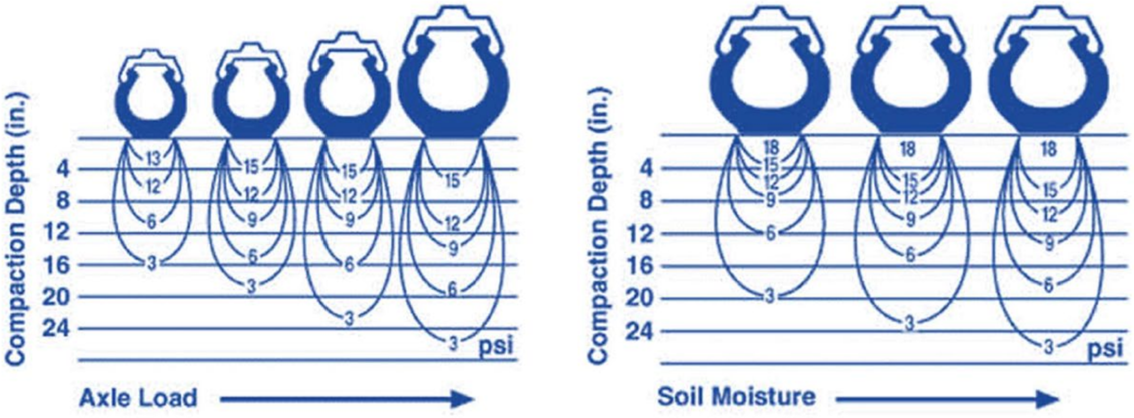

Figure 2 Curves of pressure under a range of axle load (on the left) and increasing moisture condition (on the right). Source: Sohne (1958).

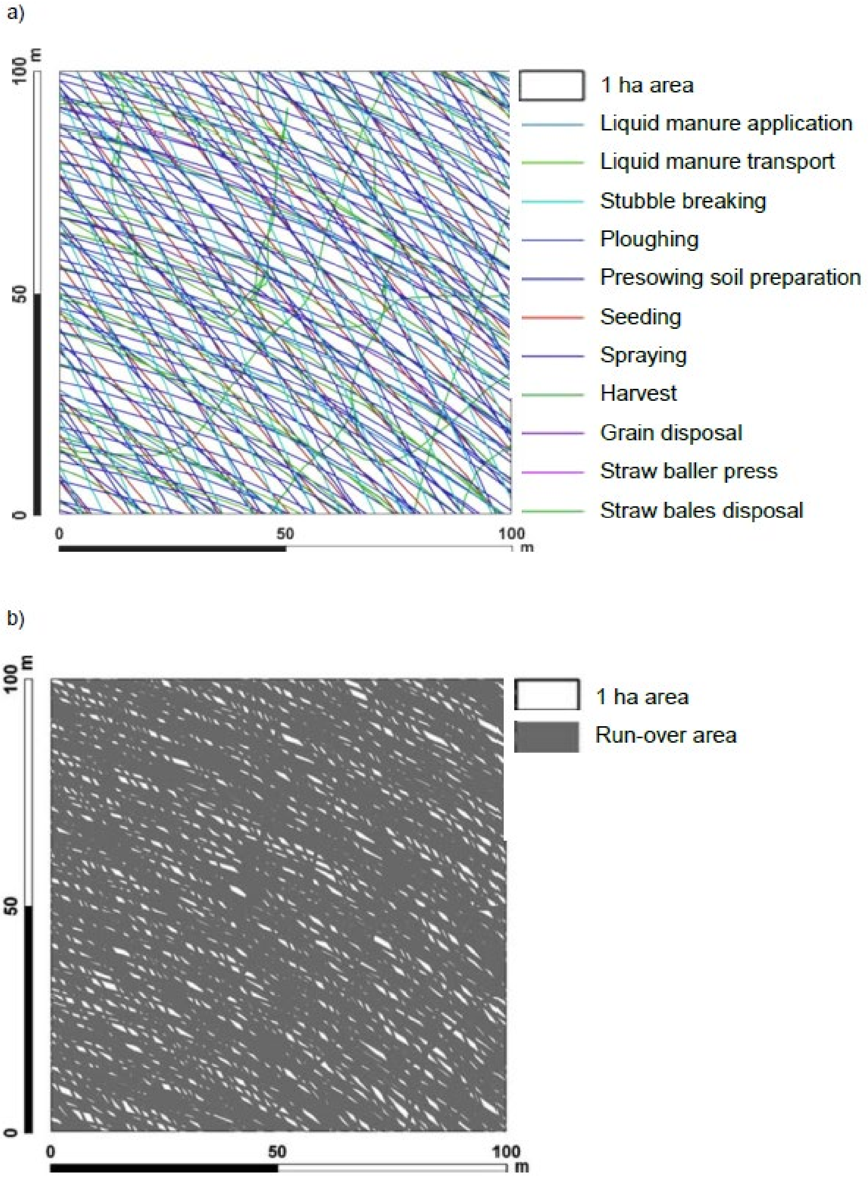

Figure 3 Graphic representation of (a) machinery trajectories, and (b) total trafficked area for random traffic farming with conventional mouldboard ploughing. Source: Reproduced from Kroulik et al. (2009).

