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A synthesis of fourteen years of controlled traffic farming systems research in Slovakia

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ABSTRACT

This work synthesizes datasets derived from a long-term field-scale experiment established in 2009 to investigate the feasibility of implementing controlled traffic farming (CTF) in Slovakia. The experimental site comprises of 16 ha and sits on Haplic Luvisol and Eutric Reductigleyic Gleysol soils with 1°–12° slopes. The CTF system has a 6-m base module and uses unmodified, commercially available machinery. Crop rotation included spring and winter cereals, oilseed rape (*Brassica napus* L.) and field peas (*Pisum sativum* L.). Key indicators of soil quality, and the agronomic and economic performance of the system, relative to a conventional mechanisation system (non-CTF), were evaluated over 14 years (13 crop seasons). Results for CTF showed significant improvements in all soil properties tested ($p < 0.01$) compared with non-CTF. Lower soil bulk density (0.05 – 0.40 m) and penetration resistance (0 – 0.80 m) where traffic was avoided explained significantly higher crop yields in non-trafficked compared with trafficked soils. These differences were between 12% and 20% depending on the topographical position and the seasonal effects of weather. No traffic in permanent crop beds reduced the spatial yield variability across the field that was evident before the CTF system was established (as compaction-induced soil variability was eliminated), together with improved inter-annual yield stability, suggesting increased reliability of cropping under CTF. Such yield improvements were more evident for spring sown crops and in drier than average rainfall seasons. Improved agronomic performance of crops grown under CTF translated into increased rainfall- and fertiliser nitrogen use efficiency compared with non-CTF. The findings from this study showed that adoption of CTF can lead to improved farming system resilience in the context of climate change, and that it is a technically viable and cost-effective mechanisation alternative for Central European conditions. This was confirmed by the system-level analyses, which showed that, following conversion to CTF, the payback period for a 1000-ha arable farm would be 2 years. Future research should focus on integrating both biophysical and economic modelling, coupled with climate scenario analysis, to aid optimisation of CTF designs and crop selection for Central European farming systems.

1. Introduction

Soil compaction is the increase in soil bulk density and the reduction in soil porosity (SSSA, 2008). Increased soil strength due to compaction impairs root penetration and root exploration of the soil profile thereby restricting access to soil water and nutrients (Shierlaw and Alston 1984; Bluett et al., 2019). Soil compaction can lead to increased risk of run-off and erosion, reduced fertiliser and water (irrigation and rainfall) use efficiency and can have adverse effects on soil biota (Lipiec and Stępniewski, 1995; Pangnakorn et al., 2026). Arable soils in Central Europe are vulnerable to soil compaction (Houšková, 2023), and soil damage due to machinery traffic is considered to be a key soil threat in most mechanised agricultural systems (Keller et al., 2019). An upwards trend in the weight of farm machinery, coupled with the projected increase in extreme rainfall events (Panagos et al., 2017; Kišš et al., 2022; UNDRR, 2022), can compound the risk of soil compaction occurring, potentially

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leading to increased costs to repair soil damage as well as loss of productivity (Gregory et al., 2015; Keller et al., 2019). It is also recognised that soil compaction has contributed to offset advances made in plant breeding to improve crop productivity, therefore, yield gaps (the difference between potential and actual yields) have remained fairly unchanged, particularly for winter cereal and oilseed rape crops (Knight et al., 2012). Several studies (e.g., Sonderegger and Pfister, 2021; Zhang et al., 2024) have shown that yield penalties in wheat, barley, corn, and soybean, due to compaction, may be as high as ~4%, 15%, 38%, and 23%, respectively. The adverse effects of compaction on crop yield are observed both in conventional and no-tillage systems. Studies have shown that each time a crop is produced, the area affected by traffic in those systems can be as large as 40%−85% of the field-cropped area (Botta et al., 2022; Kroulík et al., 2009; Tullberg 2010). The European Soil Data Centre indicated that "…*recent research showed that compaction is the most widespread kind of soil physical degradation in Central and Eastern Europe*…" (ESDAC, 2025). It is also reported that approximately 25 million ha of arable land in Central and Eastern Europe are deemed to be lightly compacted while a further 36 million ha are more severely affected by compaction, with estimated productivity losses due to subsoil compaction of up to ~35% (ESDAC, 2025).

Amelioration of soil compaction through deep tillage is energy demanding and therefore expensive, and its effect can be transient, depending upon the soil type and the soil and mechanisation management practices implemented after tillage (Spoor and Voorhees, 1986; Spoor, 2006; Botta et al., 2026). Mechanisation systems in which compaction can be reduced (e.g., low-ground pressure systems), or avoided (e.g., controlled traffic farming, including gantry systems) have the potential to increase the operating efficiency, reduce energy use and costs, and improve the overall reliability and environmental performance of farming (Hussein et al., 2021a, Hussein et al., 2021b; Chamen et al., 1992; Godwin et al., 2022; Jensen et al., 2025). Controlled traffic farming (CTF) is a mechanisation system in which (CTFA, 2017 in Antille et al., 2015): (1) all machinery has the same or modular working and track widths so that field traffic can be confined to the least possible area of permanent traffic lanes, (2) all machinery is capable of precise guidance along those permanent traffic lanes, and (3) the layout of the permanent traffic lanes is designed to optimise surface drainage and logistics.

The extent to which the operating and track widths of field equipment are matched will determine the percentage of the field-cropped area that is annually wheeled (Isbister et al., 2013). The target for CTF systems is to keep the wheeled area to less than 15% of the field-cropped area; however, due to specific equipment and planting configurations, and road transport regulations, this area can be as large as 40%, as observed in some systems in Europe (e.g., Chamen et al., 2015; Galambošová et al., 2017; Chamen and Antille, 2022). In well-designed systems in Australia, it has been possible to keep this area to ~12% (e.g., Tullberg et al., 2007; McPhee et al., 2020; Jensen et al., 2025), and the use of gantry systems (e.g., Chamen et al., 1992; NEXAT, https://www.nexat.de/) can further reduce it to less than 10%. Controlled traffic farming is complementary to no-tillage given the added agronomic, economic and environmental benefits that can be realised when both practices are jointly implemented (Tullberg et al., 2007; Bluett et al., 2019; Godwin et al., 2022). Some of these benefits include: (1) soil structure and porosity: improved water infiltration into soil, reduced risk of runoff and erosion, and increased soil water storage capacity (Ngo-Cong et al., 2021; Chyba et al., 2017; Macák et al., 2023; McHugh et al., 2009; Tullberg et al. 2001); (2) improved yield stability with reduced inter-annual yield variability, which can reduce agronomic, and therefore, financial risks, particularly in dry years (Galambošová et al., 2017; Rataj et al., 2022; Antille et al., 2019; Hussein et al., 2021a, Hussein et al., 2021b); (3) overall systems' efficiency: improved timeliness of field operations and trafficability, and energy-use efficiency (Tullberg, 2000; Jensen et al., 2025); (4) improved environmental performance through reduced soil emissions of GHG and increased fertiliser nitrogen-use efficiency (Tullberg et al., 2018; Hussein et al., 2021a, Hussein et al., 2021b; Antille et al., 2024).

Despite these benefits, global adoption of CTF is still limited; except in Australia where it is reported that approximately 35% of grain growers practice controlled traffic (Mitchell et al., 2019). Other successful examples of CTF adoption are in Canada (e.g., CTFA, 2017), with fully matched equipment, and in South America (e.g. Botta et al., 2007; Botta et al., 2022; Masola et al., 2020; Masola et al., 2026), where they rely on unmodified commercially available equipment. In Europe, adoption of CTF is also limited, but it is reported to be growing (albeit slowly) in western and northern countries (e.g., Chamen, 2015; Godwin et al., 2015). Key barriers to CTF adoption in Europe have been lack of awareness of the system's benefits under local conditions and equipment offering from machinery manufacturers, as well as limited extension, technical expertise, and availability of decision support tools (e.g., CTF Calculator, https://ctfcalculator.org/) to aid decision-making (Tamirat et al., 2022).

