The effects of traffic management systems on the yield and economics of crops grown in deep, shallow and zero tilled sandy loam soil over eight years

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Godwin, R.J., White, D.R., Dickin, E.T., Kaczorowska-Dolowy, M., Millington, W.A., Pope, E.K. and Misiewicz, P.A. (2022) 'The effects of traffic management systems on the yield and economics of crops grown in deep, shallow and zero tilled sandy loam soil over eight years', *Soil and Tillage Research*, *223* (105465).

Soil & Tillage Research 223 (2022) 105465

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

The effects of traffic management systems on the yield and economics of crops grown in deep, shallow and zero tilled sandy loam soil over eight years.

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ARTICLE INFO

Keywords:
Controlled traffic farming
Low tyre inflation pressures
Tillage systems
Crop yield
Production economics

ABSTRACT

This paper reports on a 3 × 3 factorial study to consider the effects of controlled traffic (CTF), low tyre inflation pressure (high flexion) tyres (LTP) and standard tyre inflation pressure (STP) farming systems for deep, shallow and zero tillage practices on the yield of wheat, barley, oats and field beans grown in a sandy loam soil in the UK. The main effect of tillage showed that the zero tillage option significantly (***$P < 0.001$) reduced crop yields in four out of the five of the first crop years, with no significant effect in years two, six and eight and exceeded the yield of the other tillage treatments in year seven. The specific costs of the alternative tillage systems were estimated, from which the cost saving for zero tillage compared to deep tillage was c. £ 60 ha^{-1} (US$ 80 ha^{-1}), which compensated for the overall loss in yield. There were no significant differences between the crop yields from the deep and shallow tillage treatments, with shallow tillage offering savings in operational costs of c. £ 30 ha^{-1} (US$ 40 ha^{-1}). Overall, the controlled traffic farming system, where 30% of the field was trafficked, produced 4% greater crop yields (*$P < 0.05$), worth £ 39 ha^{-1} (US$ 53 ha^{-1}) than standard tyre inflation pressures (STP). The estimated effect of reducing the trafficked area to 15% resulted in a further 3% increase in mean yield with a corresponding total increase in crop value of 7% worth £ 74 ha^{-1} (US$ 100 ha^{-1}) compared to the STP system. The beneficial effect of low inflation pressure tyres (70 kPa and 80 kPa) on crop yields, for the deep tillage treatment, was significantly greater (*$P < 0.05$) than those of the standard tyre pressure system (100 kPa to 150 kPa) returning an average 3.9% additional crop yield over the period of the experiment worth £ 39 ha^{-1} (US$ 53 ha^{-1}).

1. Introduction

Studies in Scotland by Soane (1970) showed that approximately 90% of a field growing spring barley was covered by wheels during crop establishment operations. Using global positioning system-tracking devices Kroulik et al. (2009) revealed that conventional (non-controlled, also referred to as random) traffic farming practices for wheat production covered 88%, 73% and 56% of the field with at least 1 wheel pass for mouldboard plough-based tillage, minimum tillage and direct drilling/zero-till respectively. This suggests that much could be gained from controlled traffic farming (CTF) practices (Tullberg et al., 2007; Chamen, 2011) where field operations are confined to predetermined wheelways, created by common equipment widths and matched wheel track spacing. This practice is now made easier with the use of real time kinetic (RTK) global positioning satellite guidance and auto-steer systems that guide the vehicles in exactly the same tracks year in and year out.

The potential advantages through managing compaction from this practice are:

I. Improved crop yields (Negi et al., 1981; Soane and van Ouwerkerk, 1995; Schafer et al., 1992; Millington et al., 2016 and Hargreaves et al., 2019).
II. Reduced tillage and crop establishment draught forces and energy (Chamen et al., 1992; Shaheb Md et al., 2021).

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https://doi.org/10.1016/j.still.2022.105465
Received 1 December 2021; Received in revised form 16 May 2022; Accepted 10 June 2022

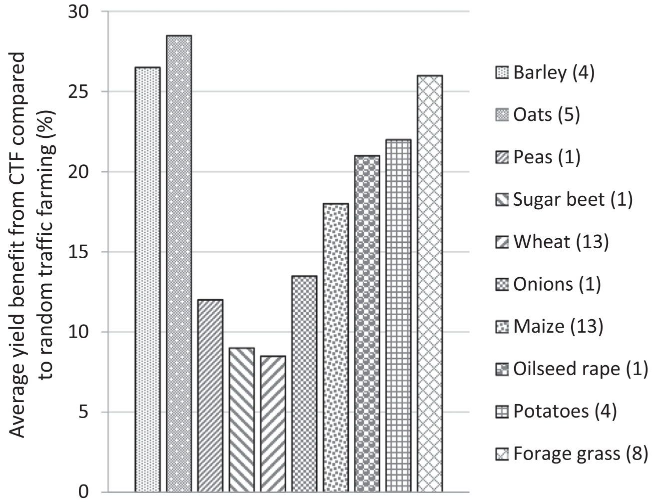

Fig. 1. Average yield benefit (%) from controlled traffic farming compared to random (conventional) traffic farming. The number of studies reported is indicated in parenthesis. Redrawn courtesy of Chamen from data in Chamen (2011).

III. Improved soil conditions and infiltration of rainfall/irrigation water which impacts upon run-off, soil erosion and flooding (Chamen, 2011; Chyba, 2012; Hussein Md et al., 2001) and
IV. Reduction in nitrous oxide and methane emissions (Gasso, and Antille et al., 2013, 2015).

All of the above assist in establishing both the environmental and economic benefits of compaction reduction. Graves et al. (2015) estimated that 39% of the £ 0.9 to £ 1.4 bn annual costs of soil degradation in England and Wales were directly attributed to soil compaction. A further 12% was attributed to soil erosion, which is indirectly influenced by soil compaction.

The advantages listed above are achievable providing that the mechanisation system can be designed to enable the correct implement width and the tractor and combine harvester track gauges to be matched. An alternative to CTF is the use of low tyre inflation pressure systems (LTP), which have become more practical for higher power tractors with the introduction of high flexion tyres (Michelin, 2021). These tyres can operate at inflation pressures down to 40 kPa (0.4 bar) depending upon the tyre size, load and speed. Typically, the recommended inflation pressures for high flexion tractor tyres are 60–70 kPa (0.6–0.7 bar) in comparison to 120 kPa (1.2 bar) and 150 kPa (1.5 bar) for standard flex radial tyres (conventional) front and rear tractor tyres. While not reducing the depth of compaction, they should, according to Söehne (1958), reduce the degree of compaction in the topsoil.

Chamen (2011) reported yield improvements between 7% and 28% for CTF systems for a range of crops in a number of different international studies, as shown in Fig. 1. These data are very promising, but not all of the results were from replicated experiments and soil compaction, if present, was not reported as being alleviated by soil loosening prior to the initiation of the experiments.

A replicated but not randomised experiment was established in Slovakia in 2010 (Galambosova et al., 2017), where a 16 ha field was managed using 6 m wide CTF systems. To compare the yield from these with conventional practice, three 33 m wide conventional traffic farming zones were established at right angles to the CTF traffic lanes. The conventional tractor tyre inflation pressures were 250 kPa (2.5 bar) for tillage and 200 kPa (2 bar) for all other operations. The results showed that CTF improved the average crop yield by 0.5 Mg ha^{-1} over the four crops/seasons (winter wheat, spring barley, maize, spring barley).

The results of a three year study in Switzerland (Latsch and Anken, 2019) with simplified CTF systems adapted for small scale agriculture where the existing heavier equipment was confined to permanent traffic lanes showed positive benefits in soil structure and a significant (16%) increase in maize yield in non-trafficked areas, with no consistent yield differences for other crops.

With the exception of the work by Cranfield University and The Arable Group (Godwin et al., 2015), the remainder of the work reported above was undertaken with a single tillage depth, which does not consider the effect of alternative traffic management systems with different tillage practices. This is a serious omission when shallow and zero tillage practices are becoming more popular. Alskaf et al. (2020) estimated that 47.6% of the arable land in England is cultivated using minimum (shallow) tillage and 7% no-tillage (zero tillage) which show an increase from 40% and 4.5% respectively as reported by Knight et al. (2012). To address this, the authors set up a long-term experiment in 2011 to determine the effects of different tillage and traffic systems on soil physical conditions, crop growth and yield.

The objective of this work was to investigate the effects of alternative traffic management systems on crops grown in deep, shallow and zero tilled soils and not to investigate the effect of alternative tillage practices per se, which have been well reported in earlier studies (Cannell et al., 1978; Carter, 1994; Soane, and Etana et al., 2012, 2020). It was important, however, that the effect of traffic should be determined for a range of soil conditions principally dictated by the associated tillage practice, hence the factorial experimental design was chosen to determine the main effects of both traffic systems and tillage practices and any potential interactions. This paper reports the crop yield and the economic costs and benefits for the first eight experimental years of this work. The economic considerations are crucial in advising farmers of the cost effectiveness of alternative soil management practices.

2. Materials and methods

2.1. Treatments

To determine the relationship between three traffic management systems and three tillage depths, a 3 × 3 factorial design was chosen for the study.

The three traffic systems were.

I. Conventional traffic farming with standard flex radial tyre inflation pressures for tillage and drilling (120 kPa and 150 kPa from 2012 to 2017 and 100 kPa and 100 kPa from 2018 to 2020 *) in the front and rear tractor tyres respectively (STP).
II. Conventional traffic farming with low inflation pressures as specified for high flexion tyres (70 kPa from 2012 to 2017 and 80 kPa from 2018 to 2020 *) for all operations in both the front and rear tractor tyres (LTP) and
III. Controlled traffic farming systems (CTF), with LTP tyres (70 kPa from 2012 to 2017 and 80 kPa from 2018 to 2020 *).

*The pressure changes followed revised load – inflation pressure recommendations from more recent performance tests conducted by the tyre manufacturer (G. Brookes, personal communication, 20 April 2022).