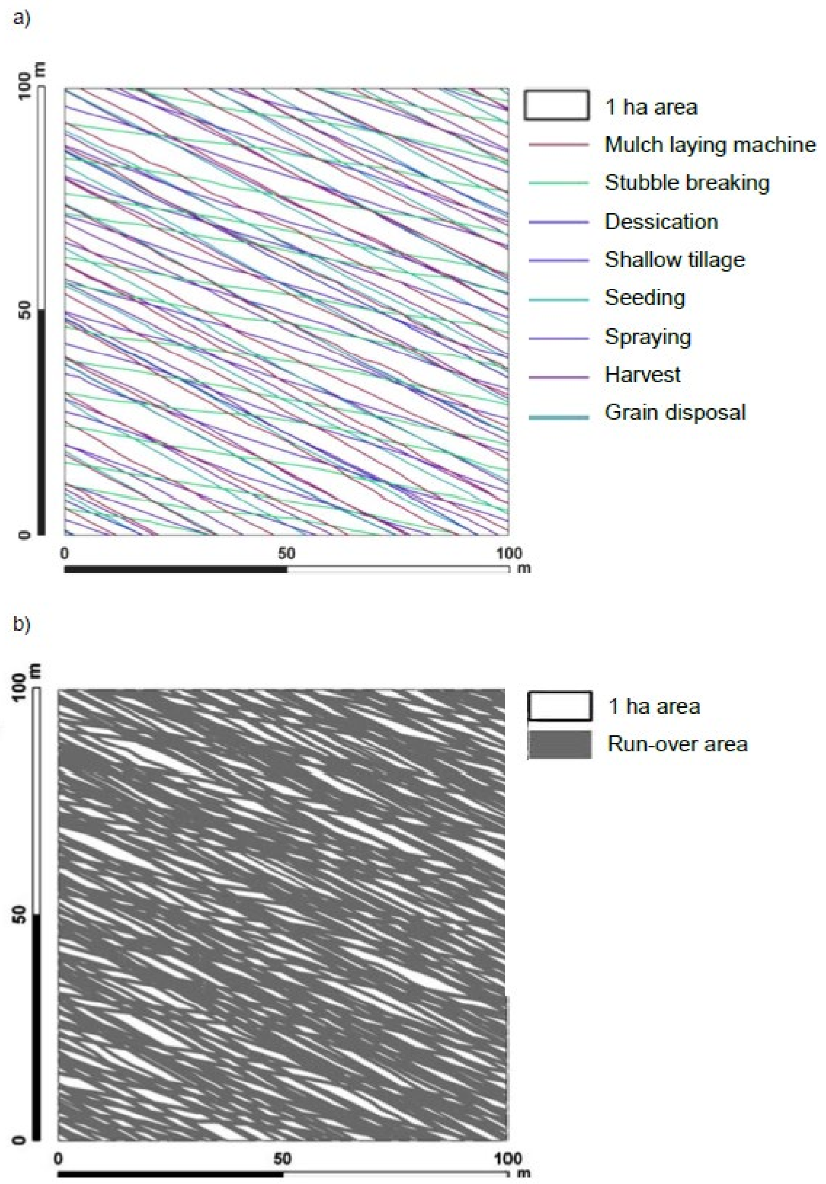

Figure 4 Graphic representation of (a) machinery trajectories, and (b) total trafficked area, for random traffic farming with shallow tillage. Source: Reproduced from Kroulik et al. (2009).

