Review: Soil compaction and controlled traffic farming in arable and grass cropping systems

D.L. Antille[1], S. Peets[2,*], J. Galambošová[3], G.F. Botta[4], V. Rataj[3], M. Macak[3], J.N. Tullberg[5], W.C.T. Chamen[6], D.R. White[2], P.A. Misiewicz[2], P.R. Hargreaves[7], J.F. Bienvenido[8] and R.J. Godwin[2]

[1]CSIRO Agriculture and Food, Black Mountain Science and Innovation Precinct, Clunies Ross Street, GPO Box 1700, Canberra ACT 2601, Australia
[2]Harper Adams University, Engineering Department, Newport Shropshire, TF10 8NB, United Kingdom
[3]Slovak University of Agriculture in Nitra, Faculty of Engineering, Tr. Andreja Hlinku 2, Nitra SK94976, Slovakia
[4]Universidad Nacional de Lujan, Departamento de Tecnología, Ruta 5 and Avenida Constitución, Luján 6700, Provincia de Buenos Aires, Argentina
[5]University of Southern Queensland, Centre for Agricultural Engineering, Handley street, Toowoomba QLD 4350, Australia
[6]CTF Europe Ltd., Church Road, Maulden, Bedfordshire, MK45 2AU, United Kingdom
[7]Scotland's Rural College, Dairy Research and Innovation Centre, Hestan House, Dumfries DG1 4TA, United Kingdom
[8]Universidad de Almería, CIMEDES. Facultad de Ciencias Económicas y Empresariales (Edificio B), Ctra. Sacramento s/n, La Cañada de San Urbano, ES04120 Almería, Spain
*Correspondence: speets@harper-adams.ac.uk

Abstract. There is both circumstantial and direct evidence which demonstrates the significant productivity and sustainability benefits associated with adoption of controlled traffic farming (CTF). These benefits may be fully realised when CTF is jointly practiced with no-tillage and assisted by the range of precision agriculture (PA) technologies available. Important contributing factors are those associated with improved trafficability and timeliness of field operations. Adoption of CTF is therefore encouraged as a technically and economically viable option to improve productivity and resource-use efficiency in arable and grass cropping systems. Studies on the economics of CTF consistently show that it is a profitable technological innovation for both grassland and arable land-use. Despite these benefits, global adoption of CTF is still relatively low, with the exception of Australia where approximately 30% of the grain production systems are managed under CTF. The main barriers for adoption of CTF have been equipment incompatibilities and the need to modify machinery to suit a specific system design, often at the own farmers' risk of loss of product warranty. Other barriers include reliance on contracting operations, land tenure systems, and road transport regulations. However, some of the barriers to adoption can be overcome with forward planning when conversion to CTF is built into the machinery replacement programme, and organisations such as ACTFA in Australia and CTF Europe Ltd. in Central and Northern Europe have developed suitable schemes to assist farmers in such a process.

Key words: axle load, fertiliser use efficiency, greenhouse gas emissions, non-controlled traffic, no-tillage cropping, traffic intensity.

INTRODUCTION

In the past few decades, there has been a continuous drive towards the development and adoption of larger, and more powerful, agricultural machinery (Jørgensen, 2012). Larger machinery is often related with timeliness, higher work rates and lower labour requirements, which has contributed to significant improvements in field efficiency and productivity (Vermeulen et al., 2010; Tullberg, 2018). A drawback of this trend has been the associated increase in the overall load of farm machinery, which has, to some extent, offset advances made by the industry in developing improved running gear, such as in tyre (e.g., radial ply tyres) and track technology (e.g., rubber belts) to reduce contact pressures (Ansorge & Godwin, 2008; Antille et al., 2013; Misiewicz et al., 2015). The progressive increase in axle loads, as observed for example with harvesting equipment (e.g., Ansorge & Godwin, 2007; Braunack & Johnston, 2014), means that soil stresses have also continued to increase, extending deeper into the subsoil (e.g., ≥ 0.3 MPa at 400-mm deep) and exceeding historic values, such as those resulting from in-furrow ploughing (Koolen et al., 1992; Chamen, 2015, Fig. 1).
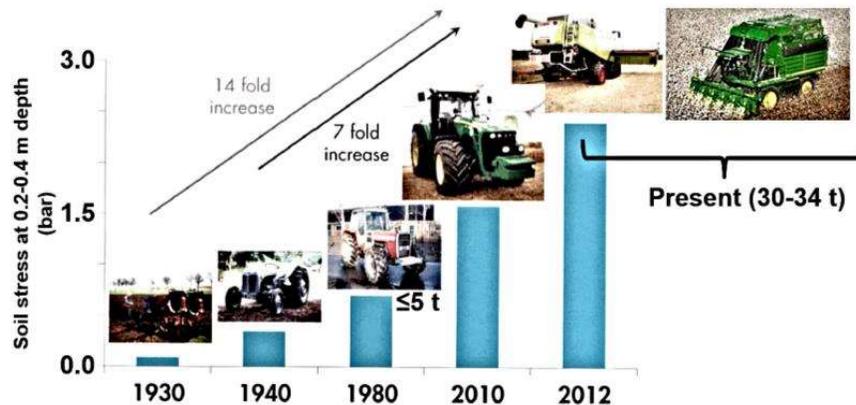
Figure 1. Changes in overall machine load over time and the effect on soil stresses at the 0.2–0.4 m depth interval (modified from Chamen, 2015).

Traffic compaction has adverse effects on the physical, chemical and biological properties of soils; thus, affecting important soil processes and functions, and crop productivity (Soane & van Ouwerkerk, 1995; Wu et al., 1995; Lipiec & Hatano, 2003). Compaction is regarded as one of the main causes of soil degradation and it is addressed in the proposed European Soil Framework Directive (EC, 2006). It compromises water infiltration into soil, increases the frequency and duration of waterlogged conditions, reduces gaseous exchange between soil and the atmosphere, and restricts root penetration and therefore exploitation of water and nutrients in the subsoil (O'Sullivan & Simota, 1995). These effects can, in turn, lead to increased risk of erosion and runoff, and therefore nutrient and sediment transport to water courses (diffuse pollution), and increased risk of flooding (Rickson, 2014; Graves et al., 2015; Alaoui et al., 2018). There is also an elevated risk of greenhouse gas emissions from soils affected by compaction due to poor aeration (Ruser et al., 1998, 2006; Antille et al., 2015a; Tullberg et al., 2018). The effects of soil compaction are often persistent, particularly in the subsoil, and they are intensified with repeated passes (Raghavan et al., 1976, 1977; Botta et al., 2009).

Soil recovery through natural processes varies widely depending on soil type, the extent of wetting and drying, and freezing and thawing cycles (Pollard & Webster 1978; Dexter, 1991). For example, heavy clay soils with shrinking-swelling properties may recover from the effect of compaction to a greater extent than typically medium- and lighter-textured soils with no shrinking-swelling capacity (Radford et al., 2007). However, in all soils, the rate of amelioration of such compaction decreases with an increase in soil depth (Kay, 1990; McHugh et al., 2009), which requires that compaction is avoided, particularly in the subsoil (Spoor et al., 2003). In intensively-managed arable cropping systems, the frequency of traffic with farm machinery does not normally allow for natural soil alleviation; therefore, tillage repair treatments are often required between crop cycles (Alakukku, 1999; Spoor, 2006). Remediation of compaction through tillage is energy-demanding as draught increases significantly with an increase in soil depth (Godwin & O'Dogherty, 2007). Consequently, remediation of deep soil compaction can prove impractical, and often uneconomical, at depths greater than approximately 400-mm (Spoor & Voorhees, 1986; Håkansson & Reeder, 1994; Tullberg, 2000). Deep loosening of soil carries the risk of re-compaction at such depth with subsequent traffic leading to a recurrent compaction-loosening cycle, which aggravates the problem (Soane et al., 1986; Spoor et al., 2003). Botta et al. (2006) showed that on an *Entic Haplustoll* (medium-textured soil) sown with sunflower (*Helianthus annus* L.), the beneficial effects of subsoiling and chiselling in removing soil compaction and reducing soil strength lasted only two years when CTF was not practiced. These effects became negligible after that time when traffic intensity was greater than about 95 Mg km^{-1} ha^{-1} because of re-compaction/re-consolidation of the soil profile; particularly, in the 300 to 600 mm depth interval. Therefore, effective technical solutions lie in 'traffic management' rather than 'tillage management'.