The work reported in this article builds upon an earlier study by Galambošová et al. (2017) and it aimed to synthetise fourteen years of continuous research conducted at the experimental site in Nitra, Slovakia (established in 2009). The interrogation and synthesis of this dataset provided an improved understanding of the long-term effects of alternative traffic treatments, and the interaction between traffic treatments and environmental conditions, on crop and soil over that period. Such analysis would have been limited in scope and depth, or not possible, in a shorter-term study, particularly, in situations where responses to treatments and management × environment interactions are influenced by properties in which change occur slowly (e.g., soil structure, which has profound effects on soil water dynamics, nutrient uptake, and ultimately crop performance). Hence, this analysis provided the opportunity to assess and document the long-term soil sustainability and crop productivity effects of traffic management systems in the study region. A key feature of this work is that the CTF system was designed to operate with commercially available (unmodified) farm equipment, which enabled testing the merits of such system under more readily adoptable conditions for Central Europe. The establishment of this experimental site has brought about increased awareness of the damaging effects of soil compaction in Slovakia and the implications that it has for the long-term sustainability of arable systems. While the work in Nitra was initially targeted to Slovakian farming systems, the strategic location of the experimental site made this body of research relevant to arable production systems across Central Europe.

We have hypothesised that controlled traffic farming would progressively improve the soil physical quality leading to increased crop productivity. It was also hypothesised that controlled traffic would reduce within field variability, and through better water economy, it will improve the inter-annual yield stability. It is envisaged that this work will go some way to drive adoption of controlled traffic farming in Central Europe as it demonstrates the technical viability and cost-effectiveness of CTF to Slovakian crop production systems. Knowledge transfer and practice change will benefit from engagement between research and extension officers and farm advisers, and this process needs to be facilitated both by government agencies and machinery manufacturers.

2. Materials and methods

2.1. Site description and climate

A 16-ha experimental field of the Slovak University of Agriculture's farm in Kolinany, located in the Žitavská upland (48°37'17" N, 18°20'75" E, elevation: 196–212 m above-sea-level) Slovakia, was used in this study (Fig. 1S, Appendix A). The land at the farm has slopes between ~1° and 12°. A detailed map showing the contour lines and slopes is provided in Fig. 2S (Appendix A). It became evident that the middle part of the field had the steepest slope while the eastern and western sides exhibited moderate slopes (≤1°). The slope distribution across the field had a significantly influence on the soil properties measured, as discussed later.

The soils at the site were characterised by Šimanský et al. (2023) as Haplic Luvisol and Eutric Reductigleyic Gleysol, based on the IUSS Working Group WRB (2015) Soil Taxonomy System, with 34.6–63.7% silt and 26.9–56.7% clay contents, respectively (Table1). Given the topography of the site, the soils are susceptible to erosion and sediment deposition in the lower parts of the landscape (Jonczak et al., 2022), and an overview of the catena is available as Supplementary Material (Appendix B). The soil pH ranges from near-neutral to slightly alkaline, and it tends to increase with depth (due to the percolation of base cations, proximity to groundwater, and carbonate formation at depth). The soils exhibit moderately high soil organic carbon (from 2.48 to 18.14 g kg^{-1}) and total nitrogen (from 0.48 to 1.96 g kg^{-1}) contents (Table 1; Jonczak et al., 2022). An earlier study by Houšková (2023) suggested that the soils at the experimental site can be classified as having 'medium' susceptibility to compaction.

Within field soil variability was determined with electromagnetic induction (EMI) survey (Doolittle and Brevik, 2014). Measurements were performed using a ground conductivity meter (EM38-MK2, Geonics Ltd., Mississauga, Ontario, Canada) in horizontal mode, carried at a height of 0.20 m above the soil surface. The data were reported as apparent electrical conductivity (ECa, mS m^{-1}). The first measurement was conducted immediately before the experiment was established in 2009 (Fig. 3S, Appendix A) and ECa readings ranged between 33.13 and 66.73 mS m^{-1}. Subsequent measurements were performed in 2014 and 2021 (Figs. 4S and 5S, Appendix A), and ECa values ranged between 22.15 and 66.21 mS m^{-1}, and between 11.02 and 50.27 mS m^{-1}, respectively. The EMI surveys were complemented with a map of yield potential (Varistar©, Czech Republic) (Fig. 6S, Appendix A). The yield zones identified from the yield map were developed from datasets of PlanetScope (https://earth.esa.int/eogateway) satellite images, which had a resolution of 3 × 3 m from the year 2016 onwards. There were five satellite images from each season (regularly stratified up to a month before the day of harvest) and this information was normalised by data derived from the DEM (Digital Elevation Model) (Varistar, 2024).

Temperature and rainfall were recorded daily during each cropping season, and based on the cumulative values, a comparison with the historical averages for the period between 1991 and 2000 was undertaken. Based on the temperature records, the cropping seasons were considered as average to warm, with exception of 2010, which had temperatures below-historical averages. Seasonal rainfall records showed that a majority of the years were drier than the long-term average, with exception of 2010, 2016 and 2023, which were wetter (Table 2S Appendix C).

2.2. Experimental layout and treatments

A 6-m base module 'out-track' CTF system with two track widths (1.83 m and 1.31 m) was introduced in 2009 using commercially available machinery in Slovakia. Full description of the CTF system used at the site and drawings are available from Galambošová et al. (2017). The layout of the field and traffic patterns are shown in Fig. 1a, and details of the farm machinery used for all field operations are provided in Table 2. There was no adjustment made to the tractor's axle width. Harvest was conducted by an external contractor who used a combine harvester equipped with a 9-m wide cutter bar and the grain was always discharged to a chaser bin located at the field's headland. This arrangement avoided creating additional in-field traffic by the tractor-chaser bin system, as shown by Botta et al. (2007).

Three 25-m wide strips (Fig. 1b) were wheeled annually from the topographically higher to the lower part of the field using the tractor listed in Table 2. This operation ensured that an area of the field was trafficked once a year to represent the wheeled soil of a 'random' or non-controlled traffic farming (non-CTF) system, with low traffic intensity. The layout of the CTF system (Fig. 1a) and the annually wheeled strips, resulted in 4 areas with different traffic intensities, which represented the traffic treatments described below:

- A – zero traffic (non-wheeled soil since 2009), which represented the permanent crop bed of the CTF system,
- B – one pass of farm machinery per year, which represented the wheeled soil of a 'random' or non-CTF system,
- C – permanent traffic lane of the CTF system, which had multiple passes of farm machinery per year, and
- D – multiple passes of farm machinery during the cropping season in two perpendicular directions (given by the intersection of the permanent traffic lanes of the CTF system with the 25-m wide strip that was annually wheeled). This treatment represented a 'high' traffic intensity scenario in a 'random' or non-CTF system.

Based on the information provided in Section 2.1, and to account for differences in the field's elevation, the experimental design comprised of three blocks that resulted from the topographic position and the associated soil wetness class (bottom, middle, and top, respectively). These three sub-field areas were later verified by Jonczak et al. (2022), who studied the local soil catena and demonstrated that the existing soil heterogeneity was, in part, explained by the depth to groundwater and the associated soil water regime. All measurements conducted as part of our work were performed separately within each block to be able to simultaneously quantify traffic treatment effects and topographical position. Consequently, each block had the four distinctive traffic intensities areas (A to D) that were routinely monitored, and each area had 3 replications (Fig. 1b, left). The area available within each sampling

Table 1
Soil characteristics of the study site. Notation: scl (silty clay loam), sc (silty clay), sl (silty loam). Textural class is based on the FAO classification system (modified and updated from Jonczak et al., 2022 modified).

Block	Depth	Sand	Silt	Clay	Texture	pH H_2O	pH KCl	$CaCO_3$ (g kg^{-1})	TOC (g kg^{-1})	N (g kg^{-1})
	cm	2.0–0.05	0.05–0.002	< 0.002						
Top	0–26	7.6	62.5	29.9	scl	6.8	5.6	2.1	13.15	1.57
	26–40	5.4	58.7	36.0	scl	7.1	5.7	3.2	5.41	0.75
	40–53	6.3	58.0	35.7	scl	8.0	6.8	8.0	4.24	0.68
	53–73	9.0	52.3	38.7	scl	8.5	7.4	62.7	9.56	0.71
Middle	0–28	9.4	63.7	26.9	sl	6.6	5.6	2.4	12.91	1.51
	28–42	7.2	61.7	31.1	scl	7.0	5.7	2.1	10.45	1.21
	42–60	6.1	58.4	35.5	scl	7.3	5.8	2.9	9.65	1.14
	60–76	6.4	53.1	40.5	sc	7.3	5.8	2.8	8.16	1.00
Bottom	0–24	7.7	62.0	30.3	scl	6.9	5.8	2.0	18.14	1.96
	24–35	6.4	61.0	32.6	scl	7.6	6.2	3.4	12.9	1.49
	35–54	5.7	59.1	35.2	scl	7.7	6.3	3.2	12.71	1.40
	54–70	6.6	54.8	38.6	scl	7.9	6.4	2.0	12.18	1.44

Table 2
Characteristics of machinery used at the experimental site.

