



Improving grass silage production with controlled traffic farming (CTF): agronomics, system design and economics

P. R. Hargreaves¹ · S. Peets² · W. C. T. Chamen³ · D. R. White² · P. A. Misiewicz² · R. J. Godwin²

Published online: 25 January 2019
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Abstract

Grassland silage management is generally semi-organised with no conscious attempt to re-use wheel ways as with arable fields. The total number of machine passes can be 15 or more with normal traffic (NT) systems resulting in potentially large areas of a field suffering from direct damage to the crop and soil. Literature suggests there can be grass dry matter yield reductions of 5 to 74% under NT through compaction and sward damage, with a mean of 13% in the UK. Commercially available grass forage equipment with widths of 3 to 12 m set up for controlled traffic farming (CTF) could reduce trafficked areas (which is typically 90% to 80% for NT) to 40% to 13% for CTF. This study compared grass dry matter yield between CTF and NT for a three-cut silage system based on a 9 m working width in a permanent silage field in the southwest of Scotland, UK in 2015. Results showed a 13.5% (0.80 t ha⁻¹) increase in yield for CTF for the 2nd and 3rd cuts combined. The CTF trafficked area covered was 57% less than the NT system (30.4% compared to 87.4%) over the three silage cuts. An economic analysis based on a 13% increase in dry matter yield (for 2- and 3-cut systems) and a reduction in trafficked area from 80% (for NT) to between 45% and 15% (for CTF), increased the yield by between 0.53 t ha⁻¹ and 1.36 t ha⁻¹ for 2- and 3-cut systems, respectively with an equivalent grass value of between £38 ha⁻¹ and £98 ha⁻¹. Introducing CTF for a multi-cut grass silage system is cost-effective by increasing yields due to a reduction in compaction and sward damage.

Keywords Grassland · Controlled traffic · Economics · Silage

✉ P. R. Hargreaves
Paul.Hargreaves@sruc.ac.uk

¹ SRUC Dairy Research and Innovation Centre, Dumfries, UK

² Harper Adams University, Newport, Shropshire, UK

³ CTF Europe, Maulden, Bedfordshire, UK

Introduction

Grassland silage management is generally conducted with no conscious attempt to re-use wheel ways as often happens with arable fields. Traffic can cause damage to the sward (Volden et al. 2002) through soil compaction with increases in bulk density and shear strength, together with reductions in porosity (Douglas et al. 1992) and reduced air and water permeability (Batey 2009; Chyba et al. 2014). Generally, as soil moisture increases towards field capacity, the more susceptible it is to compaction (Alaoui et al. 2018). Thirty-year average data (1981 to 2010) for the UK weather patterns show the greater rainfall at the start and the end of the year (Table 1), with March having greater rainfall than February. The highest rainfall is in October. Hence, in years with average weather patterns, soil/crop damage will more commonly occur as a result of operations during the wetter spring or autumn months.

The extent of compaction depends on soil texture, structure and moisture content. Clay loam soils have a wide range of moisture contents in the friable range, with silt loams and sandy clay loams having smaller friable ranges (Baver et al. 1972). At moisture contents below the friable range, soils are described as hard or cemented and are relatively strong, with field traffic causing relatively limited soil structural damage (Baver et al. 1972). However, when soils are trafficked at moisture contents in the friable range and above, in the plastic range, they deform more easily (Batey 2009). Above the critical moisture content for a particular soil, compaction declines because pores are water filled, but severe soil damage may occur through soil shear as a result of wheel slip (Raghavan et al. 2012). When soil conditions are susceptible to damage caused by field vehicles, the first wheeling causes most of the compaction (Batey 2009) with subsequent incremental effects as the number of passes increases (Pagliai et al. 2003).

The total number of machine passes on a field can be 15 or more with normal traffic (NT) systems depending on the number of silage cuts. However, these would also include an initial spring inorganic fertiliser application followed by a slurry application. If mowing for three silage cuts, these will generally be in May, July and August, with associated tedding/raking and lifting, along with a number of tractor and trailers each time to cart the silage to the clamp (average trailer load 10 t). A further application of slurry would be made following each cut of silage. The extent of coverage by field traffic for a forage harvester and a round baler in a single operation, in Shropshire, UK, was found to be 63.8% and 63.4% of the field area, respectively (Kroulík et al. 2014); hence, with no co-ordination between operations, potentially large areas of the field can suffer from soil compaction damage. The area of the field suffering from compaction can be determined through measuring the widths of the tyres and knowing the paths of vehicles across fields using a GNSS log.

Table 1 Mean monthly total rainfall total (mm) for the UK and SRUC, southwest Scotland (1981 to 2010)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean/total
UK													
Rainfall (mm)	120	87	93	70	68	69	76	87	94	124	118	117	1125
SRUC													
Rainfall (mm)	115	81	90	62	70	73	71	83	101	134	118	124	1122

Soil compaction effects on grass silage yields, mainly for UK dairy cattle (could also include beef and sheep) have been quantified by several studies in comparison with a non-compacted control. Grass yield decreases due to soil compaction in the range 5–74% have been reported by Are et al. (2015), Douglas and Crawford (1991), Douglas et al. (1992), Frost (1988a), Rasmussen and Møller (1981), and Reintam et al. (2013). Long-term yield decrease for western European temperate conditions lie within the range of 5–20% with a mean of 13% (Douglas and Crawford 1993; Frost 1988a; Hargreaves et al. 2014). Although the largest yield decrease took place during the first cut (Frost 1988a; Hargreaves et al. 2014) for the compacted areas, yield may increase significantly for the second cut of these areas. However, the total yield for the year was not significantly more for the reduced traffic compared to the zero traffic system (Elonen 1986; Hargreaves et al. 2014). Douglas et al. (1995) conducted an eight-year experiment to investigate the effect of zero and reduced ground pressure traffic on forage yield compared with a trafficked system in Scotland (ryegrass and clay loam soil). Over this period, 14.7% (13.7 t ha⁻¹) and 14.0% (13.1 t ha⁻¹) more dry matter was produced with zero traffic and reduced ground pressure systems respectively, than the traffic system, with the largest yield decrease generally in the first cut for the trafficked system. This is probably related to wet soil conditions due to the amount of rainfall following spring application of fertiliser. Traffic with wet soil conditions during cutting also decreased the yield of the next cut.