A 220 kW front wheel assist tractor (Massey Ferguson 8480) with an unladen mass of 12.4 Mg (38% front and 62% rear) with a further 1.4 Mg added to the front was fitted with high flexion tyres (Michelin Axiobib tyres (IF 650/85 R38 TL 179D, rear and IF 600/70 R30 TL 159D, front)) was used for the above. The experimental protocol was simplified by using the Axiobib tyres for both the standard and low tyre inflation pressures. This followed the recommendations of Smith (2016), who found that inflating high flexion tyres to those of the standard inflation pressure resulted in soil pressures similar to those caused by the standard flex radial tyres. The tractor track gauge was adjusted to 2.1 m to match that of the 7.5 Mg combine harvester used for plot harvesting

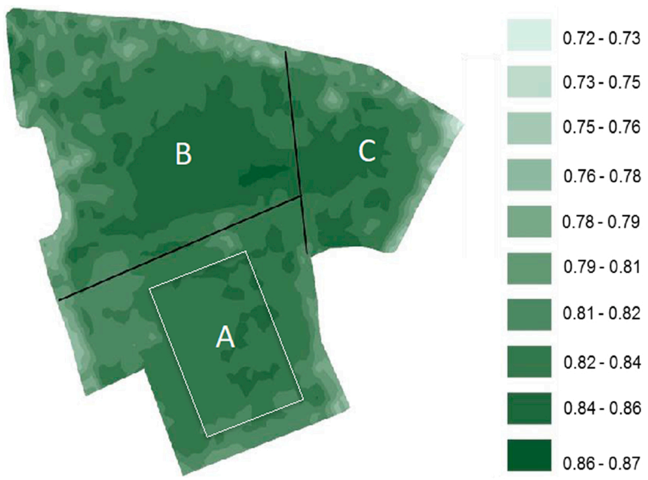

Fig. 2. Field map showing experimental area (white box) and NDVI data (Smith, 2016).

along the primary wheel ways. This tractor, with an additional mass of 0.54 Mg (front) and 1.40Mg (rear), was also used to apply additional wheel passes along the STP and LTP treatment plots to simulate the effect of other field operations following harvest to give trafficked areas of 88%, 73% and 56% in line with Kroulik et al. (2009) for the deep, shallow and zero tillage respectively. As the plot width was 4 m, this could require the tractor to simultaneously operate with a wheel in two adjacent plots, and due to plot randomisation also require different tyre inflation pressures (STP and LTP) in alternate sides of the tractor, as described by Millington (2019). This task was made easier by the use of a RTK guidance system to position the tractor, which was also used to navigate the tillage, planting and harvesting operations along the primary wheel ways. Initially a Trimble FmX integrated display unit connected to a Trimble EZ-Steer steering system was used, which was retrofitted in 2015 with a built-in auto-steer system.

The 3 tillage depths were:

I. Deep tillage (250 mm),
II. Shallow tillage (100 mm) and
III. Zero tillage (disc coulter depths of 50 mm).

The deep and shallow tillage was performed with a 4 m wide combination tillage tool comprising of discs, tines, leveler discs and packers (Vaderstad, Topdown). The deep tillage in this instance was a non-inversion tillage operation at a nominal tillage depth similar to that selected by 45% of the farmers in England (Alskaf et al., 2020) using either mouldboard ploughs or rigid tines. This should not be confused with a subsoiling operation to remove deep compaction, similar to that described for the pre-treatments in Section 2.2.

Disc drills (4 m wide) were used for all seeding operations placing the seeds at a nominal depth of 50 + /- 10 mm. A Vaderstad, Rapid drill (single disc), was used in the first year, which was replaced by a Vaderstad, Spirit (double disc) in 2013 for all subsequent crop seasons. These drills were chosen as they could operate effectively with all tillage treatments.

Variable traffic and tillage treatments were not applied in the first season to allow the site to recover from the pre-treatments and to determine the spatial uniformity of the proposed experimental site, as described in Section 2.2. The traffic treatments were applied for the first time in autumn 2012 and continued through 2019 following the traffic intensity patterns (both area and number of passes) described earlier for the different tillage systems reported by Kroulik et al. (2009), as given above.

The rotation consisted of winter wheat (*Triticum aestivum* cv. Duxford) (2012–13), winter barley (*Hordeum vulgare* cv. Cassia) (2013–14 and 2014–15), a winter cover crop (Terralife N-Fix: DSV Seeds, UK) (2015–16) followed by spring oats (*Avena sativa* cv. Aspen) (2016), spring wheat (*Triticum aestivum* cv. Mulika) (2017–17), winter beans (*Vicia faba* cv. Tundra) (2017–18), winter wheat (*Triticum aestivum* cv. Graham) (2018–19) and winter barley (*Hordeum vulgare* cv. Orwell) (2019–20). A uniform seed rate was applied to all tillage treatments between 2013 and 2016, following which the seed rate for the zero tillage treatment was increased by 25% for all subsequent years. To minimize the effect of potential variations in agrochemical application rate between the plots the crop spraying operations were conducted perpendicular to the plot length, at 24 m spacing.

2.2. *Site selection and preparation*

A very slightly stony sandy loam field (Claverley series; 65% sand, 19% clay and 15% silt) (Soil Survey of England and Wales, 1984), which had not been previously used for experimental work, was chosen for this study, with a grid reference of 52°46.7899′N, 002°25.5236′W. In preparation for this study the field was under-drained, with the addition of gravel backfill, at a nominal depth of 1.0 m with 13 m wide spacing between the drains. The field was then subsoiled to a depth of 0.5 m to disrupt the deep underlying compaction. The subsoiler was equipped with wing attachments (Spoor and Godwin, 1978) to ensure effective loosening at 0.5 m. The installation of the under drains and the subsoiling operations were both conducted perpendicular to the proposed direction of the treatment plots. The site had a topsoil depth of c. 0.35 m with a pH of 6.6 and subsoil pH of 6.1. The average bulk density for the zero tilled, un-trafficked soil in the top soil to a depth of 250 mm was 1.48 Mg m^{-3} in 2013 (Smith, 2016), 1.33 Mg m^{-3} in 2016 (Millington, 2019) and 1.36 Mg m^{-3} in 2019 (Kaczorowska-Dolowy, 2022).

To locate an area of the field with the minimum heterogeneity for the experiment, both conventional soil mapping and electromagnetic resonance techniques were used and the results suggested that the area in Fig. 2 was the most suitable. Following this, a winter wheat crop was established in forty 80 m long by 4 m wide plots with 0.6 m wide wheel tracks on a track gauge of 2.1 m using a 4 m wide mouldboard plough and power harrow/drill combination. The purpose of which was to allow the site to “recover” from the pre-treatments and to determine the spatial uniformity of the proposed plot-treatment zones.

Plot widths of 4 m were chosen to keep the experiment within the uniform soil zone and to match the available complement of field machines. With nominal tyre widths of 0.60 m, this resulted in a trafficked area for the CTF plots of c.30% (CTF$_{30\%}$) of the total area. This figure should be relatively easy for farmers to achieve, however, in practice, increasing the system width to 8 m or 9 m, should reduce this to c.15% (CTF$_{15\%}$). Which as a result of increasing the area of the field not subjected to wheel traffic, should further improve crop yields, the ultimate aim of many CTF farmers.

Fig. 2 shows crop biomass uniformity during the growing phase of the recovery year (Smith, 2016) from Normalised Difference Vegetation Index (NDVI) collected on 22nd June 2012 (growth stage 65) using Crop Circle ACS-210 (Holland Scientific Inc.). This shows a narrow range of variation for NDVI data indicative of a healthy uniform plant population (Wood et al., 2003). Each of the identically treated plots were harvested using a combine harvester (7.5 Mg) with a track gauge of 2.1 m and a 4 m wide cutter-bar equipped with a yield monitoring device and the total yield per plot weighed using a 1 Mg Novatech F204TFROKO loadcell, as the crop was unloaded at the headland. Sub-samples of the grain moisture content were recorded with a Sinar AP6060–001AG moisture analyser to enable the yield to be corrected to a standard 15%. The mean crop yield (+/- SEM) was 4.2 + /- 0.01 Mg ha^{-1} with no significant effect of the plot position in the field and a coefficient of variation of 6%. This low yield reflected the national situation where a wet summer (Fig. 3) with low solar radiation resulted in the lowest crop yield in 20 years. For comparative purposes Defra (2012) reported average wheat yields of 6.2 Mg ha^{-1} in the West Midlands and 5 Mg ha^{-1}

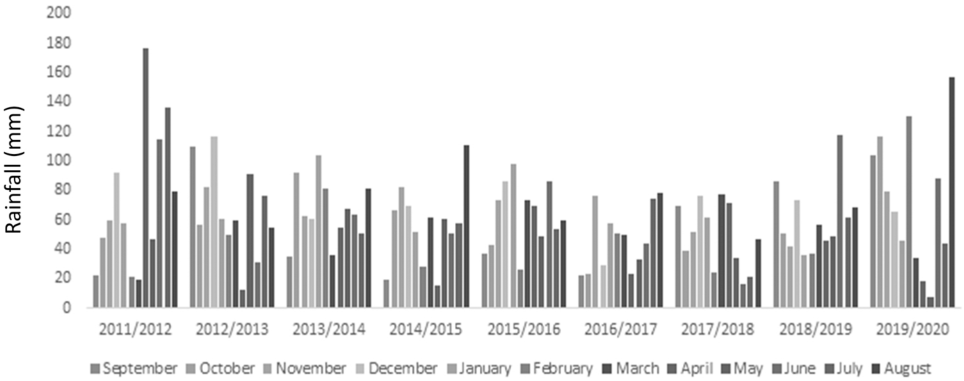

Fig. 3. Monthly rainfall (mm) for the experimental period 2011–2020 (Kaczorowska-Dolowy, 2022).

in the North West of England.

Following the crop yield results 36 treatment plots were chosen in 4 randomised complete blocks from the forty plots created, with a discard plot between each block.

2.3. *Crop measurements*

Plant establishment was calculated based on a plant count conducted in each row of a transect across the complete width of all plots, for sample row lengths of 0.5 m for the cereal crops and 5 m for the winter bean crop. The number of plants was counted for each plant row separately.

