A guide to reducing soil compaction

1. Introduction

This guide to reducing soil compaction was developed based on the results derived from the unique long-term study into alternative traffic and tillage systems at Harper Adams University (UK). The study brought together advice on the selection of appropriate Low Ground Pressure (LGP) tyres, and how to transition from standard, non-controlled traffic to Controlled Traffic Farming (CTF) to mitigate soil compaction and compare the potential benefits of these with Standard Tyre Pressure (STP) systems. An aerial view of the experimental site with 4 replications is shown in Figure 1.

Figure 1. Experimental site at Harper Adams University (Photo: Jonathan Gill)

Healthy soils have the capacity to function as a living system that supports biological activities increasing the potential for improved crop yields and reduced nutrient loss. Soil compaction is a worldwide problem that threatens the soil environment and crop yields. It is a major factor in soil degradation which is estimated to affect over 30% of arable land in Europe. The use of increasingly heavy agricultural vehicles in an uncontrolled way, a common feature of modern agriculture systems, can result in up to 85% of a field being trafficked annually for deep mouldboard plough tillage systems. This means that most of the field is at risk of having compacted soil with damaged structure and poor health, restricted crop root development and reduced nutrient and water uptake by the plants which in turn can reduce yields and profitability. Controlled Traffic Farming is the term used for a field traffic system that restricts agricultural machinery to the least possible area of the field in permanent traffic lanes. The use of LGP tyres (with low inflation pressures) is a method to reduce soil compaction in comparison with the use of standard (higher) pressure tyres which may be more readily adopted in complex mechanisation systems in which conversion to CTF is cumbersome. Preventing or reducing soil compaction has the benefit of reducing the need for expensive energy and time-consuming remedial action such as subsoiling.

2. Traffic and Tillage Project

In 2011, a long-term study was established at Harper Adams University on a slightly stony sandy loam soil with the objective of investigating the effects of three alternative traffic management systems; conventional (STP), low ground pressure (LGP) and controlled traffic farming (CTF) on a range of arable crops. These were established with either a one-pass tillage train operated at deep (250 mm) and shallow (100 mm) or with zero/no-till. The initial investigation focused on the physical condition of the soil, yield and the cost/benefits of the effect of the three traffic management systems managed with the three tillage treatments. More recently it has also included soil biological and health condition including soil carbon stocks.

Experimental plots, 80 m long x 4 m wide as shown in Figure 1, were chosen to match the constraints of the machinery available. With nominal tyre widths of 0.60 m and 4 m wide machines, this resulted in a trafficked area for the CTF plots of 30% of the total area ($CTF_{30\%}$). To mimic commercial practice, results were also considered for wider CTF system with a trafficked area of 15% ($CTF_{15\%}$).

A Massey Ferguson 8480 tractor, with a mass of 12.55 tonnes and track gauge of 2.1 m (Figure 2) was used to apply the traffic and tillage treatments, and crop sowing operations each year. The tractor was equipped with Michelin Ultraflex technology Axiobib IF tyres as tabulated below.

Treatment	Axles, tyres, load index and inflation pressures	
	Front, IF 600/70 R30 159D	Rear, IF 650/85 R38 179D
STP LGP & CTF	1.2 bar / 17 psi 0.7 bar / 10 psi	1.5 bar / 21 psi 0.7 bar / 10 psi

Tillage was carried out with a 4 m wide Väderstad Topdown multipurpose cultivator (Figure 2) and crops were sown with a 4 m wide Väderstad Spirit pneumatic seed drill. The combine harvester was equipped with a 4 m wide cutter bar and yield recording mechanism.

Figure 2. Massey Ferguson 8480 tractor with a 4 m wide Väderstad Topdown multipurpose cultivator at the experimental site

The crop rotation in this study was chosen to represent the range of arable crops grown in the UK with cereal as the main crop. The crop rotation was 2013 winter wheat; 2014 winter barley; 2015 winter barley; 2016 spring oats; 2017 spring wheat; 2018 winter beans; 2019 winter wheat; 2020 winter barley; 2021 winter barley; 2022 millet and 2023 spring oats. For each year, crop establishment, growth and yield data were recorded and analysed.

3. Project results

Soil structure

The images in Figure 3 are vertical cross sections of 50 mm diameter 300 mm long soil samples produced using X-ray Computed Tomography showing the effect of the nine traffic and tillage treatments on soil structure. The images show:

1. The increase in porosity of the non-trafficked (CTF) soil in the shallow and deep tilled soils over the no-tilled profile (compare images 1 and 4 with 7).
2. The impact that the standard tyre pressure (STP) has on recompacting the deep tillage soil profile (compare image 3 with 1).
3. The improvement in soil porosity in the deep tilled soils from the use of low ground pressure (LGP) (compare image 2 with 3).
4. The STP and LGP shallow tillage treatments do not indicate re-compaction in the upper soil horizon.