Douglas and Crawford (1989, 1991) investigated the relationships between the amount of traffic and soil dry bulk density and crop dry matter yield (Fig. 1), with 'Amount of Traffic' (kPa) defined as the product of the number of wheel passes and maximum (front axle wheels) tyre/soil contact stress. In relation to rainfall, they found that a wet June disadvantaged the swards on the denser soil, but with a dry June there was no significant difference in yield between zero traffic and the other compaction treatments.

Controlled traffic farming (CTF) is a traffic management system where all the field traffic is confined to permanent wheel ways across the field. It has the potential to improve forage grass yields by as much as 35% (Chamen 2011). To enable CTF, the track gauges

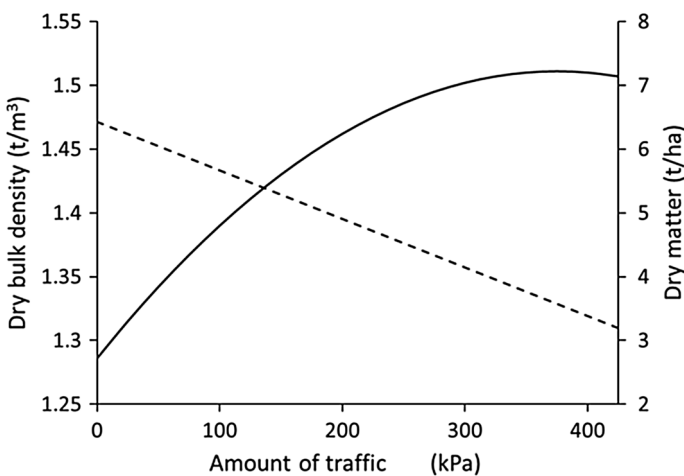


Fig. 1 The effect of the amount of traffic, as a product of the number of wheel passes and maximum (front axle wheels) tyre/soil contact stress (kPa), applied over two years on soil bulk density in upper 120 mm (continuous line) and dry matter yield (dashed line) (Douglas and Crawford 1989)

of the machines have to be matched. The working widths of the implements also have to be matched so that they are equal to, or an integer multiple of, the base module width. The base module is the narrowest working width, for example: 6–8 m systems result in approximately 25% of the field being trafficked, reducing to approximately 17% for 12 m systems (Chamen 2011). Although CTF systems are becoming accepted for cereal production in the UK currently, with approximately 50,000 ha in production (Godwin 2015), there are no robust data about CTF for grassland.

Frame and Merrilees (1996) suggested that, in practice, silage operations in the field should be conducted with the lightest equipment and fewest traffic activities. Frost (1988a) and Håkansson et al. (1990) proposed that yield reduction from a field would be decreased if the same wheel tracks could be utilised. Kjeldal (2013) and Alvarmar et al. (2017) reported that CTF is practiced for grass production in Scandinavia, with the most popular module width of 12 m (trafficked area from 13 to 26%) and mower widths from 6 to 12 m.

Commercially available equipment

A wide range of commercially available grassland equipment have been assessed to determine its potential suitability to provide a range of CTF systems of different width for grass silage production. The aim for each system was to select a combination of machinery that could be used with little or no physical modification or impact on field operations.

CTF systems with common widths ranging from 3 m to 12 m were feasible, with trafficked areas ranging from 40% to 13% (Table 2), respectively. Several options were possible, with the 5, 9 and 12 m systems leading to the lowest trafficked areas for both grassland and arable operations.

There are two shortcomings with the 4 and 5 m systems: a) a loader wagon is required and these are relatively uncommon in the UK, and b) the mower has heavily loaded wheels running on the non-trafficked bed. A 3 m system involves machines with little or no modification but requires a tractor with a track gauge of 1.5 m and, because of this narrower width, has a greater trafficked area than the wider systems.

A 9 m system is achievable based on mowers such as that shown in Fig. 2a, along with standard tedders, swathers, harvesters and dribble bar slurry applicators (Fig. 2b). Harvesting with this 9 m system relies on delivery from a self-propelled harvester to a rear hitch trailer that is swapped on the headland when full. A further reduction in trafficked area could be

Table 2 Summary of the different CTF systems proposed and their associated tracked areas

Controlled traffic base widths			Trafficked area (%)
Mowing width (m)	Other widths (m)	Forage system	Grass only
1.5 or 3.0	6.0 and 9.0	Loader wagon	35.9
		Trailed forager	34.3
3.0	6.0 and 9.0	Self-propelled	40.1
4.0	8.0	Loader wagon	27.7
5.0		Loader wagon	21.5
9.0		Self-propelled	18.2
12.0		Self-propelled	13.4

(a)



(b)

