FIELD EVALUATION OF CONTROLLED TRAFFIC FARMING IN CENTRAL EUROPE USING COMMERCIALLY AVAILABLE MACHINERY

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ABSTRACT. *The progressive increase in the size and weight of farm machinery causes concerns due to the increased risk of soil compaction that arises from non-organized vehicle traffic. Controlled traffic farming (CTF) offers an effective means to manage compaction by confining all load-bearing wheels to the least possible area of permanent traffic lanes. Although CTF is relatively well-established in Australia and in some countries in Northern Europe, its benefits and suitability for Central European conditions have not been demonstrated. A long-term experimental site was established in 2010 in Nitra, Slovakia, using a 6 m "OutTrac-CTF" system with shallow non-inversion tillage practices. The 16 ha experimental field of loam soil is representative of land used for arable cropping in Central Europe. Four traffic intensities (non-trafficked, one traffic event per year with a single pass, multiple passes with permanent traffic lanes, and random traffic) were evaluated using two traffic systems: controlled (CTF) and non-controlled traffic farming (referred to as random traffic farming or RTF). This article reports the findings derived from the first four years of the project and focuses on the effects of traffic systems on yields observed in cereal crops (winter wheat, spring barley, and maize) grown at the site in a rotation cycle. Significant differences (p < 0.1) in yield are reported due to the heterogeneity of the field and the seasonal effect of weather. The results of this investigation suggest that CTF systems have potential to increase production sustainably in arable farming systems in Central Europe. Well-designed CTF systems using commercially available machinery allow for reductions in the area affected by traffic of up to 50% compared with random, non-organized traffic systems. Results also show that in years when soil moisture was not limiting, the yield penalty from a single (annual) machine pass was relatively small (~5%). However, in dry years, compaction caused by multiple machinery passes may lead to yield losses of up to 33%. When considering the ratio of non-trafficked to trafficked area within the different CTF systems evaluated in this study, yield improvements of up to 0.5 t ha^{-1} for cereals are possible when converting from RTF to CTF. Given the assumptions made in the analyses, such yield increases translate into increased revenues of up to 117 USD ha^{-1} (1 Euro= 1.1 USD). For Central European farming systems, the main benefit of CTF appears to be improved efficiency and enhanced agronomic stability, especially in dry seasons, where the significant yield penalty from machinery passes is likely.*

Keywords. Crop performance, Economic return, Field efficiency, Soil compaction, Traffic systems, Yield penalty.

The drive toward adoption of higher-capacity machines to increase work rates and reduce costs raises concerns about the long-term effects of increased and deeply-driven soil compaction, and

the associated need for tillage repair treatments (Kutzbach, 2000; Misiewicz et al., 2015). The continuous increase in machinery size and weight has offset advances made by the industry in developing improved running gear, in both tire and track designs, to reduce contact pressures (Ansorge and Godwin, 2007; Antille et al., 2013). Soil compaction from vehicle traffic increases soil strength (Taylor and Brar, 1991) and restricts root development and penetration into the soil, which therefore reduces water and nutrient uptake by the plants and can translate into reduced crop yield and profitability (Unger and Kaspar, 1994; Lipiec et al., 2003). The trend indicated above toward the use of larger agricultural machinery means that subsoil stresses continue to increase (Keller and Arvidsson, 2004). In grain cropping situations, Chamen (2015), using models from Keller et al. (2007) and Koolen et al. (1992), calculated an average 14-fold increase in subsoil stresses at a depth of 400 mm, from 0.02 MPa for horse-plowing in 1930 to 0.28 MPa for 30 Mg combine harvesters in 2010. Subsoil compaction (depth ≥ 350 mm) is often persistent, and its alleviation is costly owing to the energy requirements for tillage repair treatments (Chamen et

al., 2003; Spoor et al., 2003). Self-amelioration of soils affected by compaction occurs slowly from the surface downward; however, the rate of self-repair of the soil structure decreases with increased depth (McHugh et al., 2009). This requires the development of strategies to avoid soil damage due to compaction or to minimize the actual damage where impact occurs. In this respect, controlled traffic farming (CTF) is an effective means to manage compaction by confining all load-bearing wheels to the least possible area of permanent traffic lanes (Tullberg et al., 2007). The Australian Controlled Traffic Farming Association (ACTFA, 2016) defines CTF as a system in which:

1. All machinery has the same working width and track gauge (distance between wheels on an axle) so that field traffic is confined to the least possible area of permanent traffic lanes.
2. All machinery is capable of precise guidance along those permanent traffic lanes.
3. A permanent traffic lane layout (or grid) is designed to optimize surface drainage and logistics.

In well-designed CTF systems, the permanent traffic lanes typically occupy less than 20% of the total cultivated area (Tullberg, 2010). Without CTF, unmatched equipment operations and track widths translate into disorganized or unconstrained traffic patterns, which can cover 85% or more of the total cultivated area each time a crop is produced (Kroulík et al., 2009; Tullberg, 2010). Research has shown that CTF has fundamental advantages in maintaining soil structural conditions, with lower inputs of energy (reduced draft) and improved trafficability and timeliness, compared to conventional traffic systems (Chamen and Longstaff, 1995; Tullberg, 2000; McPhee et al., 2015). In Australia, CTF represents a profitable technological innovation for arable land use (Kingwell and Fuchsbichler, 2011), which has additional, and significant, agronomic and environmental benefits (Gasso et al., 2013), including reduced potential for greenhouse gas emissions (GHG) and enhanced fertilizer use efficiency (Torbert and Reeves, 1995; Vermeulen and Mosquera, 2009; Antille et al., 2015, 2016). Similar observations have been reported in reviews (Tullberg et al., 2007; Chamen et al., 2015) and experimental studies conducted in Northern and Western Europe (Godwin et al., 2015). Despite this, a number of barriers, such as vehicle width regulations on public roads, cost of conversion, and loss of warranty, have restricted adoption of CTF (Chamen, 2015). Consequently, global adoption of this technology is still in its infancy (Vermeulen et al., 2010).

The need to reduce costs, increase production sustainably, and mitigate soil compaction impacts within highly productive arable land in Central Europe (Fulajtár, 2000; Houšková, 2002; Bielek, 2003; Bielek et al., 2005) motivated this research, which aims to demonstrate the benefits of controlling field traffic and further stimulate a shift toward increased adoption of these systems. Although the benefits of CTF have been demonstrated for Australian and Northern European farming systems, there is still a pressing need for robust quantitative data that demonstrate its advantages for other European conditions. Therefore, this work was undertaken to quantify the benefits of CTF on crop performance and yield under field conditions of the main production area for arable crops in Slovakia, which is representative of the central and eastern part of Europe. It was hypothesized that: (1) the yield of cereal crops could be increased in soils managed under controlled traffic, and (2) the net increase in crop yield from CTF compared with random traffic systems would result in improved economic return. This research focuses on the productivity aspects in the management of arable crops.