Prior to recording the crop yields of the whole plots using the 4 m wide combine harvester as described in Section 2.2, one set of hand harvested grain yield subsamples, cut 20 mm above the soil surface for a length of 0.3 m were collected from each of the crop rows in the trafficked and non-trafficked areas of the CTF cereal plots. The harvested length was increased to 5 m for the winter beans in 2018 and to 0.5 m in 2019 and 2020 for the winter wheat and winter barley crops. These samples were threshed with a laboratory thresher (Wintersteiger). The hand-harvested data were particularly important in assessing the effects of the compacted traffic lanes, especially with the CTF treatments as this enabled the combine harvester yields to be estimated for a CTF system with a traffic lane area of 15% ($Y_{15\%}$) using Eqs. (1) and (2).

$$Y_0 = Y_{30\%}\, Y_{nt} \,/\, (0{\cdot}7Y_{nt} + 0{\cdot}3Y_{tl}) \tag{1}$$

$$Y_{15\%} = 0{\cdot}85Y_0 + 0{\cdot}15Y_0\,(Y_{tl}\,/Y_{nt}) \tag{2}$$

Where:

Y_0 = Estimated combine harvester yield for the traffic free area (Mg ha^{-1}),

$Y_{30\%}$ = Combine harvester yield for CTF$_{30\%}$ (from Table 2) (Mg ha^{-1})

Y_{nt} = Hand harvested yield for the non-trafficked area (from Table 1) (Mg ha^{-1})

Y_{tl} = Hand harvested yield for the traffic lane (from Table 1) (Mg ha^{-1})

0·7; 0·3; 0·85 and 0·15 = % areas expressed as a proportion·

2.4. *Soil physical and biological condition measurements*

The effects of the soil management treatments on:

I. Aggregate stability: was determined using wet sieving apparatus (Eijkelamp, Model 08.13) with 1–2 mm sized aggregates, collected in 80 mm diameter cores to a depth of 50 mm (Abell, 2016).
II. Soil porosity: was determined by scanning 50 mm diameter x 300 mm long soil cores using a Phoenix v=tome|x m X-ray microfocus CT system (The University of Nottingham, 2022) at the Hounsfield Facility, the University of Nottingham (Millington et al., 2018).
III. Soil organic matter content: was determined using the loss on ignition technique (Salehi et al., 2011) conducted on samples collected at three sampling points in each experimental plot (Kaczorowska-Dolowy et al., 2019).
IV. Root development: was conducted for the winter bean crop at the full stage of flowering in May 2018. This was undertaken by carefully extracting the plants into a profile pit, washing them and measuring the tap root diameter and length (Kaczorowska-Dolowy et al., 2019). In June 2019 a similar exercise was conducted on the roots of the winter wheat crop by collecting 50 mm diameter x 300 mmm long samples and then washing, air drying, and scanning them as described by Kaczorowska-Dolowy (2022).
V. Earthworm population: was measured immediately prior to tillage and drilling in 2020 with a mustard expellant of 4 g mustard powder per litre of water and applied to the soil surface in 225 mm diameter rings (Kaczorowska-Dolowy, 2022).

2.5. *Data analysis*

Analysis of variance (ANOVA) was used to analyse data from single cropping seasons using the then-current versions of Genstat (VSN International, 2020). Post-hoc test for significant differences of means was conducted using Tukey's test.

To compare the long term effects, combine yield data (t ha^{-1}) for the harvest years of 2013 to the 2020 was standardised by calculating the yield for each plot as the percentage of the grand mean for that harvest year. The standardised yield data was analysed by repeated measures ANOVA using Genstat 20 (VSN International, 2020) with Treatment structure = Traffic x Tillage, Block Structure = Block, Time Points = Harvest Year. Examination of the histogram of residuals showed all data to be normally distributed.

2.6. *Economics*

The economic effects of different soil management systems on crop yield were calculated using November 2019 crop prices from the Agriculture and Horticulture Development Board (2019). This date was selected to avoid any short-term potential pandemic effects on commodity prices.

These were compared to:

I. The cost savings from reduced tillage practices,

Table 1
Hand harvested yields (Mg ha^{-1}) in the traffic lanes and non-trafficked zones of the controlled traffic system plots. means not followed by the same letter, from annual analyses of variance, are significantly different at 5% probability level (Tukey) (Smith, 2016; Millington, 2019; Kaczorowska-Dolowy, 2022).

	Traffic lane	Non-trafficked	Mean
Winter Wheat 2013	*Traffic* $lsd_{5\%} = 1.78$ $p = 0.003$ $p_{interaction} = 0.033$ *c.v.* = 26%		
Deep Tillage	7.69	8.97	8.33
Shallow Tillage	7.04	8.10	7.57
Zero Tillage	4.34	10.72	7.53
Mean	6.36a	9.26b	
Winter Barley 2014	*Traffic* $lsd_{5\%} = 1.27$ $p = 0.009$ *c.v.* = 20%		
Deep Tillage	6.06	8.69	7.37
Shallow Tillage	6.22	7.68	6.95
Zero Tillage	6.79	8.06	7.42
Mean	6.36a	8.14b	
Winter Barley 2015	*Traffic* $lsd_{5\%} = 1.26$ $p = 0.004$ *c.v.* = 13%		
Deep Tillage	9.87	13.24	11.55
Shallow Tillage	10.69	12.53	11.61
Zero Tillage	10.00	10.90	10.45
Mean	10.19a	12.22b	
Spring Oats 2016	*Traffic* $lsd_{5\%} = 0.75$ $p = 0.001$ *c.v.* = 12%		
Deep Tillage	7.31	8.34	7.83
Shallow Tillage	7.01	8.01	7.51
Zero Tillage	5.88	8.20	7.04
Mean	6.74a	8.18b	
Spring Wheat 2017	*Traffic* $lsd_{5\%} = 0.42$ $p = 0.77$ *c.v.* = 15%		
Deep Tillage	3.02	3.07	3.05
Shallow Tillage	3.53	3.46	3.50
Zero Tillage	2.83	3.03	2.93
Mean	3.19	3.13	
Winter Beans 2018	*Traffic* $lsd_{5\%} = 0.55$ $p < 0.001$ *c.v.* = 13%		
Deep Tillage	3.96	5.05	4.51
Shallow Tillage	4.11	6.13	5.12
Zero Tillage	4.30	5.07	4.69
Mean	4.12a	5.42b	
Winter Wheat 2019	*Traffic* $lsd_{5\%} = 0.80$ $p = 0.63$ *c.v.* = 8%		
Deep Tillage	11.46	11.64	11.55
Shallow Tillage	11.61	10.53	11.07
Zero Tillage	11.41	11.76	11.58
Mean	11.49	11.31	
Winter Barley 2020	*Traffic* $lsd_{5\%} = 1.20$ $p < 0.001$ *c.v.* = 29%		
Deep Tillage	2.38	6.37	4.38
Shallow Tillage	3.98	6.29	5.14
Zero Tillage	4.38	5.44	4.91
Mean	3.58a	6.03b	

II. The additional costs of machine guidance systems for CTF systems and
III. The additional costs for LTP systems.

The above costs were estimated using the capital costs provided by leading equipment suppliers to reflect typical farm gate prices in 2020, for two scenarios where:

I. two tractors are used, one for the tillage (either deep or shallow) operation and another for the drilling operation, and
II. one tractor is used for both the tillage (either deep or shallow) and the drilling operations.

In both scenarios the cost comparison was based upon the assumption that a single tractor conducted the zero tillage operation.

It was assumed that:

I. The cost per hectare for the alternative tillage systems would be based upon the maximum area tilled and drilled in the number of available autumn work hours, referred to as the "benchmark" area.
II. The number of available work hours for the autumn tillage and crop establishment period, was based upon 10 h of work per day for 35 autumn work days in a wet year (Soil Survey of England and Wales, 1984 for a Claverley Series soil with a mean annual rainfall of 675 mm).
III. The cost savings from both shallow and zero tillage systems would be compared to that of deep tillage at the benchmark area for deep tillage. Similarly, the cost saving from the zero tillage compared to that of the shallow tillage would be at the benchmark area for shallow tillage.
IV. The fuel consumption for the tillage and drilling operations were those recorded at a working speed of 8 km h^{-1}, in the 2012 using a positive displacement fuel metre reported by Arslan et al. (2014).
V. A satellite navigation system was required for CTF, but not for STP or LTP.
VI. The equipment for the CTF system would cost approximately the same in the long run as equipment for the non-controlled traffic options and would be part of the replacement policy. For CTF it is a matter of selecting equipment that matches the system width and vehicle track gauges.

The cost per hectare for each of the tillage systems was conducted using a simple partial budget after Hunt (2001). The calculations assumed straight-line depreciation, simple interest and equipment size and replacement practices that are consistent with common UK farm practice.

To accommodate smaller farm sizes the economics of machine guidance for CTF and LTP systems for 100–150 ha farms were also considered.

The exchange rate at the time of calculation was: £ 1.00 = US$1.35.

3. Results

3.1. Effect of tillage system on plant establishment

Tillage had no significant effect on the number of plants m^{-2} for the winter wheat and winter barley crops in 2013 and 2014, however in 2016 zero tillage significantly reduced (***$P < 0.001$) plant establishment by 33% compared to deep and shallow tillage for the spring oat crop. Following which the seed rates of zero tillage plots were increased by 25% for all subsequent years.

Despite this, in 2017, the zero tillage treatment for spring wheat (264 plants m^{-2}) was significantly (*$P < 0.01$) lower than the shallow tillage (353 plants m^{-2}). The average number of winter bean plants m^{-2} was significantly greater (***$P < 0.001$) in 2018 for the zero tilled treatments than for the deep and shallow tillage (22.0, 18.5 and 18.8 plants m^{-2} respectively). Tillage had no significant effect on the number of plants m^{-2} for the winter wheat and winter barley crops in 2019 and 2020. Data for winter barley in 2015 was not directly comparable to the other data sets.

3.2. Effect of traffic and tillage on soil physical and biological properties

The soil physical and biological conditions in the soil of the experimental plots showed that:

I. The percentage of water stable aggregates was unaffected by the traffic treatments, however, the effect of zero tillage (87.5%) was significantly greater (*$P < 0.05$) than the deep tillage treatment (77.8%) with the shallow tillage (83.4%) displaying no significant difference from either (Abell, 2016). As all of the soils were in the same condition at the outset of the experiment in 2011, the difference in aggregate stability between the zero tilled soil and the deep and shallow tilled soils can be explained by the process of aggregate creation for zero tillage systems described by Reichert et al. (2016).
II. The results of the X-ray computed tomography studies with soil cores collected in 2016 by Millington (2019), found that the

Table 2
Combine harvester yields (Mg ha^{-1}) for a range of tillage and traffic systems. Annual means not followed by the same letter, from annual analyses of variance, are significantly different at 5% probability level (Tukey) (Smith, 2016; Millington, 2019; Kaczorowska-Dolowy, 2022).