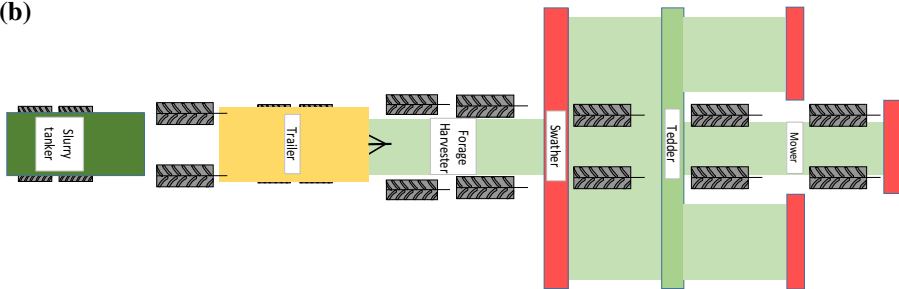


Fig. 2 **a** Triple gang mower of the type envisaged for a 9 m controlled traffic system and **b** illustration of the machines and operations involved

achieved if the gauge of the harvester and other machinery in the operation were more closely aligned (Table 3).

The greatest constraint when introducing a 9 m or any other CTF system is its effect on harvesting work rate. Extra discipline and commitment are central to the success of any CTF system used for grass forage production. In addition, there is some curtailment of harvest work rates (around 10%) associated with forage trailers running along traffic lanes rather than taking the shortest route to the harvester or field exit (Peets et al. 2017).

Although previous studies have documented reductions in grassland yield, as a result of increased traffic, few of the studies have considered the increased yield across a whole grassland silage field due to employing CTF. A comparison of the use of CTF compared to NT would quantify the yield increases, with a set working width, across field situations and conditions. Also, no studies have attempted to calculate the cost of implementation of CTF in relation to the improved margins of increased yields compared to NT.

The objectives of this work were to: (i) use a 9 m wide CTF system for one season of three silage cuts in a silage field in the southwest of Scotland, UK to assess the potential increase in grass DM yield and (ii) use the values derived to determine the economic value of implementing a CTF system for grass production.

Table 3 Machinery assumed for a 9 m controlled traffic system

Machine	Working width (m) ^a	Operating width (m) ^b	Tyres on principal axle ^c	Track gauge (m)
Claas Axion tractor	n/a	n/a	710/70 R 38	2.0
Kuhn GMD 9530 triple gang mower	9.13–9.53	9.0		
Claas Volto tedder	10.7	9.0		
Kuhn GA 9531 swather	8.4–9.30	9.0		
Claas Jaguar 980/940 harvester		9.0	710/70 R 42	2.20
Richard Western silage trailer	n/a	9.0	15×22.5—18 PR	2.0
Conor slurry tanker + trailing shoe	9	9.0	560/60 R 22.5	2.04
Agrisem Vibromulch stubble cultivator	9	9.0		
Dale Eco-Drill	9	9.0		
John Deere 9000 series combine	9.14	9.0	650/75 R 32	2.61
Grain chaser	2.91	9.0	800/40 R 26.5	2.11

^aWorking width is the actual width specified by the manufacturer

^bOperating width is the width required for the operation in the field to allow for a 9 m controlled traffic system

^cTyres on the axle that creates the widest footprint for the particular machine

Materials and methods

Experimental site and baseline measurements

An 8 ha permanent silage perennial ryegrass (*Lolium perenne*) field (freely drained sandy loam soil) at Scotland's Rural College (SRUC) Dairy Research Farm, Southwest Scotland (N55:02:45, W03:35:56) was split into two 3.5 ha areas. Management history of the grass sward was the same up to the point the field was split in April 2015. The mean annual air temperature for 2015 (9.6 °C) was marginally higher than the long-term mean (1981–2010) of 9.3 °C. This was reflected in the mean grass minimum temperature (3.9 °C) compared to the mean long-term temperature (2.7 °C). The total annual rainfall for 2015 (1532 mm) was also greater than the mean long-term total (1122 mm) (Table 1). The warmer and wetter conditions than the long-term average, would have helped to promote grass yield at or above an annual average amount of 10 t ha⁻¹.

The layout of each area, within the field, was a rectangle (218 m×160 m) with one of two traffic management treatments imposed: NT and CTF.

Forty initial measurement points were set up on a grid system across both the treatment areas before the first silage cut. Measurements of penetrometer resistance, soil bulk density (0–100 mm) and visual evaluation of soil structure (VESS) were completed at each sampling point to confirm the uniformity of soil properties. Soil samples were also taken from each point to assess the variation of phosphorous (P) and potassium (K) levels along

with the pH, which could contribute to yield differences apart from management during the season (Fig. 3).

Field management

The areas were managed as a three-cut silage system in May, July and August. Silage was harvested using a three gang 3 m-beam mower (overall working width 9 m (see Fig. 2a). Following mowing, the cut grass was spread and allowed to dry for 24 h, then raked into rows 9 m apart. The cut grass was harvested the following day with a forage harvester (width to outer edges of wheels, 3.1 m) and two tractor and trailer combinations (tractor wheels outer width 3.2 m). The latter ran alongside the harvester (approximately 2 m away) for the NT system and along the next set of parallel wheel tracks for the CTF system, thus maintaining a 9 m separation and providing a trafficked area of 19%.

Inorganic fertiliser, as urea, was applied at a rate of 60 kg N ha^{-1} after the first cut. Dairy cow slurry was applied twice through the season (May and July, after the silage cuts) at a rate of $30 \text{ m}^3 \text{ ha}^{-1}$, by tanker and splash plate; the second application in July was applied with a narrower application band as a result of the thicker consistency of the slurry. The CTF management pattern could only follow one of the wheel tracks and added a further wheeling to the original pattern resulting in 30% of the area being tracked.