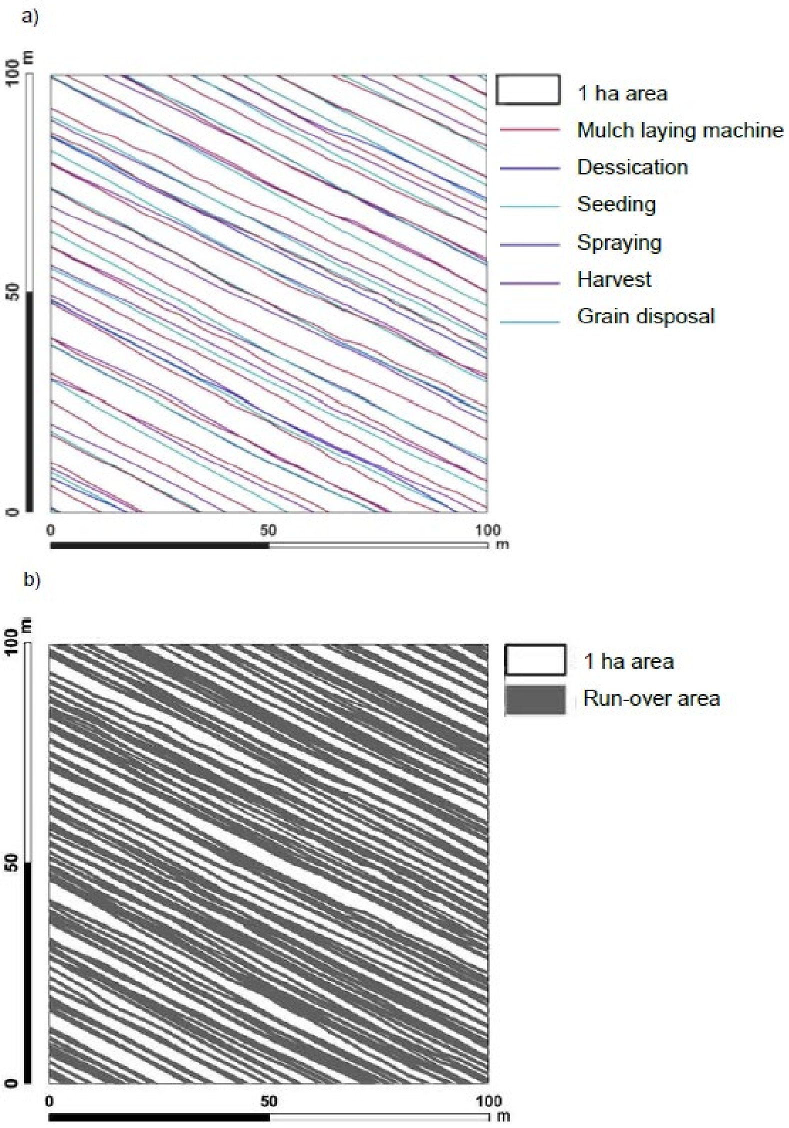

Figure 5 Graphic representation of (a) machinery trajectories, and (b) total trafficked area, for random traffic farming with zero tillage. Source: Reproduced from Kroulik et al. (2009).

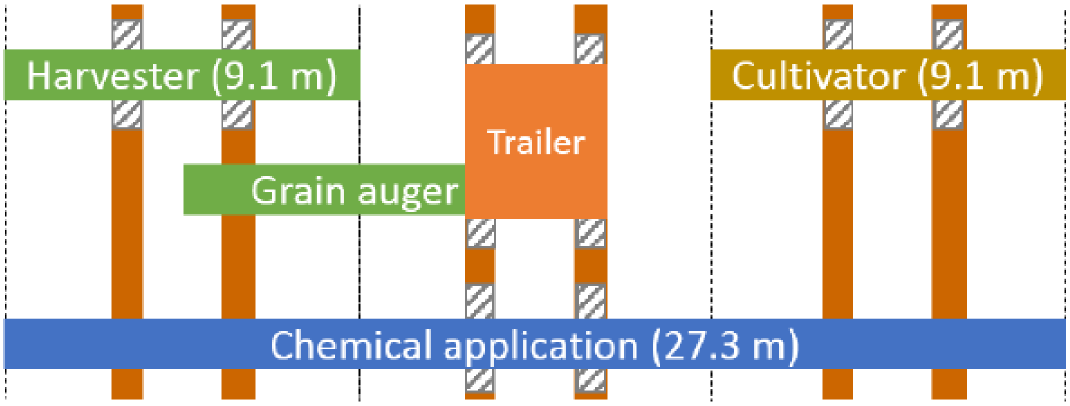

Figure 6 Layout of a “3:1 ratio” or “Com Trac” CTF system. Source: Chamen (2011).