MATERIAL AND METHODS

EXPERIMENTAL FIELD

A 16 ha experimental site was established at the Slovak University of Agriculture in Kolinany, Slovakia (48° 37′ 17″ N, 18° 20′ 75″ E) in 2010. The four-year (2010-2013) average rainfall (662 mm per year) recorded during the course of this study showed significant inter-annual variation, which was greater than the long-term (1961-1990) rainfall average (540 mm per year). The same long-term records show that the mean monthly temperatures ranged between -1.7°C in January and 19.8°C in July (fig. 1). During the first year of the study, rainfall was above historical averages in the summer and autumn of 2010 and drier in spring, whereas temperatures remained close to long-term averages. In the second year (2012), temperatures were relatively warmer in the spring, and rainfall was below average from crop establishment and for most of the growing season. In 2013, temperatures were also warmer than average, and rainfall exhibited high variability within the season. The 2014 growing season was normal to warm in terms of temperature and with normal precipitation.

Soil textural analyses were conducted prior to the experiment based on Slovak Standards (Hrivňáková et al., 2011). Soil samples were collected from the experimental site at eight monitoring points in a grid across the field, so that the entire field was covered, and at four depth intervals (50-100 mm, 200-300 mm, 350-400 mm, and 500-600 mm) based on the guidelines outlined in the above procedure and classified according to the Novak classification (Hraško et al., 1962). The topsoil (0 to 300 mm) and subsoil (350 to 600 mm) were characterized as silt loam, although they differed slightly in particle size composition. The topsoil had 51% silt (fraction size 0.001 to 0.05 mm), 30% sand (fraction size >0.05 mm), and 19% clay (fraction size <0.001 mm). The subsoil had 47% silt, 32% sand, and 21% clay. The subsoil in the southwest corner of the field exhibited slightly higher clay content (27% to 40%) than the rest of the field and was therefore characterized as clay loam. An electromagnetic induction (EMI) survey was conducted to obtain a general characterization of the site and determine the extent of soil variability (Doolittle and Brevik, 2014). Measurements were taken using a ground conductivity meter (EM38-MK2, Geonics Ltd., Mississauga, Ontario, Canada) in horizontal mode, carried at a height of 200 mm above the soil surface. The data were digitally recorded from transects approximately 20 m apart, georeferenced, and reported as apparent electrical conductivity (EC_a, mS m^{-1}). In addition, a digital elevation model (DEM) was obtained, and the data
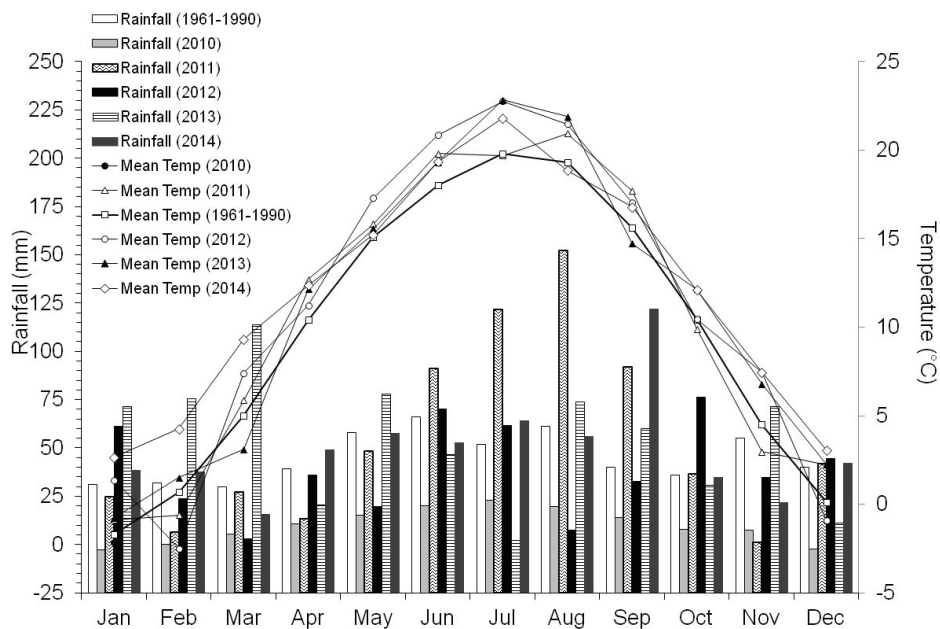
Figure 1. Rainfall represented monthly as sum of precipitations and temperature records for Koliňany, Slovakia (Slovak University of Agriculture in Nitra, 2014).

were superimposed on the data from the EMI survey (fig. 2). Transects and the locations of sampling points within those transects were defined based on the information derived from the EMI survey and the DEM. The results of the EMI survey showed two distinctive zones within the field, which exhibited EC_a values in the ranges of 33 to 48 mS m^{-1} and 48 to 67 mS m^{-1}, respectively. The DEM showed that the field elevation was between 196 and 212 m above sea level. The field exhibited a downward slope from east to west, which ranged between 3% and 7%. Soil chemical analyses were conducted prior to the experiment based on MAFF (1986) and reported the following mean values: soil pH of 6.2, 3.06% soil organic matter, 76 mg kg^{-1} of extractable P,

Figure 2. Apparent electrical conductivity (EC$_a$, mS m^{-1}) and field elevation, denoted by contour lines (m above sea level), determined for the experimental site.

328 mg kg^{-1} of exchangeable K, and 310 mg kg^{-1} of exchangeable Mg.

Spring barley (*Hordeum vulgare* L.) and sunflower (*Helianthus annuus* L.) were grown on the site in 2007 and 2008, respectively. Normalization of the soil physical conditions was a prerequisite to the establishment of the experimental site (Smith et al., 2014). Therefore, in the autumn of 2008, a deep-tillage operation using a subsoiler was performed (350 mm working depth) to remove compaction in the upper part of the soil profile.

TRAFFIC TREATMENTS AND MACHINERY DESCRIPTION

A CTF system was implemented in the spring of 2009 following the deep-loosening operations conducted in the previous autumn. Given the characteristics of the machinery available at the farm, an "OutTrac-CTF" system (Chamen, 2006) was adopted. This enabled the use of machinery available on the farm without the need for modification, which therefore had no impact on the costs associated with the experimental design. This approach was also chosen to represent a "low cost of conversion" scenario likely to be adopted by growers in Central Europe. Such a system may be subsequently upgraded based on the tier system proposed by CTF Europe (2008). This system includes the following tiers (as % of tracked area): 30% to 40% (tier 1), 20% to 30% (tier 2), 10% to 20% (tier 3), and ≤10% (tier 4). Tier 4 may only be achievable with the use of gantry systems (Chamen et al., 1992). The OutTrac-CTF system uses two track gauges on the same centerline. One gauge matches the common standard on most farm vehicles, whereas the other accommodates the wider gauge found on most combine harvesters. Field operations were performed with the equipment listed in table 1.