A GNSS system with a $\pm 150 \text{ mm}$ pass to pass accuracy and sight posts set up at the ends of each A–B line, for a manual check on the accuracy, allowed the same wheel tracks to be followed in the CTF system. Each field was cut around the headlands three times and then the A–B lines completed using the headlands for turning. A GNSS tracked all vehicle



Fig. 3 Sampling points across the NT and CTF plots. The area coloured (light green) is a brown forest soil of the Hollywood association and is imperfectly drained and the area coloured (dark green) is a brown forest soil of the Hollywood association and freely draining (Color figure online)

movements across both treatment fields (NT and CTF) during grassland management. The GNSS systems enabled operators to return to the same location in the field repeatedly to within ± 250 mm for the CTF system. The intensity and spatial coverage of traffic across each treatment for each operation were identified from the traffic maps.

Total yield off-takes from both areas were recorded at each harvest by weighing each full trailer using a static weighbridge. DM contents were calculated from samples from each trailer after it had been weighed.

Statistical analysis

Data from the individual sampling points of VESS, P, K, soil resistance and soil bulk density were analysed using GenStat version 16 (VSN International, Hemel Hempstead, UK). The main treatments of tractor passes and NT compared to CTF were analysed on a randomised basis using ANOVA. Any significance was investigated with a student *t* test at a level of significance of $p < 0.05$.

Results

Field experiment

The baseline physical measurements, prior to the silage cuts, taken at the initial 40 sampling points in the field grid, showed no significant differences in soil structural conditions between the fields. The chemical assessment of the soil at the same sampling points across the two separate areas of the field revealed a significant difference ($p < 0.001$) between the NT (13.0 mg l^{-1}) and CTF (9.5 mg l^{-1}) areas for soil extractable phosphorous (P). However, the concentration of P (mg l^{-1}) would indicate that extra P was unlikely to provide any additional growth response to grass (PDA 2011) on either the NT or CTF area. Although, there was lower P in the CTF area where there was more free draining soil (Fig. 4), the within-field variation for P was similar in NT (CV% 21.2) and CTF (CV% 24.0). The soil pH and potassium (K) for the sampling points across the two fields gave no significant difference. However, there was a greater variation in soil concentration for soil K (mg l^{-1}) (CV% 23.7) and P (CV% 22.6) compared to the pH (CV % 4.7). The within-field variation was similar for the pH with a CV% of 4.6 for CTF and CV% of 4.8 for NT, with mean pH values for the NT and CTF fields of 6.47 and 6.42, respectively. However, there was no pattern to pH values across either of the two fields. Again with K, the within-field variation was of a similar value for the CTF (mean 96.0 mg l^{-1} (CV% 21.5)) and NT (mean 107.0 mg l^{-1} (CV% 26.0)), although there were lower K concentrations again for the CTF with the free draining soil (Fig. 5).

The soil compaction assessments (bulk density, soil resistance and VESS) showed no pattern of change across either the NT or the CTF fields. Soil compaction increased with vehicle passes for both the NT and CTF. This was indicated by a 14.7% ($p < 0.001$) increase in soil bulk density for the NT area and 18.2% ($p < 0.001$) in the traffic lanes for the CTF field between zero and 6+ vehicle passes (Table 4). These increases were also reflected in the penetrometer resistance with a 48% ($p < 0.002$) increase for the NT field and a 70% ($p < 0.001$) increase for the CTF traffic lanes. There were significant increases ($p < 0.001$) in the soil visual evaluation of soil structure VESS score between zero and 6+ passes for both the NT and CTF fields. However, although there was greater soil structural damage

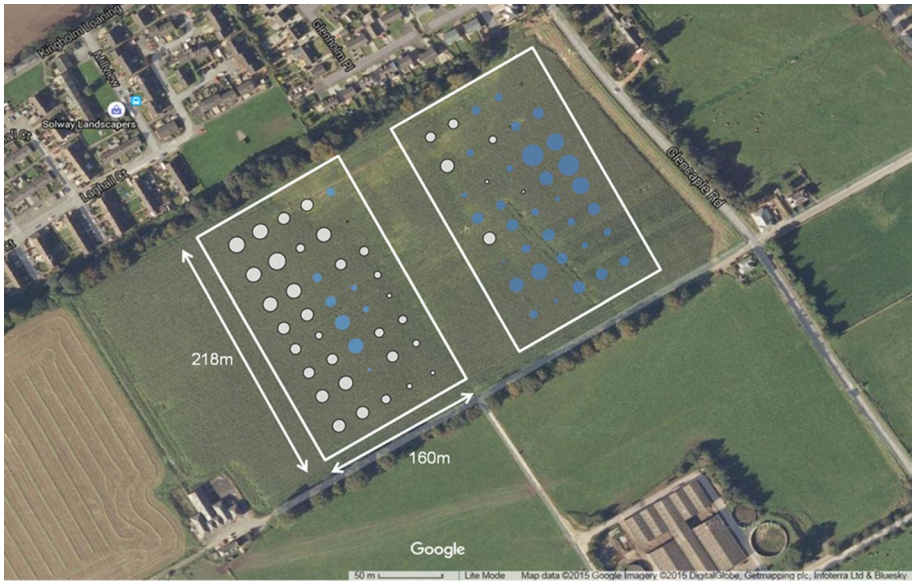


Fig. 4 Baseline soil analysis phosphorous (P) (mg l^{-1}) results greater (blue circles) and less (white circles) than the average value for both fields for the forty grid sampling points across the normal traffic (NT) (right) and controlled traffic (CTF) (left) fields (Color figure online)