Operation	Year performed	Tractor	Machine	Overall load, kg	Tyre specs., tyre inflation pressure
All tillage	2009–2024	John Deere 8230	6 m disc harrow Lemken Rubin	11406	Front: 600/70 R30, 0.25 MPa Rear: 650/85 R38, 0.25 MPa
Sowing	2009–2017, 2021	New Holland T6080	6 m Lemken Solitair 9	5524	Front: 480/65 R28, 0.2 MPa Rear: 600/65 R38, 0.2 MPa
	2018 2018	Fendt 936 Vario	6 m Sumo DTS 6 Farmet Falcon 6/FERT+	10900	Front: IF 650/65 R34, 0.22 MPa Rear: IF 710/75 R42, 0.22 MPa
	2021	John Deere 8345 R	Bourgault CD872	12100	Front: 600/70 R30, 0.21 MPa Rear: 710/75 R42, 0.21 MPa
	2024	John Deere 8370 R	Kuhn ESPRO 6000 RC	14828	Front: 380/80 R38, 0.25 MPa Rear: 480/80 R50, 0.25 MPa
Drilling	2013, 2020	New Holland T6080	6 m Monosem (only for maize drilling)	5524	Front: 480/65 R28, 0.2 MPa Rear: 600/65 R38, 0.2 MPa
Spraying	2009–2017	New Holland T6080	24 m sprayer Agrio NAPA	5524	Front: 480/65 R28, 0.2 MPa Rear: 600/65 R38, 0.2 MPa
	2018–2024	self-propelled	Agrifac CONDOR	10500	Front: 380/105 R50, 0,3 MPa Rear: 380/105 R50, 0,3 MPa
Fertilizer application	2009–2024	New Holland T6080	24 m spreader AMAZONE ZA-M 1500	5524	Front: 480/65 R28, 0.2 MPa Rear: 600/65 R38, 0.2 MPa
Rolling	2018, 2020, 2021	John Deere 8230	6,3 m Kverneland ACTRIOL 630	11406	Front: 600/70 R30, 0.25 MPa Rear: 650/85 R38, 0.25 MPa
Harvest	2011–2012	self-propelled	CLAAS Lexion 480; 9 m header	18150	Front: 800/65 R32, 0.26 MPa Rear: 600/55–26.5, 0.26 MPa
	2013		CLAAS Lexion 550; 9 m header	17250	Front: 800/65 R32, 0.32 MPa Rear: 500/70 R24, 0.24 MPa
	2014–2018		CLAAS Lexion 600; 9 m header	17500	Front: 800/65 R32, 0.32 MPa Rear: 600/55 R26.5, 0.22 MPa
	2019, 2022–2024		John Deere T670i; 9 m header	16500	Front: 800/70 R32, 0.30 MPa Rear: 500/80R28, 0.22 MPa
	2021		Claas Lexion 6900; 9 m header	17950	Front: 680/85 R32, 0.30 MPa Rear: 500/85 R24, 0.22 MPa
	2020		Claas 780 TerraTrac; 9 m header	18200	Front tracks: 635 mm wide Rear: 500/85 R30, 0.22 MPa
Wheeling of strips	annually	John Deere 8230	no	11406	Front: 600/70 R30, 0.25 MPa Rear: 650/85 R38, 0.25 MPa

location (A to D) was 5 m^2.

During the 13 growing seasons, the crop rotation at the site followed the same crop sequence as the commercial farm, which is common in the region, and it included the following winter and summer crops: wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), maize (*Zea mays* L.), oilseed rape (*Brassica napus* L.), and field peas (*Pisum sativum* L.), which were introduced in 2018. Table 3S (Appendix C) provides detailed information pertaining to the crops and crop rotation implemented at the experimental site, and other relevant farm records including retail price. All crops were established using minimum tillage, which involved a light disc harrowing operation to a working depth of 0.15 m for stubble incorporation and seedbed preparation with no other tillage implement used afterwards (Table 2). Other field operations included routine crop protection with a sprayer rig and fertilisation using a standard twin-disc fertiliser spreader. Soil and crop measurements and analyses are described in detail in the following sections, including determination of grain yield by hand from replicated quadrats and the yield recorded from the combine harvester.

2.3. Soil measurements and analyses

Soil bulk density (ρ_b) was determined in the laboratory from non-disturbed soil samples taken from 2 depth intervals, topsoil (0.05–0.15 m) and subsoil (0.3–0.4 m), and measurements replicated three times for each depth interval. Soil cores were taken with Kopecky push tubes (100 cm^3, dimensions 53 mm in diameter and 51 mm height, manufactured by Royal Eijlkelkamp, Giesbeek, Netherlands) based on the method described by Fiala et al. (1999). Soil bulk density measurements were conducted in 2012, 2015, and 2019, and were reported on a dry basis (after drying the soil at 105°C for 48–72 h). The frequency chosen to measure ρ_b was considered to be appropriate given the non-swelling nature of the soils at the site and the expected rate of change in this attribute (Radford et al., 2007; McHugh et al., 2009). Soil sampling was consistently conducted during the autumn period, thereby minimizing the influence of annual tillage operations on the results derived from these analyses. Soil penetration resistance was measured to a depth of 800 mm using a cone penetrometer (Penetrologger model P1.52, Eijlkelkamp, Giesbeek, The Netherlands) fitted with an 8-mm diameter and 800-mm long rod, and a cone with 60° apex angle and 1 cm^2 base area. The gravimetric soil water content was simultaneously measured using disturbed soil samples (Reynolds, 1970). The soil water content was used as a co-variate of penetration resistance (ASABE, 2019). Cone penetrometer measurements were conducted in 2010, 2012, 2013, 2015, 2018, 2019, 2020, and 2021.

2.4. Crop measurements and analyses

Crop (grain) yield was determined in two ways: (1) by taking quadrats and harvesting by hand, and (2) by reporting the yield recorded by the yield monitor fitted to the combine harvester. The quadrats allowed for accurate determination of the yield from each of the traffic treatments (A, B, C, D). The quadrat samples were taken each year from every block and traffic treatment with 3 replications per block. The crop samples from the quadrats were threshed using a laboratory threshing machine and the moisture content of the grain was determined by oven-drying the samples at 40°C for 72 h. Grain yield was then estimated and reported on a per ha basis at 14% (w/w) grain moisture content, which is the standard for commercialisation.

The combine harvester used at the site was equipped with a yield monitoring and mapping system device, and the yield data recorded on-the-go (Table 2). These data showed the yield along the path of the combine harvester, integrated across the width of the cutter bar. Since the unit was set to operate at a high frequency, it was possible to pick-up the yield variability of the field. Raw data were processed in SW