The 6 m OutTrac-CTF system, which tracked 45% of the area, was introduced during the establishment of spring barley in 2009 and was maintained for the remainder of the ex-
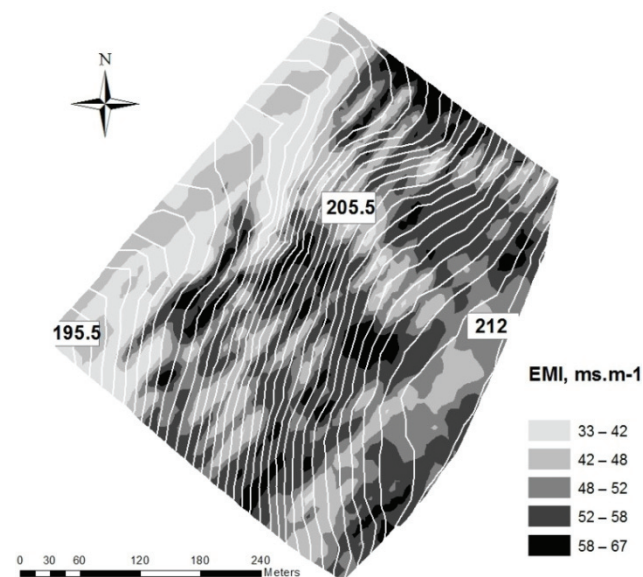
Table 1. Characteristics and uses of machinery at the experimental site.

Machine	Associated Operation	Overall Load	Tires and Inflation Pressure
John Deere 8230 tractor and	All tillage	11,406 kg	Front: 600/70 R30, 0.25 MPa
Lemken Rubin 6 m disc harrow			Rear: 650/85 R38, 0.25 MPa
New Holland T6070 tractor and:		5,524 kg	Front: 480/65 R28, 0.2 MPa
Lemken Solitair 6 m disc harrow	Sowing		Rear: 600/65 R38, 0.2 MPa
Monosem 8 m planter	Drilling		
Agio NAPA 24 m sprayer	Spraying		
Amazone ZA-M 1500 24 m spreader	Fertilizer application		
CLAAS Lexion 480 combine	Harvest in 2011 and 2012	18,150 kg	Front: 800/65 R32, 0.26 MPa
			Rear: 600/55-26.5, 0.26 MPa
CLAAS Lexion 550 combine	Harvest in 2013 and 2014	17,250 kg	Front: 800/65 R32, 0.32 MPa
			Rear: 500/70 R24, 0.24 MPa

periment. Following spring barley, winter oilseed rape (*Brassica napus* L.) was sown in autumn 2009. Tillage and all other implements had a common working width of 6 m, and the traffic plan is given in figure 3. With the exception of tramlines (permanent wheel tracks for spraying), all intermediate traffic lanes (tracks used for harvesting and other non-spraying operations) and non-trafficked areas were sown and constituted two of the treatment areas, as described below. A third treatment representing standard harvest traffic in the region was introduced in autumn 2010 and was applied annually thereafter. This was achieved by tracking a 25 m wide strip at right angles to the controlled traffic lanes following harvest (figs. 3 and 4). The fourth treatment, as a surrogate for random traffic farming (conventional practice or RTF), was represented by the crossing strips of the intermediate traffic lanes within the harvest traffic strip, as illustrated in figure 3. The four treatments, from within which measurements were taken, were denoted as follows:

A = Permanently non-trafficked soil (referred to as "non-trafficked").

B = Simulated harvest traffic, a single pass each year applied across a 25 m strip with a 11.4 Mg tractor and lifted disc harrow at right angles to the controlled traffic lanes (referred to as "single pass").

C = Cropped permanent intermediate traffic lane experiencing all annual traffic as tillage, sowing, and harvest operations with the exception of chemical applications (referred to as "multiple pass").

D = Same as treatment C but within treatment B (referred to as "random traffic" or RTF).

Treatment D was also considered to be representative of conservation tillage and RTF in the region based on the work of Kroulík et al. (2009). The experimental approach was based on that adopted by Galambošová et al. (2010) and Smith et al. (2014) for simulating the effects of random traffic patterns on crop and soil. Comparison of the agronomic performance of crops established under these differently trafficked systems for a period of four years from 2010 is presented.

Tillage and other field operations included the following:
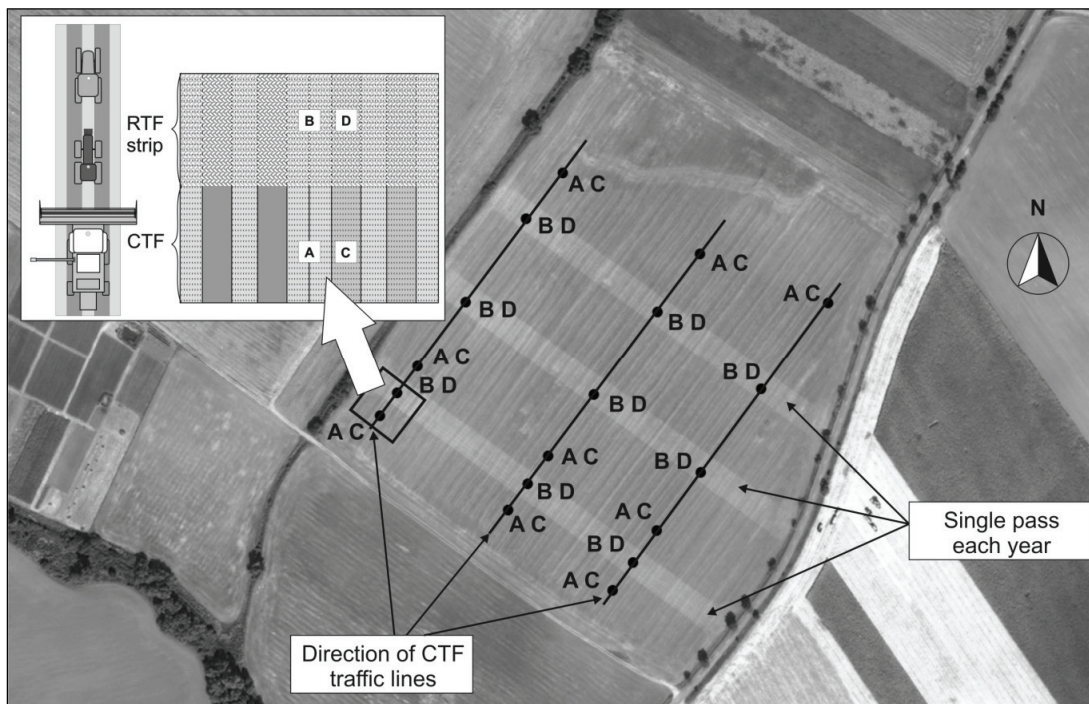
Figure 3. Aerial view of the experimental field in Kolinany (48° 37′ 17″ N, 18° 20′ 75″ E) established at the University farm of the Slovak University of Agriculture in Nitra, Slovakia. Note the position of the replications. Along each traffic lane there are three replications per treatment (A = permanently non-trafficked soil, B = harvest traffic with a single pass each year, C = cropped permanent intermediate traffic lane experiencing all annual traffic with the exception of chemical applications, and D = same as C but within treatment B and denoted as random traffic).