	Standard Tyre Inflation Pressure STP	Low Tyre Inflation Pressure LTP	Controlled Traffic $CTF_{30\%}$	Mean	Controlled Traffic $CTF_{15\%}$
Winter Wheat 2013 $p_{traffic} = 0.073$ $p_{tillage} < 0.001$ *c.v. = 6.7% Traffic and Tillage* $lsd_{5\%} = 0.43$					
Deep Tillage	7.29	7.71	7.93	7.65b	8.11
Shallow Tillage	7.67	7.93	8.39	8.00b	8.56
Zero Tillage	6.87	7.02	7.01	6.97a	7.78
Mean	7.28a	7.55ab	7.78b	7.54	8.15
Winter Barley 2014 $p_{traffic} = 0.68$ $p_{tillage} = 0.86$ *c.v. = 6.5%*					
Deep tillage	8.50	8.50	8.50	8.50	8.92
Shallow Tillage	8.60	8.20	9.10	8.63	9.37
Zero Tillage	8.80	8.60	8.40	8.60	8.61
Mean	8.63	8.43	8.67	8.58	8.97
Winter Barley 2015 $p_{tillage} < 0.001$ *c.v. = 7.4% Tillage* $lsd_{5\%} = 0.66$					
Deep Tillage	10.67	10.96	11.02	10.88b	11.93
Shallow Tillage	11.02	11.09	10.89	11.00b	11.39
Zero Tillage	9.49	9.54	9.82	9.62a	10.07
Mean	10.40	10.53	10.58	10.99	11.13
Spring Oats 2016 $p_{traffic} = 0.057$ $p_{tillage} < 0.001$ *c.v. = 6.5% Traffic and Tillage* $lsd_{5\%} = 0.46$					
Deep Tillage	8.61	8.96	9.12	8.90b	9.28
Shallow Tillage	8.81	8.86	9.06	8.91b	9.23
Zero Tillage	6.70	6.91	7.60	7.07a	7.95
Mean	8.04a	8.25ab	8.60b	8.29	8.82
Spring Wheat 2017 $p_{tillage} < 0.001$ $p_{interaction} < 0.001$ *c.v. = 4.6% Tillage* $lsd_{5\%} = 0.14$ *Traffic x Tillage* $lsd_{5\%} = 0.24$					
Deep Tillage	3.70	3.77	3.72	3.73b	3.74
Shallow Tillage	3.51	3.62	3.78	3.64b	3.76
Zero Tillage	3.68	3.19	3.12	3.33a	3.18
Mean	3.63	3.53	3.54	3.57	3.56
Winter Beans 2018 $p_{traffic} = 0.005$ *c.v = 5.3% Traffic* $lsd_{5\%} = 0.18$					
Deep Tillage	3.79	4.17	4.07	4.01	4.21
Shallow Tillage	3.85	3.87	4.19	3.97	4.42
Zero Tillage	3.82	4.02	4.13	3.99	4.23
Mean	3.82a	4.02ab	4.13b	3.99	4.29
Winter Wheat 2019 $p_{tillage} < 0.001$ *c.v. = 1.8% Tillage* $lsd_{5\%} = 0.16$					
Deep Tillage	10.60	10.80	10.90	10.75a	10.91
Shallow Tillage	10.70	10.60	10.70	10.67a	10.52
Zero Tillage	11.10	11.40	11.00	11.17b	11.10
Mean	10.80	10.93	10.87	10.86	10.84
Winter Barley 2020 $p_{traffic} = 0.068$ $p_{tillage} = 0.077$ *c.v. = 10.7% Tillage and Traffic* $lsd_{5\%} = 0.44$					
Deep Tillage	4.24	4.52	5.16	4.64	5.76
Shallow Tillage	4.78	4.70	5.57	5.02	5.91
Zero Tillage	5.13	5.31	4.95	5.13	5.10
Mean	4.72	4.84	5.23	4.93	5.59

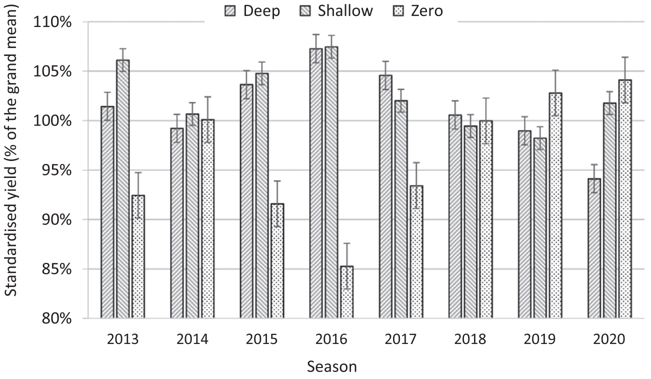

Fig. 4. Standardised crop yield (treatment means expressed as a percentage of the yearly grand mean) for deep, shallow and zero-tillage for the duration of the experiment. The whiskers on each bar represent the standard error (Kaczorowska-Dolowy, 2022).

differences ($**P < 0.01$) in soil macro porosity between unwheeled CTF (17.1%) and those trafficked with LTP (11.7%) and STP (11.7%) were restricted to the soil layers from 50 mm to 200 mm. Subsequent studies showed that in 2019 the soil macro porosity had reduced, however, the unwheeled CTF (13.7%) soil remained significantly greater ($***P < 0.001$) than LTP (8.4%) and STP (6.8%) (Kaczorowska-Dolowy, 2022).

III. The soil organic matter content, in the surface layer (0–100 mm), was significantly greater ($*P < 0.05$) in both the zero and shallow tillage (4.44% and 4.35% respectively) than the deep tillage treatments (4.11%). The traffic system had no significant effect on soil organic matter (Kaczorowska-Dolowy, 2022).

IV. The root length and diameter (at a depth of 100 mm) of the winter bean crop were both significantly ($***P < 0.001$) greater for the CTF plots (177 mm and 3.4 mm) than STP (126 mm and 1.4 mm) and LTP (131 mm and 1.7 mm). The tillage system had no significant effect (Kaczorowska, Dolowy et al., 2019). This also applied in 2019 when the tillage system had no significant effect on the root density of the winter wheat crop but the effect of traffic was significant ($**P < 0.01$). In this case the root density of the CTF (0.152 cm^2 cm^{-3}) was greater than STP (0.114 cm^2 cm^{-3}) and the LTP (0.124 cm^2 cm^{-3}) was not statistically different to either (Kaczorowska-Dolowy, 2022).

V. The earthworm numbers for the zero tillage treatment (183 m^{-2}) were significantly greater ($***P < 0.001$) than the deep and shallow tillage treatments (80 m^{-2} and 128 m^{-2} respectively). The traffic system had no significant effect on the earthworm population (Kaczorowska-Dolowy, 2022).

3.3. *Effect of the CTF traffic lane on crop yield*

The yield data for the main effects of the hand harvested grain in Table 1 show that yields in the traffic lane of the CTF treatments were significantly less than that of the non-trafficked zone for all seasons/crops with the exception of the spring wheat in 2017 and winter wheat in 2019. The data also show that the mean yield was not affected by the tillage system. There was, however, a significant interaction ($*P < 0.05$)

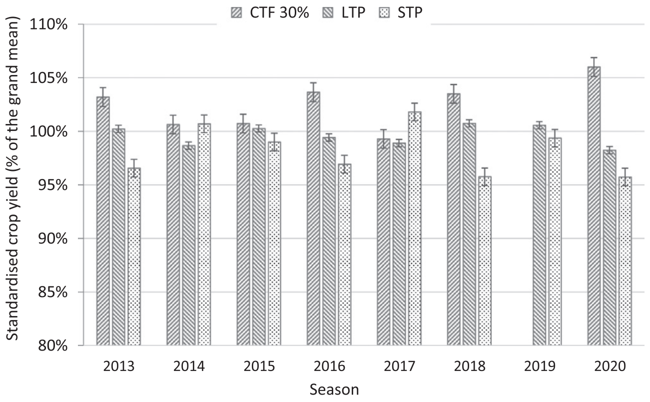

Fig. 5. Standardised crop yield (treatment means expressed as a percentage of the yearly grand mean) for controlled traffic ($CTF_{30\%}$); low tyre inflation pressure (LTP) and standard tyre inflation pressure (STP) systems for the duration of the experiment. The whiskers on each bar represent the standard error (Kaczorowska-Dolowy, 2022).

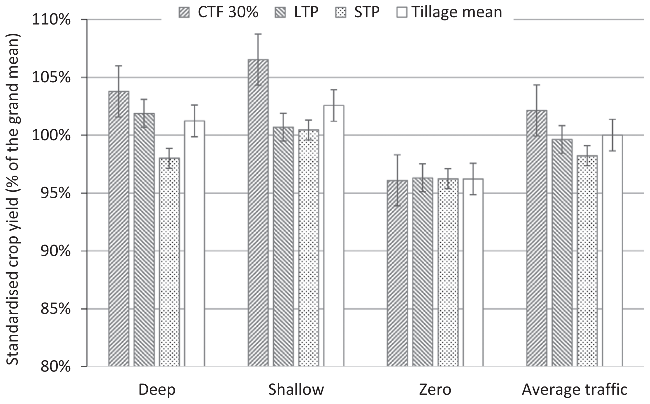

Fig. 6. Standardised crop yield (treatment means expressed as a percentage of the yearly grand mean) for controlled traffic ($CTF_{30\%}$); low tyre inflation pressure (LTP) and standard tyre inflation pressure (STP) systems for deep, shallow and zero tillage systems for the duration of the experiment. The whiskers on each bar represent the standard error (Kaczorowska-Dolowy, 2022).

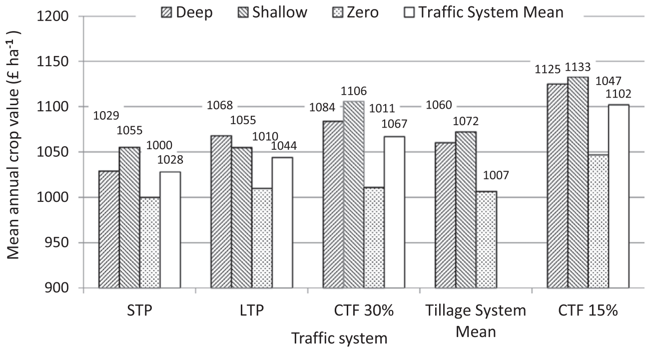

Fig. 7. Effect of deep, shallow and zero tillage for standard tyre inflation pressure (STP), low tyre inflation pressure (LTP) and controlled traffic ($CTF_{30\%}$ and $CTF_{15\%}$) systems on the mean annual crop value (£ ha^{-1}) from 2013 to 2020.

between traffic and tillage in 2013, with a 6.38 Mg ha^{-1} difference in the winter wheat yield for the zero tillage treatments where the traffic lane effects resulted in a yield of 4.34 Mg ha^{-1} whilst the non-trafficked zone was higher than all other treatments at 10.72 Mg ha^{-1}.