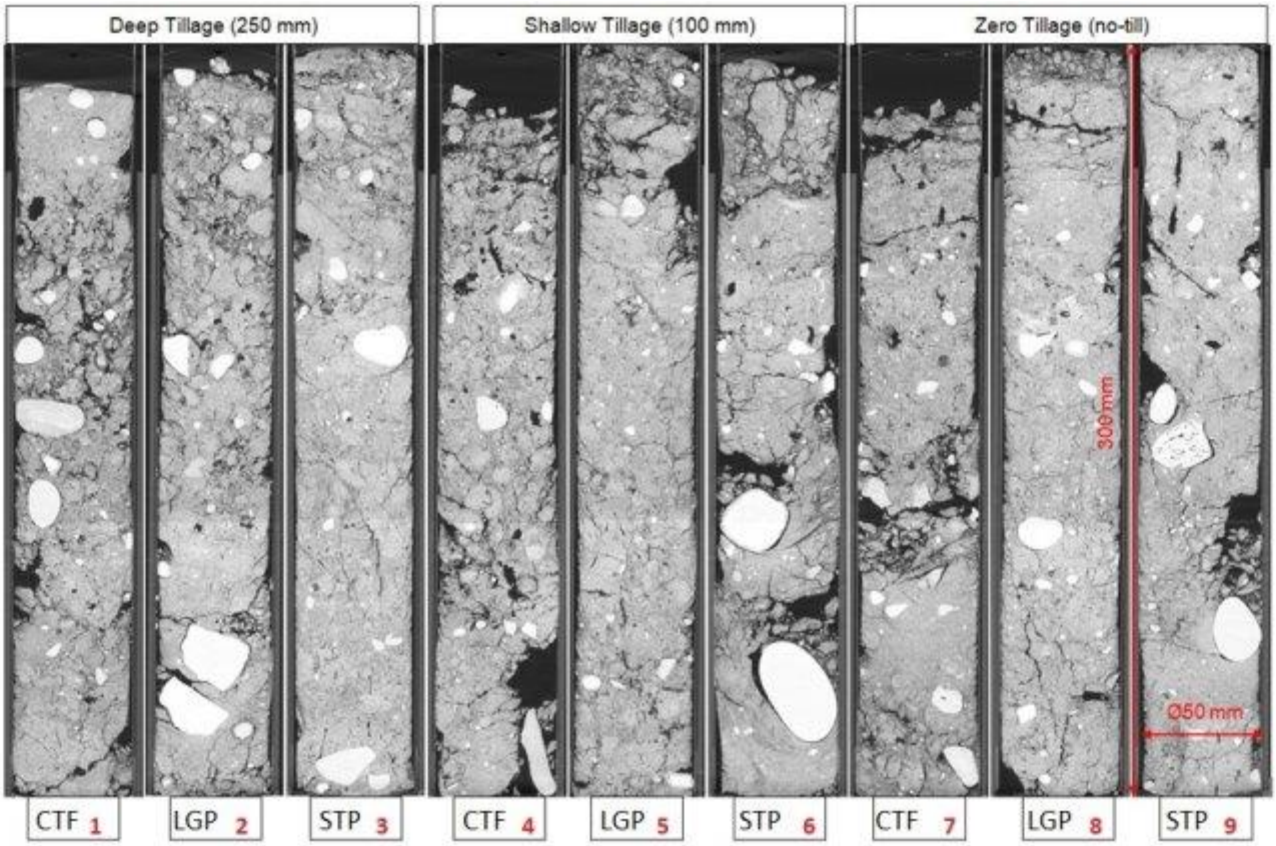

Figure 3. X-ray Computed Tomography images of the soil profile for standard tyre pressure (STP), low ground pressure (LGP) and non-wheeled controlled traffic (CTF) systems; for the deep, shallow tillage, and no-till soils. *Grey - soil particles/aggregates, white - stones, and black - pores*

Soil health

Soil biological factors, namely: the number of earthworms, the number of springtails (Collembola), soil microbial carbon (fungi and bacteria), soil organic matter (SOM) and the feeding activity of soil organisms (FA), together with soil physical properties of aggregate stability (strength), soil porosity and hydraulic conductivity (water flow rates), can provide an indication of soil health. The relative effects of the traffic and tillage systems on these indicators are given in Figure 4 and show:

1. Non-trafficked CTF soils had increased feeding activity of soil organisms and springtail density when compared to soils trafficked using STP tyres. Feeding activity of soil organisms in soils trafficked with LGP was significantly greater than that from STP.
2. The number of springtails was significantly greater under shallow tillage than zero tillage.

3. Deep tillage reduced the number of earthworms in comparison to shallow and zero tillage.
4. The hydraulic conductivity in non-trafficked CTF systems was almost 6 and 8 times greater than under LGP and STP, respectively.
5. Soil total porosity under non-trafficked CTF system was almost two-fold greater than under STP and by 60% greater than under LTP. Tillage had no significant effect on total porosity.