Figure 4. Establishment of the compacted traffic treatments (left) and the resulting soil surface conditions (right).

Table 2. Description of crops grown during the course of the study, including sowing dates and seeding rates. Row spacing was 125 mm for wheat and barley and 0.75 m for maize.

Year	Crop and Variety	Ground Working Operations	Sowing Date and Seeding Rate	Harvest Date
2010-2011	Winter wheat, *Triticum aestivum* L. cv. Augustus	17 July, 14 October, and 22 October 2010	22 October 2010, 225 kg ha^{-1}	16 July 2011
2011-2012	Spring barley, *Hordeum vulgare* L. cv. Signora	20 July, 10 September, and 13 March 2011	20 March 2012, 220 kg ha^{-1}	12 July 2012
2012-2013	Maize, *Zea mays* L. cv. Kessos	12 July 2012 and 25 April 2013	26 April 2013, 70,000 plants ha^{-1}	3 October 2013
2013-2014	Spring barley, *Hordeum vulgare* L. cv. Kangoo	28 October and 10 November 2013, and 5 March 2014	6 March 2014, 220 kg ha^{-1}	11 July 2014

stubble breaking, seedbed preparation, sowing, chemical applications, and harvesting using the equipment described earlier. The timing for all field operations was in accord with standard farm practices in the region (table 2), including sowing and harvesting (typically beginning of July).

EXPERIMENTAL DESIGN

The sampling locations within the field were decided based on the information derived from the initial characterization of the site using the EMI survey data. Apparent electrical conductivity (EC$_a$) readings changed gradually from east to west, which was consistent with the changes observed in elevation and slope (fig. 2). The spatial variability encountered on the site influences the yield potential at the sub-field scale, as shown in an earlier study by Galambošová et al. (2014). Therefore, crop yield and yield components were measured for all four traffic treatments (A, B, C, and D) replicated three times at each of the three tramlines, as shown in figure 3. This results in an experimental design with nine replications for each treatment across the field ($n = 9$). The rationale for the assessment of the CTF and RTF systems is based on the assumption that the measurements recorded from treatments A and C represent the conditions typical of any CTF system, while the measurements from treatment B represent a CTF system with a single traffic pass outside the traffic lanes. Treatment D refers to a system representative of random traffic (RTF).

CROP AND SOIL MEASUREMENTS

For winter wheat and spring barley, grain yield (t ha^{-1}) was determined by weighing the grain from three crop samples taken at each of the nine replicates (treatments A, B, C, and D) using a 0.25 m^2 quadrat ($n = 27$). Ear counts (ears m^{-2}) and height of crop (m) were based on measurements taken from a count of 100 tillers. For maize, grain yield (t ha^{-1}), number of cobs (cobs ha^{-1}), and crop height (m) were also determined. For maize grain yield, samples were taken from 13.3 m long sections to represent 10 m^2 given the crop row configuration. For all crops, grain moisture content was determined based on MAFF (1986). Subsequently, grain yield was adjusted to 14% (by weight) moisture content.

Soil bulk density was measured in 2010 immediately before the compacted (RTF) treatments were introduced and subsequently in 2012 after three annual compaction treatments had been applied. Bulk density was determined in laboratory conditions from non-disturbed samples taken with Kopecky push tubes following a standard methodology (Fiala et al., 1999). Cone penetrometer resistance was measured to a depth of 800 mm in 2012 and 2013, which were respectively four and five years after the deep loosening operation (350 mm depth) was performed and two and three years after the single-pass treatment had been introduced. Penetrometer resistance was measured using a Penetrologger (model P1.52, Eijlkelkamp Soil & Water, Giesbeek, The Netherlands) with ten insertions ($n = 10$) at each of the nine replicates (treatments A, B, C and D). Soil moisture content was measured simultaneously at each of the locations using disturbed samples that were analyzed using the gravimetric method (Reynolds, 1970).

ASSESSMENT OF CTF EFFICIENCY

In terms of crop productivity, the overall efficiency of CTF systems is dependent on the ratio of non-trafficked to trafficked area, which tends to increase with increased nominal width of the CTF system. Equally, studies have shown that improved agronomic (yield) and economic performance is achieved as this ratio is increased (Chamen, 2011). In well-designed CTF systems (e.g., tiers 3 and 4), the area affected by traffic is less than 20% of the cropped area. Calculations of efficiency were based on 6 m, 8 m, and 12 m CTF systems because implements of these widths are commonly used in Europe, albeit in non-CTF systems. However, if arranged to meet the requirements of a CTF system, the efficiency improves with an increase in width (Vermeulen et al., 2010). The extrapolated yield for these systems is determined based on equation 1 using the input data presented in table 3:

$$\text{Extrapolated yield} = \frac{(Y_A \times A) + (Y_B \times B) + (Y_c \times C) + (Y_D \times D)}{Z} \quad (1)$$

where

Y_{A-D} = grain yield (t) recorded in areas A, B, C, and D, respectively

A = non-trafficked area (ha)

B = trafficked area with a single pass (ha)

C = permanent traffic lane (ha)

D = trafficked area with multiple passes (random traffic) (ha)

Z = total area of the field (ha).

This approach for estimating the efficiency of CTF using the area affected by traffic has been satisfactorily applied in previous studies (e.g., Kroulík et al., 2011; Vermeulen et al., 2010). Therefore, the extent of areas A to D allowed for realistic comparisons between RTF and CTF systems. Gross revenue calculations were undertaken for the two traffic treatments (CTF and RTF) based on the average yield and the corresponding price of grain for the year of harvest (MPSR, 2012-2014) using equation 2 (after Frank, 1977):

$$GR = Y \times P_G \quad (2)$$

where

GR = gross revenue (USD ha^{-1})

Y = grain yield (t ha^{-1})

P_G = price of grain (USD t^{-1}).

STATISTICAL ANALYSES

The experiment was constrained by the traffic pattern of the CTF system (fig. 3) and the establishment of the compacted treatments (fig. 4); hence, full randomization of the monitored treatments was impractical. While this constraint could in the purest of terms make the design statistically invalid, there are precedents (e.g., Barrraclough and Weir, 1988) in which the physical constraints of a major field experiment prevent full randomization. Statistical analyses were undertaken for all traffic treatments and yield components using Statistica (StatSoft, 2013). These involved tests of normality (Shapiro-Wilks test), descriptive statistics followed by the Leven test of variance homogeneity, and analysis of variance (ANOVA) with the least significant differences (LSD) used to compare the means using probability levels of 5% and 10% based on an earlier study by Godwin et al. (2015). The tests were conducted as one-factor analyses, which included the traffic intensity (A, B, C, and D). The same statistical approach was applied to the modeled data for the different operating widths of the CTF systems.