Concerns over the long-term sustainability of arable cropping associated with progressive deterioration of the soil resource have contributed to the development of more efficient field-traffic management strategies; namely, controlled traffic farming (CTF) systems. These systems have evolved in response to evidence of significant soil damage from compaction caused by field traffic. Reviews by Tullberg et al. (2007) and Chamen (2015) provide in-depth analyses of the factors that motivated the development of CTF systems using purposely-modified commercially-available machinery. Research (e.g., Taylor, 1983; Chamen et al., 1992; Tullberg, 2010) and on-farm practice (e.g., Gold, 2013) have shown that CTF systems are effective means of avoiding widespread compaction by confining all load-bearing wheels to the least possible area of permanent traffic lanes. Controlled traffic systems have fundamental advantages in maintaining 'good' soil structural conditions of non-trafficked crop beds (e.g., McHugh et al., 2009; Millington et al., 2017), with improved trafficability and timeliness compared with conventional traffic systems.

Review Aim

This article reviews some of the benefits that may result from the adoption of controlled traffic farming in arable and grass production systems, and provides a brief overview of the requirements of such traffic systems. Those benefits are explored in terms of overall 'system' efficiency while considering the need for sustainable approaches to soil management in intensive agriculture.

OVERVIEW OF CONTROLLED TRAFFIC FARMING SYSTEMS

Arable Cropping

Controlled traffic farming (CTF) was adopted in commercial-scale farming in the 1990s, initially in Australia (Webb et al., 2004; Tullberg et al., 2007), and subsequently in northern and central Europe (Chamen, 2015; Galambošová et al., 2017), and Canada (CTFA, 2017), respectively. Modification of commercially-available machinery and development of precision (± 0.02-m accuracy) guidance systems (RTK-DGNSS: Real Time Kinematic-Differential Global Navigation Satellite System) greatly facilitated on-farm adoption of CTF (Dijksterhuis et al., 1998; Vermeulen & Chamen, 2010).

The Australian Controlled Traffic Farming Association Inc. (ACTFA, http://actfa.net/) defines CTF as a system in which: (1) all machinery has the same or modular working and track width so that field traffic can be confined to the least possible area of permanent traffic lanes, (2) all machinery is capable of precise guidance along those permanent traffic lanes, and (3) the layout of permanent traffic lanes is designed to optimise surface drainage and operational logistics. These elements are essential components of a CTF system. The following practices are also facilitated by and in agreement with CTF (after ACTFA, 2018): (1) minimal soil disturbance (e.g., shallow tillage and no-tillage). Strategic or occasional tillage may be required in long-term no-tillage systems for mechanical control of herbicide-resistant weeds or to restore optimal growing conditions on some (e.g., hard-setting) soils (Melland et al., 2017; Dang et al., 2018). In sandy soils with hardpans, deep tillage (e.g., 500 mm) with topsoil slotting (soil inclusion plates attached to the rear of deep ripper tines) is an effective technique to prolong the de-compaction response in those soils (Blackwell et al., 2016), (2) increased frequency of rain-fed cropping and cover crops to maximise biomass production, residue returned to soil and therefore greater opportunities for carbon sequestration. In Australia, typical cropping frequencies in CTF systems under no-tillage vary between 1.0 and 1.2, which compares to about 0.7 or less in non-CTF with conventional tillage (Antille et al., 2015a), (3) precise management such as inter-row seeding and accurate placement of agrochemicals and fertilisers, and (4) spatial (subfield-scale) monitoring, mapping and management at progressively finer resolution within a defined spatial framework, which distinguishes between permanent traffic lanes and crop beds (spatially-fixed environment, McPhee et al., 2019). This is assisted by continuous regeneration of soil structure in crop beds (e.g., McHugh et al., 2009; Hulugalle et al., 2017) and elimination of traffic compaction-induced soil variability (Barik et al., 2014).

Conversion from a conventional system, with unmatched machinery and different track gauge widths, to CTF should consider the following (after Isbister et al., 2013, 2018): (1) accurate guidance systems (e.g., GNSS RTK, ± 0.02-m correction) to enable machinery to return consistently and precisely to the same (permanent) traffic lanes, (2) machinery matching so as to match wheel track spacing and also choose a convenient operating width (e.g., seeder and combine harvester-to-sprayer ratio of 3:1) and match in multiples (Fig. 2), (3) optimise the design, management and orientation of permanent traffic lanes, and (4) field layout in regards to risk of erosion and safe discharge of runoff, and subsequent application of variable rate technology.
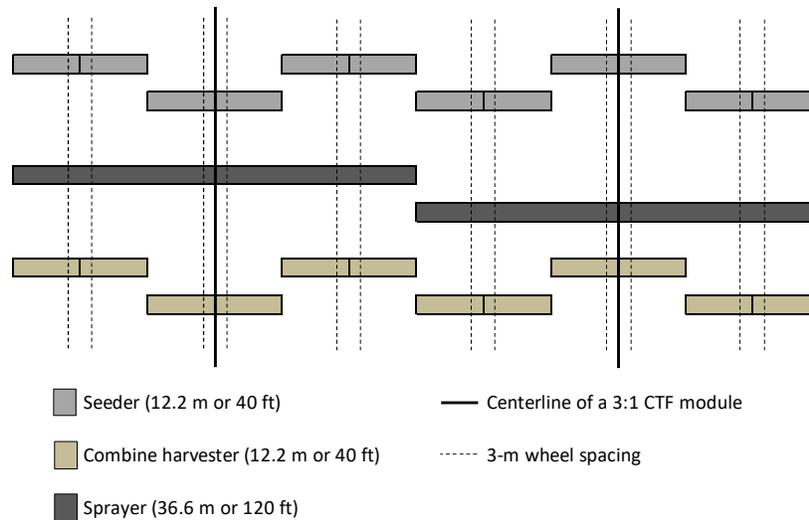
Figure 2. Diagram of a CTF system setup showing a 3-to-1 seeder and combine harvester-to-sprayer matching ratio (re-drawn from Isbister et al., 2018). For all machinery, the wheel spacing shown in this example is 3-m.

In well-designed CTF systems, such as those commonly used in grain-cropping in Australia (e.g., 9 or 12-m module), permanent traffic lanes typically occupy about 15% or less of the cultivated field area, provided that the section width of heavy load-bearing tyres is 500 mm or less (Tullberg et al., 2007; Tullberg, 2014). Without CTF, varying equipment and track gauge widths often translate into disorganised or '*ad hoc*' traffic patterns, which can cover more than 85% of the total cultivated area each time a crop is produced. In non-CTF systems, even when no-tillage is practiced, the field area affected by traffic can be as high as 45%. Alternative CTF systems to the single track width (known as 'Com-Trac') have been also developed, and many of these are more readily adoptable within European farming systems (e.g., Galambošová et al., 2017). For 'Com-Trac' systems, the width of the track matches that of the vehicle that is most costly or difficult to modify, typically the harvesting equipment. For combine harvesters in which the front axle has single tyres configuration, the standard track width is 3-m; hence, all other equipment needs to have equal wheel spacing (Fig. 3).

Figure 3. A 8400-series John Deere CTF-compatible tractor (left) with front and rear axles extended to 3-m. Note the tractor positioned on the permanent traffic lanes of a 9-m module CTF system in no-tillage. The machinery width ratio is 3:1, that is, 9-m front combine harvester and planter bar, and 27-m boom width sprayer (right), also with both axles extended to 3-m.