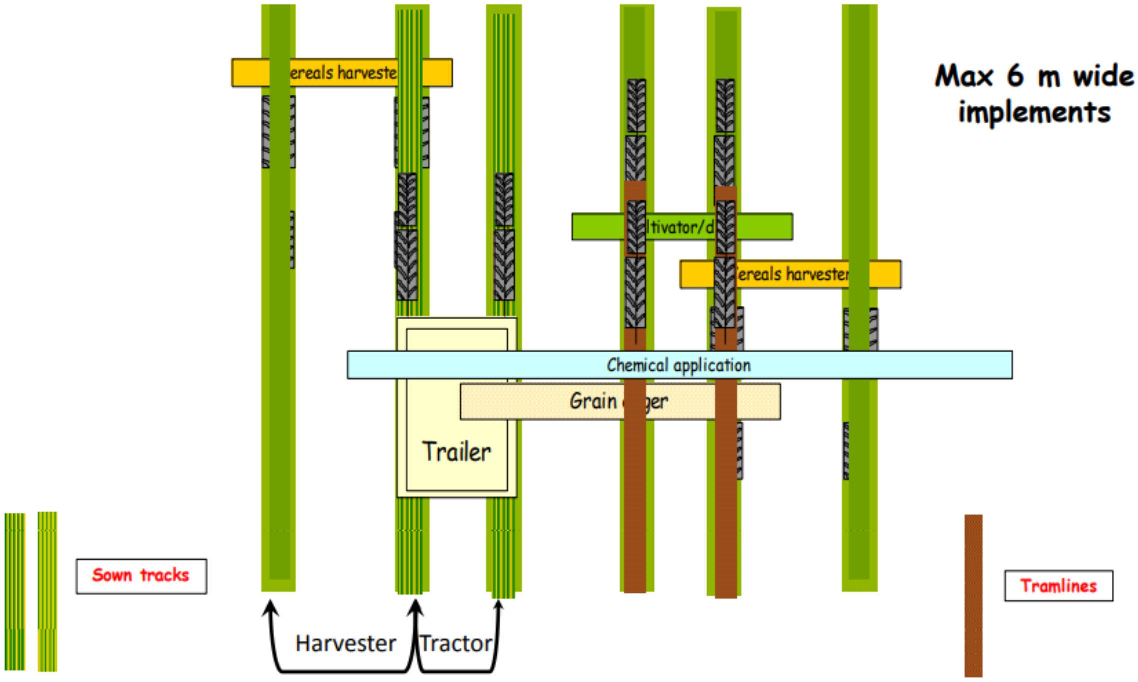

Figure 7 Twin Track CTF system where tractor straddle harvester passes. Source: Adapted from Chamen (2011).

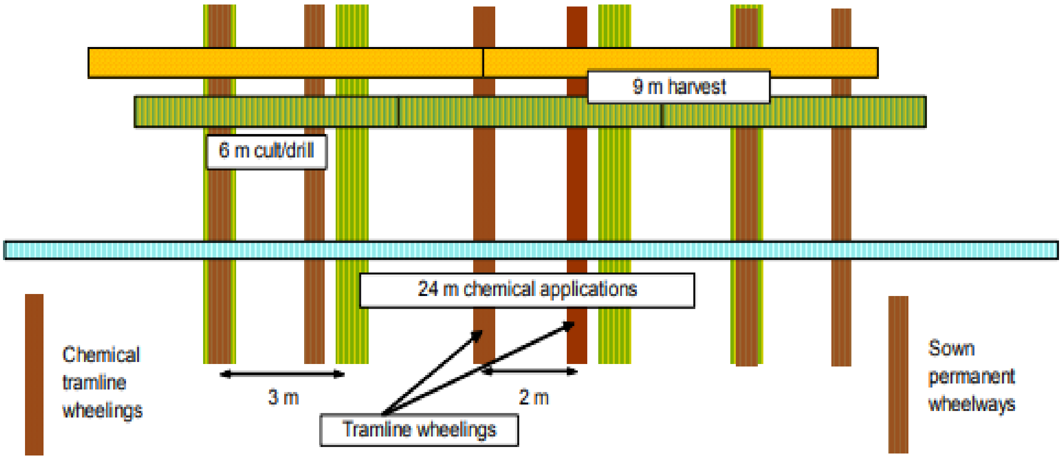

Figure 8 Ad2Trac CTF system with two track and two implement widths. One wheel of the narrower track (e.g. tractor) coincides with the harvester track. Source: Adapted from Chamen (2011).

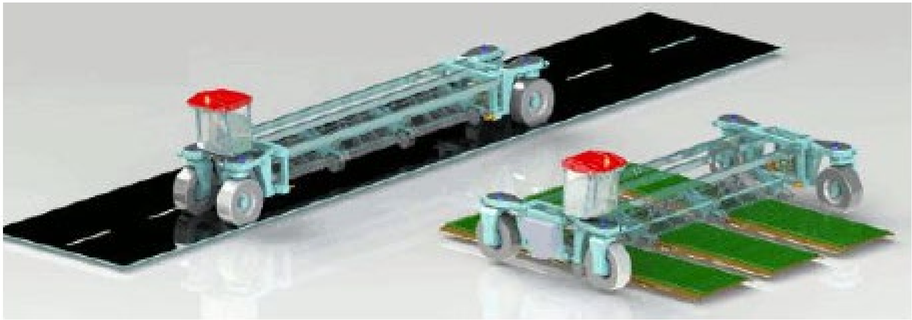

Figure 9 Wide-span gantry system transport on the highway and working in the field. Source: Adapted from CTF Europe (2020).