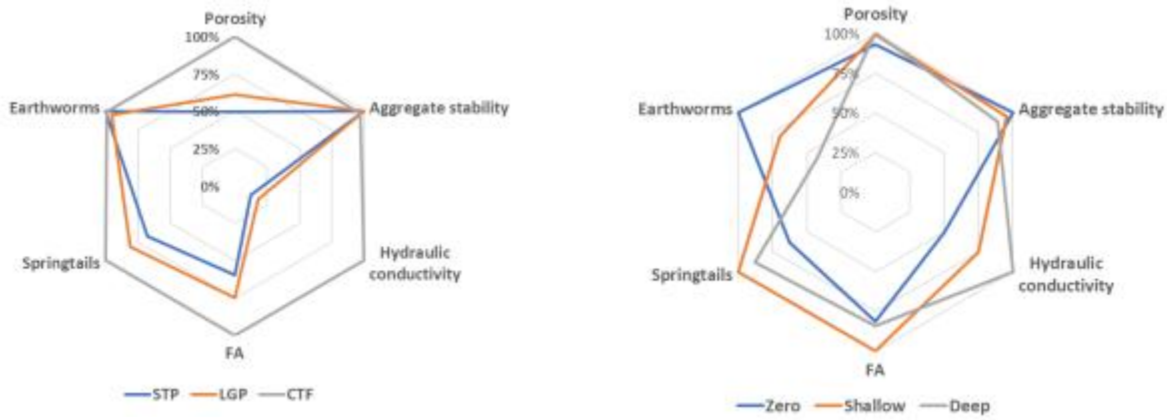

Figure 4. The relative effects of traffic (left) and tillage (right) systems on indicators of soil health.

Soil organic carbon (SOC), a component of soil organic matter, provides chemical bonding that allows nutrients to be stored and easily exchanged with plants. Microorganisms within the soil continually break down SOM and release the carbon into the atmosphere. Maintaining SOC requires continual replenishment from the decomposition of plant roots and residues or from additions to the soil from material such as manure.

Results show that the lack of soil disturbance in non-trafficked CTF zero tilled soil enhances SOM retention. Soil analysis showed that:

1. The highest SOC stocks were in CTF zero tillage system with an average of 68.95 t/ha compared to STP deep tillage of 62.36 t/ha and LTP zero tillage of 62.48 t/ha in 0-300 mm soil depth.
2. Non-trafficked CTF systems had the highest SOM (4.77%) compared to LGP (4.59%) and STP (4.52%) in 0-100 mm soil depth.
3. Deeply tilled soils (4.48%) have less SOM in the surface layers compared to soils subjected to shallow (4.72%) and zero (4.68%) tillage systems in 0-100 mm soil depth.

Crop establishment

The effect of the traffic and tillage treatments on crop establishment was measured and analysed for each crop. The effect of traffic and tillage on the plant number m^{-2} varied between crops. Results from establishment measurements showed that:

1. Vehicle traffic reduced plant establishment (e.g. spring oats establishment was significantly reduced by 28%).
2. STP zero tillage tended to have the lowest establishment.
3. Shallow tillage was better than deep tillage at producing favourable conditions for plant establishment in soils previously compacted by vehicular traffic.

Root development of winter beans

Studies of most agricultural crops has found that soil compaction can reduce root and plant growth. Root growth parameters were measured and analysed throughout the project. As dicotyledons such as beans have been found to be more sensitive to soil compaction than cereal crops, a more extensive study was undertaken using winter beans. The results showed that:

1. Plants in the CTF system had significantly greater root biomass (1.07 g) than LGP (0.71 g) and STP (0.42 g).
2. Compacted soils led to shortening of winter bean roots.

Figure 5 illustrates the effect that traffic can have on root development.

Figure 5. Differences in winter bean root morphology due to traffic on deep tilled soils: Left: soil trafficked with STP tyres; Centre: soil trafficked with LGP tyres, and Right: non-trafficked CTF soil.

Long-term effects on crop yield

The relative long-term effects of the traffic systems on crop yields (tonnes/ha) for 2013 to 2023 (standardised by calculating the yield for each system as the percentage of the grand mean for that harvest year) is shown in Figure 6. $CTF_{30\%}$ generally produced the highest yield and LGP yields were more consistent and generally higher than STP yields. The mean yields for the traffic systems for all years are shown in Figure 7, with the STP yield being significantly lower than for $CTF_{30\%}$.

Traffic effects

1. The effects of mitigating traffic ($CTF_{30\%}$ and LGP compared to STP) on crop yields appear in the first year and are consistent over time with average benefits of 3.6% and 1.2%, respectively, for all tillage systems (see Figure 6).
2. Deep tilled soils benefit the most from traffic mitigation, indicating that loosening and re-compaction causes the most damage to soils with $CTF_{30\%}$ and LGP benefiting by 6% and 5%, respectively.
3. Zero tilled soils show the least response to traffic mitigation, indicating that they are more resilient to traffic.