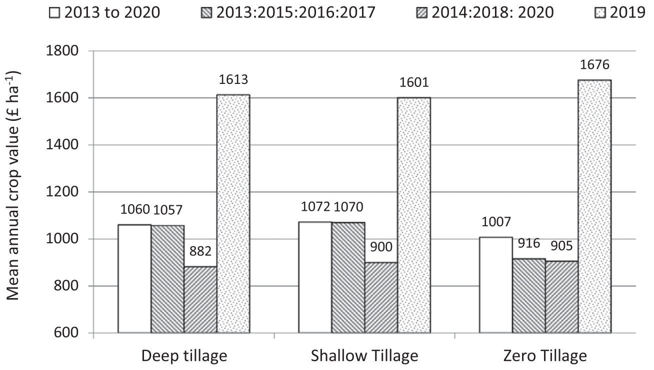

Fig. 8. Effect of deep, shallow and zero tillage systems on the mean annual crop value (£ ha^{-1}) from 2013 to 2020, together with the data for 2013:2015:2016:2017, 2014:2018:2020 and 2019.

The effect of traffic reduced the mean yield by 2.90, 1.78, 2.03 and 1.44 Mg ha^{-1} for each of the 2013–2016 harvest dates and 1.30 and 2.45 Mg ha^{-1} for 2018 and 2020 respectively. These are equivalent to yield differences of 31%, 22%, 17%, 18% and 24% and 41% respectively, giving a mean annual yield reduction in the traffic lanes of 19% when the non-significant effects (0%) of 2017 and 2019 are included in the mean.

3.4. Effect of traffic and tillage systems on crop yield

The combine harvester grain yields for all seasons/crops are given in Table 2, which also shows the estimated yield for a $CTF_{15\%}$ system based on Eqs. (1) and (2). The effects of tillage and traffic over the period of the study, expressed as a percentage of the grand mean for that year is shown in Figs. 4, 5 and 6.

The repeated measures ANOVA showed that on average for the eight seasons the effect of tillage was significant (***$P < 0.001$) with both deep and shallow tillage producing a significantly (*$P < 0.05$) greater yield than zero tillage. The yields from zero tillage were 6% and 5% less than from shallow and deep tillage respectively. Caution must be applied before dismissing zero tillage because the interaction between tillage and harvest year was significant (***$P < 0.001$) showing that the effect of tillage was not consistent across the eight years. Individual ANOVAs on each year's data showed that zero tillage gave the lowest yield in 2013, 2015, 2016, and 2017; no significant effect of tillage in 2014, 2018 and 2020, and zero tillage gave the highest yield in 2019, as shown in Fig. 4.

The average crop yield from zero tillage was 11.6% and 10.7% lower than the average for shallow and deep tillage respectively across five of the eight years. In 2019 the average crop yield from the zero tillage treatments was 3.9% and 4.7% greater than the average shallow and deep tillage yields respectively. Table 2 shows that there was no significant difference between the crop yields from deep and shallow tillage in any year.

The repeated measures analysis showed that the main effect of traffic, shown in Fig. 5, was significant (***$P < 0.001$) and consistent over all eight years, with no significant interaction between traffic and harvest year. Overall $CTF_{30\%}$ produced a significantly (*$P < 0.05$) 4% greater yield than standard tyre inflation pressure (STP) as shown in Fig. 6. On average the yield of low tyre inflation pressure (LTP) treatment was not significantly ($P > 0.05$) greater than STP, but there was a significant interaction between tillage and traffic (*$P < 0.05$).

The standardised crop yield data given in Fig. 6 shows that for the yield of the:

I. Deep tillage treatment: both $CTF_{30\%}$ and LTP gave a significantly (*$P < 0.05$) greater yield than STP.

Table 3
Cost of tillage and drilling for the “benchmark” areas in 350 h.

	2 Tractor scenario (Deep or Shallow Tillage and Seed drill and a single tractor for Zero tillage)		1 Tractor scenario (All operations)	
Tillage System	Benchmark Area (ha)	Cost (£ ha^{-1})	Benchmark Area (ha)	Cost (£ ha^{-1})
4 m Deep Tillage	900	108	540	120
4 m Shallow Tillage	900	83	540	88
4 m Zero Tillage	900	46	540	64
4 m Shallow Tillage	1350	67	675	72
4 m Zero Tillage	1350	36	675	55
9 m Deep Tillage	2000	115	1200	124
9 m Shallow Tillage	2000	87	1200	89
9 m Zero Tillage	2000	48	1200	64
9 m Shallow Tillage	3000	73	1500	80
9 m Zero Tillage	3000	40	1500	56

Table 4
Cost savings (£ ha^{-1}) between alternative tillage systems for given “benchmark” areas for 4 m and 9 m wide systems. * Benchmark area is unattainable with deep tillage ** Inappropriate benchmark area for the shallow – zero comparison.

	Cost savings between tillage systems (£ ha^{-1})		
Tillage system width (m) & Benchmark area (ha)	Deep - Zero	Deep - Shallow	Shallow - Zero
One Tractor Scenario			
4 m & 540 ha	56	32	* *
4 m & 675 ha	*	*	17
9 m & 1200 ha	60	35	*
9 m & 1500 ha	*	*	19
Two Tractor Scenario			
4 m & 900 ha	62	25	* *
4 m & 1350 ha	*	*	31
9 m & 2000 ha	67	28	*
9 m & 3000 ha	*	*	33

II. Shallow tillage treatment: CTF$_{30\%}$ gave a significantly (*$P < 0.05$) greater yield than both LTP and STP treatments, with no significant difference between LTP and STP.
III. Zero tillage: there was no significant difference between any of the traffic treatments.

The estimated mean crop yield for a CTF$_{15\%}$ system for the three tillage systems for each crop/year shows a 4.8%, 3.5%, 5.2%, 2.6%, 0.0%, 3.9%, 0.0% and 6.9% yield differential with respect to CTF$_{30\%}$ with an overall mean annual yield improvement of 3%.

3.5. Crop yields and tillage system costs

The mean annual value of the crops for the different tillage and traffic systems (including the computed CTF$_{15\%}$ values) for the 8 years of data is given in Fig. 7. These are based upon the November 2019 crop values for the UK given by AHDB Cereals and Oilseeds (2019) for: wheat £ 150 Mg^{-1}, barley £ 125 Mg^{-1}, beans £ 250 Mg^{-1} and oats £ 130 Mg^{-1}.

The tillage system data given in both Figs. 7 and 8 for the period 2013 – 2020 show that the mean annual crop values of zero compared to the mean of the shallow and deep tillage systems was reduced by £ 59 ha^{-1}.

Fig. 8 shows that the mean crop value from the deep and shallow tillage systems for years 2013, 2015, 2016 and 2017 was effectively the same as for the full 8 years. Zero tillage, however, returned £ 148 ha^{-1} less value over the 4 year period when zero tillage yields were significantly lower than those of the deep and shallow tillage.

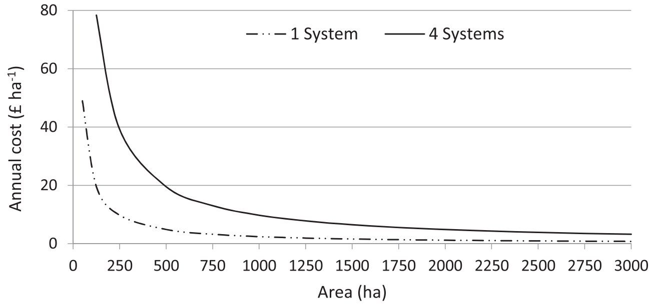

Fig. 9. Annual cost (£ ha^{-1}) for one and four RTK-GPS fully integrated steering guidance systems.

Table 5
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	45	26
Shallow tillage	48	31
Zero tillage	223	52

Table 6
Increase/Decrease in annual income and payback period from CTF$_{30\%}$ and CTF$_{15\%}$ systems for the three tillage systems for “benchmark” areas of 540 ha and 2000ha with 4 guidance systems, together with those for 100 and 150 ha farms with two guidance systems.

	CTF$_{30\%}$		CTF$_{15\%}$	
Area (A), ha	Increase/Decrease in annual income (I), £ year^{-1}	Payback period (T), years	Increase/Decrease in annual income (I), £ year^{-1}	Payback period (T), years
Deep Tillage				
100	600	50	4700	6.4
150	3350	8.9	9500	3.2
540	19,900	3.0	42,040	1.4
2000	100,200	0.6	182,200	0.3
Shallow Tillage				
100	200	150	2900	10.3
150	2750	10.9	6800	4.4
540	17,740	3.4	32,320	1.8
2000	92,200	0.7	146,200	0.4
Zero Tillage				
100	-3800	Not viable	-200	Not viable
150	-3250	Not viable	2150	14
540	-3860	Not viable	15,580	3.9
2000	12,200	4.9	84,200	0.7

Tillage had no significant effect on yield and hence the crop value in 2014, 2018 and 2020 with an overall mean of c. £ 900 ha^{-1}. In 2019, the year with the highest yield, the mean annual value of the crop from zero tillage was £ 69 ha^{-1} greater than the mean of deep and shallow tillage respectively.

The costs of tillage and drilling for the range of “benchmark” areas estimated in the Appendix are given in Table 3. These enable comparisons to be made between the cost of the tillage systems for both the 4 m and 9 m wide systems, for both tractor scenarios. These range from c. £ 40 ha^{-1} for zero tillage to c. £ 120 ha^{-1} for deep tillage, depending upon the number of tractors and the operating width.

Table 4 shows that for the different tillage and tractor systems the cost savings for zero tillage compared to deep tillage are £ 58 ha^{-1} (+/- £2 ha^{-1}) and £ 65 ha^{-1} (+/- £3 ha^{-1}) for the one and two tractor scenarios respectively, similarly the shallow tillage compared to deep

Table 7
Additional capital costs (£,) annual cost (£ year^{-1}) and annual cost per hectare (£ ha^{-1}) and breakeven areas (ha) for LTP tyres compared to STP tyres for 4 m and 9 m wide systems.