Fig. 4 shows the output of Trackman® (Newell et al., 1998) used to estimate and illustrate the relative footprint of mechanisation systems representing conventional tillage and zero-tillage with unmatched machinery and track gauge widths, and CTF with 3-m wheel spacing. Trackman® is a wheel-track mapping software, developed to determine both the extent and location of wheelings within a field given the mechanisation system available at the farm. The software can be used for decision-making to investigate 'what if' scenarios when considering conversion to CTF. This is possible by making repetitive adjustments to equipment widths and wheel spacing options until the mechanisation system is optimised to suit the farm-specific application. By providing information on the machinery modifications required, an economic evaluation can be then undertaken to assist decision-making. Different colours in Fig. 4 denote different pieces of farm equipment. In the conventional tillage scenario, the same tractor (red), a front wheel assist (FWA) fitted with dual tyres, is associated with the seeder, scarifer and blade plough. In the CTF and zero-tillage scenarios, the tractors (also in red) are displayed as FWA, but fitted with single instead of duals tyres. The combine harvester (blue) is consistent across all situations. The 'footprint' displayed at the bottom of each section represents the accumulation of all wheel tracks for the associated pieces of equipment and for each scenario (note the footprint colours are consistent with the colours displayed in Fig. 4). When the 'footprints' align as shown in the CTF example, the area of the field affected by compaction is significantly reduced. However, where random traffic occurs with multiple passes of equipment, the 'footprint' or compacted area is significant. In this latter situation, some areas of the field have up to 7 passes of load bearing wheels during a single cropping cycle.
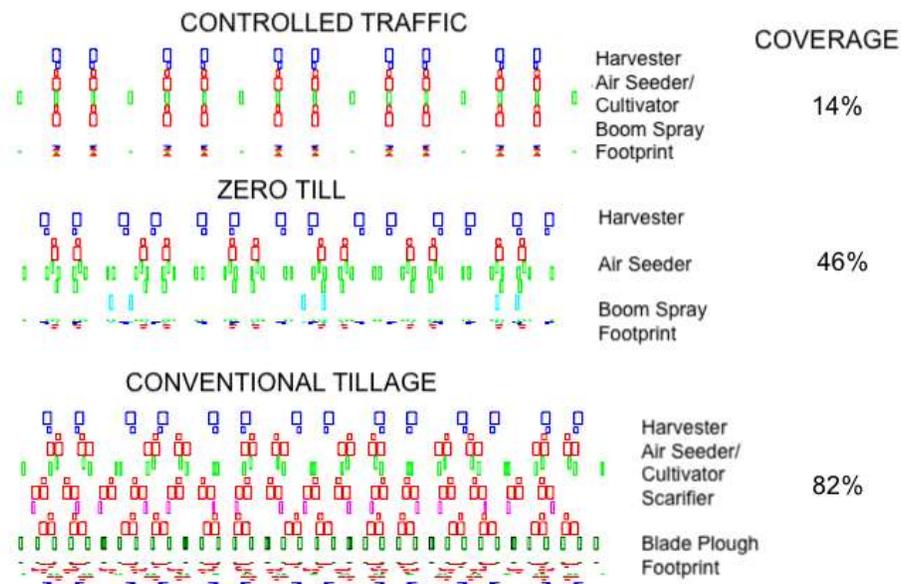
Figure 4. Typical wheeled areas for controlled traffic (3-m centre, 9-m module, zero-tillage), and unmatched machinery in zero-tillage and conventional tillage systems, respectively, determined with the use of Trackman® (Newell et al., 1998).

Alternatives to the common CTF system, in which all vehicles have 3-m wheel spacing, include the following mechanisation arrangements, which are based on the relative widths of farm equipment tracks (after Chamen, 2006; Vermeulen & Chamen,

2010): (1) 'Half-Trac': a system with two track widths, one exactly half the width of the other. Implement widths are a direct multiple of one or other of the track widths, (2) 'Twin-Trac': a system that uses two track widths; the wider track straddles adjacent passes of the narrower track, and implement width is the addition of the two track widths or a direct multiple of it, (3) 'Out-Trac': a system that uses a single common standard track width, but allows the widest vehicle (usually the harvester) to track 'outwith' the narrower tracks while centred on them. Implements may be any common width or direct multiple, and (4) 'Ad-Trac': a system with two track widths, the narrower using one track of the wider, resulting in an additional track. Implements may be any common width or direct multiple.

Schematic examples of the above arrangements are also shown by Vermeulen & Chamen (2010). For these alternative systems, CTF Europe Ltd. proposed a 'tier' approach that aims to encourage farmers to progressively reduce the area of the field subject to vehicular traffic through improvements in the design of the CTF system. This tier system includes the following (as percent of tracked area): 30% to 40% (tier 1), 20% to 30% (tier 2), 10% to 20% (tier 3), and 10% or less (tier 4). Tier 4 may be only achievable with the use of gantry systems (e.g., Chamen et al., 1992, 1994; Taylor, 1994), which have been used in horticulture with satisfactory results (e.g., Pedersen et al., 2015, 2016). Seasonal controlled traffic systems have also been adopted and are designed to confine most field operations, usually with the exception of harvesting, to semi-permanent traffic lanes (Vermeulen & Mosquera, 2009). These systems represent a technical solution for the vegetable, sugar and cotton industries, for example, where incompatibilities between harvesting equipment used with different crops in the rotation are common (Braunack & McGarry, 2006; McPhee & Aird, 2013). Technical manuals (e.g., Webb et al., 2004; Isbister et al., 2013) are available and provide practical guidance on how to match machinery for CTF.

Grass Cropping

Adoption of CTF in grass production systems has been limited. In Scandinavia, Kjeldal (2013) reported the use of CTF for forage production with mower widths from 6 to 12-m, and wheeled areas between 13% and 26% depending on the module. In the U.K., Crathorne Farm, an AHDB (Agriculture and Horticulture Development Board) Dairy demonstration farm located in Yorkshire, has experimented with CTF for clamp silage forage production (James, 2016). A 9-m module width for mower, rake and harvester was used, the spreader was operated at swaths of 18-m, and the wheeled trafficked area was about 24%.

The width of commercially available cutting equipment used for grass silage production restricts the adoption of CTF in grass production systems. These machines tend to be offset rear mounted or trailed, or a combination of front mounted and rear mounted or trailed (triple gang). CTF systems based on combinations of existing machinery (with little or no physical modification or impact on field operations) in the range of common widths of 3, 4, 5, 9 and 12-m are feasible, with trafficked areas of 40%, 28%, 22%, 18%, and 13%, respectively. If arable operations were included, the trafficked areas increase to about 65%, 41%, 31%, 22%, and 18%, respectively (Peets et al., 2017). As a comparison, conservative estimates suggested that the wheeled area under standard, non-controlled traffic management in grass systems can be as high as 80% to 90% of the total field area (Peets et al., 2017). A 3-m system involves machines