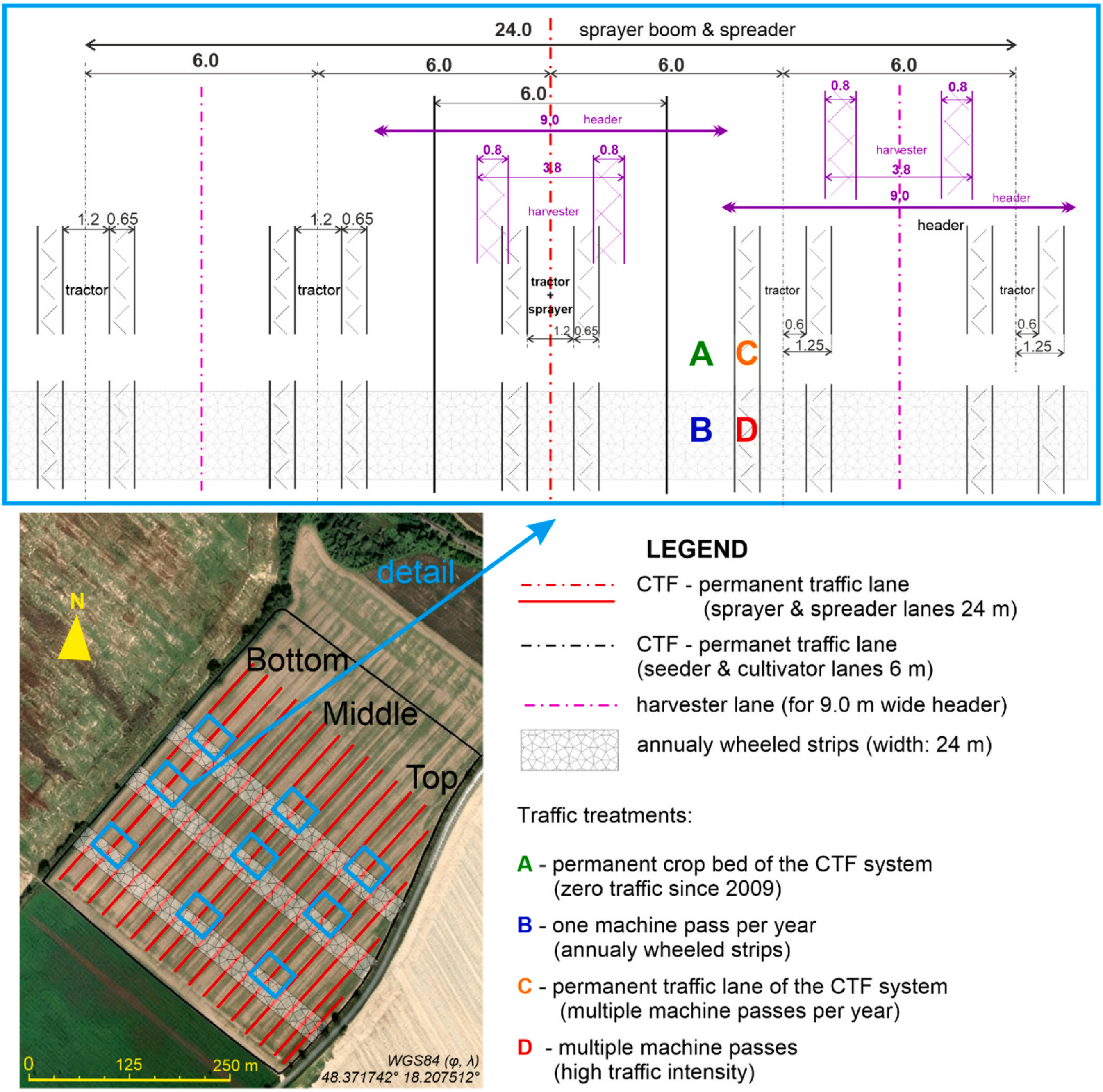

Fig. 1. Layout of the long-term experimental site established in Nitra (Slovakia) in 2009, and details of the controlled traffic farming system (CTF) used at the site. The image shows the three blocks (bottom, middle, and top), which denote the topographic position, the traffic treatments (A, B, C, D), which denote different traffic intensities, and the annually wheeled traffic strips. The drawing also shows the permanent traffic lanes and permanent crop beds of the CTF system. Notation for traffic treatments: A (zero traffic), B (one pass of farm machinery per year), C (permanent traffic lane of the CTF system), and D (multiple passes of farm machinery per year). Drawing shows dimensions but it is not to scale.

Agrocom MAP 8.92 (CLAAS, 2022) based on the methods described by Ingeli et al. (2015) and Ping and Dobermann (2005), which enabled removing spatial outliers as well as extreme and zero values.

Using GIS tools and software (ArcGIS 10.1, ESRI ArcGIS; ESRI, 2012), the yield data obtained from the yield monitoring system were spatially processed using overlay analysis (Walke et al., 2012). Yield data points were overlaid with the delineated yield potential zones (Fig. 6S, Appendix A) and subsequently classified according to their spatial affiliation with the traffic management system (CTF areas or annually wheeled strips, as shown in Fig. 1b left) and individual field blocks (bottom, middle, and top). Based on this spatial intersection, each data point was assigned to the corresponding attributes of yield potential zone, traffic system, and block position. This approach enabled a direct comparison of the yield responses to traffic between different yield potential zones, and between CTF areas and the annually wheeled strips shown in Fig. 1b (left).

Comparison of yield data from across 13 cropping seasons required a standardisation procedure, which was achieved by applying the following two methods:

- Method 1: Z-score standardisation; this is a standard statistical procedure that provides information about the departure of a value from the mean relative to the standard deviation (Schenatto et al., 2017):

$$Z = \frac{(x - \mu)}{\sigma} \quad (1)$$

where: Z is the Z-score, x is the value being evaluated, μ is the mean, and σ is the standard deviation.

- Method 2: Standardisation via grand mean such that each value was calculated as a percentage of the grand mean for the corresponding harvest year. This method was better suited to the data derived from the yield monitoring system available in the combine harvester as it improved the visualisation of differences between data points (Godwin et al., 2022).

The standardised yield data were analysed in the context of variability between the three blocks as well as the climate data for the season. Once the crop yield data were standardised, it was possible to determine the rainfall-use efficiency (RUE) for each crop and year. For this, the critical crop growth stages were first identified (Table 3S, Appendix C). For each time interval comprised between-critical growth stages, rainfall was summed up and the yield obtained from the different traffic areas (A to D) plotted as a function of cumulative rainfall (French and Schultz, 1984; Hussein et al., 2021b).

Nitrogen (N) fertiliser rates applied over the course of the experiment are recorded in Table 4S (Appendix C) for each cropping season. These records were used to provide an estimation of the N use efficiency (NUE), based on the partial factor productivity of applied fertiliser N (Antille and Moody, 2021), as shown in Eq. (2).

$$NUE = \frac{Y_N}{N_{Rate}} \quad (2)$$

where: NUE is the fertiliser N use efficiency expressed as the partial factor productivity of applied N (kg kg^{-1}), Y_N is the grain yield corrected to 14% (w/w) moisture content, and N_{Rate} is the N fertiliser application rate, all in kg ha^{-1}.

2.5. CTF system level analysis

The experiment was designed to be operated with conventional (unmodified), commercially available farm machinery. The CTF system tested at the experimental site was subsequently used to inform a performance analysis of hypothetical CTF systems designs with potential to be adopted in farming systems of Central Europe (namely: 8-m and 12-m systems). These systems were modelled based on the methodology described by Galambošová et al. (2017), which used theoretical trafficked areas (Table 5S, Appendix C). The calculation of theoretical trafficked areas was derived from width of the base module and the track gauge width of the farm vehicles used. Potential yield increments relative to the conventional, non-CTF system, were estimated from the average standardised yield (Eq. 1), the design of the modelled CTF system, and by considering the specific topographical location within the field (namely: bottom, middle, top).

The extent of areas ‘A, B, C and D’ allowed for realistic comparisons between non-controlled traffic and the CTF system. Gross income calculations were undertaken for the established and modelled CTF systems, by multiplying the yield achieved with a given traffic system by the price of the crop for the year of harvest (Table 5S) as shown by Eq. 3 (after Frank, 1977):

$$GI = Y \times P_G \quad (3)$$

where: GI is gross income (EUR ha^{-1}), Y is grain yield (Mg ha^{-1}), and P_G is the price of grain for the corresponding year of harvest (EUR Mg^{-1}).

Whilst it is acknowledged that the total variable costs associated with the operation of different CTF systems may not be identical, an assumption was made to consider such costs to be same regardless of the system used to be able to simplify the analysis. However, it is expected that operational costs may reduce as the base module of the CTF system is increased, due to improved timeliness of field operations. Hence, it is expected that the gross margin will improve as the base module of the CTF becomes wider (Chamen et al., 2015).

2.6. Statistical analyses

The effects of traffic were determined on measured soil and crop variables as well as NUE and RUE, which were derived from measured data. Measured and estimated data were graphically tested for normal distribution and normalisation of the data was not required. The annual effect of traffic on yield was determined using one-factor ANOVA applied to yield data at field level (neglecting the block). The yield data, expressed as Z-score standardized data, were analysed using a two-factor ANOVA (traffic areas and block). This procedure was applied to the yield data grouped by crops as well as for the entire crop dataset across the 13 seasons. The least significant differences (LSD) were used to compare means with probability level of 5%. All statistical analyses were undertaken in Statistica Cz10 (StatSoft, 2011).

3. Results

3.1. Effect of field traffic on soil properties

Detailed soil bulk density (ρ_b) data for specific topographic locations are provided in Figs. 2a-2f. In 2012, measurements of ρ_b in the topsoil showed no significant effect of traffic ($p > 0.05$). However, a 10% increase in ρ_b was recorded at location D compared with A in the ‘bottom’ and ‘middle’ blocks. The changes in ρ_b observed in the block ‘top’ were small (≤1%). In 2015, all traffic treatment areas had significant effects on ρ_b ($p < 0.01$). There was a significant difference in ρ_b between locations A and D in the ‘middle’ and ‘top’ blocks, which showed increasements of 7% and 5%, respectively, compared with non-trafficked soil (Figs. 2a-2c). In 2019, only the ‘bottom’ block exhibited a significant increase in ρ_b (~ 6%). The ‘middle’ and ‘top’ blocks showed an increase in ρ_b of ~3% and 5%, but these were not statistically significant ($p > 0.05$). Differences in ρ_b between locations A and D were ~ 7% ($p < 0.05$).