	Additional costs (£)	
	4 m	9 m
Tractor: 400 kW tillage		940
Tractor: 300 kW drill		870
Tractor: 180 kW tillage	2200	
Tractor: 135 kW drill	2200	
Tractors: general duty: for 2 and 4 tractors (4 m & 9 m respectively)	4400	8800
Trailers: tandem axle: for 3 and 6 trailers (4 m & 9 m respectively)	540	1080
Combine harvester(s): for 1 and 2 (4 m & 9 m respectively)	1430	2860
Sprayer(s): for 1 and 2 (4 m & 9 m respectively)	5180	10,360
Total difference in capital cost – two tractor system (P)	15,950	24,910
Total difference in capital cost – one tractor system (P)	13,750	24,040
	£ year^{-1}	
Total annual cost difference: two tractor system (C_a) for 900 ha & 2000 ha	2054	3207
Total annual cost difference: one tractor system (C_a) for 540 ha & 1200 ha	1770	3095
	£ ha^{-1}	
Annual cost/ha: for 2 tractor system for 900 ha and 2000ha	2.28	1.60
Annual cost/ha: for 1 tractor system for 540 ha and 1200 ha	3.28	2.58
	Area (ha)	
Breakeven area: for 2 tractor system: 4 m and 9 m systems	53	82
Breakeven area: for 1 tractor system: 4 m and 9 m systems	45	79

I. The higher additional cost for the low pressure tyres for the 135 kW and 180 kW tractors in comparison to the additional cost of tyres for 300 kW and 400 kW tractors reflect the fact that the cost of the standard pressure tyres for the lower power range are relatively inexpensive.
II. The higher additional cost for the sprayer tyres relative to the combine harvester tyres is due to the complexity in design and construction to meet the design standard for "narrow" tyres with small volumes compared to the "wider floatation" tyres for combine harvesters. (G. Brookes, personal communication, 20 April 2022)

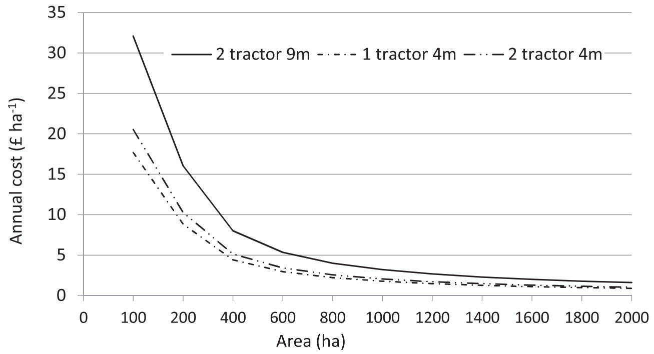

Fig. 10. Additional annual cost (£ ha^{-1}) for the low (LTP) compared with the standard (STP) tyre pressure system for the 2 tractor 9 m and 4 m systems and the 1 tractor 4 m system.

tillage are £ 33 ha^{-1} (+/- £2 ha^{-1}) and £ 27 ha^{-1} (+/- £2 ha^{-1}) and the zero tillage compared to shallow tillage are £ 18 ha^{-1} (+/- £1ha^{-1}) and £ 32 ha^{-1} (+/- £1 ha^{-1}).

3.6. *Crop yields and CTF system costs*

The additional cost of CTF systems was based upon the additional expenditure on vehicle guidance and auto-steering systems (Godwin et al., 2017 and Hargreaves et al., 2019). It was assumed that a farmer or contractor contemplating CTF would initially adapt existing equipment. The cost of any adaptions would be difficult to estimate as they would be specific to the machinery compliment of the individual farm. Future improvements to equipment matching would be part of the longer - term replacement policy, such that in the longer term the equipment for CTF would have a similar cost to that used in conventional non - controlled traffic systems.

In this analysis the costs are based on the preferred practical, albeit most expensive system, namely: a high repeatable positioning accuracy (Real Time Kinematic (+/- 20 mm)) fully integrated vehicle guidance system with auto-steering (Hargreaves et al., 2019). With a capital cost (*P*) of £ 15,000, an assumed cost of capital of 3%, a depreciation rate of 10% per year and an annual subscription fee of £ 500 per year, the total annual cost (*Ca*) is £ 2450 year^{-1}. The small costs (< £0.50 ha^{-1}) of repair and maintenance are not included. Fig. 9 shows the annual cost per hectare for a single system ranging from £ 49 ha^{-1} to < £1.00 ha^{-1} for areas from 50 ha to 3000 ha. The cost per hectare for larger enterprises where 4 guidance systems may be required is also shown.

The breakeven areas for $CTF_{30\%}$ and $CTF_{15\%}$ shown in Table 5 for each tillage system were obtained by dividing the annual cost of £ 2450 for a single guidance system, by the mean annual crop benefit of the CTF system over STP. Using data from Fig. 7, the mean annual crop benefit over STP for $CTF_{30\%}$ and $CTF_{15\%}$ was £ 55 ha^{-1} (5.14%) and £ 96 ha^{-1} (9.33%) for deep tillage; £ 51 ha^{-1} (4.83%) and £ 78.00 ha^{-1} (7.39%) for shallow tillage and £ 11 ha^{-1} (1.1%) and £ 47.00 ha^{-1} (4.7%) for the zero till. Table 5 shows that the breakeven areas for zero tillage for the 2011–2020 period were greater than those for the deep and shallow tillage, reflecting the lower overall yield benefit from CTF for the zero tillage treatment. This is not unexpected, as the zero tillage yields, despite the overall improvement in yield for 2019, given in Table 2, show no benefit of CTF over STP. The zero tillage data in particular highlight the benefit of reducing the traffic lane area to 15% of the field.

The increase/decrease in annual income (*I*) (Eq. (3)) and the payback period *T* (Eq. (4)) for $CTF_{30\%}$ and $CTF_{15\%}$ compared with STP for the three tillage systems using "benchmark" areas of 540 ha and 2000 ha with 4 guidance systems are given in Table 6. Also shown are those for 100 ha and 150 ha farms with two guidance systems (one for the combine harvester and one for the tillage and drilling tractor).

$$I = Y_b\,A - C_a \tag{3}$$

$$T = P/I \tag{4}$$

Where:

I = Increase in annual income (£ year^{-1})

Y_b=Yield benefit over STP (£ ha^{-1} year^{-1})

A= Area (ha)

C_a= Total annual cost (£ year^{-1})

T= Payback Period (years)

P = Capital cost (£)

3.7. *Crop yields and LTP costs*

The beneficial effect of LTP on crop yields was significantly greater (*$P < 0.05$) than those of STP for the deep tillage treatments. The average additional yield (Fig. 7) over the period of the experiment was 3.9%, worth £ 39 $ha^{-1}year^{-1}$.

The additional cost of fitting LTP tyres to all field going equipment was based upon the total difference in capital cost between standard (STP) and low pressure (high flexion) (LTP) tyres, assuming: a tyre life of 8years (4000 hrs at 500 hrs $year^{-1}$, G. Brookes, personal communication, 20 October 2020) and a cost of capital of 3%, as given in Table 7, for:

I. Tillage and drilling tractors,
II. General duty tractors servicing the grain trailers, the combine harvester(s) and sprayer(s) as recommended by Godwin et al. (1992),
III. Tandem axle grain trailers that operate in the adjacent wheel tracks to the combine harvester into which the grain is unloaded "on the move",
IV. Combine harvesters that harvest up to 1200 ha $year^{-1}$ at a harvest rate of c.60 Mg hr^{-1}, requiring the support of 3 × 20 t tandem axle trailers,
V. Sprayers that spray an area up to 1500 ha $year^{-1}$ (P. C. H. Miller, personal communication, 16 April 2021).

Based on the above assumptions the cost curves (£ ha^{-1}) in Fig. 10 show the additional annual cost per ha of equipping the tractors, combine harvester(s), trailers and crop sprayers with low pressure tyres for 4 m and 9 m wide non-controlled traffic LTP systems. The difference in the cost curves (£ ha^{-1}) between the one and two tractors is negligible for the 9 m systems; hence the data shown in Fig. 10 is for the two-tractor case only. The 4 m wide systems show, as an example, a reduced cost of c. £ 0.60 ha^{-1} in favour of the single tractor for an area of 500 ha.

Table 7 also shows the additional costs per hectare of the LTP tyres compared to the STP tyres for the benchmark areas given in Table 3. These range between £ 1.60 ha^{-1} and £ 3.28 ha^{-1} for the two tractor 9 m system and the single tractor 4 m system for 2000 ha and 540 ha respectively.

Total increases in annual income (Eq. (3)) ranged from £ 19,290, £ 33,046, £ 43,705 and £ 74,793 for the 4 and 9 m systems cultivating 540, 900, 1200 and 2000 ha respectively. Yielding payback periods (Eq. (4)) of 0.71, 0.48, 0.55 and 0.33 years respectively.

While the additional costs, shown in Fig. 10, should be acceptable for larger farm sizes they are not economically viable for smaller enterprises, hence a lower cost option was considered for a 100 ha farm. In this case it was assumed that:

I. Low inflation pressure tyres are fitted to a single 180 kW tractor (£2200) (which performs both the tillage and drilling operations) and to the combine harvester (£1430),
II. The combine harvester discharges the harvested crop into stationary trailers at the field headland, rather than "on the move" (as assumed for the larger enterprises), hence dispensing with the need for LTP tyres for the general duty tractors and grain trailers.

In this case the additional capital cost (P) was £ 3630, with an annual cost (Ca) of £ 467 giving a current annual cost per hectare of £ 4.67 ha^{-1} with an increase in annual income of £ 3433, a breakeven area of 12 ha and a payback period of 1 year.

4. Discussion

4.1. *Crop yields and tillage system costs*

Given the significance of the effect of tillage it is logical, to discuss the implications of alternative tillage systems prior to the traffic effects. Considering the conclusions from Cannell et al. (1978), Morris et al. (2010) and Soane et al. (2012) it was not unexpected that the yield from zero tillage would be less than those of deep and shallow tillage in the early years of the work, as the study was conducted in a sandy soil, in climatic conditions that are less well suited for zero tillage. A different perspective, however, was given by Campbell et al. (1986) who showed that the crop yields from soils in Scotland, that would have been classified as being unsuitable for zero tillage with conventional traffic was satisfactory with zero traffic.