with little or no modification, but it requires a tractor with a track gauge of 1.5 m and because of its narrow width, the wheeled area is inevitably larger than that of wider systems (Fig. 5, a). The 4- and 5-m systems require a loader wagon, and the mower has heavily loaded wheels running on the non-trafficked bed. The 9- and 12-m systems are achievable based on triple gang mowers (Fig. 6, a) along with standard tedders, swathers, harvester and dribble bar slurry applicator (Fig. 5, b). Harvesting relies on delivery from a self-propelled harvester to a rear hitch trailer (Fig. 6, b) that is swopped on the headland when full or to a specialised trailer on the adjacent traffic lane.
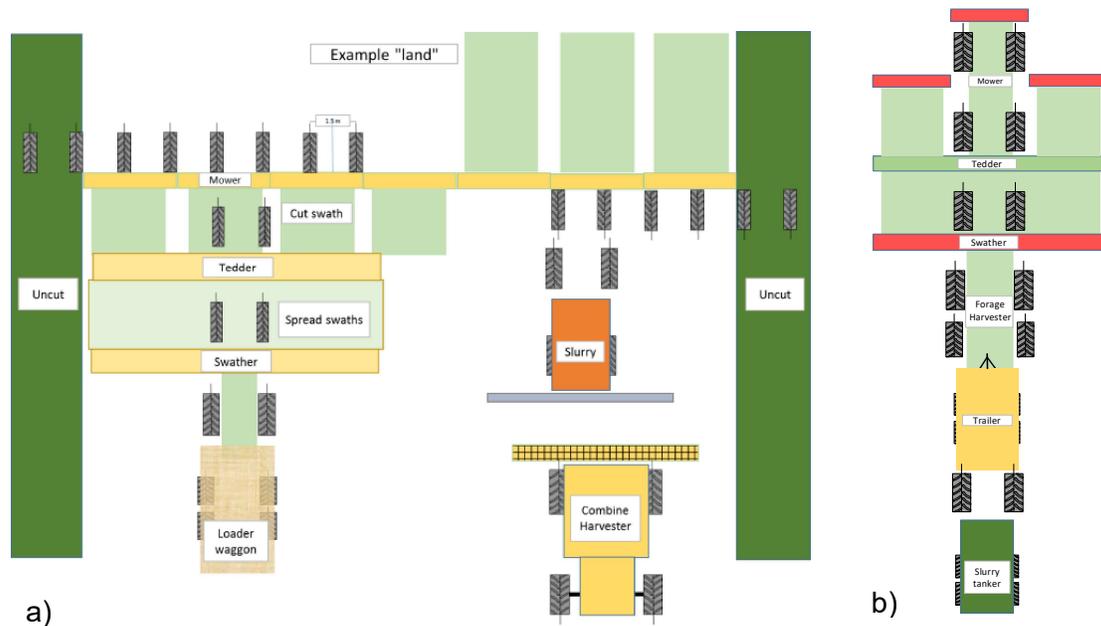
Figure 5. In (a) Tractor on 1.5-m track gauge operating with a 3-m mower, and 9-m tedder and swather. A second tractor on 1.8-m track gauge is used with a loader wagon and to pull a slurry tanker having a 6-m trailing shoe. In (b) Machines and operations in a triple gang mower based (9- and 12-m) controlled traffic forage grass operation.

Figure 6. n (a) Triple gang mower of the type envisaged for 9- and 12-m systems. In (b) Example of a self-propelled harvester loading into a towed trailer.

An important constraint when introducing CTF in grass systems is the associated effect on harvesting work rate with forage trailers running along traffic lanes rather than taking the shortest route to the harvester or field exit. As this may compromise areas of

non-trafficked soil, extra discipline and commitment are therefore critical to the success of any CTF system used for grass forage production.

SYSTEM BENEFITS OF CONTROLLED TRAFFIC FARMING

Confinement of field traffic such as in CTF systems has beneficial impacts on: (1) overall soil health, (2) crop performance and yield, (3) fertiliser and water (rainfall and irrigation) use efficiency, and (4) greenhouse gas emissions. Research and farm practice have also shown that the overall improvements in efficiency that can be achieved with CTF usually translate into increased system resilience and therefore profit margins.

Soil Properties and Function
The adverse effects of traffic-induced compaction on overall soil health are well documented (e.g., van Ouwerkerk & Soane, 1995; Soane & van Ouwerkerk, 1995). These effects are cumulative and can lead to a progressive decline in crop productivity (Alakukku, 1996; Shah et al., 2017). Soil compaction affects soil permeability to air and water movement into and through the profile (Vomocil & Flocker, 1961; Lipiec & Hatano, 2003), which is caused by reduced pore size and disruption of pore connectivity, with the associated reduction in surface water infiltration and hydraulic conductivity (Meek et al. 1992; Mossadeghi-Björklund et al., 2016). Hussein et al. (2017) found that differences in terminal infiltration rates in Red Ferrosols were up to ten-fold higher in the crop beds of a CTF system compared with the same soil managed under conventional traffic (non-CTF). The effect of traffic compaction on soil hydraulic properties is exemplified in Fig. 2 of Antille et al. (2016b). This example shows that disruption in the connectivity of soil pores caused by compaction occurs mainly between larger, vertically-oriented drainage pores, and that compaction has relatively little impact on pores holding water at potentials greater than 1,000 kPa; a response that was also shown by Connolly et al. (2001).

Reduced soil (macro)-porosity impairs internal drainage (Vero et al., 2014), which can set conditions for increased runoff and erosion (Rickson, 2014), increase the frequency and duration of waterlogged conditions (Alaoui et al., 2018), and enhance nitrogen (N) losses through denitrification (Torbert & Wood, 1992; Ball et al., 1997; Antille et al., 2015a; Tullberg et al., 2018). Modelling work by Owens et al. (2016, 2019) showed that up to 90% reduction in soil erosion rates from the Great Barrier Reefs catchments, with the associated reduction in sediment, nutrient and pesticide discharge to surface waters, may be achieved when changing management practices from conventional tillage with no traffic control to no-tillage and CTF (Fig. 7). These results agree with those from earlier studies by Tullberg et al. (2001) and Li et al. (2009), which suggested that tillage and traffic effects on runoff and sediment yield appear to be cumulative. Owens' analyses assumed that 15% of the cultivated field area of the CTF system was affected by traffic (permanent traffic lanes) and that recommended management practices for erosion control (e.g., contour banks) were also in place.

Soil structural development in non-trafficked crop beds is also observed when the soil is tilled annually (e.g., Chamen et al., 1990; Vermeulen & Klooster, 1992), but faster rates of natural amelioration are expected when CTF is coupled with no-tillage (Bullock et al., 1985; McHugh et al., 2009). Good soil structural conditions are necessary for adequate functioning of soil organisms (Rabot et al., 2018), and these contribute to

aggregate formation and development of biopores, which are largely implicated in soil water retention and transmission in soil (Leeds-Harrison et al., 1986; Kautz, 2015).
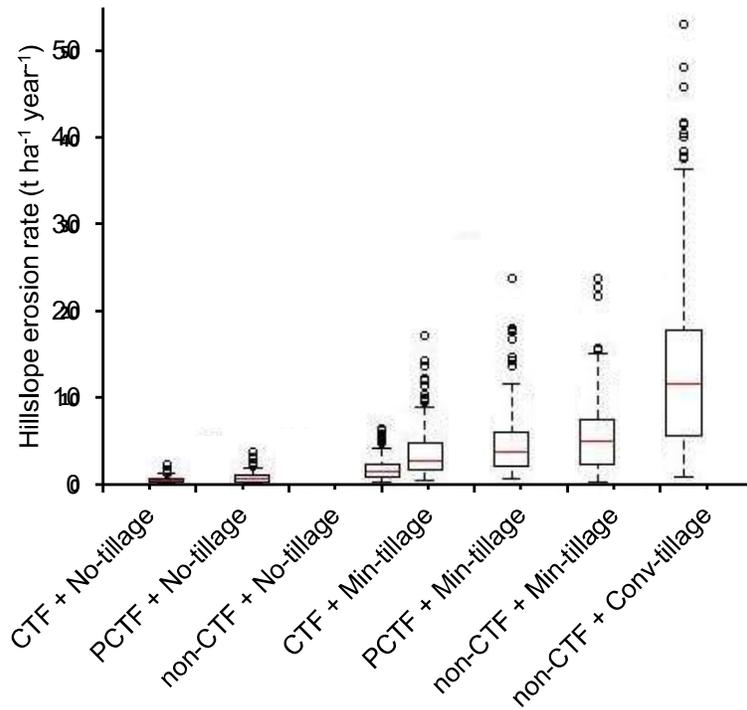
Figure 7. Average annual soil erosion in the Fitzroy Basin (Queensland, Australia) for soil management scenarios that include controlled (CTF) and partially controlled (PCTF) traffic farming, no-tillage, minimum (Min-) and conventional (Conv-) tillage, respectively (after Owens et al., 2016, 2019). Variation for each management scenario denotes inter-annual variation (1970–2015) for soils and climates. Box plots show: Min, Q_1, Med, Q_3, and Max, respectively. Points numerically distant from the rest of the data are outliers.
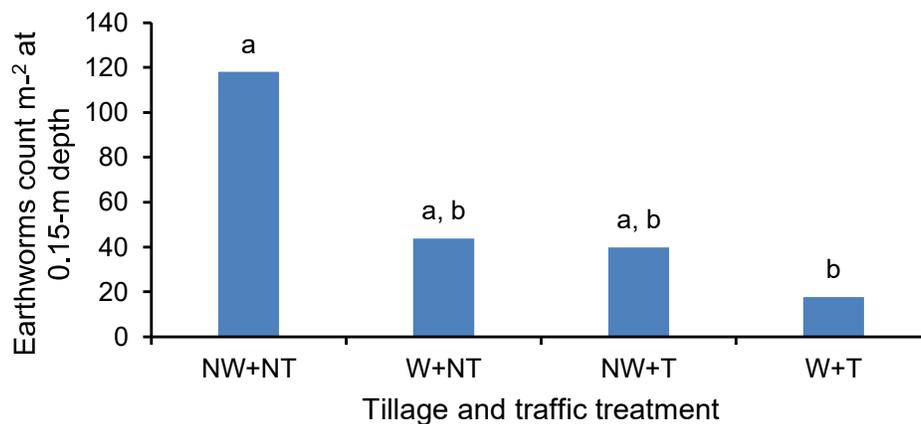
Figure 8. Mean of earthworm counts per m^2 at 0.15 m depth of soil as affected by different combinations of traffic and tillage. NW: non-wheeled soil, NT: no-tillage soil, W: wheeled soil, T: tilled soil. Different letters denote statistically different mean values (after Pangnakorn et al., 2003).

