Acta Agriculturae Scandinavica, Section B — Soil & Plant Science

ISSN: 0906-4710 (Print) 1651-1913 (Online) Journal homepage: https://www.tandfonline.com/loi/sagb20

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To cite this article: Ararso Etana, Lena Holm, Tomas Rydberg & Thomas Keller (2020) Soil and crop responses to controlled traffic farming in reduced tillage and no-till: some experiences from field experiments and on-farm studies in Sweden, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 70:4, 333-340, DOI: 10.1080/09064710.2020.1728372

To link to this article: https://doi.org/10.1080/09064710.2020.1728372

Published online: 28 Feb 2020.

ACTA AGRICULTURAE SCANDINAVICA, SECTION B — SOIL & PLANT SCIENCE
2020, VOL. 70, NO. 4, 333–340
https://doi.org/10.1080/09064710.2020.1728372

Soil and crop responses to controlled traffic farming in reduced tillage and no-till: some experiences from field experiments and on-farm studies in Sweden

Ararso Etana[a], Lena Holm[a], Tomas Rydberg[a] and Thomas Keller[a,b]

[a]Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden; [b]Department of Agroecology and Environment, Agroscope Research Institute, Zürich, Switzerland

ABSTRACT
The purpose of this study was to investigate the impact of controlled traffic farming (CTF) with respect to soil physical properties and crop yield for Swedish conditions. Three field trials were conducted for six growing seasons in central and southern Sweden. In two of the trials, we compared CTF with random traffic farming (RTF) in deep chiseling (DC, 15–20 cm), shallow cultivation (SC, 5–10 cm) and no-till. The third trial was on farm study by using the existing CTF module at the farm. In the tracks of CTF (traffic zone) dry bulk density was increased and water movement was decreased. Soil penetration resistance was greater in the traffic zone than in the crop zone in some of the trials but the difference was not statistically significant. On average, crop yield was similar between CTF and RTF for all trials. Yield in the traffic zone was significantly less than that in the crop zone in the on-farm trial, but the yield in both zones were similar in the field trial at Lönnstorp, south Sweden. On the contrary, in the field trial at Säby 1 in Uppsala, central Sweden, crop zone produced less yield than traffic zone probably because of too loose soil, which impaired the uptake of nutrients and water. We conclude that if vehicle weight is not very high and the soil is not vulnerable to compaction, dual wheels and CTF are equal options.

ARTICLE HISTORY
Received 14 November 2019
Accepted 7 February 2020

KEYWORDS
Deep cultivation; dual wheels; on-farm trial; shallow cultivation; soil compaction

Introduction

Soil compaction has negative consequences on farm economy and the environment. Traffic on arable land for tillage or other field operations causes uneven track distribution and intensity. The traffic intensity depends mainly on the type of tillage system, level of mechanisation, working width, soil conditions, the preceding crop and the crop to be grown. Track area for one cropping season in a conventional tillage varies from 300% to 650% of the field area and it is less (170–400%) in reduced tillage (Håkansson 2005). In both systems, a large part of the field will be often over compacted due to heavy machinery and repeated passes leading to low soil productivity and quality. Since soil compaction was identified as a serious problem in crop production, various counter-measures have been implemented. Some wide spread measures are low axle load (Håkansson 1985), reducing ground pressure (Soane et al. 1981; Erhbach 1994), gantry system (Chamen et al. 1994) and controlled traffic system (Taylor 1983; Chamen 2015; Antille et al. 2019). In a random traffic farming (RTF) even low ground pressure or low axle load can cause soil over-compaction due to repeated passes over a large portion of the field (Håkansson 2005). Thus, controlled traffic farming (CTF), which implies driving in the same track (permanent lane), could be one alternative to minimise soil compaction. CTF was introduced in the early 1980s and now widely used in several countries particularly in Northern America and Australia (Tullberg et al. 2007; Gasso et al. 2013; Gasso et al. 2014; Antille et al. 2015; Chamen 2015; Tullberg et al. 2018; Wang et al. 2018) but little applied in Europe. The main barrier for converting from RTF to CTF has been equipment incompatibilities (Antille et al. 2019). In Scandinavia, the research and application of CTF are very limited but some progress is underway especially for grass silage production since the time of grass harvesting and fertilisation coincides with heavy rainfall, which makes soil more vulnerable for compaction (Alvemar et al. 2017). The purpose of this study was to investigate the impact of controlled traffic farming (CTF) with respect to soil physical properties and crop yield for Swedish conditions.