Soil bulk density data for the subsoil are reported in Figs. 2d-2f, which show the changes observed for each topographic position (bottom, middle, top). Overall, there were no significant differences in ρ_b in the subsoil between areas A, B, C or D in none of the years ($p > 0.05$).

Overall, there were significant differences in penetration resistance (PR) between years, traffic treatments, and soil depths ($p < 0.01$). A summary of the ANOVA, which involved two factors (depth and traffic treatment) are reported in Fig. 3. Across all years and measured soil depths, PR was consistently lower at area A compared with all other traffic treatments. Area B exhibited significantly higher PR compared with area A up to a depth of 0.3 m, but there were no differences below that depth. Overall, location B was statistically different from locations C and D. Locations C and D only exhibited significant differences in PR at the 0.1–0.15 m depth interval.

Detailed statistics for measurements of penetration resistance (PR) are provided in Table 6S (Appendix C), which includes the LSD values (5% probability level). Figures 7–16S (Appendix A) provide a graphical comparison between traffic treatments as well as gravimetric soil water measurements.

3.2. Effect of field traffic on crop performance

3.2.1. Effect of traffic treatment

The yield data recorded at the experimental site since 2010, as determined from hand harvested quadrats, are presented in Table 3. These data represent field average values for the 4 traffic treatments (A

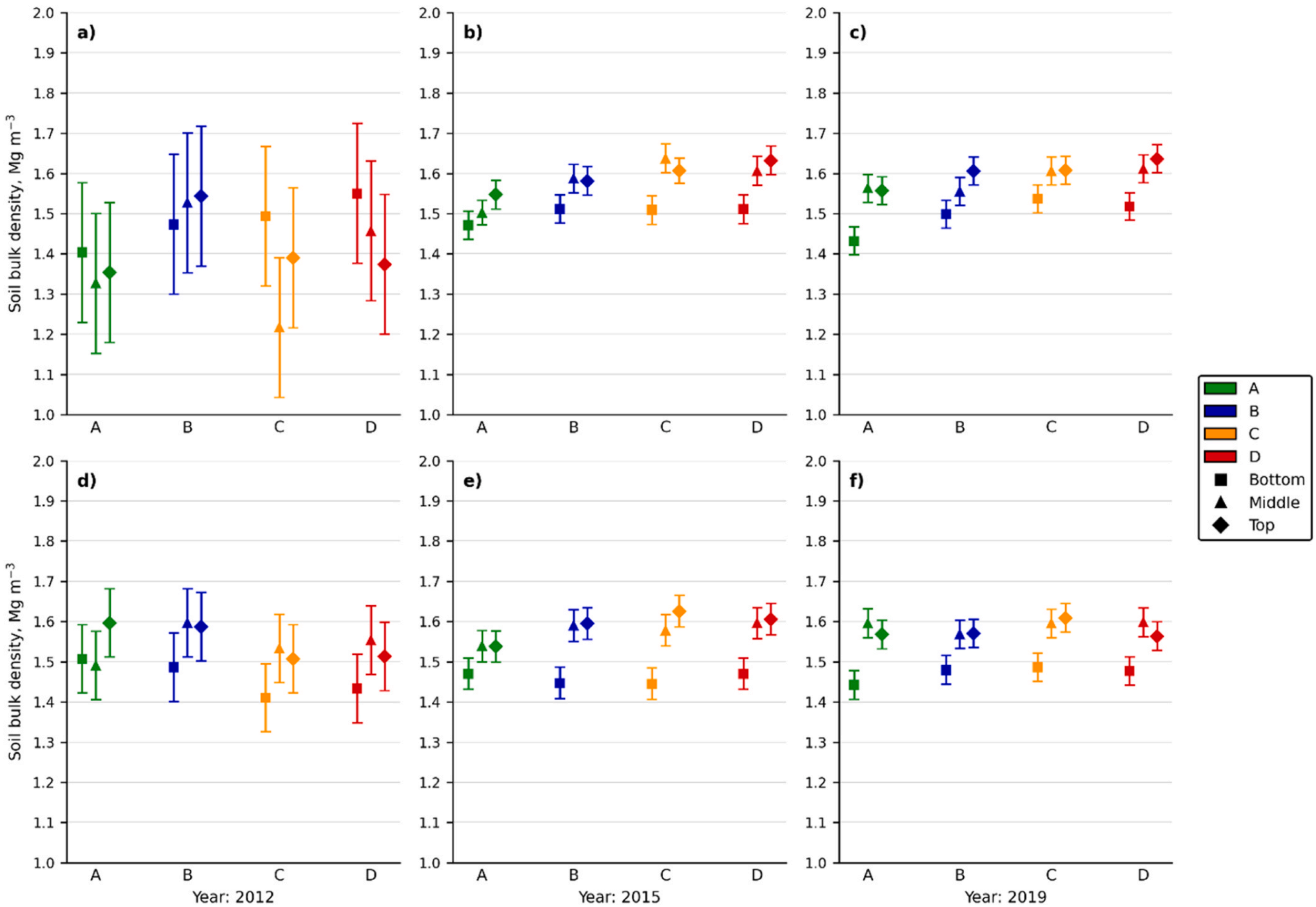

Fig. 2. Soil bulk density values determined in the topsoil (0.05 – 0.15 m) (images a, b, c) and subsoil (0.30 – 0.40 m) (images d, e, f) by year of measurement (2012, 2015, 2019) and traffic treatment: A (zero traffic), B (one pass of farm machinery per year), C (permanent traffic lane of the CTF system), and D (multiple passes of farm machinery per year), respectively. Vertical error bars denote the 95% confidence interval.

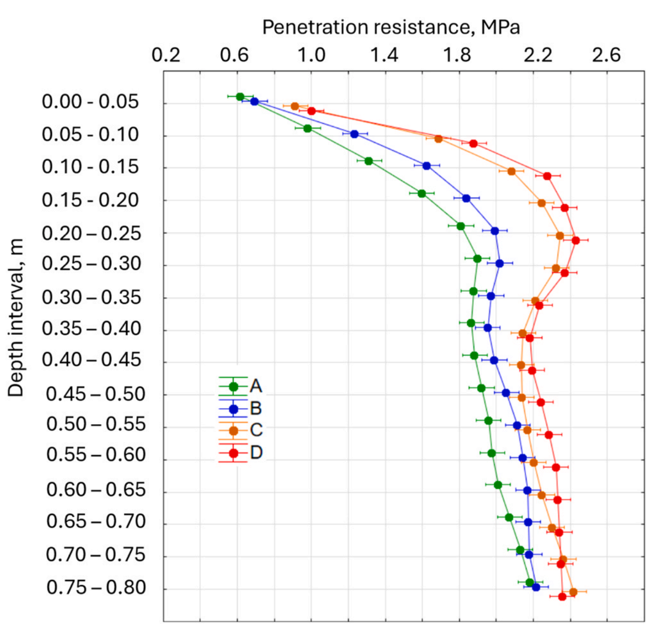

Fig. 3. Mean soil penetration resistance measured between 2010 and 2021 by traffic treatment: A (zero traffic), B (one pass of farm machinery per year), C (permanent traffic lane of the CTF system), and D (multiple passes of farm machinery per year). Horizontal error bars denote the 95% confidence interval.

to D). During the first 7 years of the study, statistical differences between traffic treatments were only observed for spring barley. However, after this period, differences between traffic treatments were observed each year.

Fig. 4 shows the results of the LSD test and ANOVA for *Z*-scored yields across all 13 seasons and considering block as a factor. Yield differences between traffic-treatments (A, B, C, D) and between-blocks (bottom, middle, top) were all significant (p-values < 0.05; Fig. 4). In the ‘bottom’ block, differences in yield between ‘A’ and the rest of the treatments were ~10%. These differences became larger in blocks ‘top’ (~12%) and ‘middle’ (~20%), particularly for treatments ‘C’ and ‘D’. Fig. 5 shows the analyses by crop type. In general, the effect of traffic was more evident in spring crops (spring barley, maize) compared with winter crops (except for winter barley and field peas), and the impact of traffic on yield increased in the order A-to-D, particularly in drier years (Fig. 5). In wetter than average rainfall years, winter wheat and oilseed rape were not significantly affected by the traffic treatment (p-values $>$ 0.05), and rainfall records showed that three out of four seasons were ‘wet’ (Table 2S).