A study by Pangnakorn et al. (2003) in rainfed cropping in southern Queensland showed that earthworm counts under conventional (random) compared with controlled traffic (and no-tillage) were approximately three and eight times higher, respectively, than under annually wheeled, tilled soil (Fig. 8). Wheel traffic reduced earthworm count, but wheeling followed by tillage had significantly less effect. Soil compression during wheeling did not appear to be the main cause of earthworm death, but rather restricted movement and oxygen depletion (Pangnakorn et al., 2003).

Crop Productivity and Nitrogen Use Efficiency

A distinction is made between direct and indirect effects of soil compaction on crop productivity (Chamen, 2006). Direct effects refer to the extent to which crop growth and physiological development are restricted by processes such as water and nutrient uptake, which are adversely affected by soil mechanical impedance (e.g., root expansion and exploration, biomass accumulation and partitioning). By contrast, indirect effects are those that relate to timeliness. This includes the time required to fix pre-existing compaction to enable satisfactory establishment of the next crop in due time, and the ability to complete in-season field operations (e.g., sowing, spraying and fertilisation) due to trafficability conditions (Antille et al., 2015c). In most circumstances, the opportunities to conduct such operations occur within a relatively narrow window as it is determined by the crop (e.g., physiological stage), weather and soil conditions being appropriate (field access, trafficability and workability) for traffic with farm machinery (Earl, 1997; De Toro, 2005; Gut et al., 2015). Failure to conduct in-season operations at the right time will impact crop productivity (e.g., mismatch between fertiliser application and nutrient demand by the crop). Impacts on crop quality may also occur, for example, as a result of delayed spraying for crop protection purposes or late harvest; in all circumstances with an associated impact on crop profit margins (Bednarz et al., 2002). In crops established on soil with 'residual' compaction, such as that originated during harvest of the previous crop, the impact on yield is commonly explained by reduced plant stand and greater plant stand variability. For example, in cotton a 20% reduction in plant stand below a target of about 10–12 plants per m^2 (at 40-inch (1-m) row spacing) due to compaction can result in up to 15% reduction in yield or more if the effect is due to variability in plant stand (Hadas et al., 1985). For Australian broadacre grain production, the daily loss of crop value caused by delays in sowing (outside the optimum) was estimated at approximately 1.5% per day of the total crop value (Tullberg, 2014). Tullberg's analysis was conducted to determine the sowing capacity required to establish a crop within the optimum window for that crop, without significant financial losses. The same concept is applied here to show that delays in 'field access' due to unsuitable trafficability conditions can have financial impacts of the same magnitude. Permanent traffic lanes in CTF largely eliminate this problem. Table 1 summarises reported information on impacts of soil compaction on crop yield. Optimum soil bulk density values are dependent on crop and soil type, and seasonal effects of weather (Negi et al., 1981). Therefore, optimum values for a given crop vary within a range, and these may be narrower or wider depending on year-specific conditions.

Because yield (and dry matter) is affected by compaction, the amount of fertiliser recovered in crop (agronomic efficiency) is concurrently reduced (Wolkowski, 1990), which has financial implications for growers and adverse effects on the environment (Soane & van Ouwerkerk, 1995). The mechanisms by which fertiliser use efficiency is

affected by compaction are discussed in several studies (e.g., Lipiec & Stępniewski, 1995; Arvidsson, 1999), and the effect on plant uptake and subsequent recovery in crop is nutrient-specific as it depends on the complex interactions between root growth, soil water and aeration status, and degree of compactness. Generally, factors that restrict water movement within the soil profile (e.g., pore connectivity) and from the soil matrix to the roots will affect nitrogen (N) uptake since the main mechanism implicated in N transport to plant roots is mass flow (Barber et al., 1963; Kirkby et al., 2009). Nitrogen recovered in cereal (grain) and grass (dry matter) correlates well with soil water availability or rather with water used by the crop during the crop cycle (Melaj et al., 2003; Antille et al., 2013, 2015b, 2017). Factors that affect root elongation, such as increased soil mechanical strength, will restrict nutrient absorption through root interception, and this mechanism is particularly important for phosphorus, because of its relatively low mobility within the soil (Wiersum, 1962; Prummel, 1975). Threshold values of soil strength above which root elongation stops vary depending upon the crop, but these typically range between 2 and 2.5 MPa for most arable crops (Taylor & Ratliff, 1969a, 1969b). Traffic with harvesting equipment (overall load: 32–35 Mg) on Vertisols (moisture content: ≈25–30%, w/w) was reported to increase cone index in the 0–500 mm depth range from about 1 MPa prior to traffic to more than 3 MPa after traffic (Braunack & Johnston, 2014). Observations from that work were in close agreement with those reported by Ansorge & Godwin (2007) and Antille et al. (2013), albeit on medium-textured soil with relatively lower moisture content.

Table 1. Yield of common crops achieved in the absence of field traffic relative to yield obtained when the crop was grown under traffic intensities that are typical of the cropping system (100% means no difference). Winter cereals: wheat, barley. Summer cereals: grain sorghum, maize. Grain legumes: soybeans. Oilseeds: oilseed rape, sunflower. Cotton: includes lint or lint + seed

Crop type	Relative yield (or range)	Soil type	Reference
Winter cereals	112%	Red Ferrosol	Hussein et al. (2017)
Winter cereals	104–135%	Loam, Sandy loam	Hamilton et al. (2003); Galambošová et al. (2017); Godwin et al. (2017)
Winter cereals	114–127%	Heavy clay	Radford et al. (2001); Tullberg et al. (2001)
Grain legumes	110–143%	Clay, clay loam, sandy loam	Khalilian et al. (1991); Botta et al. (2007); Kaczorowska-Dolowy et al. (2019)
Summer cereals	100–175%	Loam, Clay	Ngunjiri & Siemens (1995); Radford et al. (2001); Hussein et al. (2018)
Cotton	106–128%	Silt loam, Sandy clay loam, Clay	Hadas et al. (1985); Akinci et al. (2004); Kulkarni et al. (2010); Hulugalle et al. (2017)
Oilseeds	128–195%	Clay loam, Clay	Bayhan et al. (2002); Chan et al. (2006)
Grass (silage)	105–174%	Clay loam, Sandy clay loam, Sandy loam	Peets et al. (2017); Hargreaves et al. (2019)

Hussein et al. (2018) showed significant differences in N fertiliser use efficiency from sorghum (*Sorghum bicolor* L., Moench) established under CTF and non-CTF systems (Fig. 9).