RESULTS

EFFECT OF TRAFFIC ON SOIL CONDITIONS

Figure 5 shows the soil dry bulk density (SBD) recorded at the site prior to introducing the compaction treatment in November 2010 (treatment B), which replicated the effect of harvest traffic, and the soil conditions observed in November 2012, two years after the traffic treatments had been imposed. Overall, SBD decreased ($p < 0.05$) on the non-trafficked soil (treatment A), although these changes were relatively small (~4.0%). The data for 2012 show significant differences in SBD in the topsoil between the non-trafficked soil (treatment A) and the single-pass treatment (B) and multi-pass treatment (D). SBD values recorded in the subsoil show significant differences ($p < 0.05$) for measurements conducted in permanent traffic lanes (C) and treatments A and B, which represent the non-trafficked soil and single traffic event, respectively. However, these differences are very small and may not have an impact in practice even though they were picked out by statistics.

Overall, measurements of soil penetration resistance showed lower strength ($p < 0.05$) in non-trafficked soil compared with wheeled soil in both 2012 and 2013, which was expected (fig. 6). The traffic intensity had a significant effect ($p < 0.05$) on soil strength at any measured depth in both years, except for treatments B and C in 2012, which showed almost equal penetration resistance ($p > 0.05$). Despite this, the overall effect of traffic intensity on increased soil strength agrees closely with observations made in earlier studies (e.g., Botta et al., 2006). The soil strength observed at location D was near or above 2 MPa, which is a reference

Table 3. Trafficked and non-trafficked areas as a percentage of total cropped area within the experimental field for the simulated RTF and 6 m CTF systems as well as hypothetical 8 m and 12 m CTF systems.

Traffic System	Percentage of Cropped Area			
	Non-Trafficked Area[a]	One Traffic Event per Year[b]	Two or More Traffic Events per Year[c]	Reference
RTF	36%	39%	25%	Kroulík et al. (2011)
CTF 6 m	55%	22%	23%	Authors' data
CTF 8 m	77%	13%	10%	Vermeulen et al. (2010)
CTF 12 m	85%	-	15%	CTF Europe (2015)

[a] Non-trafficked area corresponds with location A.
[b] Single traffic event per year corresponds with location B.
[c] Multiple traffic events per year correspond with locations C and D in the RTF system.
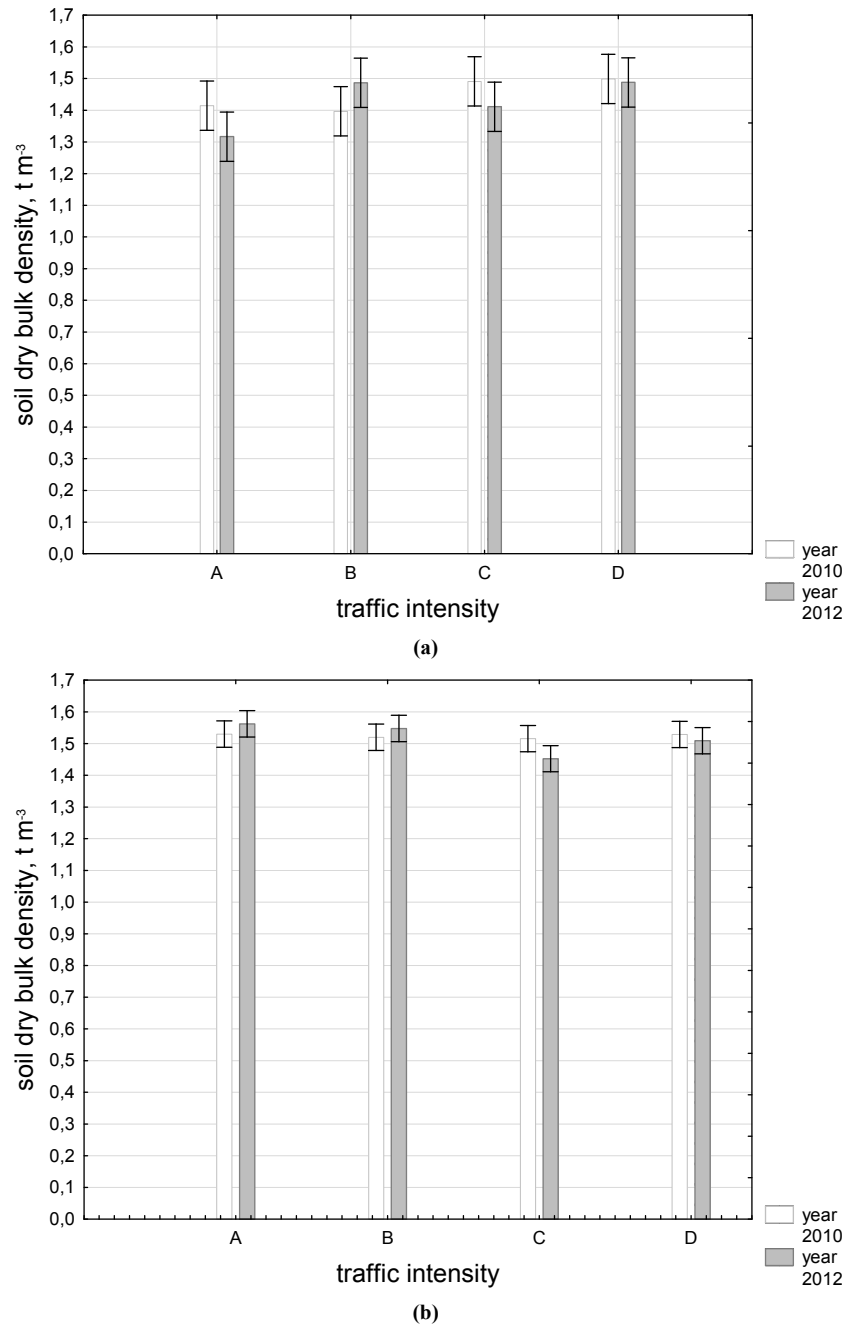
(a)

(b)

Figure 5. Soil dry bulk densities recorded at the site in 2010 and 2012 in (a) topsoil (0-350 mm) and (b) subsoil (350-600 mm). A = permanent crop bed of the CTF system (non-trafficked soil), B = single traffic event per year, C = permanent intermediate traffic lane, and D = multiple passes per year. LSD (5% level) = 0.11 (topsoil) and 0.06 (subsoil).

value above which root growth is increasingly restricted (Whiteley et al., 1981).