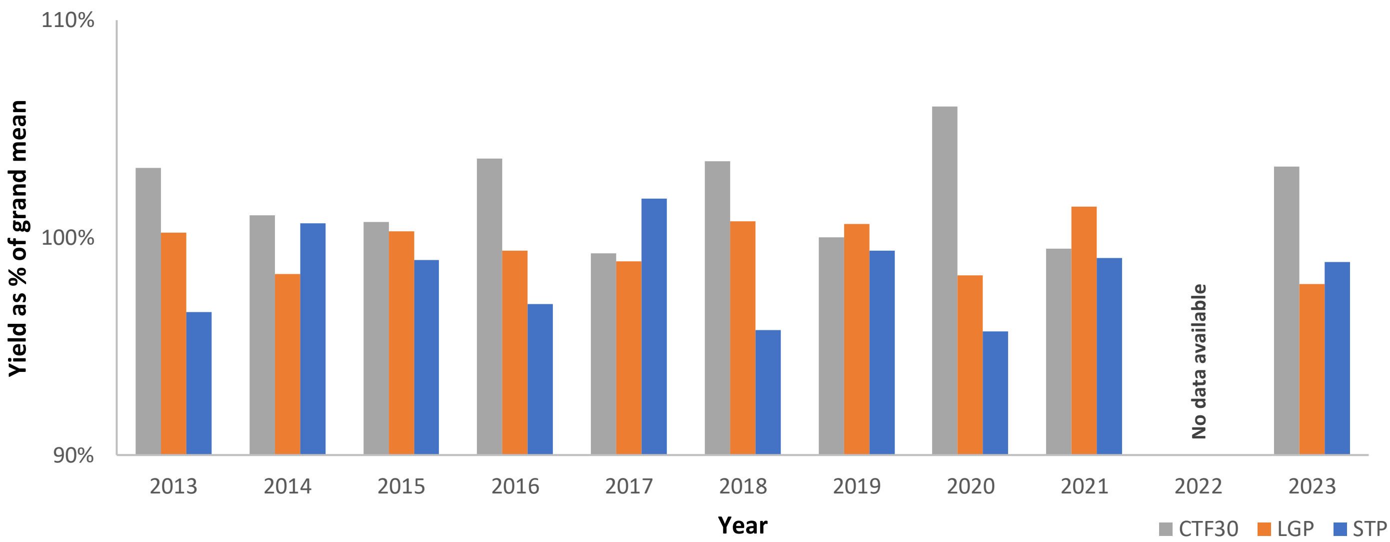

Figure 6. The relative effect of traffic system on crop yield for years 2013 - 2023.
Yield is given as a percentage of the grand mean.

Tillage effects

1. Deep tillage gives no yield advantage over shallow tillage (see Figure 7).
2. Shallow tillage gives the best compromise between yield and soil structure.
3. Zero tillage produces lower yields initially, though yield recovers over time as the soil structure develops. Zero tillage mean yields were significantly lower than for the deep and shallow systems.

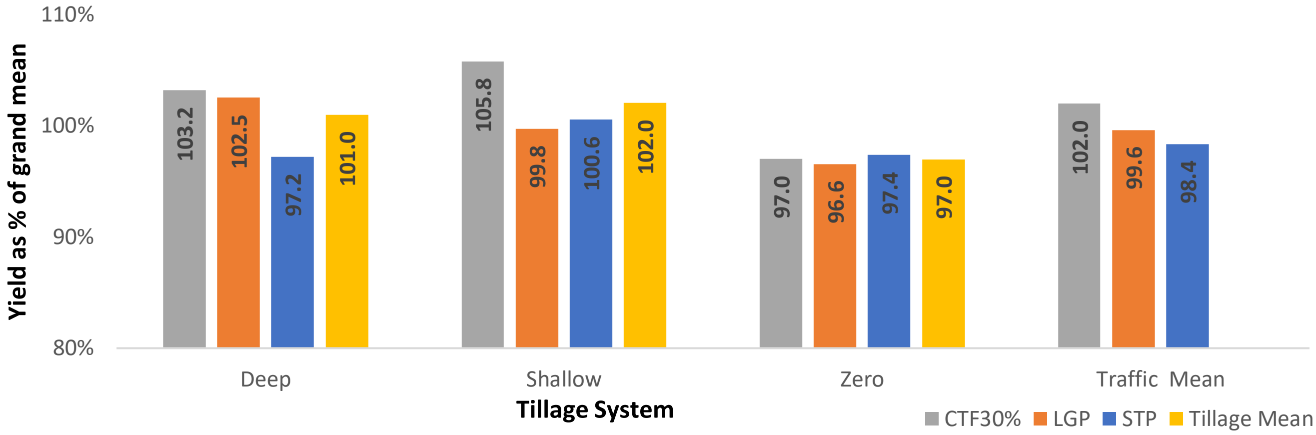

Figure 7. The cumulative effect on yields for three traffic and tillage systems (2013 - 2023).
Yield is given as a percentage of the grand mean.

The design of the experimental plots meant that the area compacted was higher than could be expected (i.e.30%) in a normal CTF system. The estimated mean yield from using a CTF system with a field trafficked area of 15% indicates that yield values would be 5% higher than reported here for $CTF_{30\%}$.