Furthermore, differences in N recovered in grain between the two traffic treatments were irrespective of fertiliser-N formulation. Hussein et al. (2017)'s work agreed closely with Gregorich et al. (2014) demonstrating that significant improvements in fertiliser-N recoveries may not be realized with enhanced N formulations alone (e.g., slow and controlled-released fertilisers) and that avoidance of (random) traffic compaction is a pre-requisite for improved fertilizer use efficiency. This is an important practical consideration for N management as much research effort is currently spent on the role of novel fertiliser formulations in improving nutrient use efficiency (e.g., Watts et al., 2014), without necessarily accounting for the fact that this is largely explained by overall soil condition.
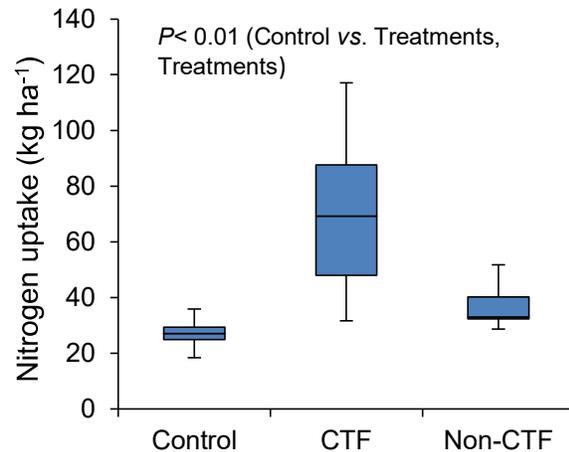
Figure 9. Controlled (CTF) and non-controlled (non-CTF) traffic effects on nitrogen (N) fertiliser use efficiency in sorghum. Box plots show: Min, Q_1, Med, Q_3, and Max, respectively, for N rates between 100 and 300 kg ha^{-1}, except for control (N=0). 'Control' is the zero-N treatment from both CTF and non-CTF traffic systems, respectively, and denotes the contribution of soil N to crop uptake (after Hussein et al., 2018).

Energy Use and Greenhouse Gas Emissions

Crop production systems that reduce the need for tillage will significantly reduce on-farm energy use and associated emissions. These include direct emissions from fuel use during tillage operations (e.g., Burt et al., 1994) and carbon dioxide (CO_2) that is released to the atmosphere through oxidation of soil organic matter (e.g., Chatskikh & Olesen, 2007). This process is enhanced by tillage, particularly in warm and moist environmental conditions (Ding et al., 2002). There exists a relationship between traffic-induced soil compaction and tillage whereby increased traffic intensity leads to increased need for tillage repair treatments (Arndt & Rose, 1966). Consequently, energy requirements of primary and secondary tillage could increase by factors of up to 2.5 and 3.25, respectively, depending on the depth of the operation and the specific soil conditions under which such operations are conducted (Williford, 1980; Hadas et al., 1986; Chamen et al., 1996). In CTF systems, Lamers et al. (1986) reported energy savings of up to approximately 50% due to lower rolling resistance and wheel-slip on permanent traffic lanes compared with trafficking over cultivated and relatively soft soil. Tullberg (2000) showed that the effect of wheeling on the draft of tillage implements (chisel and sweep tines positioned behind a 90 HP tractor in a black Vertisol, 250 mm depth) increased total draft by 30% compared with the same implement operated in non-wheeled soil. Tullberg used these observations to demonstrate that approximately 50% of a tractor's power output can be squandered in the process of creating and subsequently disrupting its own wheel compaction in tillage operations.

Evidence from growers who practice CTF and no-tillage indicates up to 50% reduction in tractor fuel use for field operations. Of the total area used for arable cropping in England (about 1.8M ha), approximately 0.5M ha were established using reduced or no-tillage (DEFRA, 2009). For cereal cropping, where reduced tillage is not practiced, average diesel fuel use was approximately 95 L ha^{-1} (see also Taylor et al., 1993). If CTF and no-tillage allow for a reduction of 50% in fuel use (of 95 L ha^{-1}) by avoiding compaction across the arable cropping area in England, this would save approximately 82×10^6 L of diesel fuel per year, equivalent to 220 Mg CO_2e or 125 kg ha^{-1} of CO_2e per year (assume 1 L of diesel ≈ 2.7 kg CO_2e). In Australian grain production systems, Tullberg (2014) showed that tillage-based systems required 52 L ha^{-1} of diesel for field operations whereas the most efficient non-CTF system under no-tillage required a minimum of 25 L ha^{-1}. When energy losses due to rolling resistance were minimised by driving over consolidated soil (permanent traffic lanes) of a CTF system, diesel use was reduced to approximately 13 L ha^{-1} (Tullberg, 2014). Note that in Australia, grain production systems that rely on tillage typically practice minimum ('conservation or non-inverting') shallow tillage with stubble retention (Reicosky, 2015; Aikins et al., 2019).

For arable systems that rely on tillage, reductions in energy use where traffic is controlled are mainly due to: (1) lower soil specific resistance in the absence of compaction, (2) tillage operations conducted at shallower depths when remediation of deep compaction is not required, (3) fewer tillage operations and reduced power loss in tractive efficiency because of lower motion resistance and reduced wheel-slip (Dickson & Ritchie, 1996; Tullberg, 2000).

Life cycle analyses conducted by Gasso et al. (2014) suggested that potential emissions reductions from adoption of CTF in intensively-managed arable cropping systems would be between 20% and 45% for N_2O, and between 370% and 2100% for CH_4, and that direct emissions from field operations could be reduced by at least 20% compared with non-CTF systems. Such emissions reduction potential agreed with measured data available in the literature, as compiled by Antille et al. (2015a, c). Higher N fertiliser use efficiencies (NUE) typically achieved in CTF systems (Fig. 9) are consistent with the above observations, and suggest disproportionally lower NUE at high N application rates (e.g., ≥ 200 kg ha^{-1} N) in non-CTF systems because of the non-linear response relationship between N rate and (direct) N_2O emissions (Millar et al., 2010; Scheer et al., 2016). A study by Tullberg et al. (2011) investigated short-term (45 days) emissions of N_2O after injection of anhydrous ammonia (82% N) at a rate of 80 kg ha^{-1} N to a black Vertisol sown with wheat in southern Queensland (Australia). Results showed that mean N_2O emissions from simulated 'random' traffic were similar to those from permanent traffic lanes of the CTF system, and significantly higher than those from permanent non-trafficked crop beds. A negative sum of CH_4 fluxes (absorption) was observed in permanent crop beds whereas the sum of fluxes from both wheeled soils was positive (emission). Hence, overall traffic treatment effects were significant (P < 0.05). Total emissions of N_2O and CH_4 over the measured period post-seeding (45 days) were 58 (permanent crop bed), 325 (permanent traffic lanes) and 370 (random traffic) kg ha^{-1} CO_2e, respectively. This indicates a 45-day post-seeding total CO_2e emission from the CTF system used in the study of 90 kg ha^{-1}, that is, 39 kg ha^{-1} from the 12% cropped area occupied by permanent traffic lanes and 51 kg ha^{-1} from the remaining 88% permanent crop beds. Such losses represent approximately 40% of the emissions of 214 kg ha^{-1}

likely from a randomly-trafficked soil where 50% of the cropped field area is wheeled. Relatively higher N_2O fluxes from the random traffic treatment compared with permanent traffic lanes simply reflects the combined N-fertiliser × traffic effect on emissions. This effect was not observed in permanent traffic lanes because fertiliser is placed at or prior to planting next to the plant row, and in the system used in Tullberg's study, traffic lanes were not cultivated. Further studies by Tullberg et al. (2018) supported those initial observations, and confirmed that adoption of CTF could reduce total soil emissions by 30–50%, which was consistent across a wide range of soil types, crop rotations and environmental conditions.