EFFECT OF TRAFFIC ON CROP YIELD AND YIELD COMPONENTS

Yield and yield components determined at the four traffic treatments are given in table 4. The LSD analyses (table 5) showed the following differences between treatments:

- The yields of wheat in 2011 were without significant differences for all treatments (p > 0.05), except at treatments C and D where differences in yield were significant (p < 0.05). When considering a 10% prob-

ability level, there was a significant difference in yield between treatments D and A as well as between D and C. Crop components were different at treatments A and B and at C and D (p < 0.05).

- The yield of barley in 2012 was significantly lower at location D compared with all other treatments (p < 0.05). Yield was also significantly lower at location C than at A (p < 0.05). The difference between A (non-trafficked) and D (random traffic) was approximately 35%. Crop yield components recorded from wheeled and non-trafficked areas were consistent with yield data and showed improved performance in the absence
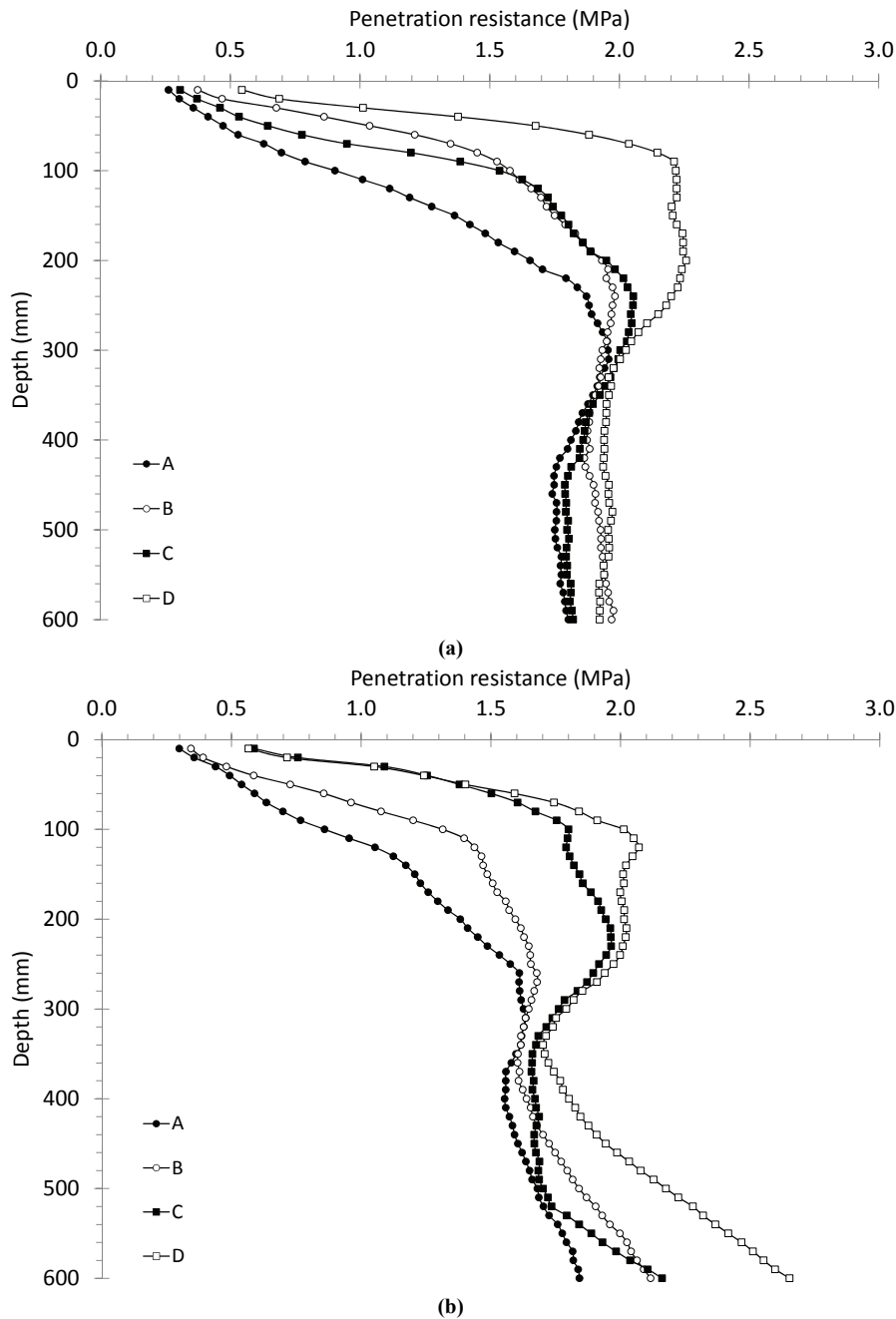
Figure 6. Soil penetrometer resistance recorded at treatments A, B, C, and D in (a) 2012 and (b) 2013. For 2012, LSD (5% level) = 0.13 and 0.03 for the 0-350 mm and 350-600 mm depth intervals, respectively. For 2013, LSD (5% level) = 0.08 and 0.04 for the 0-350 mm and 350-600 mm depth intervals, respectively. A = permanent crop bed of the CTF system (non-trafficked soil), B = single traffic event per year, C = permanent intermediate traffic lane, and D = multiple passes per year.

of traffic. In 2014, no differences in yield and yield components were recorded (p < 0.05), except for a relatively lower ear count at location D compared with B, with a difference of 23%.

- The maize crop showed no significant differences in yield or yield components (p > 0.05) in any of the treatments.

Because spring barley was grown in two growing seasons during the monitored crop rotations, an ANOVA with two factors (traffic intensity and year) was performed and showed a significant effect of season as well as traffic inten-

sity (p < 0.05). Differences in yield between the non-trafficked area (A) and the areas with different levels of traffic intensity (B, C, D) ranged from 5% to 9% for winter wheat, from 9% to 33% for the 2012 spring barley, from 7.5% to 25% for maize, and from 7.7% to 13.4% for the 2014 spring barley. Despite this, the differences were not always significant, as shown in table 5. Where statistical significance was not observed, it may be attributable to the fact that the experiment was designed as a whole-field experiment. This resulted in samples with relatively large coefficients of variation, which reflected the variability encountered in the field

Table 4. Mean and standard deviations of grain yield and measured crop parameters recorded for winter wheat in 2011, spring barley in 2012, and maize in 2013 as affected by traffic intensity ($n = 27$).