4. Economic implications

The mean annual value of the crops

The mean annual value of the crops for the different tillage and traffic systems, including the estimated $CTF_{15\%}$ for the experimental period are given in Figure 8. These are based on the February 2024 crop values for the UK given by Farmers Weekly for: wheat £171/t, barley £148/t, beans £242/t and oats £ 175/t.

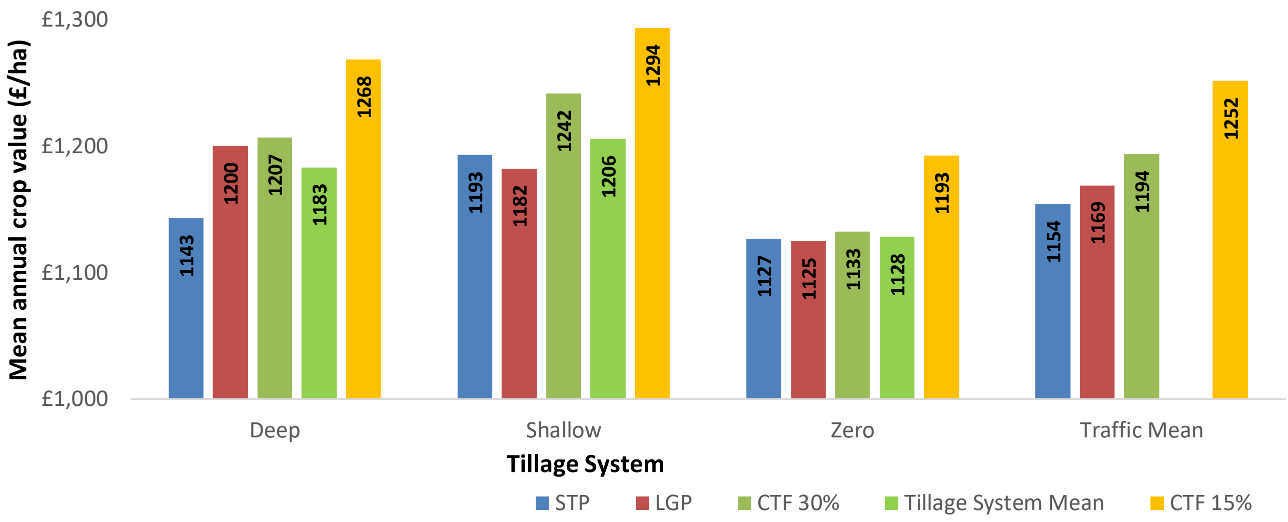

Figure 8. Effect of deep, shallow and zero tillage for standard tyre inflation pressure (STP), low ground pressure (LGP) and controlled traffic ($CTF_{30\%}$ and $CTF_{15\%}$) systems on the mean annual crop value (£/ha) from 2013 to 2023.
As the $CTF_{15\%}$ data are estimated from $CTF_{30\%}$ they are not included in the Tillage System Mean values.

Tillage systems

The data for the different tillage systems in Figure 8 show a significant reduction in crop yield from zero tillage compared to the mean yield of the deep and shallow tillage systems (which are not significantly different) of £67/ha (-5.5%). However, the estimated operational cost for zero tillage at £75/ha (a saving of £56/ha) compared to deep tillage at £131/ha (Table 1) together with the added benefits of faster work rates and improved timeliness, should compensate for this loss in crop yield. With no crop yield differences between the deep and shallow tillage treatments, shallow tillage at £118/ha offers operational cost saving of an estimated £13/ha over deep tillage costs. The actual farm costs (£/ha) may vary dependent upon the area tilled and drilled.

Table 1. Estimated tillage costs from the NAAC Contracting Price Survey 2023

Tillage system and estimated cost (£/ha)
Deep tillage = one-pass tillage train + conventional cereal drill = 74 + 57 = 131
Shallow tillage = disc tillage* + conventional cereal drill = 61+ 57 = 118
Zero/direct drilling tillage = 75

*Selected as the more appropriate shallow tillage operation for practical agriculture

Controlled Traffic Systems

Using the data from Figure 8, the mean annual crop benefits for $CTF_{30\%}$ and $CTF_{15\%}$ respectively compared to STP are:

i. £64/ha an increase of 5.6% and £125/ha an increase of 10.9%, for deep tillage,
ii. £49/ha an increase of 4.1% and £101/ha an increase of 8.5%, for shallow tillage and
iii. £6/ha an increase of 0.5% and £66/ha an increase of 5.8%, for zero tillage.

The CTF system costs are based on the direct costs of the vehicle guidance and auto-steering system. It was assumed that a farmer or contractor contemplating CTF would initially adapt existing equipment and plan their future expenditure upon the required machine compliment for the unique requirements of the individual farm, including the number of guidance systems. In cases where the guidance system is a non-optional feature included in the capital cost of the tractor the only additional cost is the annual fee for the RTK differential correction subscription (approx. £750). While the tillage and drilling tractors may be equipped with non-optional guidance and auto steering systems, that may not be the case for general duty tractors and combine harvesters, and as a result is considered below.