Economic Considerations
Arable

In Argentina, Botta et al. (2006) showed that over two consecutive crop seasons, soil loosened with a subsoiler resulted in significantly higher sunflower yield than no-tillage and chiselling (Table 2). Yield increases of ≈25% and ≈13% were recorded in the first and second seasons relative to the control (no-tillage), respectively. No statistical differences in yield were observed between the chisel and control treatments.

From an economic perspective, yield increases observed in year 1 (after the tillage operation) were sufficiently

Table 2. The response of sunflower to tillage over two growing seasons (after Botta et al., 2006). Different letters within each year denote statistical difference between tillage treatments ($P < 0.01$, Duncan's multiple range)

Tillage treatment	No-tillage	Subsoil	Chisel
Crop yield (Mg ha^{-1}, 2003)	2.20[a]	2.74[b]	2.38[a]
Relative increase (%)	–	24.5	8.3
Crop yield (Mg ha^{-1}, 2004)	2.25[a]	2.54[b]	2.30[a]
Relative increase (%)	–	12.8	2.3

high to offset the cost of subsoiling, which ranged between USD15 and 50 ha^{-1}, but not the chiselling. In the second year, yield increases for the subsoiler treatment represented a benefit of about USD10 ha^{-1}. Further work by Botta et al. (2007) on soybean grown on a *Typical Argiudol* showed that over three crop seasons, field traffic intensities of up to ≈39 Mg km^{-1} ha^{-1} resulted in yield penalties of up to about 8% compared with untrafficked control soil (Table 3). The economics of soybean production based on yield increases for CTF with a traffic intensity of 15.2 Mg km^{-1} ha^{-1} improved by USD102 ha^{-1} in the first year, by USD124 ha^{-1} in the second year, and by USD134 ha^{-1} in the third year, respectively, based on an average soybean price of USD170 tonne^{-1}. Compared with the standard practice (non-CTF), savings of up to USD1.40 ha^{-1} in diesel were possible.

Another study by Botta et al. (2010) also on a *Typical Argiudol*, traffic with heavy equipment (185 kN, tractor and planter) caused a significant reduction in soybean yield, which was observed in all three tillage treatments (no-tillage, chisel, subsoil) used in that study. In the first year of that study, critical values of cone Index for soybean root growth (Riley et al., 1994) were found in the topsoil (0–150 mm). Thus, the yield reduction observed after the first year was attributed to high ground pressure caused by this equipment (> 110 kPa) at relatively shallow depth. In subsequent years, critical values

of cone Index were also found in the subsoil (below 150 mm deep). This effect was attributed to high axle loads, which affected the crop performance in subsequent years. The work by Botta et al. (2010) concluded that (crop yield for the 2004 season used as reference for comparison with other years: (2.9 Mg ha^{-1}): (1) subsoiling followed by traffic with light equipment (127 kN), yield increased by about 3% to 21%, depending on the season, which agreed closely with data reported in other studies (Jorajuria et al., 1997; Botta et al., 2004); (2) subsoiling followed by traffic with heavy equipment (185 kN), yield penalties were between 3% and 5%; (3) no-tillage soil trafficked with heavy equipment (185 kN), yield penalties were between 14% and 17%, also depending on the season; (4) chiselling followed by traffic with light equipment (127 kN) showed a 13.7% increase in yield above the reference yield in year 1, and between 1% and 3.5% in the subsequent two years. The overall economic result from the soybean crop that relied on 'light' seeding equipment (127 kN), compared to the heavy equipment (185 kN), showed a relative benefit of USD130 ha^{-1} in the first year, USD65 ha^{-1} in the second year, and USD22 ha^{-1} in third year, respectively, using an average soybean price of USD216 tonne^{-1}.

Table 3. The effect of traffic intensity on soybean yields over three consecutive growing seasons (2003–2005) in Argentina (after Botta et al., 2007). Different letters within each year denote statistical difference between tillage treatments ($P < 0.01$, Duncan's multiple range)

Traffic intensity	T$_1$ (38.45 Mg km^{-1} ha^{-1})	T$_2$ (20.11 Mg km^{-1} ha^{-1})	T$_3$ (15.2 Mg km^{-1} ha^{-1})
Yield (Mg ha^{-1}, 2003)	2.67[b]	3.12[a]	3.30[a]
Yield (Mg ha^{-1}, 2004)	2.52[b]	3.14[a]	3.23[a]
Yield (Mg ha^{-1}, 2005)	2.48[b]	3.14[a]	3.19[a]

Table 4 summarises costs and revenues involved in conversion from conventional to CTF systems for farming systems representative of central Europe. Revenue is mainly derived from increased crop yield in CTF compared with non-CTF, with potentially additional revenue from improved crop quality that may be possible in some years due to improved timeliness of field operations (Parvin et al., 2005; Chamen, 2015). The long-term profitability of a typical farm can increase by up to 50% when CTF is practiced due to a combination of improved, more stable yields in soils susceptible to compaction with relatively less inter-annual yield variability. About two thirds of the additional profit expected in CTF systems (relative to non-CTF) are explained by increased yield and yield stability (Galambošová et al., 2017). Savings in input costs are possible if CTF is combined with precision agriculture (PA), but may not be significant relative to non-CTF in which PA (e.g., variable rate technology) is also applied (Barát et al., 2017).

Table 4. Relative costs and revenues likely associated with conversion from a conventional system to controlled traffic farming

Category	Item	Anticipated effect	Source
Revenue	Yield	Increased	Chamen (2015).
	Price	Equal or higher	
Capital cost	Investment in modification of machinery, adjustments and replacement of existing by new equipment	Increased	Chamen (2015).
	Investment in RTK and annual fees	Increased if not in use by farmer	
Variable costs, field operations	Fuel, energy (draft)	Decresed	Tullberg (2000); Chamen (2015); Kingwell & Fuchsbichler (2011); Bochtis (2010).
	Field efficiency	Incresed	Galambošová & Rataj (2011).
	Equipment wear and tear	Decresed	

Machinery guidance with high accuracy RTK will have a significant economic impact on the efficiency of the system due to reduced overlap (Galambošová & Rataj, 2011; Jensen et al., 2012). Despite the fact that investment in RTK could be significant, this tends to have a large in-built payback in terms of operational efficiency, savings on inputs and operator stress, as well as forming the basis for automated spatial measurements (Chamen, 2015). The main costs of conversion to a CTF system include: modification (track gauge extension) or replacement of existing machinery by CTF-compatible equipment (Chamen, 2015; Galambošová, 2017). In some circumstances, the transition to CTF may result in zero cost because (deep) tillage equipment becomes redundant and may be sold to pay out the investment in CTF-compatible farm equipment. The 'tier' approach, originally proposed by Vermeulen et al. (2010) to assist farmers wanting to convert to CTF, was used by Galambošová (2017) to exemplify a progressive conversion from non-CTF and unmatched machinery to fully matched CTF. The examples show 'low-cost' CTF systems that simply rely on the re-organisation of field traffic using commercially available machinery to systems that require full modification of the equipment, that is, matching track gauge and module widths (Table 5).

Tier 1 is represented by a 6-m 'out-track' system. Here, conventional, non-modified machinery is used and therefore no investment is needed, but simply the re-organisation of in-field traffic.The system uses two or three track gauges and the field area affected by traffic is less than about 45% of the cropped field area. Tier 2 is represented by an 8-m 'out track' system, which uses two different track widths. In this system, implements for primary and secondary tillage would be replaced by 8-m wide implements, as well as the planter. The tractor and sprayer do not need to be replaced or modified. This system would allow for about 75% of the field cropped to

Table 5. The 'tier' system approach for conversion to CTF used in Europe, with the investment costs derived from local dealers (after Galambošová, 2017)

Tier level	Design	Base module	Investment (€)
Tier 1	Out-track	6-m	N/A
Tier 2	Out-track	8-m	247,285
Tier 3	Com-track	8-m	253,585
Tier 4	Com-track	12-m	1,040,396

be free of traffic. Tiers 3 and 4 are represented by 'Com-track' systems, which use only one track width. Here, the track width of the tractor has to be modified to match that of the combine harvester. Base modules of 8-m or 12-m are included in the calculations. The 12-m system allows for the non-trafficked area to be as high as 85% of the field cropped area, but this requires modification or replacement of all machinery. Only systems with a base module of 8-m or more are likely to achieve a Tier 4 system and again, only if one of the tracks is used on the adjacent pass. Results derived from a long-term CTF experiment in Slovakia (Galambošová, 2017) are shown in (Table 6). These results show yield, and therefore revenue ($€$ 59 to 81 ha^{-1} on average), increase proportionally to the reduction in traffic footprint of the CTF system. Given the assumptions made in Galambošová's 2017 analyses, the breakeven area to overcome the investment needed for conversion to an 8-m CTF system is 528 ha (Table 7).