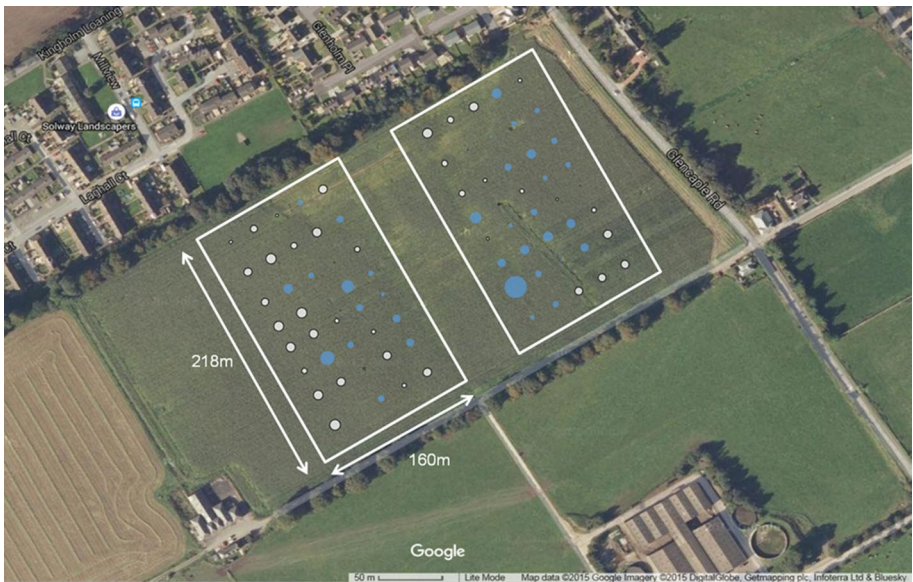


Fig. 5 Baseline soil analysis potassium (K) (mg l^{-1}) results greater (blue circles) and less (white circles) than the average value for both fields for the forty grid sampling points across the normal traffic (NT) (right) and controlled traffic farming (CTF) (left) fields (Color figure online)

Table 4 Effect of vehicle passes on soil bulk density – 0 to 100 mm (g cm^{-3}), soil resistance (penetrometer – 0 to 200 mm) (kPa) and visual evaluation of soil structure (VESS) (score 1 to 5) (all values average per field)

No of passes	Soil bulk density (kg m^{-3})		Soil resistance (kPa)		VESS (score 1 to 5)	
	NT	CTF	NT	CTF	NT	CTF
0	1000	990 (990)	1.35	1.20 (1.24)	1.95	1.90 (1.91)
2	1080	1070 (1080)	1.51	1.18 (1.24)	2.34	2.47 (2.48)
4	1130	1120 (1120)	1.71	1.68 (1.66)	3.15	3.09 (3.09)
6	1140	1130 (1130)	1.79	1.87 (1.87)	3.56	3.60 (3.55)
6+	1150	1170 (1180)	1.99	2.04 (1.96)	3.75	3.91 (3.89)

Figures in brackets are mean values from the same soil type in CTF field (excluding the free draining soil)

for the CTF 6+ passes compared to the NT, the values measured were lower for CTF for cases where there were 4 passes or less (Table 4).

The greatest single increase in bulk density compared to the overall change was the difference between zero and 2 passes with a 54% increase for the NT area and a 45% increase in the CTF field. The CTF field, with concentrated passes, showed a greater increase in overall soil bulk density between the 6 and 6+ passes (23.8%) compared to the NT field (9.1%).

As expected, there was no significant difference in yield for the NT and CTF treatments during the first cut (Table 5) as this was when the CTF practices were initiated. The 2nd silage cut gave a 0.30 t ha^{-1} increase in DM yield for the CTF compared to the NT field ($p=0.72$) and (0.5 t ha^{-1} ($p < 0.01$)) for the 3rd silage cut compared to the NT.

Economic analysis

The economic analysis followed a similar format to Godwin et al. (2003) for assessing the potential for precision farming in cereal production. It considered the direct economic advantages from any improvements in forage yield alongside the additional costs of implementation, but did not include other less tangible benefits such as the savings in re-establishment, which was not a requirement in this study. The potential saving in fuel costs was conducted using the data in Table 6, which indicated that despite the increase in the total distance travelled for CTF (in agreement with Bochtis et al. 2010) by 10% and a reduction in the work rate of 2.5%, the fuel consumption per hectare was reduced by 2.16 l ha^{-1} (27%). At the time of the study, the cost of agricultural diesel was approximately $\text{£}0.50 \text{ l}^{-1}$

Table 5 Total Dry Matter (DM) off-take and differences (t ha^{-1}) with the standard error of differences of the mean (SED) from the areas of the field under normal traffic (NT) and controlled traffic farming (CTF) (p values in bold indicate significant difference)

Silage cut/date	Field system		Difference	SED	p value
	NT	CTF			
1st silage cut/22nd May	5.28	5.43	0.15	0.019	0.27
2nd silage cut/2nd July	3.58	3.88	0.30	0.007	0.72
3rd silage cut/10th Sept	2.34	2.84	0.50	0.001	0.01
2nd + 3rd silage cut	5.92	6.72	0.80	0.016	0.05
Total silage	11.29	12.15	0.96		

Table 6 Results from an AHDB Demonstration Farm in Yorkshire (Peets et al. 2017)

	Normal	Controlled traffic farming
Mower (m)	9	9
Rake (m)	12	9
Spreader (m)	24	18
Harvester (m)	12	9
Trailer	Random	Offset one track lane
Total distance (km ha ⁻¹)	5.63	6.17
Trafficked area	57.4%	23.5%
Work rate (ha h ⁻¹)	12.47	12.15
Fuel consumption (l ha ⁻¹)	7.98	5.82
Fuel consumption (l t ⁻¹)	0.66	0.52

giving a benefit of £1.08 ha which, whilst of benefit to the farmer and contractor, are relatively small in comparison to the yield benefit.