The additional annual cost of a Real Time Kinematic - GPS fully integrated vehicle guidance system with auto-steering with a capital cost of (£15,000), an assumed 10 year working life at an interest rate of 8%, together with the £750 subscription fee is £3450. From which the breakeven areas for $CTF_{30\%}$ and $CTF_{15\%}$ shown in Table 2 for each tillage system are obtained by dividing the annual cost of £3450 for a single guidance system, by the mean annual crop benefit of the CTF system over STP. Table 2 shows that the breakeven areas for zero tillage are greater than those for the deep and shallow tillage, reflecting the lower overall yield benefit from CTF for the zero tillage treatment. The zero tillage, however, highlights the benefit of reducing the traffic lane area to 15% of the field.

Table 2. Breakeven area for a single guidance system for each tillage system for $CTF_{30\%}$ and $CTF_{15\%}$.

	Breakeven area (ha)	
Tillage system	$CTF_{30\%}$	$CTF_{15\%}$
Deep tillage	54	28
Shallow tillage	70	34
Zero tillage	575	52

Low Tyre Pressure Systems

The beneficial effect of LGP over STP for the deep tilled soils (as shown in Figure 8) is significant, with a 5% increase in crop value, worth £57/ha. The additional costs of equipping LGP (Michelin Ultraflex Technology) tyres to field going equipment for "on the move" combine harvester discharge, namely: (1 cultivation tractor (greater than 300 hp), 3 general duty tractors (greater than 200 hp), 3 tandem axle trailers, 1 combine harvester and 1 sprayer) over those equipped with STP tyres was given by Michelin in 2024 as £33,600. Hence, the total annual cost difference between LGP and STP tyres based on a tyre life of 8 years and an interest rate of 8% was £6890, giving a breakeven area of 120 ha.

For smaller enterprises of 150 ha for example, where the combine harvester discharges the crop into "stationary" trailers at the field headlands, rather than "on the move" as assumed above, the additional capital cost to fit LGP tyres to a 180kW tractor (£2730) and combine harvester (£1690) is £4424. Based on a tyre life of 8 years and an interest rate of 8%, this investment has a total annual cost of £900 and an annual cost per hectare of £6, with a breakeven area of 16 ha, an increase in annual income of £7650, and a payback period of less than a year.

Footnotes:

1. The additional costs of adding Michelin Ultraflex Technology tyres to the tandem axle trailers include the cost of matching replacement wheels and are compared with the cost of standard tyres from other suppliers.
2. For simplicity it was assumed that the sprayer would be equipped with one set of Ultraflex tyres that could operate throughout the winter-spring and summer spraying seasons.

5. Changing to low ground pressure tyres

Yield advantage from using LGP tyres

Combine harvest yield data (tonnes/ha) for the harvest years of 2013 to the 2023 (excluding 2022 as no data were available) was standardised by calculating the yield for each plot as the percentage of the grand mean for that harvest year. Figure 9 shows the percentage yield advantage of using LGP compared to STP tyres on deep tilled soils. The yield advantage ranged between 0% (2014) to 11% (2021).

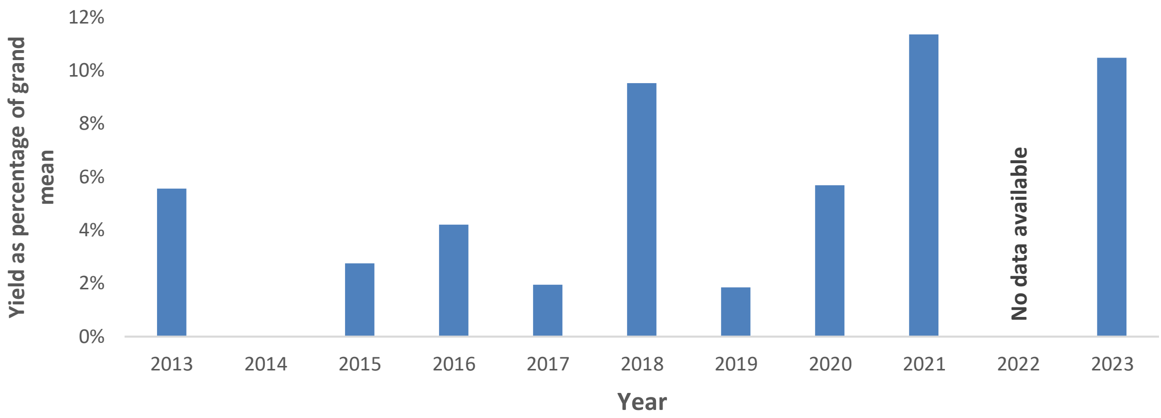

Figure 9. Mean benefit of LGP compared to the STP tyre system for deep tilled soils.
Yield is given as a percentage of the grand mean.