The data in Section 3.2 showed that, after a number of years, zero tillage had significantly beneficial effects on soil aggregation (*$P < 0.05$), organic matter content (*$P < 0.05$) and earthworm numbers (***$P < 0.001$). These results help to explain the return in crop yield with time, with similar crop yields from all tillage treatments in 2018 and 2020, agreeing with the trends reported by Carter (1994) and Morris et al. (2014). The results for the winter bean crop may be explained by the significantly higher plant population for the zero tillage treatments in 2018. The most noteworthy effect is that in 2019 the yield benefit from the zero-till treatment of £ 69 ha^{-1} was greater than the mean of the deep and shallow tillage, an increase in yield that cannot be attributed to the plant population as tillage had no significant effect on the number of plants m^{-2}. The benefit of the increase in zero tillage yield when added to the cost saving in tillage operations, given in Table 4, for the one and two tractor scenarios respectively of £ 58 ha^{-1} and £ 65 ha^{-1} gave benefits worth £ 127 ha^{-1} and £ 134 ha^{-1} compared to deep tillage; and similarly, £ 87 ha^{-1} and £ 101 ha^{-1} for shallow tillage.

Further comparisons show that:

I. Over the eight-year period of the experiment the cost saving from zero tillage compared to:
  a. deep tillage, for the one and two tractor scenarios, of £ 58 ha^{-1} and £ 65 ha^{-1} compensated for the mean overall loss in crop value of £ 59 ha^{-1}
  b. shallow tillage, for the one and two tractor scenarios, of £ 18 ha^{-1} to £ 32 ha^{-1} failed to compensate for the mean overall loss in crop value of £ 59 ha^{-1}.
II. With no significant difference between deep and shallow tillage yields, shallow tillage would save £ 33 ha^{-1} and £ 27 ha^{-1} per year in establishment costs for the one and two tractor scenarios.
III. In 2014, 2018 and 2020 when tillage did not significantly affect crop yield and hence value, there was a benefit from the reduction in cost from zero tillage of:
  a. £ 58 ha^{-1} and £ 65 ha^{-1} for the one and two tractor scenarios of over the costs of the deep tillage and
  b. £ 18 ha^{-1} and £ 32 ha^{-1} for the one and two tractor scenarios of over the costs of the shallow tillage system.

The comparison between the estimated tillage costs given in Table 3, for the one tractor scenario for both 4 m and 9 m systems, shows that they are similar to the costs published by the National Association of Agricultural Contractors (2020) from their contractor survey of £ 110 ha^{-1}, £ 87 ha^{-1} and £ 59 ha^{-1} for the deep, shallow and zero tillage respectively.

4.2. *Crop yields and CTF system costs*

Controlled traffic farming (CTF) showed significantly (**$P < 0.01$ and P * **<0.001) higher soil macro porosities in 2016 and 2019, together with significantly (***$P < 0.001$) improved root length and diameter for the winter beans in 2018 compared to both LTP and STP.

CTF also significantly (**$P < 0.01$) improved root density of the winter wheat over that of STP in 2019. All of which help to explain the yield benefit over the eight years of the experiment compared to the other traffic systems. These benefits were primarily associated with the deep and shallow tillage practices with 4% and 7% increases in yield from $CTF_{30\%}$ and $CTF_{15\%}$ respectively. These results are:

I. Substantially different to those shown by Etana et al. (2020) in Sweden who concluded that on average there was no difference between the crop yields from CTF and random traffic farming systems.
II. Similar to the results reported by Galambosova et al. (2017) of a 0.5 Mg ha^{-1} increase in yield for winter wheat, barley and maize.
III. Similar to the results reported by Chamen (2011) of a c.7% increase in yield for wheat as shown in Fig. 1, but less than the mean of c.17% for the range of arable crops. The data for forage grass is not included because the grass crop benefits from a reduction in the direct impact of traffic on the grass crop in addition to the compaction effects (Hargreaves et al., 2019).

The differences between the CTF benefits given in these experiments compared to those reported by Chamen (2011) could be due to the constraints imposed by having relatively narrow plots, requiring a 4 m wide cutter bar on a smaller lighter combine (c.7.5 Mg) than those used in current commercial practice (20–30 Mg) (W. C. T. Chamen, personal communication, 15 April 2021).

However, with the exception of the $CTF_{30\%}$ with zero tillage, CTF systems have relatively low breakeven areas as shown in Table 5 and substantial increases annual income for 540 and 2000 ha farms, with short payback periods as shown in Table 6, making the investment in guidance and auto-steer equipment for CTF worthwhile. The data in Table 5 show that for a farm requiring four guidance systems, the breakeven areas (c.100 to c .200 ha) are substantially less than the "benchmark" areas worked in 350 hrs. Similarly, with the exception of $CTF_{30\%}$, smaller farms requiring two guidance systems have a breakeven areas of less than c .100 ha.

Table 6 shows substantial increases in income for both the deep and shallow tillage treatments on 540 and 2000 ha farms for both $CTF_{30\%}$ and $CTF_{15\%}$ systems. These ranged from £ 17,740 to £ 182,200, with payback periods (*T*) (Eq. 4) from 3.4 to 0.3 years. The returns were less for zero till where the $CTF_{30\%}$ system was not economically viable for 540 ha. For a 100 ha farm with two guidance systems $CTF_{15\%}$ produced small gains for deep and shallow tillage, however with payback periods of 6.4 and 10.3 years respectively. The either small (with long payback periods) or negative increase in annual income for $CTF_{30\%}$ for all tillage systems and the $CTF_{15\%}$ for zero tillage are in agreement with the breakeven area data in Table 5 by confirming that the return from 100 ha is insufficient to cover the costs of the guidance systems for $CTF_{30\%}$. Increasing the area to 150 ha produces an increase in annual income (I) and reduces the payback periods (T) for both $CTF_{30\%}$ and $CTF_{15\%}$. While $CTF_{30\%}$ is marginal with payback periods of 8.9 and 10.9 years for both the deep and shallow tillage, $CTF_{15\%}$ has payback periods of 3.2 and 4.4 years. With non-viable or 14 year payback periods for zero tillage.

4.3. *Crop yields and LTP costs*

Subtracting the annual costs of the LTP tyres of between £ 1.60 ha^{-1} and £ 3.28 ha^{-1} (Table 7) from the mean annual value yield (£39 ha^{-1}) result in an overall benefit of between £ 36 ha^{-1} to £ 37 ha^{-1} for larger farms, and £ 34 ha^{-1} for the 100 ha farm with a tyre cost of £ 4.67 ha^{-1}. These benefits result in breakeven areas of c. 50 ha and c. 80 ha for the 4 m and 9 m wide systems respectively, and 12 ha for the 100 ha farm, with substantial increases in farm income and payback periods within 1 year.

The overall benefit, with short payback periods, of the use of LTP tyres on deep tilled soils showed that this was cost effective. The increase in benefit, however, is less than the £ 44 ha^{-1} found by Shaheb (2020) for deep tilled silty clay loam soils during a parallel and similar study in a maize/soybean rotation in Illinois. This study also showed significant crop yield benefits from shallow (£23 ha^{-1}) and zero (£28 ha^{-1}) tillage treatments. The difference in the yields for the shallow and zero tillage treatments between the two studies could be attributed to the:

I. Finer particle sizes of the silty clay loam in Illinois being more susceptible to compaction than the sandy loam. Harris (1971) refers to Hovanesian (1958) who states that the changes in bulk density for a given mean soil stress were significantly different between sandy loam (0.12 Mg m^{-3}) and silt loam (0.42 Mg m^{-3}) soils at 20% moisture content.
II. Effect of the greater mass (18 Mg) of the combine harvester used in Illinois inflicting greater soil damage during the harvesting operations.
III. Greater vulnerability of maize to compaction (Bennie and Botha, 1986 and Latsch and Anken, 2019) than the crops in this UK study.

5. Conclusions

The results of this continuing long term study have shown that the effect of both traffic management and tillage systems can have significant effects on the crop yield and farm economy. Irrespective of the traffic system, there was no statistically significant difference between the yields of the deep and shallow tillage systems, hence the adoption of shallow tillage benefits from the savings in tillage costs of between £ 27 ha^{-1} and £ 33 ha^{-1}.

The initial lower yields of the zero tillage treatment improved with time, producing the same or higher yields as the deep and shallow tillage systems in the final three years. It was also shown that the savings of c. £ 60 ha^{-1} in zero tillage costs compared to deep tillage could compensate for the yield differences from zero tillage over the eight years of the study.

The main effect of traffic was significant and consistent over all eight years, with $CTF_{30\%}$ producing a 4% higher yield than conventional traffic with standard tyre pressures (STP). The effect of reducing the trafficked area to 15% ($CTF_{15\%}$) produces an estimated further increase in mean crop yield of 3.0%. With the exception of $CTF_{30\%}$ with zero tillage systems, the cost of RTK-GPS and auto steering systems are affordable for CTF systems; with short payback periods and substantial increases in farm income.

Where deep tillage practices are required, the use of LTP tyres is cost effective. Additional annual costs of between £ 1.60 ha^{-1} to £ 3.28 ha^{-1} are recovered by the increase in crop yield from LTP over STP systems of 3.9% which is worth a mean annual benefit of £ 39 ha^{-1}.

With careful selection of the equipment, both CTF and LTP systems can be cost effective for relatively small (<100–150 ha) farms.

These results should be of value to farmers, advisors and policy makers in selecting soil management systems when attempting to maintain crop yields in an economically sustainable manner when aiming to improve soil health.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Paula Misiewicz reports financial support and equipment were provided by Manufacture Francaise Des Pneumatiques Michelin and Vaderstad UK Ltd.

Acknowledgements

The authors would like to express thanks to: The Douglas Bomford Trust (UK), The Morley Agricultural Trust (UK), Manufacture Francaise Des Pneumatiques Michelin (France) and Vaderstad UK Ltd. (UK) for sponsoring the work. Vaderstad UK Ltd., Manufacture Francaise Des Pneumatiques Michelin, AGCO, Rea Valley Tractors, Claas UK, Precision Decisions and SOYL for the provision of equipment, equipment specifications, costs and services. W. C. T. Chamen (CTF Europe), G. Brookes (Michelin Tyre plc), M. Alsop (Vaderstad UK Ltd) and J. Lowenberg-DeBoer (Harper Adams University) and P. C. H. Miller (Silsoe Spray Applications Unit) for their advice. The staff of Harper Adams University, particularly Tim Dicker and Sean Lewis for their unstinting help with the field operations.