3.2.2. *Effect of field variability (block)*

Generally, all crops performed better in the ‘bottom’ block compared with all other blocks, consistent with soil water availability in this part of the field. Yield comparisons between the blocks showed that the difference between the ‘bottom’, and ‘middle’ and ‘top’ blocks was ~15% in treatment A. For all other traffic treatments (B, C, D), the topographic position of the field had a greater effect. Differences in yield between the ‘bottom’ and ‘middle’ blocks were 23%, 12% and ~22% for

Table 3
Crop yields expressed in absolute values (Mg ha^{-1}) and corresponding nitrogen-use efficiency (NUE, kg grain per kg N applied) by traffic treatment (A: zero traffic, B: one pass of farm machinery per year, C: permanent traffic lane of the CTF system, D: multiple passes of farm machinery per year) recorded at the site between 2010 and 2023. 'Year' denotes the year in which the crop was established. The analysis shows the results of the one-factor ANOVA for each monitored year. The lower-case letters (a, b, c) denote homogenous groups for traffic treatments (A, B, C, D). Use $p < 0.05$ (LSD test).

Year	Crop	Scientific name and cultivar	Crop yield, Mg ha^{-1}				NUE, kg [grain] kg^{-1} [N applied]			
-	-	-	A	B	C	D	A	B	C	D
2010	Winter Oilseed rape	*Brassica napus* L. cv. Ontario	1.7 a	1.6 a	1.8 a	1.5 a	12.8	12.3	13.5	11.0
2011	Winter wheat	*Triticum aestivum* L. cv. Augustus	8.0 ab	7.6 ab	8.2 b	7.3 a	57.1	54.3	58.3	52.0
2012	Spring barley	*Hordeum vulgare* L. cv. Signora	5.4 a	4.9 ab	4.5 b	3.6 c	119.8	109.0	99.2	79.5
2013	Maize	*Zea mays* L. cv. Kessos	7.3 a	6.7 a	6.3 a	5.5 a	61.5	56.9	53.6	46.4
2014	Spring barley	*Hordeum vulgare* L. cv. Kango	6.5 a	6.5 a	5.6 a	6.0 a	62.00	62.3	53.7	57.2
2016	Winter wheat	*Triticum aestivum* L. cv. Mifi/hifi	11.0 a	10.7 a	10.7 a	10.0 a	64.9	62.9	62.9	58.7
2017	Winter barley	*Hordeum sativum* L. cv. Wintmalt	8.1 a	7.6 ab	7.7 ab	7.2 b	58.7	55.2	56.0	52.5
2018	Field peas	*Pisum sativum* L. cv. Salamanca	5.4 a	5.4 a	4.0 b	4.0 b	179.3	179.4	132.5	131.6
2019	Winter wheat	*Triticum aestivum* L. cv. RGT Reform	8.5 a	8.9 ab	8.9 ab	9.2 b	52.9	55.1	55.5	57.2
2020	Maize	*Zea mays* L. cv Milanno	11.9 a	9.4 b	10.7 ab	10.3 ab	80.5	63.5	72.8	69.9
2021	Spring barley	*Hordeum vulgare* L. cv. IS Maltigo	5.2 a	4.6 ab	4.4 b	4.3 b	125.4	109.8	104.8	103.7
2022	Field peas	*Pisum sativum* L. cv. Balltrap	7.3 a	6.8 ab	6.7 ab	6.6 b	326.4	301.5	299.2	291.5
2023	Winter wheat	*Triticum aestivum* L. cv. Variato E3	9.5 a	9.6 ab	10.3 c	10.1 bc	67.1	67.6	72.7	71.3

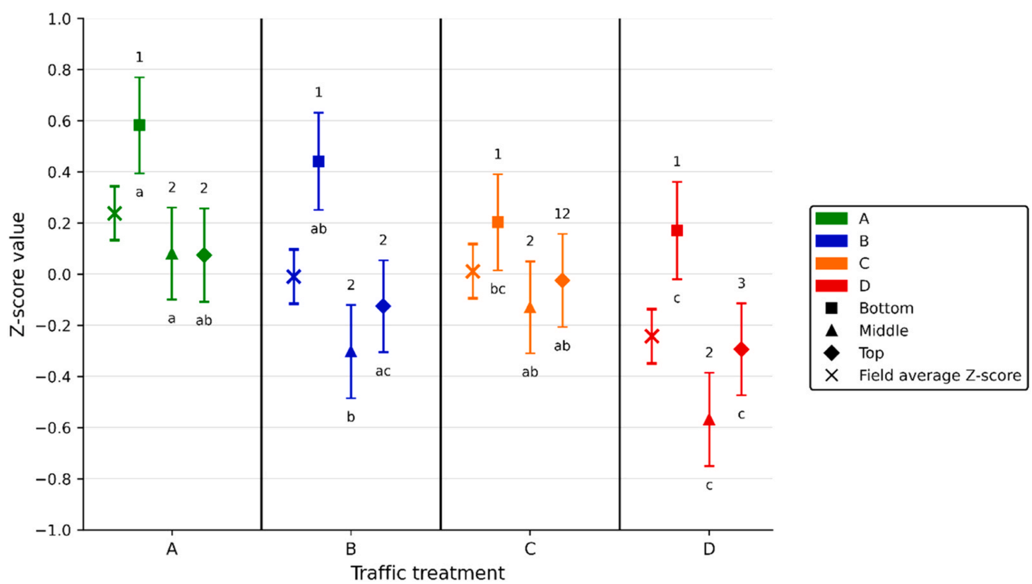

Fig. 4. Summary of ANOVA (5% probability level) applied to the *Z*-score normalised data across 13 growing seasons. The field average is denoted by the symbol X, and results for the three topographical position (Bottom, Middle, Top) are provided for each traffic treatment: A (zero traffic), B (one farm machinery pass per year), C (permanent traffic lane of the CTF system), and D (multiple farm machinery passes per year). The lower case letters (a, b, c) denote homogenous groups for traffic treatment, and the numbers (1, 2, 3) denote homogenous groups for blocks (bottom, middle, top). Use $p < 0.05$ (LSD test). Vertical error bars denote the 95% confidence interval.

treatments 'B', 'C', and 'D', respectively. These results showed that soil compaction due to farm machinery traffic increased the inherent variability of the field, as reflected on the wider differences in crop yield observed between the blocks. Such differences increased with an increase in traffic intensity. The data presented in Fig. 4 shows the effect of traffic on crop yield, consistent with differences in ρ_b between trafficked and non-trafficked soils; these differences were in the order of 10% on average.

Data retrieved from the combine harvester showed that in the bottom part of the field, the crop under CTF performed better than the crop grown on annually wheeled soil strips. The spatial analysis of yield data for the low (LY) and medium (MY) yield potential zones is shown in Table 4. Results indicated that within field variability was significantly reduced under CTF. The differences in yield observed across yield zones of non-trafficked soil were less than 50% those of the trafficked soil (annually wheeled soil strips). These effects were more evident in spring barley followed by maize and field peas. For example, for spring barley, yield differences determined at the medium and lower yielding zones were ~3.25 times lower in CTF than non-CTF.

Estimates of rainfall-use efficiency (RUE) and nitrogen-use efficiency (NUE) are presented in Fig. 6 and Table 3, respectively. Results showed that RUE, expressed as the ratio mm of rain per kg of grain, generally decreased with traffic intensity in the treatment order 'A'-to-'D'. However, differences between-traffic treatments were smaller in wetter compared with drier years. Fertiliser NUE calculations are presented in Table 3. Results were consistent with RUE calculations suggesting increased conversion of applied fertiliser N to grain as traffic intensity decreased (that was, in the treatment order 'D'-to-'A').