CONTACT Ararso Etana ararso.etana@slu.se Department of Soil and Environment, Swedish University of Agricultural Sciences, PO Box 7014, 75007 Uppsala, Sweden

Materials and methods

Site and treatment description

Three field trials were carried out from 2010 to 2016 in eastern and south Sweden. One was an on-farm trial, established on Lydinge farm (56°5′N; 12°52′E) in Skåne, and the other two trials were established on the experimental stations of the Swedish University of Agricultural Sciences (SLU) in Skåne (Lönnstorp, 55°40′N; 17°6′E) and in Uppsala (Säby 1, 59°50′N; 17°41′E). Precipitation during the trial years is given in Tables 1–3. Soil particle-size distribution and organic matter content in the topsoil of the trial sites are presented in Table 4. The trials in Lönnstorp and Säby 1 were designed as a split-plot design with tillage system as main treatment and traffic system as sub-treatments. The main treatment included three levels as follows:

(1) Deep cultivation (DC) to a depth of 15–20 cm; (2) shallow cultivation (SC) to 5–10 cm; (3) no-till. The sub-treatments included permanent traffic lane, i.e. controlled traffic farming (CTF), and random traffic farming (RTF). The CTF plots were 9 m wide and 20 m long, with a basic module of 3-m width, providing a maximum of 43% traffic. Annual tillage in DC and SC included the wheel tracks of CTF so cumulative compaction in the loosened layer was not expected. RTF plots were 12 m wide and 20 long to allow random traffic. In addition to these treatments, conventional tillage (mouldboard ploughing + seedbed preparation) was included just for comparison. The yield from the treatments were computed as a percentage of that from the conventional tillage. Main vehicles and machinery

Table 4. Particle size distribution (% by weight) and organic matter content (g 100 g^{-1}) in topsoil.

Site	Clay (<2 µm)	Silt (2–60 µm)	Sand (60 µm–2 mm)	Organic matter (%)
Lönnstorp	15.8	27.6	56.6	2.8
Säby 1	46.4	44.8	8.8	4.2
Lydinge, field 2	52.5	39.1	8.4	5.1
Lydinge, field 10-2	47.6	38.3	14.1	3.7
Lydinge, field 10-3	37.6	45.4	17.0	4.9
Lydinge, field 18-2	34.0	48.0	18.0	3.0

Table 1. Precipitation during trial years in Lydinge (SMHI climate station 611) and mean precipitation (1961–1990, SMHI station 6204).

År	January	February	March	April	May	June	July	August	September	October	November	December
2010	*	*	*	*	*	*	13	110	54	80	93	35
2011	58	30	23	27	59	101	127	110	69	41	9	54
2012	80	36	12	30	40	88	63	32	89	70	57	66
2013	60	28	9	22	64	67	10	134	51	82	56	78
2014	59	56	26	39	84	46	41	112	40	81	34	94
2015	79	46	65	38	48	59	75	47	71	9	119	93
2016	41	54	43	45	15	66	125	61	17	0	*	*
1961–1990	50.3	30.9	44.1	40.3	43.2	58.9	78	66.6	67.5	61.2	66.8	60.9

Table 2. Precipitation during trial years in Lönnstorp (SMHI climate station 635) and mean precipitation (1961–1990, SMHI station 5235).

Year	January	February	March	April	May	June	July	August	September	October	November	December
2010	*	*	*	*	*	*	18	210	60	54	114	67
2011	53	37	28	25	62	91	153	131	44	39	11	66
2012	96	32	10	31	16	61	62	36	44	70	49	67
2013	62	29	10	18	40	96	23	37	56	68	82	67
2014	57	52	33	25	53	55	71	191	46	120	29	152
2015	101	21	64	33	42	57	85	53	77	19	143	92
2016	39	51	30	54	27	95	85	63	*	*	*	*
Mean	68	37	29	31	40	76	71	103	55	62	71	85
1961–1990	48	30	40	38	41	52	61	58	59	57	61	58

Table 3. Precipitation during trial years in Säby (SMHI climate station 20000) and mean precipitation (1961–1990, SMHI station 9749).

Year	January	February	March	April	May	June	July	August	September	October	November	December
2010							69	89	42	28	50	0
2011	36	10	13	12	21	57	11	105	64	61	23	62
2012	37	42	12	52	42	111	56	106	68	58	39	27
2013	22	21	1	50	11	48	16	48	48	63	52	48
2014	29	49	45	33	55	67	18	88	50	66	36	28
2015	64	25	39	10	70	36	56	8	61	5	62	38
2016	34	42	14	53	28	40	59	74				
Mean	37	32	21	35	38	60	41	74	49	42	35	34
1961–1990	34	25	26	29	33	45	69	67	58	50	50	41

Table 5. Main vehicles used in the trials.