Location	2011 Winter Wheat			2012 Spring Barley			2013 Maize			2014 Spring Barley		
		Ear			Ear			Ear			Ear	
	Yield (t ha^{-1})	Count (m^{-2})	Height (m)	Yield (t ha^{-1})	Count (m^{-2})	Height (m)	Yield (t ha^{-1})	Count (m^{-2})	Height (m)	Yield (t ha^{-1})	Count (m^{-2})	Height (m)
A	7.98	599	0.80	5.39	610	0.53	5.46	53,000	1.94	6.49	621	0.68
Non-wheeled	±1.42	±89	±0.07	±1.20	±120	±0.05	±1.48	±8,514	±0.15	±0.95	±63	±0.06
B	7.59	583	0.79	4.91	601	0.51	5.05	53,666	1.82	6.53	666	0.66
Single pass	±1.35	±88	±0.05	±1.02	±135	±0.0	±1.6	±6,480	±0.15	±0.92	±120	±0.05
C	8.15	493	0.73	4.46	509	0.45	4.76	42,222	1.84	5.62	539	0.69
Multiple pass	±1.63	±53	±0.03	±1.41	±101	±0.02	±2.3	±16,437	±0.22	±1.23	±91	±0.06
D	7.27	459	0.71	3.58	431	0.45	4.12	47,555	1.76	5.99	543	0.67
Random traffic	±1.43	±45	±0.04	±1.24	±154	±0.03	±1.8	±19,046	±0.23	±1.42	±159	±0.05

Table 5. Differences between means and significance of pairwise comparisons.[a]

Traffic Treatment Comparison		2011 Winter Wheat (LSD$_{0.05}$ = 0.79 t ha^{-1}, LSD$_{0.1}$ = 0.66 t ha^{-1})	2012 Spring Barley (LSD$_{0.05}$ = 0.66 t ha^{-1}, LSD$_{0.1}$ = 0.55 t ha^{-1})	2013 Maize (LSD$_{0.05}$ = 1.73 t ha^{-1}, LSD$_{0.1}$ = 1.43 t ha^{-1})	2014 Spring Barley (LSD$_{0.05}$ = 1.07 t ha^{-1}, LSD$_{0.1}$ = 0.87 t ha^{-1})
A	B	0.39 ns	0.49 ns	0.41 ns	-0.04 ns
	C	-0.17 ns	0.93 **	0.70 ns	0.87 *
	D	0.71 *	1.81 **	1.34 ns	0.50 ns
B	C	0.56 ns	0.44 ns	0.29 ns	0.90 *
	D	0.31 ns	1.33 **	0.93 ns	0.53 ns
C	D	0.87 **	0.89 **	0.64 ns	-0.37 ns

[a] Asterisks indicate differences larger than LSD at p < 0.10 (*) and LSD at p < 0.05 (**); ns = not significant.

Table 6. Results after combining probabilities from independent tests of significance, which include all four datasets. This approach is based on the methodology proposed by Sokal and Rohlf (1981).[a]

Year and Crop	p	ln(p)
2011 Winter wheat	0.1237	-2.0659
2012 Spring barley	0.00004	-12.4292
2013 Maize	0.45	-0.7985
2014 Spring barley	0.299	-1.2073
Σ ln(p)	-	-16.5009
-2Σ ln(p)	-	33.0018
$\chi^2_{0.01}$ probability and 12 degrees of freedom	-	20.09
$\chi^2_{0.001}$ probability and 12 degrees of freedom	-	26.12

[a] With -2Σ ln(p) greater than χ^2 at 0.01, the null hypotheses that there is no difference between the crop yield of the traffic systems in the four seasons can be rejected.

Table 7. Model grain yield in t ha^{-1} for winter wheat in 2011, spring barley in 2012 and 2014, and maize in 2013 for different traffic systems when considering headline yields as indicators of crop response.

Year and Crop	RTF	CTF 6 m	CTF 8 m	CTF 12 m
2011 Winter wheat	7.65	7.93	7.95	8.01
2012 Spring barley	4.74	5.13	5.23	5.25[a]
2013 Maize	4.96	5.21	5.39	5.36
2014 Spring barley	6.32	6.30	6.41	6.36

[a] Statistically different from RTF (p < 0.1).

(fig. 2). For example, in the 2013 growing season, the coefficients of variation for yield data ranged from 27% to 43% depending on the traffic treatment. Similar observations were reported by Godwin et al. (2015) for field-based studies dealing with the effects of traffic on crop yield and fertilizer use efficiency. Assessment of the effects of traffic treatments on crop performance was conducted by combining probabilities from independent tests of significance, using the approach proposed by Sokal and Rohlf (1981). The four-year dataset (2011, 2012, 2013, and 2014, respectively) was used. After combining the probabilities from independent tests of significance, it was shown that there was an overall difference in crop yield for the four growing seasons (table 6).

POTENTIAL YIELD IMPROVEMENT AND ECONOMIC IMPACT OF CTF

Based on the combined probabilities for the four-year study, the headline yields were used as an indication of the type of responses that might be achieved. These data can be extrapolated for the different proportions of trafficked and non-trafficked soils under CTF systems of different widths, as shown in table 7. These yields were calculated using the components of equation 1; for example, the CTF treatments were determined from $(Y_A \times A) + (Y_C \times C)$. This analysis showed that for the yield data corresponding to the 2011 to 2014 crops, the CTF system outyielded RTF. The differences in yield were converted into economic returns (table 8) based on the price of grain for the corresponding year of harvest. This shows that the conversion from RTF to an 8 m CTF system has the potential to significantly increase gross income. Estimates suggest that over the crop rotation, an additional 191, 277, or 278 USD ha^{-1} may be realized when RTF is converted to a 6 m, 8 m, or 12 m CTF system, respectively. A small financial penalty was observed in the 2014 spring barley crop, which was due to the fact that a slightly higher yield was recorded in the single traffic treatment (location B) compared with the non-trafficked soil, and because of the proportions of A and B for RTF and CTF 6 m (table 3) and the lower yield that was obtained at treatment A compared to B.

Table 8. Potential increase in gross income compared with RTF for the different traffic systems when considering headline yields as indicators of crop response.

Year and Crop	Retail Price (USD t^{-1})	USD ha^{-1}		
		CTF 6 m	CTF 8 m	CTF 12 m
2011 Winter wheat	216	60	65	78
2012 Spring barley	230	90	113	117
2013 Maize	184	46	79	73
2014 Spring barley	230	-5	21	9
Sum for crop rotation		191	277	278

DISCUSSION

Avoidance of traffic compaction had a favorable effect on soil conditions, which is indicated by the differences in soil bulk density before and after the traffic treatments were introduced in 2010. The limit value of soil bulk density for root growth density ($\sim$1.45 t m^{-3}) suggested by Lhotský et al. (1991) in central Europe was exceeded at treatments B and D in 2012, which is consistent with cone index data recorded in 2013. Assessment of traffic effect on crop yield consisted of two steps. The first step gathered data derived from measurements conducted in field conditions. This analysis was followed by a modeling approach that used extrapolated yields for different CTF systems most likely to be adopted in Europe (i.e., 6 m, 8 m, and 12 m widths) and subsequently compared them with yields determined for a random traffic system. Significant ($p < 0.05$) differences in yield were only recorded in 2012 for the spring barley crop, which was the third crop season after CTF had been introduced. The absence of traffic compaction in permanent beds (treatment A) increased grain yield by approximately 35% compared with the multi-pass treatment (D) and by 9% compared to the single-pass treatment (B). In contrast, there was no effect of traffic on yield in the 2014 spring barley crop. For barley, the effect of traffic on yield observed in 2012 may be explained by the relatively dry weather conditions recorded during the spring of that year; improved soil structural conditions under treatment A (non-trafficked soil) may have provided increased plant-available water and rainfall use efficiency (Li et al., 2001).