3.3. System level analysis

The expected benefits of adopting a CTF system with a wider base module than the system used in this study (6-m) were explored based on a previous study by Galambošová et al. (2017) This earlier work showed that an 8-m base module was the most appropriate system for the farming conditions of Central Europe. The experimental results obtained

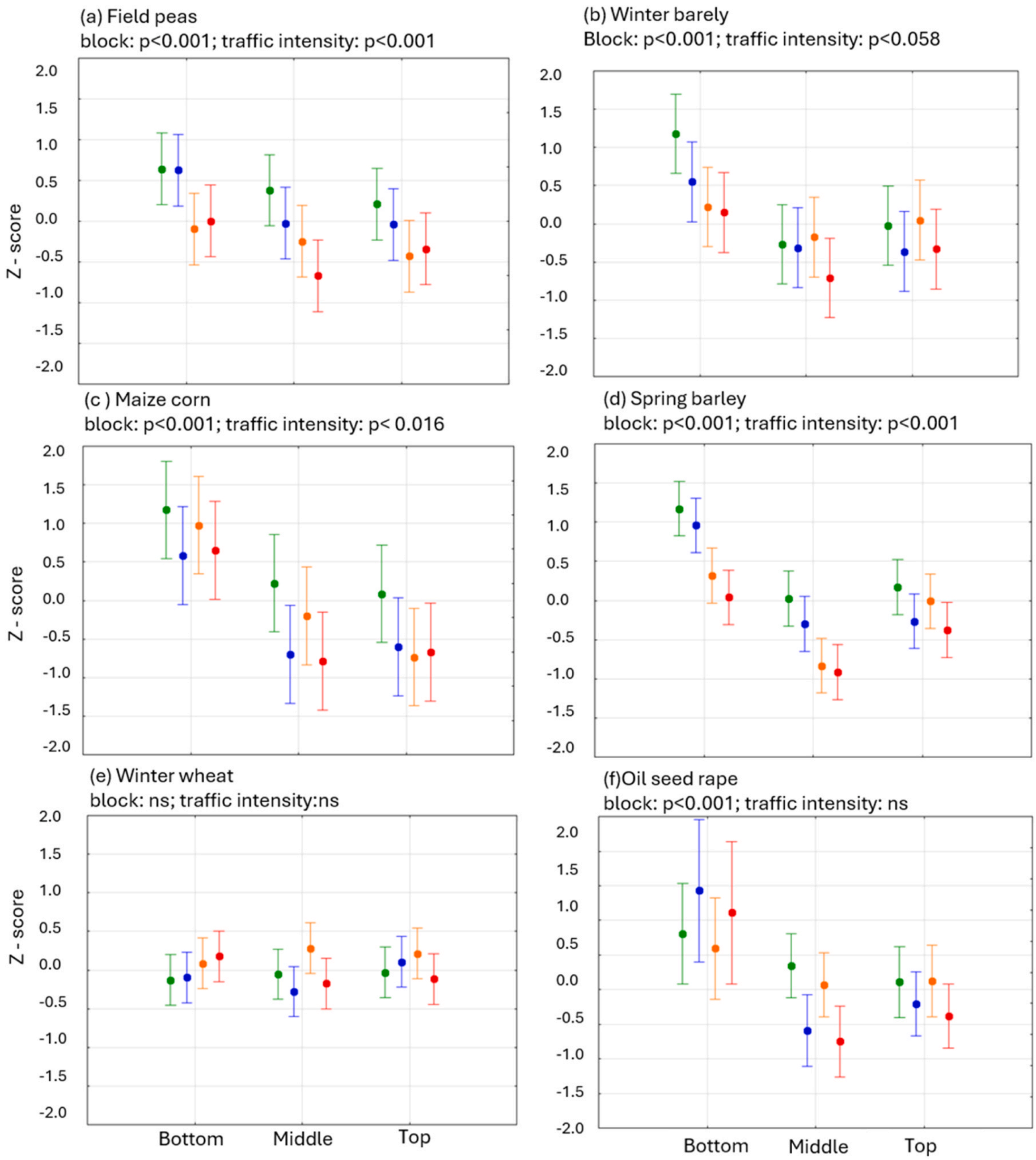

Fig. 5. Standardized yields (Z-scores) by traffic treatment (A, B, C, D) and block or topographic position (bottom, middle, top). In: (a) field peas grown in 2018 and 2022; (b) winter barley grown in 2017; (c) maize grown in 2013 and 2020; (d) spring barley grown in 2012, 2014, and 2021; (e) winter wheat harvested in 2011, 2016, 2019, and 2023; and (f) oilseed rape grown in 2010. Traffic treatments are: A (zero traffic), B (one pass of farm machinery per year), C (permanent traffic lane of the CTF system), and D (multiple passes of farm machinery per year). Vertical error bars denote the 95% confidence interval.

at the site with the 6-m system were used to inform the theoretical yield and economic benefit that would be obtained if that system was converted to 8-m and 12-m base modules, respectively. In these wider systems, the area affected by traffic is reduced and therefore the yield is proportionally increased. Table 5 shows that the 8-m, out-track system appears to be a viable option, with an estimated yield increase between 4.3% and 8.6% compared to non-CTF. As shown in Section 3.2, adoption of CTF contributed to stabilise yields across seasons (equally, the inter-annual yield variability was reduced) by reducing the impact of drought in drier than average rainfall years and by improving the agronomic performance of the crop in lower-yielding zones.

The annual gross income that may be realised after the mechanisation system is converted to CTF was determined for the different CTF system options considered in this analysis and for a range of farm sizes (Figure 17S). If the system was converted to 8-m (out-track), new tillage and drilling equipment would be needed to ensure operating widths can be matched. Such conversion would attract a cost of ~EUR250,000, based on the market price of commercially available equipment in Slovakia in late 2025. However, this investment could be recovered in 2 years if the area of land farmed annually was 1000 ha.

4. Discussion

4.1. *Effect of field traffic on soil and crop performance*

Soil bulk density (ρ_b) values in non-trafficked soil (A) (1.08 – 1.62 Mg m^{-3}) were below the root growth-limiting ρ_b (>1.65 Mg m^{-3}) suggested by USDA-NRCS (2019) for the soil type (textural classes) encountered at

Table 4
Standardized crop yields expressed as a percentage of the mean yield determined in the middle and top blocks, and the medium and low yielding zones in CTF and in areas with one pass of farm machinery per year. Data retrieved from the yield map. Notation: MY – medium yielding zone, LY – low yielding zone. The symbol 'Δ' denotes the difference between crop yielding zones. Crops' scientific names and cultivars are as described in Table 3.

Crop	Block	Standardised yield (%) CTF			Standardised yield (%), one machine pass/year		
-	Zone	MY	LY	Δ	MY	LY	Δ
Field peas	Middle	107.4	102.3	**5.1**	103.2	97.2	**6.0**
Maize		101.5	95.9	**5.6**	89.4	97.7	**−8.3**
Spring barley		89.5	86.6	**2.9**	93.8	84.5	**9.3**
Winter barley		96.6	92.6	**4.0**	97.2	95.0	**2.1**
Winter wheat		99.7	96.8	**2.9**	100.8	98.4	**2.4**
Field peas	Top	108.0	95.9	**12.1**	106.1	93.1	**13.0**
Maize		104.1	91.3	**12.8**	106.8	85.8	**21.1**
Spring barley		102.7	88.9	**13.8**	109.7	81.0	**28.6**
Winter barley		103.8	99.1	**4.7**	106.1	99.5	**6.6**
Winter wheat		105.6	105.2	**0.4**	105.6	107.8	**−2.2**

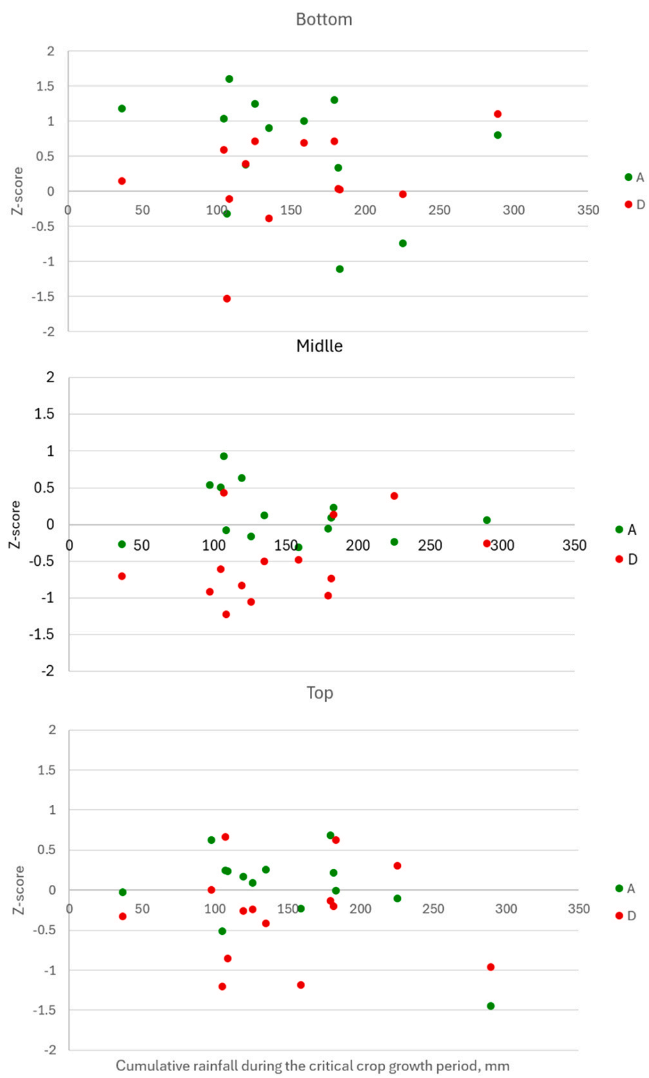

Fig. 6. Standardised rainfall-use efficiency using the Z-score by block or topographic position (bottom, middle, top) and traffic treatment (A: zero traffic, and D: multiple passes of farm machinery per year), as a function of cumulative rainfall during the critical growth period of the crop. Results are presented for the 13 seasons over which this study was conducted.