Vehicle	Lönnstorp	Säby 1	Lydinge
Tractor	MF 6475	MF 6290	N. Holland 8970; Challenger 685
Total weight, kg	5400	5500	11,500; 24,500*
Tyre (track) width, mm	650	650	650; 700
Inflation pressure, kPa	100	80 (40)	80
Harvester	Claas Dominator 76	N.Holland TC52	Claas 770
Empty weight, kg	8800	7000	20,000
Tyre width, mm	460	580	770 (caterpillar)
Inflation pressure, kPa	180	170	

used in the trials are given in Table 5. The two experimental stations lack CTF-adopted machinery system. Therefore, we used the conventional machinery system available at the stations. In CTF, only single-wheeled vehicles were used to minimise the track area, while for RTF at Säby 1 both single and dual wheels were used. In this case, single and dual wheels were inflated to 100 and 40 kPa, respectively. Fertiliser and pesticide applications occurred across all treatments, but no measurements were made in the wheel tracks from these operations. On Lydinge farm, we compared the existing 9-m module CTF with random traffic (RTF). The tillage on this farm is non-inversion with chisel or disc harrows and the permanent traffic lane is 15.5% of the field. The comparison was conducted in four fields by designing plots of 96 m by 105 m for each CTF and RTF. The RTF in the on-farm experiment was imposed on the existing CTF, which was started in 2006. The RTF in the on-farm experiment was more real since the area of the treatments was much bigger than in the other two traditional experiments in Lönnstorp and Säby 1. All machinery used in the experiment were those at Lydinge farm. Tine cultivators used in all three trials were similar but the number of passes to produce seedbed varied depending on soil conditions. Since soil texture in the on-farm trial varied between the fields (Table 4), a pair of CTF and RTF on each field were considered as a block in statistical analyses. The distance between the RTF and CTF plots was about 25 m. The farm's crop rotation was used, which meant that crop for a given year could vary between the fields. The time of soil tillage and crop type is given in Table 6.

Measurements

Crop yields were recorded from a combine harvester. In addition, crops were manually harvested by sampling at four points in each plot by cutting a rectangular area of 0.5 m by 0.5 m (0.25 m^2). The harvested crop was pooled together making sampling area of 1 m^2/per plot. In CTF, samples were harvested separately in the middle of the crop zone (area without wheel track) and in the middle of the traffic zone. In RTF, crop samples were harvested at random points in the plot. Some soil physical characteristics were investigated in the third (2013) and sixth (2016) trial years. Soil penetration resistance (P) was measured using an Ejikelkamp penetrologger 06.15 (www.ejikelkamp.com) equipped with a cone of 1.0 cm^2 base area and 60° top angle (according to NEN 5140). The measurements were at 10 points in each RTF, crop zone and traffic zone of CTF. Soil water content was near field capacity at the time of measurements except in Lönnstorp in 2012 when the soil moisture content

Table 6. Date of tillage, sowing and type of crop.

Site	Harvesting year	Primary tillage	Secondary tillage & sowing	Crop
Lönnstorp:	2011	20/09-2010	20/09-2010	Winter wheat
	2012	08/11-2011	29/03-2012	Barley
	2013	28/08-2012	29/08-2012	Winter oilseed rape
	2014	12/09-2013	14/09-2013	Winter wheat
	2015	04/11-2014	27/03-2015	Barley
	2016	22/08-2015	23/08-2015	Winter oilseed rape
Säby 1:	2011	19/09-2010	13/05-2011	Barley
	2012	19/09-2011	04/05-2012	Spring oilseed rape
	2013	26/10-2012	15/05-2013	Barley
	2014	11/09-2013	13/09-2013	Winter wheat
	2015	03/10-2014	27/04-2015	Barley
	2016	19/10-2015	11/05-2016	Spring wheat
Lydinge, all fields	2011		11/04-2011	Spring wheat
Field 2, 18	2012		03/04-2012	Spring wheat
Field 10-2, 10-3	2012		08/04-2012	Spring oil seed rape
Field 2	2013		21/04-2013	Spring oil seed rape
Field 10-2, 10-3	2013		12/09-2012	Winter wheat
Field 2, 10-2, 10-3	2014		10/09-2013	Winter wheat
Field 18	2014		02/09-2013	Winter oil seed rape
Field 2	2015		18/03-2015	Field beans
Field 10-2, 10-3	2015		24/04-2015	Oats
Field 18	2015		08/09-2014	Winter wheat
Field 2, 10-2, 10-3	2016		08/10-2015	Winter wheat
Field 18	2016		23/04-2016	Field beans

was greater than that at field capacity. Soil dry bulk density and saturated hydraulic conductivity (ksat) were measured on triple-core samples in the traffic zone and crop zone per plot (5 cm high, 7 cm diameter) collected in 10–15 cm soil layer in all three trials, and in addition, in 30–35 cm layer at Lydinge farm. The samples were collected randomly in RTF, and separately in traffic zone and crop zone of CTF. The cores were first used to determine saturated hydraulic conductivity by the constant head method (Andersson 1955), and then dried at 105°C to compute dry bulk density. In 2015, field-saturated hydraulic conductivity (kfs) was measured at Lydinge farm at 10, 30, 50 and 70 cm depths. The measurement was accomplished using the simplified falling-head technique according to Bagarello et al. (2004) and Keller et al. (2012). The measurements were carried out when soil water content was near field capacity using infiltration rings of 0.156 m diameter and 0.15 m height. The steel rings were inserted into the soil to a depth of 8 cm. All measurements were made using 0.50 L of water. The time it took for water to infiltrate the soil was registered. Three replicates were done in each crop zone and traffic zone at each depth.