High Flexion tyre technology

Compared with standard tyres, Low Ground Pressure tyres have an increased area of footprint, which reduces the soil stresses in both the top and the subsoil. LGP tyres can be run at lower inflation pressures (operating at inflation pressures of 0.7 bar where the same tractor equipped with conventional tyres would have tyres inflated to 1.2 bar and 1.5 bar for the front and rear tyres respectively) suitable for both field and road use. A correctly inflated LGP tyre will give an evenly distributed contact pressure which reduces soil compaction risk and increases traction efficiency. Michelin Ultraflex Technology tyres (Figure 10), which provide an extended footprint length thanks to the flexible construction of the casing, were first introduced to the market in 2004 and the portfolio has been developed and upgraded to bring further improvements to performance. In addition, expanding the size range of these fitments has allowed them to be applied to a wider range of machinery. The current Ultraflex range is designed to cover the entire crop growing cycle, which includes tyres for combine and forage harvesters, self-propelled spreaders, crop sprayers and trailers. The larger footprint of the Ultraflex casing spreads the weight of the vehicle over a larger surface area. Increasing the contact patch on the ground improves traction and reduces wheel slip, which in turn reduces field time, limits smearing of the soil, improves productivity and saves fuel. By using a central tyre inflation system (CTIS) with LGP tyres, working pressures can be adapted at the touch of a button.

Figure 10. Michelin Ultraflex Technology tyres fitted to a Massey Ferguson tractor

6. Adopting a CTF system

Yield advantage from using CTF

Figure 11 shows the percentage yield advantage from using CTF_{30} and CTF_{15} (estimated) systems for the three tillage systems compared to using the STP tyre system.

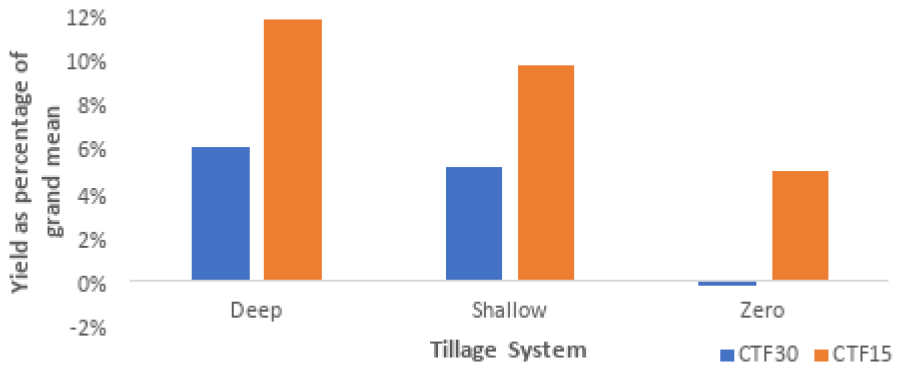

Figure 11. Mean benefit of $CTF_{30\%}$ and $CTF_{15\%}$ for deep, shallow and zero tillage systems compared to using the STP tyre system. *$CTF_{15\%}$ data is estimated from $CTF_{30\%}$.*

Controlled Traffic Farming

Controlled traffic farming is a whole farm approach to the separation of crops and wheels. By using satellite guidance and autosteer technology, carefully matched field machinery can be kept to permanent traffic lanes that minimise the area of soil damaged by compaction. The Real Time Kinematic Global Positioning System (RTK-GPS) technology improves positional accuracy less than ± 20 mm, making it possible to drive field equipment on the same permanent traffic lanes every year. High quality guidance and autosteer provide both accuracy and reduced driver fatigue. Generally, the bigger the cropping area, the greater the savings can be from using electronic guidance. The compatibility of electronic guidance technology with other technologies on the farm needs to be considered.

To achieve this
(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 the permanent traffic lanes is designed to optimize surface drainage and logistics.

Without CTF, varying equipment operating and track widths translate into random traffic patterns, which can cover up to 85% of the cultivated field area each time a crop is produced. Alternative CTF systems to the single (common) track width have also been developed, and many of these are more readily adoptable within European farming systems.

CTF track layout

Ideally, all machinery tracks and widths should match, but combine harvesters with wide wheel tracks can make matching difficult. The diverse range of agricultural machinery and road traffic width restrictions in the UK and Europe means that there is no universal optimal CTF track layout. As the combine harvester is usually the most expensive piece of equipment to modify, the most popular solution is an 'OutTrac' system where all other machinery is adapted or replaced to run on the same track gauge and the combine harvester runs on its own wider track gauge as shown in Figure 12.