Although CTF outperformed RTF on average in all other years, the differences between the systems were significant only at $p < 0.1$. Godwin et al. (2015) suggested that this is not uncommon when dealing with field-scale trials in which soils exhibit moderately high heterogeneity, resulting in significant variability in the experimental data. This observation also agrees with experimental results reported by Negi et al. (1981), which showed that the effect of traffic compaction on crop yield is dependent on the seasonal effect of weather. Godwin et al. (2015) claimed that there is a risk of overly rigorous statistical significance levels impeding sensible adoption of improved soil management methods. This is the reason why the 10% level was preferred when modeling the possible effect of converting from a random system to a 6 m, 8 m, or 12 m CTF system. The benefits of converting to CTF are clear from the comparison of extrapolated yields, which showed that 8 m and wider CTF would bring a significant yield benefit for 2012 spring barley grown in dry conditions. The effects for maize and spring barley grown in conditions where water is not a limiting factor were less strong. This is also supported by Li et al. (2008a), who reported that CTF outyielded the conventional practice to a greater extent in lower rainfall years than in average or above-average rainfall years. These results are also consistent with observations reported in earlier work (Chamen et al., 1990; Arvidsson, 1999; Radford et al., 2000), which indicated reduced water and nutrient use efficiencies, and therefore yield, of winter cereal crops grown in soils affected by traffic compaction.

The potential to improve yields within a given traffic system may be assumed to be a function of the area affected by compaction when all other crop management practices are constant and recommended practices are adopted. Therefore, for CTF systems, the potential to increase the yield, or to reduce the yield penalty, depends on the area ratio of permanent traffic lanes to permanent crop beds. As indicated earlier, well-designed systems typically have 20% or less of the cropped area occupied by traffic lanes (Tullberg, 2010). Based on the results obtained, the yield penalty from crops within the permanent traffic lanes was approximately 17% (2012), which is consistent with data obtained by Smith et al. (2014) and Godwin et al. (2015) for Northern European conditions. The yield data obtained from the traffic treatments applied in this study were used to provide yield estimates for farming systems with varying equipment and track widths. Therefore, yield was calculated in relation to the cropped area affected by compaction for CTF systems with 6 m, 8 m, and 12 m widths. We found a statistically significant increase in yield if the system was converted to a 12 m width. For the spring barley crop, the yield improvement following conversion represented, approximately, an additional 113 or 117 USD ha^{-1} increase in gross income for the 8 m and 12 m CTF systems, respectively. When considering the headline yields across the four-year crop rotation, the improvement in gross income can be approximately 191 to 278 USD ha^{-1} depending on the CTF system used (table 8).

Further outcomes that may be expected from reduced wheeled areas are progressive improvement in soil structural conditions and water availability to crops (Vermeulen and Chamen, 2008; McHugh et al., 2009; McPhee et al., 2015). This is likely to result in higher inter-annual stability of crop yields (Radford et al., 2000; Li et al., 2008b) and enhanced sustainability of the farming enterprise (Kingwell and Fuchsbichler, 2011). Improved environmental performance of the farming system, such as reduced GHG emissions and reduced nutrient and sediment loss in runoff, may also be expected if CTF was coupled with zero tillage, which is common in Australia (Tullberg et al., 2001; Li et al., 2007; Antille et al., 2015). This is also relevant to our work, given the relatively complex topography and soil type of the experimental field. CTF systems in Australia are often designed to have mechanization systems with 3 m track gauge, meaning that the tracked area can be as low as 15%, depending on the width used. However, such systems are less readily adoptable in Central Europe (Vermeulen and Chamen, 2008; Tullberg, 2010) because of restrictions in transporting farm machinery that is wider than the standard allowed on roads.

The crop sequence used in this study does not strictly reflect the rotation typically practiced under European conditions, which would also include oilseed crops. Additional economic benefits would be expected with CTF when such crops are included as part of the rotation due to their relatively high responsiveness to improved soil conditions, which has been widely reported (e.g., Lipiec and Simota, 1994; Goodman and Ennos, 1999; Chan et al., 2006). As highlighted earlier, soil structural conditions, and consequently the response of the crop to such conditions, are reported to improve progressively following establishment of CTF (McHugh et al., 2009; McPhee et al., 2015). The economic result may therefore be further improved in CTF compared with RTF, particularly if tillage costs are computed in the analysis (Kingwell and Fuchsbichler, 2011; Chamen et al., 2015). Reduced cost of tillage in CTF is achieved through: (1) reduced need for removal of soil compaction and hence savings in the energy required, implement wear, and labor; and (2) reduced draft because it may be possible to conduct

tillage operations at shallower depths and in soils with relatively lower specific resistance (Tullberg, 2000; Galambošová and Rataj, 2011; Rataj et al., 2013; Jensen et al., 2012). The results reported in this study agree with earlier work (Kingwell and Fuchsbichler, 2011; Chamen et al., 2015) and therefore are supportive of further adoption of CTF in Europe. While quantifying the potential environmental benefits associated with CTF was not the task of this study, it is expected that improved resource use efficiency, including fertilizer, water, and energy, as well as increased soil protection will enhance the overall environmental performance compared with random field traffic (Li et al., 2007; Masters et al., 2013; Gasso et al., 2013; Chyba et al., 2014; Antille et al., 2016).

CONCLUSIONS

The results of this investigation suggest that CTF systems have potential to increase production sustainability in arable farming systems in central Europe. This conclusion is supported by the following findings:

- Adoption of CTF using commercially available machinery can reduce the cropped area affected by traffic by more than 50% compared with random traffic systems.
- Under the conditions of this study, it was shown that the yield penalty from a single annual traffic event (e.g., using a heavy tractor on otherwise non-trafficked soil) was relatively small, particularly when in-crop season rainfall was not a yield-limiting factor. However, compaction caused by multiple passes of machinery may lead to yield losses of up to 33% in dry seasons.
- The experiment was designed as a whole-field experiment. Therefore, statistical differences between traffic treatments were not always observed when analyzing growing seasons separately. However, differences were significant when results from all four seasons were combined. Using the headline yield and the ratio of non-trafficked to trafficked area within different CTF systems, it was shown that yield improvements of up to 0.5 t per ha may be possible when converting from RTF to CTF. This can improve gross revenues by up to 117 USD ha^{-1}.

Based on the four-year experimental results of this study, the main benefit of CTF appears to be enhanced agronomic stability of the system, which will ultimately reduce risk. The use of well-developed models for simulating long-term effects of CTF adoption on crop and soil, supplemented by technical and economic analyses, will enable quantification of the benefits of compaction avoidance at the farm scale. The results from this research confirm the hypotheses formulated prior to this study and therefore are supportive of increased adoption of CTF in Central Europe.

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