Statistical analysis

Analysis of variance (ANOVA) in SAS software (SAS Institute Inc., Cary, NC, USA) was performed using the 'mixed' procedure, considering the experimental design at Lönnstorp and Säby 1 as a split plot. In this case, tillage system was considered as a main plot and traffic system as subplot. Paired comparison of block design, i.e. two treatments and four blocks, was performed on the data from Lydinge farm. In all cases, Kenward and Roger method (Littell et al. 2006) was applied for calculating degrees of freedom, and the significance level was set at $P < 0.05$. Statistically significant differences are denoted by different letters and lack of significant differences are indicated with ns (no significant difference).

Results and discussion

Soil physical properties

Soil at Lönnstorp is dominated by coarse particles (Table 4) including flintstones, which make the soil well aerated and easily drained and the risk for soil compaction during tillage is low. Soil in Säby 1, on the other hand, is dominated by fine particles and is prone to compaction and impaired drainage, especially if field traffic occurs in early spring or late autumn. In Lydinge, soil compaction with drainage problems in some fields with high clay content forced the farmer to switch to CTF in 2006. Monthly precipitation during trial years is presented in Tables 1–3. Precipitation in southern Sweden during March and April is crucial for soil compaction if planting occurs in spring. The precipitation in those months was near to the long-term mean (1961–1990). In central Sweden, both snow thawing and precipitation in early spring have an impact on soil compaction if field traffic occurs in spring. However, the precipitation in winter and early spring during the trial years in Säby 1 has been low or near the annual mean (1961–1990). Primary tillage was accomplished in autumn and secondary tillage was done immediately before sowing. Primary tillage (cultivation with chisel) for Lydinge was at similar time as in Lönnstorp.

Soil dry bulk density and saturated hydraulic conductivity (Ksat) were measured in crop zone and traffic zone of CTF. In both Lönnstrop and Säby 1, the dry bulk density was greater in traffic zone than in crop zone irrespective of the tillage system or sampling year (Table 7). Similar result was obtained for Lydinge topsoil but no statistically significant difference was obtained for the subsoil. This shows that the machinery load during the trial years did not reach the threshold for subsoil compaction, or the subsoil was already compacted before the start of CTF. Water transport seemed to be greater in the crop zone than in the traffic zone but statistical analyses of Ksat did not always indicate the difference due to high variability. In general, the bulk density values obtained in crop zone were low. We estimated the reference bulk density (Keller and Håkansson 2010)

Table 7. Dry bulk density and saturated hydraulic conductivity[a] in 2013 and 2016.

Trial & treatment	Dry bulky density ($g\ cm^{-3}$) 2013	2016	Ksat ($cm\ h^{-1}$) 2013	2016
Lönnstorp				
DC-crop zone	1.29b	1.41b	10.6a	24.0a
DC-traffic zone	1.42a	1.45a	7.99a	18.6a
SC-crop zone	1.30b	1.46b	14.5a	15.4a
SC-traffic zone	1.39a	1.58a	9.49b	12.3a
NT-crop zone	1.49b	1.50b	12.9a	22.3a
NT-traffic zone	1.56a	1.56a	10.4a	15.7b
Säby 1				
DC-crop zone	1.20b	1.19b	81.9a	45.5a
DC-traffic zone	1.30a	1.31a	17.7b	2.99b
SC-crop zone	1.25b	1.18b	65.6a	34.5a
SC-traffic zone	1.35a	1.29a	14.8b	21.2b
NT-crop zone	1.29b	1.31b	44.0a	44.2a
NT-traffic zone	1.35a	1.35a	34.2a	25.5a
Lydinge (topsoil)				
Crop zone		1.32b		10.3a
Traffic zone		1.35a		11.5a
Lydinge (subsoil)				
Crop zone		1.40a		0.27a
Traffic zone		1.41a		0.47a

Notes: Measurements in Lydinge were conducted only in 2016. Significant difference test for ksat was after log-transformation. * refers to statistics for saturated hydraulic conductivity was computed after log-transformation. Pair comparisons for Lönnstorp and Säby 1 were done within each tillage system.

and used the values to calculate the degree of compactness (Håkansson 1990), which is related to crop yield irrespective of soil texture (Table 8). In Lydinge and Lönnstorp (in DC and SC), the degree of compactness (D) in the crop zone was near the optimum (87%) but in no-till (NT) of Lönnstorp, it was higher than the optimum. In Säby 1, D was lower than the optimum in DC and SC treatments but it was higher than the optimum in no-till. The D values in the crop zone, especially in Säby 1, indicate that the cultivated layer may have been too loose and would have need some recompaction by rollers. In no till, D was greater than the optimum value. In this case, however, roots may grow through stable macropores, which is favoured by not-till (Reichert et al. 2009).