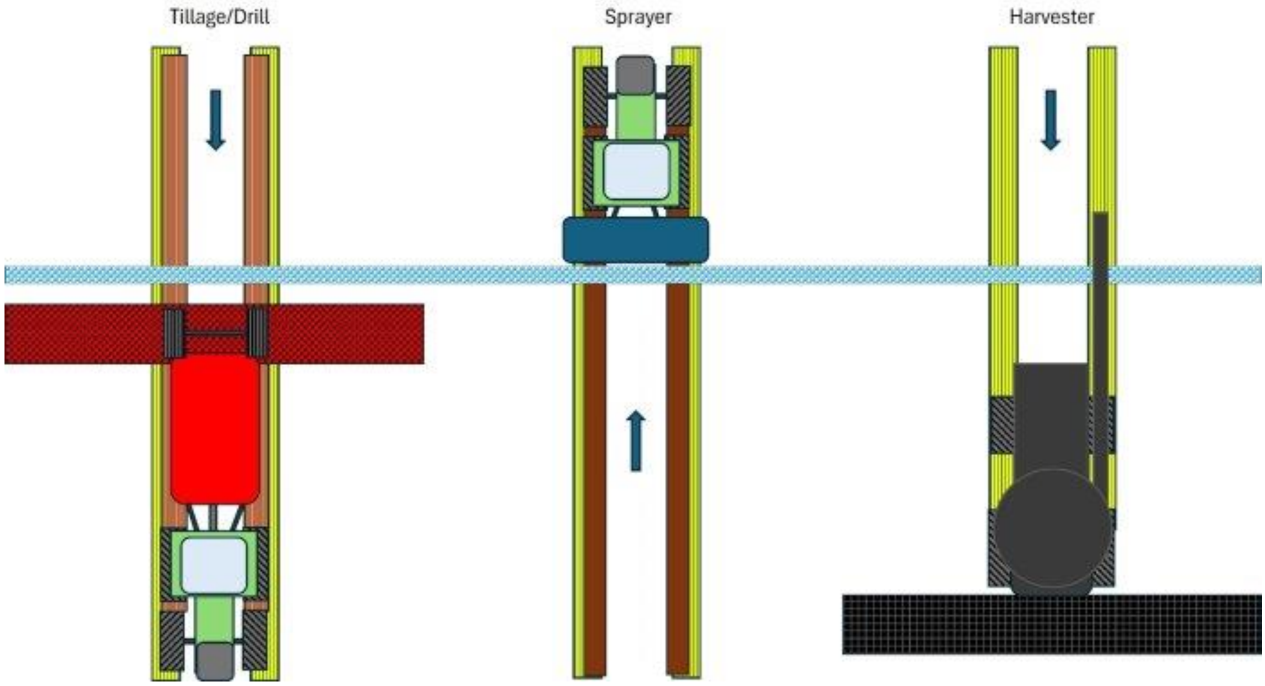

Figure 12. Typical CTF OutTrac system layout showing the harvester tracks outside the tractors.
This scales 12m system on selected tyres would track around 18% of a field.

Forward planning

Planning is probably the most important aspect of conversion to CTF because it ensures that the net cost is kept to a minimum. There will be a timescale/cost interaction that depends on the degree of complexity and compatibility of existing equipment. Some farms may be able to convert within 12 months others may require planning and change extending over several years. Things to consider are:

- How to manage soil which now needs little or no tillage, e.g.:
    a. how will the residue be left after the combine harvester - if chopped, how well spread will it be? If baled, can machines be kept on the traffic lanes?
    b. how well will the cultivator (existing or new) work when it cannot be used at an angle to the last pass?
    c. will the existing or proposed seed drill work in the presence of surface residues?
- What machines can be sold, what machines need to be bought, what tractor power will be needed and what will the future labour requirements be considering a greatly reduced tillage input?

Machinery matching

The objective is to match implement working widths and machinery track gauges (centre distance between wheels on the same axle) to minimise tracked area. Calibration of machine track gauges can be either wheel track centre to centre, or synchronising wheel extremities, which is most likely to be 3m to comply with UK highway regulations (other countries may differ). Most transitions will start with examination of existing equipment to consider its adaptability (the system will work better if the nominal cutting width of the combine is one third or one fifth of the width of the chemical applicators). Ascertain measurements as follows, working to the nearest centimetre:

- the track gauge of the combine and its cutting width (which must be at least 20 cm wider than the common width chosen for your implements and have no centre offset),
- the track gauge of all the tractors, trailers, baler and any other field machines and their adjustability together with the tyres or tracks that are or will be fitted,
- the width of any existing implements or drill you plan to use or buy (dimensions given in the literature are nominal, therefore measure or ask the supplier to measure – those cm really do matter!).

Farms have been able to convert to CTF employing many different widths (6, 7.33, 9, 10, 12, 13.3 m) using readily available or adapted machines (e.g. Figure 13). For smaller farms a 4.8 m CTF system can often be achieved with existing commercial equipment.

The CTF calculator (see: Some further information) produced by the Department of Agriculture and Food Western Australia, allows estimating of traffic footprint (in terms of wheeled area as a percentage of field cropped area) based on the configuration of equipment and can be used to aid decision-making.

Figure 13. A combine harvester and chaser wagon remaining on track in a CTF system.

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References:
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AHDB: https://ahdb.org.uk/news/uk-ex-farm-milling-oat-prices-reach-19-month-high-grain-market-daily
NAAC Contracting Price Survey 2023: https://www.naac.co.uk/wp-content/uploads/2023/04/NAAC-Contracting-Prices-Survey-2023-1.pdf

Some further Information:
Controlled Traffic Farming Technical Manual - NACC (Australia): CTF Technical Manual - Australia
CTF Network: Controlled Traffic Farming
Michelin Ultraflex Technology tyres: MICHELIN ULTRAFLEX Technology tyres | MICHELIN UK