Appendix. Tillage system costs

The objective of this appendix was to estimate the relative cost of deep, shallow and zero tillage practices as a function of farm size, to enable them to be considered along with the value of the corresponding crop yields when comparing the economic performance of the alternative tillage systems. Which in addition to the benchmark areas chosen in this analysis, would enable comparisons to be made for other sizes of farm.

The relative tillage and planting costs were determined by undertaking a cost analysis for two scenarios with either: i. two tractors (one for deep or shallow tillage and one drilling) or ii. a single tractor for both tillage and drilling operations. In both scenarios the cost comparison was based upon the assumption that a single tractor conducted the zero tillage operation.

This enabled direct comparisons to be made based upon the 2020 capital costs of the 4 m wide equipment used in the field experiment and a 9 m wide system, a width adopted by many farmers with larger enterprises.

The costs were based upon the capital costs (P) of the tractors, cultivators and seed drills used in each of the tillage systems as given in Table A.1. The tractor power for the individual operations was based upon the recommendations of the tillage equipment supplier for UK soils (M. Alsop, personal communication, 20 October 2020). To reflect commercial practice, the shallow tillage operation was based upon the capital cost of a lighter duty cultivator comprising of a double bank of serrated discs followed by a packer roll (Vaderstad Carrier) rather than the Vaderstad Topdown used in the field experiment. The same seed drill was selected for operation with all tillage systems, while there could be changes in specification of the drill (namely different attachments) between the alternative tillage systems, the difference in cost would be small (M. Alsop, personal communication, 16 April 2021).

The annual cost (Ca) of the equipment also shown in Table A.1 was estimated using the cost determination factors given by Hunt (2001), Nix (2001) and Redman (2020):

I. Cost of capital (interest rate): assumed as 3% (base bank rate over the study period of 0.5% + 2.5%).
II. Depreciation: assumed as straight-line depreciation as a percentage of capital cost: tractors 10% per year (J. Lowenberg-DeBoer, personal communication, 20 October 2020), cultivators and seed drills 13% per year.
III. Repair and Maintenance cost (R): assumed as a % of capital cost (P) per 100 work hours: 0.8% tractors, 7% cultivators and 5% for the seed drills, as given by Equation A.1.

$$R = \%\ P/10^4\ r \tag{A.1}$$

Where:

r = the work rate ha $\mathrm{h^{-1}}$ (e.g., 2.56 ha $\mathrm{h^{-1}}$ for 4 m wide system, with an operating speed of 8 km $\mathrm{h^{-1}}$ and a field efficiency of 80% (Hunt, 2001 and Davies et al., 2001)).

Hence, the repair and maintenance costs (R) for a 4 m wide deep cultivator with a capital cost of £ 56,000 is £ 15.30 $\mathrm{ha^{-1}}$.

IV. Tax and Insurance, assumed as 1% of tractor capital cost.

The total annual costs of both 4 m and 9 m tillage and drilling systems are given in Table A.2 by combining the annual cost of the individual machines. The total annual equipment costs range from £ 23,300 for the 4 m wide zero tillage system to £ 107,740 for the 9 m wide deep tillage system.

The annual costs per hectare are given in Figure A.1 by dividing the total annual equipment cost by the tilled area up to 1500 ha and 3000 ha for the 4 m and 9 m systems respectively. Also included in the annual cost per hectare are:

I. Labour charges at £ 15 $\mathrm{h^{-1}}$ and
II. Fuel costs of £ 0.50 $\mathrm{l^{-1}}$ (Agriculture and Horticulture Development Board, 2020) based upon the tractor fuel consumption rates (Arslan et al., 2014) of 13.4 l $\mathrm{ha^{-1}}$ and 7.7 l $\mathrm{ha^{-1}}$ for deep and shallow tillage respectively and all drilling operations of 8.8 l $\mathrm{ha^{-1}}$ for the 4 m wide systems at 8 km $\mathrm{h^{-1}}$ in 2012. It was assumed that for wider and faster operations the fuel consumption increased with the tractor power requirement (i.e., linearly with tillage system width and tractor forward speed).

The tilled area ranges were selected to provide the annual costs per hectare equal to and above a "benchmark" tilled and drilled area, assuming:

I. A working period of 350 working hours (e.g., 35 machinery workdays x 10 h day^{-1}).
II. Nominal working speeds of 8 km h^{-1} for deep tillage and 12 km h^{-1} for both shallow tillage and drilling (M. Alsop, personal communication, 20 October 2020).
III. A field efficiency of 80%.

Hence, in 350 h a 4 m deep tillage system could till and plant an area of 900 ha and because they have the same speed of work, both the shallow and zero tillage systems areas of 1350 ha. Correspondingly a 9 m deep tillage system would till and drill 2000 ha and both the shallow and zero tillage system 3000 ha.

The cost per hectare given in Figure A.1 for the 4 m and 9 m system widths show the typical decline in cost per hectare as the tilled area increases. This figure also shows the costs for a single tractor undertaking both the tillage and drilling operations, where the benchmark tilled areas (*A*) in the number of available work hours (*T*) are less than for two tractors, as given by Equation A.2.

$$A = T/(1/r_t + 1/r_d) \tag{A.2}$$

Where:
A = benchmark tilled area for a single tractor undertaking both tillage and drilling operations, ha.
T = number of available work hours (350 h).
r_t = tillage work rate (2.56 and 5.76 ha h^{-1} for the deep and 3.84 and 8.64 ha h^{-1} for the shallow 4 m and 9 m systems respectively).
r_d = drilling work rate (3.84 and 8.64 ha h^{-1} for the 4 and 9 m systems).

Where the work rates are calculated from the machine widths (4 and 9 m), the working speeds of 8 and 12 km h^{-1} as specified by the tillage machine manufacturer and a field efficiency of 80%.

Hence, the benchmark tilled areas are 540 ha and 675 ha for the 4 m wide deep and shallow tillage systems and 1200 ha and 1500 ha for the 9 m wide deep and shallow tillage systems respectively (shown with vertical arrows in Figure A.1). Providing the benchmark tilled areas of the single tractor system is equal to or greater than the proposed tilled area of the farm then the costs per hectare are substantially reduced for the deep and shallow tillage operations.

The corresponding costs per hectare for the appropriate benchmark areas are given in Section 3.3 Table 3 (columns 3 and 5) for the two and single tractor scenarios respectively. The cost savings between the different tillage systems at the attainable benchmark areas are given in Table 4.

Figure A.1 also provides the cost per hectare date to enable comparisons to be made for alternative sizes of farm.

Table A.1
Capital and annual costs of tractors, tillage, seed drilling equipment. Data provided by leading suppliers to reflect typical farm gate prices in 2020.

Equipment	Capital Cost, *P* (£)	Annual Cost, *Ca* (£)
Tractor 400 kW	300,000	42,000
Tractor 300 kW	205,000	28,700
Tractor 180 kW	125,000	17,500
Tractor 135 kW	95,000	13,300
4 m Cultivator Deep	56,000	8960
9 m Cultivator Deep	111,000	17,760
4 m Cultivator Shallow	26,700	4272
9 m Cultivator Shallow	60,300	9648
4 m Seed Drill	62,500	10,000
9 m Seed Drill	120,500	19,280

Table A.2
Total annual equipment costs (£) for deep, shallow and zero tillage for 4 m and 9 m wide operating systems.

	Deep Tillage		Shallow Tillage		Zero Tillage	
System width	4 m	9 m	4 m	9 m	4 m	9 m
Tractor 400 kW		£ 42000				
Tractor 300 kW		£ 28700		£ 28700 × 2		£ 28700
Tractor 180 kW	£ 17500					
Tractor 135 kW	£ 13300		£ 13300 × 2		£ 13300	
Cultivator Deep	£ 8960	£ 17760				
Cultivator Shallow			£ 4272	£ 9648		
Seed Drill	£ 10000	£ 19280	£ 10000	£ 19280	£ 10000	£ 19280
Total annual cost	£ 49760	£ 107740	£ 40872	£ 86328	£ 23300	£ 47980

Based upon the yield data from this study and the tractor power requirements, there is a low probability that a 9 m wide deep tillage system would be adopted in practical agriculture, however, it is included for completeness.

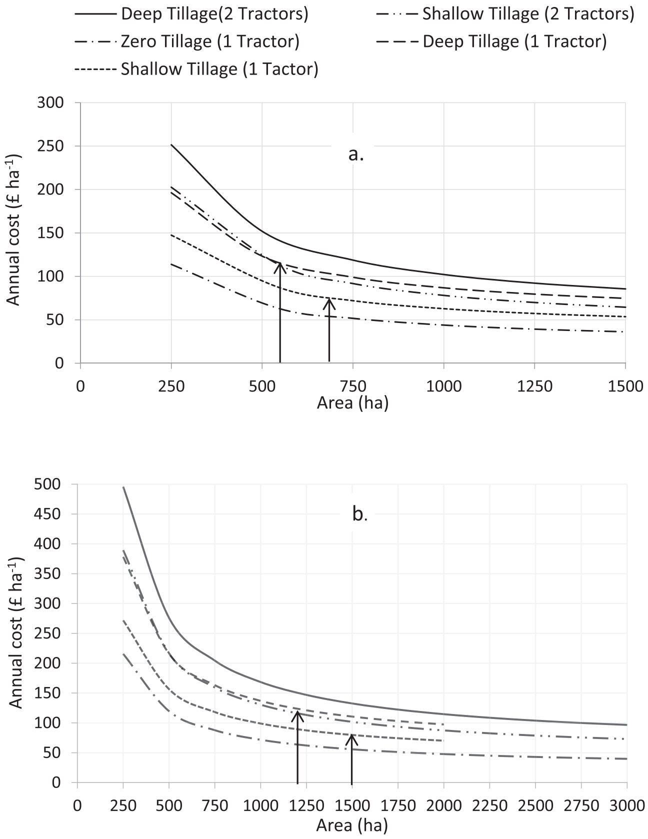

Fig. A.1. Annual cost of tillage and drilling for deep, shallow and zero tillage for the 1 and 2 tractor scenarios for (a) 4 m and (b) 9 m wide systems. The arrows show the benchmark area and cost for the single tractor as given in Table 3.

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