Generally, saturated hydraulic conductivity (ksat) in both Lönnstorp and Säby 1 was greater in the crop zone than in the traffic zone but the differences were often not statistically significant. In Lydinge, ksat was very low and similar between crop and traffic zone in the topsoil and subsoil (Table 7). Water infiltration measured in summer of 2015 in Lydinge at four depths showed greater infiltration rate in the crop zone than in the traffic zone in the topsoil but no significant difference was observed for the subsoil (Figure 1).

Soil penetration resistance (PR) for all sites is presented in Figure 2. In Lydinge, the PR measured in autumn 2013 showed very low values with insignificant differences between treatments, but in 2015, the traffic zone showed significantly greater penetration resistance than the crop zone starting from about 10 cm soil depth. The low penetration resistance in the upper soil layer (0–10 cm) in the traffic zone is due to the loosening by shallow tillage. Consolidation of the tracks in CTF is good for the bearing capacity and trafficability of the soil, but loosening of the tracks is inevitable during tillage. Avoiding of loosening of the tracks is technically possible but it may increase weed infestation leading to more use of herbicides. In Lönnstorp, penetration resistance in autumn of 2012 in growing crops was very low with small differences between treatments as well as between zones. The low penetration resistance in the autumn was due to the high soil moisture since it rained 82 mm in September 2012. In 2016, penetration resistance was slightly over 2 MPa starting from about 10 cm depth. In Säby 1, similar patterns between PR values in 2013 and 2016 were observed. Cultivated plots (DC and SC) showed low PR while traffic zone and NT showed higher PR near 10 cm soil depth. The measurements were conducted in growing crops and the obtained values do not seem to be detrimental for root growth.

Table 8. Reference bulk density (RF) and degree of compactness

Field	Reference bulk density (g cm^{-3})	Tillage	Position	Degree of compactness (%) 2013	2016
Lönnstorp	1.654	DC	Crop zone	78	85
		DC	Traffic zone	86	88
		SC	Crop zone	79	88
		SC	Traffic zone	84	96
		NT	Crop zone	90	91
		NT	Traffic zone	94	94
Säby1	1.420	DC	Crop zone	85	84
		DC	Traffic zone	92	92
		SC	Crop zone	88	83
		SC	Traffic zone	95	91
		NT	Crop zone	91	92
		NT	Traffic zone	95	95
Lydinge, field 2	1.458		Crop zone		91
			Traffic zone		93
Lydinge, field 10-2	1.504		Crop zone		88
			Traffic zone		90
Lydinge, field 10-3	1.475		Crop zone		88
			Traffic zone		92
Lydinge, field 18-2	1.543		Crop zone		87
			Traffic zone		90

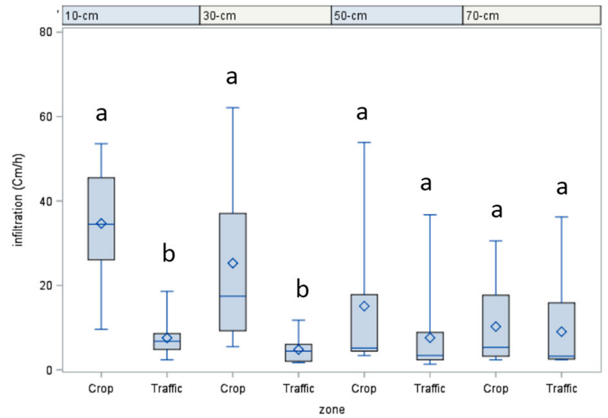

Figure 1. Water infiltration measured in 2015 in Lydinge.

Crop yield

Table 9 Shows crop yield in Lydinge. The crop yields in CTF and RTF were similar except in 2016, when CTF produced 3% greater yield. The mean yields for six years were similar between CTF and RTF. Table 10 shows yield in crop zone and traffic zone in CTF. The mean yield in traffic zone was significantly less than that in crop zone but statistically significant yield differences for individual experimental years were found only in 2011 and 2016. Crop yield in Lönnstorp is presented in Tables 11 and 12. In deep cultivation (DC) and shallow cultivation (SC), we found no trend in favour of CTF and the mean yields for six years were similar between the two systems. Comparison crop yields between crop zone and traffic zone also showed no significant differences (Table 12). In 2012 and 2013, snail damage was