A range of trafficked areas (%) was used in the calculations, as the trafficked area depends upon the track gauges, tyre widths and operating widths of the available equipment. This information should enable farmers and/or contractors to estimate the benefits of CTF for their system, as well as future benefits accruing from appropriate machinery replacement. As the cost ha⁻¹ is influenced by the area cut/harvested, the analysis was conducted for a range of areas up to 1500 ha cut⁻¹, based upon harvesting rates of 75 ha day⁻¹ (Farmers Weekly 2016; Cottey, personal communication, 2016) and 20 work-days cutting period⁻¹. The annual benefits of CTF were based upon the following assumptions:

- (i) The average yield for 2 and 3 “cut” managed grassland harvest systems in the UK is 12 t ha⁻¹ and 16.6 t ha⁻¹ of dry matter respectively, with a value of £72 t⁻¹ (SRUC, personal communication, 2016),
- (ii) Normal traffic management covers 80% of the field area, given the trafficked area for a single harvest operation of 65% (Kroulfk et al. 2014) and during a growing season there could be in excess of 11 sets of operations. The value of 80% selected is higher than the 74% chosen by Alvemar (2014) but more conservative than assuming a total trafficked area of 100%.
- (iii) A 13% increase in forage yield from the removal of traffic was assumed, based on the most robust UK data of 14.7% (Douglas et al. 1992, 1995), 12.1% (Frost 1988a, b) and the experimental results shown above (13.5%).

The additional annual cost of CTF over NT farming was estimated for four different levels of investment in vehicle guidance systems (Table 7); ranging from low accuracy—manual steered—to high accuracy—fully integrated steering. As discussed earlier, it was assumed that a farmer or contractor would employ the guidance systems in existing machinery, where possible. Further machinery purchases that conformed to the working widths that had been decided on farm would be a normal part of a longer-term replacement policy. Therefore, costs are only focused on the outlay and use of the guidance systems. The total annual costs were comprised of interest rate (4.5%), depreciation (15%), maintenance (5%), an annual RTK service fee (where appropriate) and training (£100 year) (Nix 2015). Figure 6 shows the total annual cost for the area harvested in a given “cut”, showing the typical cost ha⁻¹ reduction as the harvested area increases.

Table 7 Current typical commercial equipment guidance costs/system

Investment	Equipment	Repeatable positioning	Initial capital cost	RTK annual fee	Total annual cost
Level 1	Low accuracy ^a Manual steering	No	£1500	–	£467.5
Level 2	Low accuracy ^a Assisted steering	No	£5000	–	£1325
Level 3	High accuracy ^b Assisted steering	Yes	£10,000	£500	£3050
Level 4	High accuracy ^b Integrated steering	Yes	£15,000	£500	£4275

^a(± 150–200 mm) These will result in an increased trafficked area due to their inaccuracy and non-repeatable positioning

^b(± 20 mm) real time kinematic (RTK)

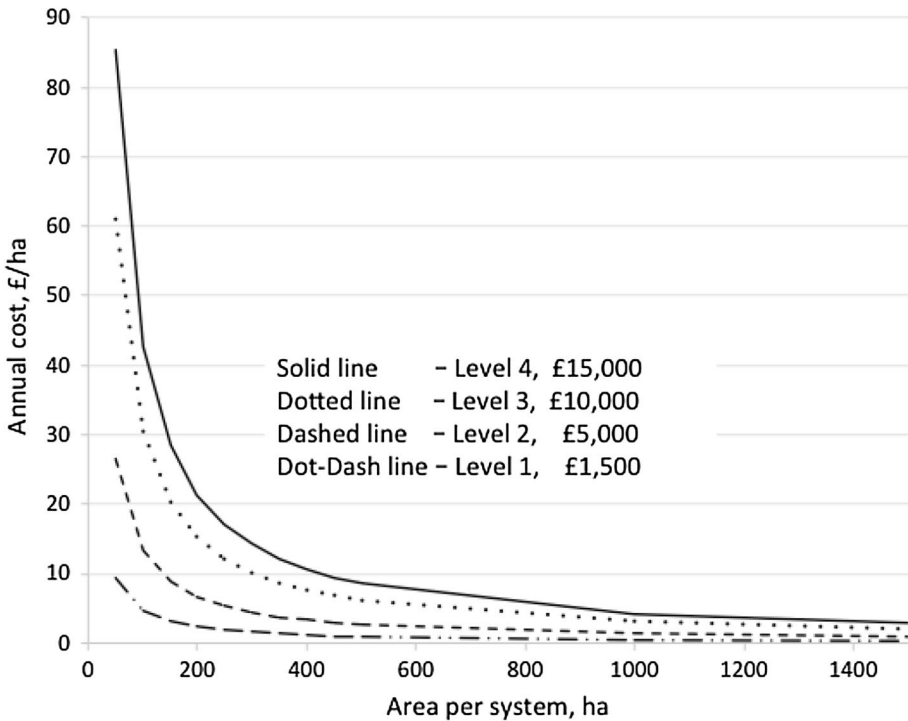


Fig. 6 Annual cost ha⁻¹ of the guidance system for four levels of capital expenditure