Table 5
Estimated crop yields for different controlled traffic farming (CTF) system designs by topographic position (bottom, middle, top). Yields were calculated based on the mean standardised yield across 13 seasons. The corresponding wheeled areas are expressed as a % of the field-cropped area.

CTF System	Traffic intensity	Wheeled area, %	Estimated crop yield by topographic position, %			
-	-	-	Bottom	Middle	Top	Average
Non-CTF	Non-wheeled soil	36	113.7	93.4	94.0	101.4
	One traffic event per year	39				
	Multiple traffic events per year	25				
6-m CTF	Non –wheeled soil	55	115.0	98.7	100.3	104.6
	One traffic event per year	22				
	Multiple traffic events per year	23				
8-m Com-track	Non-wheeled	77	115.7	101.4	101.8	109.6
	One traffic event per year	-				
	Multiple traffic events per year	23				
8-m Out-track	Non-wheeled	82	117.2	101.5	101.8	110.7
	One traffic event per year	10				
	Multiple traffic events per year	8				
12-m	Non-wheeled	85	116.7	102.1	102.2	110.9
	One traffic event per year	-				
	Multiple traffic events per year	15				

the site. For traffic treatments 'B', 'C' and 'D', average ρ_b (1.70 Mg m^{-3}) exceeded the suggested limit. Differences in penetration resistance between trafficked and non-trafficked soil were always significant, regardless of the number of machinery passes applied each year ($p < 0.001$). The effect of traffic on soil penetration resistance was proportional to the traffic intensity (number of passes performed annually), and it extended below 0.3 m deep.

Crop yield, and rainfall- and fertiliser nitrogen-use efficiency were measured over 13 crop seasons (from 2010 to 2023). The period over which the study was conducted was predominately dry, with seasonal rainfall below the historical average (except for 2010, 2016, and 2023, in which the rainfall recorded was above the average). In these wetter seasons, soil compaction (traffic treatments 'B', 'C' and 'D') had a limited effect on the agronomic performance of winter wheat and oilseed rape as the crops did not appear to have been stressed by water. Yield penalties due to compaction in higher-yielding seasons were small as water (rainfall) was not limiting. For lower-yielding seasons (rainfall below average), yield penalties in non-CTF were significantly greater (up to ~25%) than in CTF, consistent with earlier studies (e.g., Galambošová et al., 2017; Hussein et al., 2021a, Hussein et al., 2021b), highlighting that the yield response to compaction is dependent on the seasonal effect of weather (McKyes et al., 1979; Negi et al., 1981). There was a significantly higher inter-seasonal yield variability in non-CTF, with less reliability of cropping compared with CTF, as shown by the standard deviation values obtained for the yield data (Appendix D). Yield penalties in non-CTF were explained by a combination of reduced plant available water capacity and reduced ability of the crop to extend its root system to access water and nutrients in compacted soil (Antille et al., 2016b; Dexter, 2004), which was supported by measurements of penetration resistance. In above-average rainfall years, crop yield was less constrained by rooting depth because water supply through rainfall was not a limiting factor (Hussein et al., 2021a, Hussein et al., 2021b). Therefore, in wet years, any reduction in infiltration or increases in runoff due to compaction would have less effect on plant available water. In contrast, in average- and below-average rainfall years, reduced plant available water coupled with reduced rooting depth in compacted soil, as shown by Antille et al. (2016a), would have a significant effect on crop yield. For most years, the main part of the growing seasons recorded drier than long-term average conditions. Consequently, areas where traffic was not applied, did not exhibit any significant yield penalty, which was evident in spring crops. Field peas grown in 2018 and 2022 exhibited highly significant increases in yield in treatment 'A' (no traffic), which agreed with earlier work by Barik et al. (2014).

Estimates of rainfall and N use efficiency suggested that a co-limitation of water and N was a key factor affecting crop yield, and that such effect was exacerbated by compaction (as shown by treatments B, C, and D). Stronger soil in drier years indicated that compaction had detrimental effects on the simultaneous acquisition of soil water and N by the crop. Hence, traffic compaction in those treatments amplified crop water stress and reduced crop N uptake (Antille and Moody, 2021). This is an important consideration for crop management under shifting climate patterns, particularly, with less reliable rainfall, to be able to sustain productivity (Lavalle et al., 2009).

4.2. Mechanisation system considerations

If the CTF system used in this study was modified to operate in either 8-m or 12-m wide modules, it may be possible to increase long-term yields by an average of 4–8%, consistent with results published by Godwin et al. (2022) in the U.K. Given the inherent soil variability present at the experimental site, additional yield gains may be realised from site-specific management; however, this should be preceded by implementation of CTF. Our study showed that by practicing CTF, within field variability induced by traffic is eliminated, which can therefore facilitate site-specific management. A range of precision agriculture techniques are available for quantifying such variability including historical yield maps, satellite images and soil proximal sensing (e.g., Godwin and Miller, 2003, Schenatto et al., 2017, Georgi et al., 2018, Adamchuk et al. 2004).

The 6-m out-track system used in our study represents a first tier CTF system with unmodified machinery. The case served to exemplify that the traffic footprint can be reduced by up to ~45% only by re-organising field traffic and before machinery is modified to fit a fully-matched CTF system. For an 8-m out-track system, the cost of conversion was estimated at ~EUR250,000. Conversion would require the equipment for primary and secondary tillage to be replaced by 8-m wide implements, including the planter. The tractor and sprayer do not need to be replaced. The non-trafficked area of such system was estimated to be ~77%. A higher tier would be the case of a com-track system, which uses only one-track width. In this design, the track width of the tractor needs to be extended (typically to 3 m) to match the track width of the combine harvester. However, this option would attract a 3% cost increase due to the adjustments needed on the tractor's wheel spacing. Conversion to a 12-m system represents a four-time greater financial commitment as it would require replacing all equipment (tractor, sprayer, planter and tillage implements). The 8-m out-track system would have a payback period of 2 years for a 1000-ha farm, based on the yield increments assumed in the analyses.

5. Conclusions

The work reported in this article synthetised experimental data derived from 14 years (13 consecutive crop seasons) of field-scale traffic systems research in Slovakia. A key feature of this work is that the CTF system used in the study was designed to operate with commercially available (unmodified) farm equipment, which enabled testing the merits of such system under more readily adoptable conditions for Central Europe. This work highlighted the damaging effects of soil compaction and the importance of its management under shifting climate patterns to ensure long-term crop productivity can be sustained. The main conclusions derived from this work are summarised below:

1. There was a significant improvement in all soil physical properties under controlled traffic farming (CTF), which suggested concurrent improvements in soil water retention and infiltration, rainfall- and nitrogen-use efficiency, and the overall crop agronomic performance, particularly in dry years.
2. Crop yield increased significantly in CTF, which also reduced within field yield variability and improved inter-annual yield stability compared with non-CTF. These observations suggested increased reliability of cropping, particularly in drier than average rainfall years, which should therefore translate into reduced financial risk, and were supported by increased rainfall- and nitrogen-use efficiency under CTF.
3. At a system-level, it was shown that conversion from non-CTF to CTF appeared to be an economic proposition, and either the 6- or 8-m systems would have positive returns on investment. The cost of conversion to CTF can be recovered in two years.

This long-term experimental site established at Nitra, Slovakia, offers opportunities to expand the scope of this work. Future research should consider quantifying the environmental impact of alternative mechanisation systems by focusing on soil erosion, GHG emissions, and carbon sequestration. Biophysical modelling can be used to simulate the performance of the system under projected climate scenarios and assist system design optimisation for improved climate adaptation. This information may be used to support the development of science-based policy aimed at improving soil security by transitioning to more sustainable mechanisation systems.

CRediT authorship contribution statement

Jana Galambošová: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Data curation, Conceptualization. **Miroslav Macák:** Validation, Methodology, Investigation, Data curation, Conceptualization. **Diogenes L. Antille:** Writing – review & editing, Validation, Supervision. **Vladimír Rataj:** Supervision, Project administration, Methodology, Funding acquisition, Data curation. **Marek Barát:** Formal analysis, Data curation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or. personal relationships that could have appeared to influence the work reported in. this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2026.107374.

Data availability

Data will be made available on request.

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