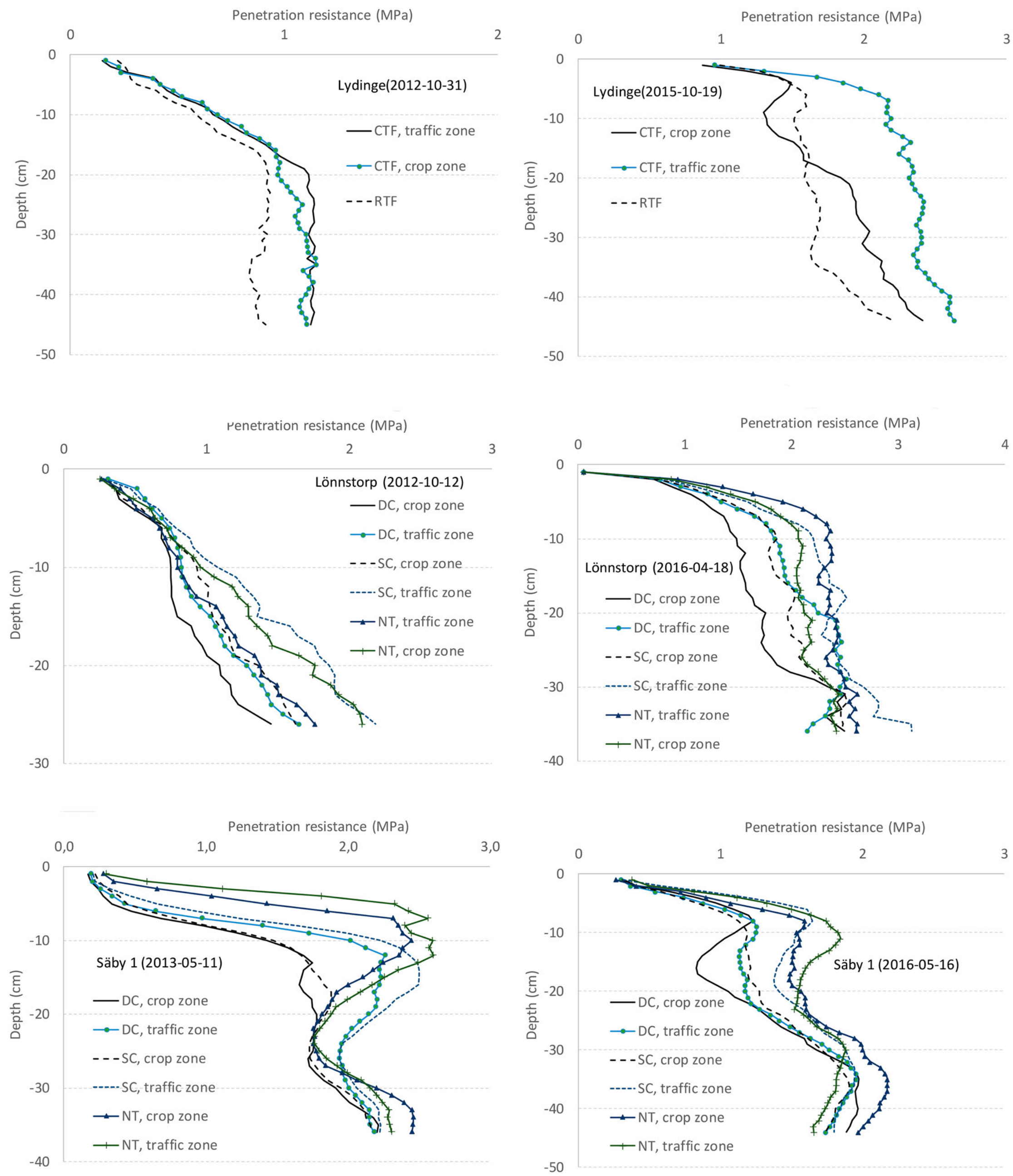

Figure 2. Penetration resistance measured in third and six trial years. Soil water content was measured only in Säby 1 in2016. Gravimetric water content was in the range of 25% and27% in topsoil, and 27% and 30% in the subsoil.

Table 9. Relative yield in RTF and CTF in Lydinge.

Traffic	2011	2012	2013	2014	2015	2016	Mean
RTF	100a	100a	100a	100a	100a	100b	100a
CTF	100a	103a	100a	104a	97a	103a	101a

Note: Relative yield in RTF is given as 100.

Table 10. Relative yield in crop zone and traffic zone of CTF in Lydinge. Relative yield in RTF is expressed as 100.

Zone	2011	2012	2013	2014	2015	2016	Mean
Crop zone	105a	112a	96a	110a	93a	92a	102a
Traffic zone	82b	96a	85a	101a	80a	80b	88b

observed in treatments SC and NT making it difficult to compare CTF and RTF effects.

The effect of CTF on crop yield in Säby 1 (Tables 13 and 14) is different from that in Lönnstorp due to differences in soil texture. In Säby 1, crop yields in DC (15–20 cm) were slightly greater in CTF than in RTF for five years of the six trial years, and the mean for all years was greater by 4.2% though the difference was not statistically significant. In SC and no-till CTF tended to produce more yield than RTF.