Figure 6 shows that the Level 1 system costs less than £4.68 ha⁻¹ for areas in excess of 100 ha and the more expensive Level 4 system, costs £21.38 ha⁻¹ for areas in excess of 200 ha reducing to £2.85 ha⁻¹ for areas in excess of 1500 ha. With CTF systems in grassland, it is not only the harvester that needs to be equipped with machine guidance

systems but also the tractors drawing trailers and conducting other field operations. A minimum number of guidance systems would be 4, as at harvest there would need to be one system on the harvester and 3 further systems installed in three tractors pulling the trailers taking the cut silage to the clamp. Adding the data from the individual “curves” in Fig. 6 for the number and types of systems required at the chosen level of technology and harvested area allows the total cost for field operations to be determined (Godwin et al. 2017). For example, should 4 guidance systems be required, the cost ha⁻¹ year⁻¹ for 4 low accuracy—manually steered systems is less than £18.70 for areas in excess of 100 ha harvest⁻¹, while 4 high accuracy (RTK)—integrated systems cost less than £85.50 for areas in excess of 200 ha harvest⁻¹, reducing to £11.40 for areas greater than 1500 ha harvest⁻¹.

The yield increases given in Table 8 for the range of trafficked areas were estimated by adding the trafficked (Y_t) and non-trafficked (Y_o) yields given by Eqs. 1–5 below in proportion to the trafficked and non-trafficked areas

$$Y_t(\text{t ha}^{-1}) = \frac{\text{Average forage dry matter yield (t ha}^{-1}\text{)}}{((\text{trafficked area} + (1 - \text{trafficked area})(1 + \text{average yield benefit}))} \quad (1)$$

$$Y_o(\text{t ha}^{-1}) = \text{trafficked yield (t ha}^{-1}\text{)} \times (1 + \text{average yield benefit}) \quad (2)$$

Hence for a 2-cut system with an average forage dry matter yield of 12 t ha⁻¹ and a yield benefit of 13%, the trafficked yield is:

$$Y_t = 12(\text{t ha}^{-1}) / (0.8 + (1 - 0.8)(1 + 0.13)) = 11.70 \text{ t ha}^{-1} \quad (3)$$

and the non-trafficked yield

$$Y_o = 11.70 \text{ t ha}^{-1} \times (1 + 0.13) = 13.22 \text{ t ha}^{-1} \quad (4)$$

Giving a combined yield Y_c (t ha⁻¹) for a 45% trafficked area:

$$Y_c = ((0.45 \times 11.70) + ((1 - 0.45) \times 13.22)) = 12.53 \text{ t ha}^{-1} \quad (5)$$

These data show that reducing the trafficked area from 80% (normal traffic) to 45% increased the yield by 0.53 t ha⁻¹ and 0.73 t ha⁻¹ for 2- and 3-cut systems, respectively. However, if the trafficked area were reduced to 15%, the yield benefit will be increased to 0.99 t ha⁻¹ and 1.36 t ha⁻¹ for the 2- and 3-cut systems, respectively.

At £72 t⁻¹ these yield increases are worth between £38 ha⁻¹ and £98 ha⁻¹ and agree with the benefits from earlier studies (Stewart et al. 1998) when adjusted for retail price inflation (Alvemar 2014). A 1% reduction in the trafficked area increased the benefit of CTF at rates between £1.10 ha⁻¹ and £1.50 ha⁻¹ for the 2- and 3-cut systems, respectively.

Table 8 Estimated yield and yield increase as affected by reductions in the trafficked area (%) for 2- and 3-cut systems

Trafficked area (%)	2 cuts/season NT yield = 12.0 t ha ⁻¹		3 cuts/season NT yield = 16.5 t ha ⁻¹	
	Yield (t ha ⁻¹)	Yield increase (t ha ⁻¹)	Yield (t ha ⁻¹)	Yield increase (t ha ⁻¹)
45	12.53	0.53	17.23	0.73
35	12.68	0.68	17.44	0.94
25	12.83	0.83	17.65	1.15
15	12.99	0.99	17.86	1.36

Comparing the costs and potential benefits (yield and fuel (at £1 ha⁻¹)), the break-even area (*A*) can be estimated as given below:

$$A \text{ (ha year}^{-1}\text{)} = \textit{Total cost} \text{ (£ year}^{-1}\text{)}/\textit{benefit (yield and fuel)} \text{ (£ ha}^{-1}\text{)} \quad (6)$$

Hence for 4 low accuracy—manually steered systems with a 45% trafficked area, a CTF system with 2 cuts/year is:

$$A = 4 \times £467.5 \text{ year}^{-1}/(£38 \text{ ha}^{-1} + £1 \text{ ha}^{-1}) = 48 \text{ ha year}^{-1} \quad (7)$$

The breakeven area increases to 438 ha year⁻¹ for 4 high accuracy (RTK)—integrated steering systems. For a 35% trafficked area with 3 cuts a year, the break-even area for four low accuracy—manually steered systems is 27 ha year⁻¹ increasing to 77 ha year⁻¹ for 4 low accuracy/assisted steering systems and 249 ha for 4 high accuracy (RTK)—integrated steering systems. A 3-cut CTF system with a trafficked area of 15% using 4 high accuracy (RTK)—integrated steering systems has a break-even area of 173 ha.