Table 6. Relative increase in revenue as a result of increased crop yield for different CTF systems (with prices from the Ministry of Agriculture, Slovak Republic) (after Galambošová, 2017)

Year	Retail Price ($€$ tonne^{-1})	Revenue increase ($€$ ha^{-1})			
		6-m Out track	8-m Out track	8-m Com track	12-m Com track
2011	196	55	59	73	71
2012	209	82	102	92	107
2013	167	42	72	57	67
Mean revenue		59	78	74	81

Table 7. Breakeven area analyses and return of investment (after Galambošová, 2017)

Tier level	Investment, $€$	Breakeven area to overcome investment	Return of investment [δ]
Tier 1: 6-m Out Track	N/A	N/A	N/A
Tier 2: 8-m Out Track	247,285	528	within 4 years for 500 ha of farmed land (or 2.5 for 1,000 ha).
Tier 3: 8-m Com Track	253,585	571	within 4 years for 500 ha of farmed land (or 2.5 years for 1,000 ha)
Tier 4: 12-m Com track	1,040,396	2,140	6 years for 1,000 ha of farmed land (or 4 years for 2,000 ha)

[δ]The analysis assumes a 2.12% inflation rate (average 2010–2014) and a risk of investment of 10% to discount the returns in the future.

The natural in-field variability means that different areas of the field (or farm) will respond differently to CTF. However, traffic-induced variability is expected to decline with time after adoption of CTF. Sensitivity analyses (Fig. 10) show the required yield increase for different areas that positively respond to CTF technology. The 75% scenario would require an increase in yield of about 0.5 Mg ha^{-1} for farm sizes above 500 ha while the 25% scenario will require a concurrently higher yield increase. For example, considering a realistic 0.5 Mg ha^{-1} yield increase in 50% of the cropped area, the farmed area would have to be at least 50% of the farmed area that positively responded to the system; therefore, CTF would need to be implemented in approximately 800 ha to be profitable.
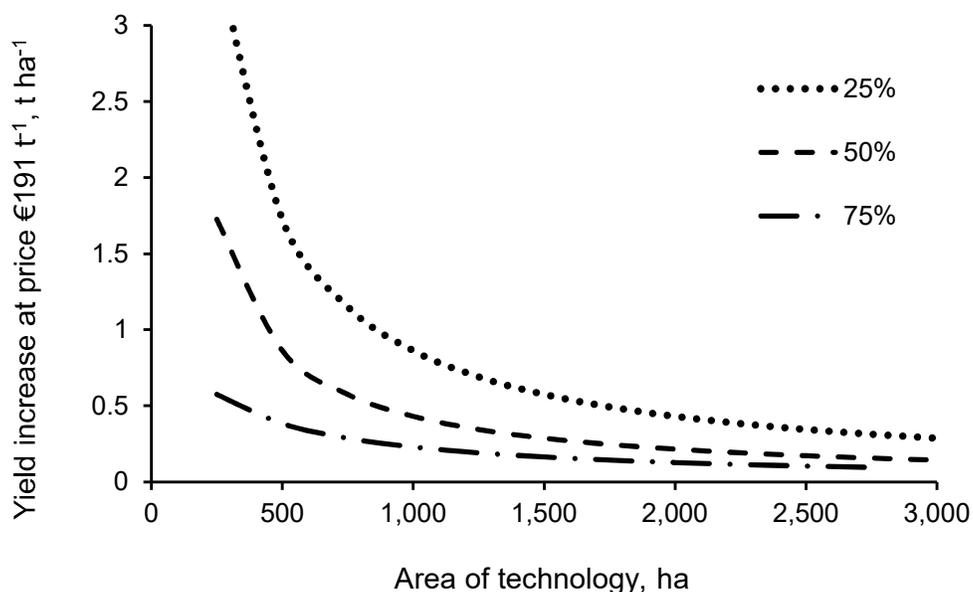
Figure 10. Sensitivity analyses for yield increases needed to convert a standard non-CTF system to an 8-m (out-track) CTF system in central European conditions (after Galambošová, 2017). The different curves show % of farm area which positively respond to CTF.

Grass

Economic analyses of CTF for grass (silage) production in the U.K. by Peets et al. (2017), based on the approach of Godwin et al. (2003), showed that reducing the field trafficked area from about 80% to 45% increased grass silage yield by 0.53 Mg ha^{-1} and 0.73 Mg ha^{-1} for two and three cut systems, respectively. If the field trafficked area was further reduced (to about 15%), this would increase yield by 1.00 Mg ha^{-1} and 1.36 Mg ha^{-1} for the two and three cut systems, respectively. Assuming a dry matter value of € 84 Mg^{-1}, these yield increases represent an additional € 44 to € 114 ha^{-1} and agreed with suggested economic benefits reported in earlier studies (e.g., Stewart et al., 1998) after being adjusted for retail price inflation (Alvemar, 2014). A 1% reduction in the trafficked area increased the benefit of CTF by between € 1.28 ha^{-1} and € 1.74 ha^{-1} for the two and three cut systems, respectively. These results were based upon the assumptions that only the cost of the guidance system would be needed to implement CTF, and that four guidance systems would be required to equip the harvester and the accompanying tractors (Peets et al., 2017). The cost of low accuracy[1] and non-repeatable positioning manually steered systems is less than € 22 ha^{-1} for areas in excess of 100 ha. For fully integrated, high accuracy systems, the cost is about € 100 ha^{-1} for areas in excess of 200 ha reducing to about € 13 ha^{-1} for areas greater than 1,500 ha per cut. The break-even area for implementing CTF ranges from 28 ha for low accuracy, manually steered systems with a 35% trafficked area with three cuts per year, to 250 ha for the fully integrated, high accuracy real-time kinematic navigation systems, reducing to 175 ha with a trafficked area of 15% (Peets et al., 2017).

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[1] Low accuracy means that a larger area will be tracked compared with the theoretical.

CONCLUSIONS

There is both circumstantial and direct evidence which demonstrates the significant productivity and sustainability benefits associated with adoption of controlled traffic farming (CTF). These benefits may be fully realised when CTF is jointly practiced with no-tillage and assisted by the range of precision agriculture technologies available. Farmers often recognise the synergistic effect of integrating CTF with no-tillage and PA; hence, producing outcomes that are greater than the sum of the parts. Important contributing factors are those associated with improved trafficability and timeliness of field operations, and those associated with greater precision and uniformity. Adoption of CTF, and its allied technologies, is therefore encouraged as a technically and economically viable option to improve productivity, resource-use efficiency and other dimensions of sustainability in arable and grass cropping systems. Studies on the economics of CTF consistently show that it is a profitable technological innovation for both grassland and arable land-use. Despite these benefits, large-scale adoption of CTF has been low, with the exception of grain production systems in Australia where approximately 30% to 40% of the total grain-producing area is managed under CTF. The main barriers for adoption of CTF have been equipment incompatibilities and the need to modify machinery to suit a specific system design, often at the own farmers' risk of loss of product warranty. Other barriers include reliance on contracting operations and land tenure systems. These structural barriers may be overcome with forward planning when conversion to CTF is built into the machinery replacement programme, and organisations such as ACTFA in Australia and CTF Europe Ltd. in northern Europe have developed suitable schemes to assist farmers in such a process.

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