The small plots in the treatments in Lönnstorp and Säby 1 and the machinery system used on them could

Table 11. Relative crop yield (taking crop yield in conventional tillage as 100) in Lönnstorp.

Tillage and zone	2011	2012	2013	2014	2015	2016	Mean
Deep cultivation (15–20 cm)							
RTF	88.8a	99.9a	91.0a	98.4a	96.3a	112.6a	97.8a
CTF	102.7a	97.4a	91.3a	97.6a	99.4a	102.3a	98.4a
Shallow cultivation (5–10 cm)							
RTF	100.3a	97.3a	98.8a	97.9a	98.5a	123.8a	102.8a
CTF	98.4a	95.4a	89.8a	102.5a	101.7a	106.4a	99.0a
No-till							
RTF	100.0a	97.8a	*	104.9a	98.6a	110a	102.1a
CTF	94.6a	88.5b	*	102.0a	95.4a	104.5a	97.0a

Note: *represents crop failure due to damage by snails.

Table 12. Relative crop yield (taking crop yield in conventional tillage as 100) in crop zone and traffic zone in Lönnstorp.

Tillage and zone	2011	2012	2013	2014	2015	2016	Mean
Deep cultivation (15–20 cm)							
Crop zone	102.0a	99.6a	92.3a	96.6a	99.2a	99.1a	98.1a
Traffic zone	103.7a	94.1a	89.7a	99.1a	99.6a	107.1a	98.9a
Shallow cultivation (5–10 cm)							
Crop zone	96.6a	92.3b	89.4a	101.6a	101.4a	110.9a	98.7a
Traffic zone	101.0a	100.0a	90.5a	103.9a	102.1a	99.6a	99.5a
No-till							
Crop zone	97.2a	89.8a	*	102.1a	98.0a	104.8	98.4a
Traffic zone	90.8a	86.6b	*	101.8a	91.4a	104.0	94.9a

Note: * represents crop failure due to damage by snails.

Table 13. Relative crop yield (taking crop yield in conventional tillage as 100) in Säby 1.

Tillage and zone	2011	2012	2013	2014	2015	2016	Mean
Deep cultivation (15–20 cm)							
RTF	81.0a	96.5a	99.0a	97.8a	89.4a	109.0a	95.5a
CTF	84.8a	107.3a	89.1a	104.4a	94.0a	118.7a	99.7a
Shallow cultivation (5–10 cm)							
RTF	86.0a	109.6a	106.6a	104.5a	89.1b	103.6a	99.9a
CTF	83.6a	94.7a	88.7a	102.2a	96.6a	108.8a	95.8a
No-till							
RTF	81.0a	106.4a	82.3a	103.8a	89.7a	116.4a	96.6a
CTF	81.1a	101.2a	87.5a	99.0a	89.9a	106.6a	94.2a

Table 14. Relative crop yield (taking crop yield in conventional tillage as 100) in Säby 1.

Tillage and zone	2011	2012	2013	2014	2015	2016	Mean
Deep cultivation (15–20 cm)							
Crop zone	81.1a	99.7a	88.8a	103.0a	93.4a	117.8a	97.3a
Traffic zone	90.6a	118.6a	89.5a	106.4a	94.8a	119.9a	103.3a
Shallow cultivation (5–10 cm)							
Crop zone	79.9a	91.0a	81.5a	102.8a	96.2a	107.0a	93.1a
Traffic zone	89.2a	100.3a	99.4a	101.5a	97.2a	106.8a	99.1a
No-till							
Crop zone	76.0a	104.0a	88.0a	95.8a	90.2a	105.5a	93.2a
Traffic zone	88.8a	97.0a	86.7a	103.8a	89.4a	108.2a	95.7a

not simulate real CTF experiment. Thus, reliable comparison between CTF and RTF was only in the experiment on Lydinge farm, where we used big plots and CTF-adopted machinery. However, the experiments in Lönnstorp and Säby 1 illustrated some soil conditions in track zones and crop zones.

Water infiltration rate was much faster in crop zone than in traffic zone down to 30 cm in Lydinge where heavy machinery was used. Although other soil physical characteristics were more affected in the track zone than in the crop zone, the changes were not too severe to affect crop yield. We conclude that if vehicle weight is not very high and the soil is not vulnerable to compaction, dual wheels and CTF are equal options.

Acknowledgments

The authors are grateful to the Swedish Farmers Foundation for Agricultural Research for financing this study. The project was initiated by the late Prof Johan Arvidsson. We are also grateful to Berth Mårtensson, Carl Johan Wallenqvist and Erik Rasmusson for conducting the field trials at Lönnstorp and Säby 1, and Jan Jönsson for allowing us to use his machinery and farm to carry out the on-farm trial. Liselott Evasdotter has helped with data collection. Anton Lindesson, Marie Gardesson and Louice Lejon have contributed by conducting their MSc thesis work within this project.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Swedish Farmers Foundation for Agricultural Research [grant number H1233176].