Discussion

That there were differences between the soil structure for the zero and six plus passes for both CTF and NT was not unexpected, even with the same soil type for the majority of the two areas (Fig. 3). The greater penetrometer resistance, increased VESS score and greater bulk density for both the CTF and NT wheeling areas (six plus) demonstrated the effect of a greater amount of traffic and axle pressure. Although there were similar total amounts of traffic across the two fields, this was concentrated on a smaller wheeled area in the CTF field than in the NT field. It has been shown in previous studies (Taylor et al. 1982; Bakker and Davis 1995) that even a limited number of vehicle passes reduced yield. The NT field had a greater coverage of various numbers of vehicle passes than the CTF field where the majority of activity was confined to predefined wheel tracks. The results from the sampling points for the soil structure agreed with previous work that the first one or two passes by a vehicle produced the greatest compaction and subsequent yield reductions (Hamza and Anderson 2005).

The weather during the growing season for the experimental work was warmer and wetter than the long-term average and supported above average silage production. As an estimated average for UK silage production is 11.7 t ha⁻¹ and for Northern Ireland (closer in climatic conditions to the experimental site) 10.6 t ha⁻¹ (AHDB 2011). As expected, there was a non-significant difference in DM yield of 0.15 t ha⁻¹ ($p=0.27$) between the two field management systems for the first silage cut, as the CTF system had not been established prior to this cut and hence the same vehicle traffic pattern had been applied to both field areas. The chemical and physical assessment of the NT and CTF field areas showed no overall significant differences in pH, K, soil bulk density, soil resistance or visual structure (VESS) and, although P was greater in the NT field, the levels measured in both fields would not have limited grass growth. Increased P and K would have encouraged greater yield for the NT field, especially as the more freely draining side of the CTF field had potentially promoted the loss of both P and K by soil water drainage. The differences in yield between the two areas increased as the CTF management operations were instigated for the 2nd and 3rd silage cuts. DM yield of the second and third cuts combined gave a 13.5% (0.80 t ha⁻¹) increase with the 9 m CTF system compared to the NT ($p<0.05$), which was very similar to the 13% from the literature. The mean rainfall for April and May in 2015 was 85.3 mm which was 19.5 mm greater than the long-term mean (65.8 mm) but the yields for the NT and CTF fields were not significantly

different, inferring no advantage for the more freely draining western side of the CTF field. Again, even though the rainfall during the growing period between the first and second cut was 29.4 mm greater than the long-term mean, there was no significant difference between the yield from the NT and CTF fields. It was only during the third cut that a significant difference was seen between the yields as this period had 19.5 mm less precipitation than the long-term average. This should have given an advantage to the NT field over the CTF field as the former would have retained more moisture as a result of the general compaction. In contrast, the CTF had the more freely draining area on the western side which would have lost water through drainage much more readily, with less available for growth. As 2015 was an above average growing season, the differences in yield may have been greater than a growing season with less favourable conditions. However, further work would have to be done to compare yield differences in further years with different weather conditions to confirm this. It has been shown that the amount and date of rainfall, especially after the first cut, can affect second cut yields (Douglas 1997).

The use of the GNSS guidance systems and details of the working and tyre widths of the machinery involved allowed the area covered by the wheelings and the overall distances covered by the CTF and NT systems to be calculated. The area covered by the CTF system (excluding the second slurry application) was 19.4%, a reduction of 68% compared to the coverage of the NT (87.4%) over the whole of the three silage cuts. The greater trafficked area for the NT system was mainly as a result of the tractors and trailers moving the cut silage to the pits as they always took the shortest route to the field exit or back to the harvester. In contrast, the tractor and trailers that collected the cut silage from the CTF field followed the next set of wheelings, thus ensuring that a reduced area was covered. The actual area covered by the CTF operations was 30.4%, due to the narrower spread of the second slurry application.

The economic analysis of the data used the four levels of investment to allow farmers and consultants a range of cost options to choose for implementation of a grassland controlled traffic management system. As expected, the reduction in the trafficked areas across grassland fields led to an enhanced yield compared with the NT field thus improving the cost margins. As these margins are offset against the cost of implementing controlled traffic for a minimum of four vehicles (i.e. one harvester and three tractor—trailers to transport the cut silage to the clamp), the size of the area harvested has a very dramatic effect in reducing the cost per hectare (economies of scale) of the vehicle guidance systems. The break-even points were reasonable for UK farm areas, from low level investment on smaller farms, i.e. 50 to 100 ha, to larger farmers over 250 ha.

In the case of contractor harvested systems, a financial agreement would have to be made between the farmer and the contractor. Some of the benefit of any additional yield/revenue to the farm would have to be offset against the extra cost and operational complexity experienced by the contractor. The economic information should permit the benefits, costs and break-even areas of individual systems to be estimated and investment choices to be made.

Conclusions

There are suitable ranges of commercially available equipment to enable farmer/contractors to design CTF systems with module widths from 3 m to 12 m. However, a width of 9 m appears most suitable with current machinery.

It is possible, within one forage harvesting season, to gain a yield advantage of 13.5% (0.8 t ha^{-1}) by introducing a CTF system compared with operating under a normal traffic

regime. However, this may be dependent on the individual growing season and could be less in growing seasons that have less advantageous weather conditions than those experienced during the experimental work reported here. Nevertheless, this yield gain and reduction in trafficked area with CTF can be achieved by aligning the use of existing equipment and operating with vehicle guidance.

Overall, economic analysis showed that CTF in grass silage production can be cost effective, provided the navigation systems selected are based on the size of the operation. The data also provides a basis for negotiation between a farmer and contractor when considering the benefits and costs of grass CTF systems.

Acknowledgements This work was funded by AHDB Dairy as part of the Grassland, Forage and Soils partnership. SRUC work is funded by The Scottish Government.

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