Notes on contributors

Dr Ararso Etana is associate professor and researcher at the Department of Soil and Environment, Swedish University of Agricultural Sciences, specializing in soil tillage and mechanics.

Lena Holm (agronomist) is a consultant in soil and plant production management. She worked earlier as a researcher and teacher at the Department of Biosystems and Technology, Swedish University of Agricultural Sciences, Sweden.

Dr Tomas Rydberg (agronomist) is emeritus at the Department of Soil and Environment, Swedish University of Agricultural Sciences, and an expert in soil tillage and soil management.

Prof Thomas Keller is a professor of soil mechanics and soil management at the Department of Soil and Environment at the Swedish University of Agricultural Sciences, and a scientist at the Department of Agroecology and Environment at the Agroscope research institute in Zürich, Switzerland.

References

Alvemar H, Andersson H, Pedersen HH. 2017. Profitability of controlled traffic in grass silage production – economic modelling and machinery systems. Adv Animal Biosci Precis Agric. 8(2):749–753.

Andersson S. 1955. Markfysikaliska undersökningar I odlad jord. VIII. En experimentell metod. Grundförbättring. 8:35–44.

Antille DL, Chamen WCT, Tullberg JN, Lal R. 2015. The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in arable land: a critical review. Transactions of the ASABE. 58 (3):707–731.

Antille DL, Peets S, Galambošová J, Botta GF, Rataj V, Macák M, Tullberg JN, Chamen WCT, White DR, Misiewicz PA, et al. 2019. Review: soil compaction and controlled traffic farming in arable and grass cropping systems. Agron Res. 17(3):653–682.

Bagarello V, Iovino M, Elrick D. 2004. A simplified falling-head technique for rapid determination of field-saturated hydraulic conductivity. Soil Sci Soc Am J. 68:66–73.

Chamen T. 2015. Controlled traffic farming – from worldwide research to adoption in Europe and its future prospects. Acta Technol Agric. 3:64–73.

Chamen WCT, Dowler D, Leede PR, Longstaff DJ. 1994. Design, operation and performance of a gantry system: experience in arable cropping. J Agr Eng Res. 59:45–60.

Erhbach DC. 1994. Benefits of tracked vehicles in crop production. In: B.D. Soane, C. Van Ouwerkerk, editors. Soil compaction in crop production. Amsterdam: Elsevier; p. 501–520.

Gasso, V., Oudshoorn, F.W., Sørensen, C. A.G., Pedersen, H.H. 2014. An environmental life cycle assessment of controlled traffic farming. J Cleaner Prod 73: 175–182.

Gasso V, Sørensen CAG, Oudshoorn FW, Green O. 2013. Controlled traffic farming: a review of the environmental impacts. Eur J Agron. 48:66–73.

Håkansson I. 1990. A method for characterizing the state of compactness of the plough layer. Soil Tillage Res. 16:105–120.

Håkansson I. 1985. Swedish experiments on subsoil compaction by vehicles with high axle load. Soil Use Manag. 1(4):113–116.

Håkansson, I. 2005. Compaction of arable soils. Incidence – consequences – counter-measures. Uppsala: Department of Soil Sciences, Reports from the division of soil management. 153 p.

Keller T, Håkansson I. 2010. Estimation of reference bulk density from soil particle size distribution and soil organic matter content. Geoderma. 154:398–406.

Keller T, Sutter J, Nissen K, Rydberg T. 2012. Using field measurement of saturated soil hydraulic conductivity to detect low-yielding zones in three Swedish fields. Soil Tillage Res. 124:68–77.

Littell RC, Milliken GA, Stourup WW, Wolfinger RD, Shabenberger O. 2006. SAS for mixed models. 2nd ed. SAS Institute Inc. Cary, NC.

Reichert JM, Suzuki LEAS, Reinert DJ, Horn R, Hakansson I. 2009. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res. 102:242–254.

Soane BD, Blackwell PS, Dickson JW, Painter DJ. 1981. Compaction by agricultural vehicles: a review II. compaction under tyres and other running gears. Soil Tillage Res. 1:373–400.

Taylor JH. 1983. Benefits of permanent traffic lanes in a controlled traffic crop production system. Soil Tillage Res. 3:385–395.

Tullberg J, Antille DL, Bluett C, Eberhard J, Scheer C. 2018. Controlled traffic farming effects on soil emissions of nitrous oxide and methane. Soil Tillage Res. 176:18–25.

Tullberg J, Yule DF, McGarry D. 2007. Controlled traffic farming-from researchto adoption in Australia. Soil Tillage Res. 97 (2):272–281.

Wang X, Gao H, Tullberg JN, Li H, Kuhn N, McHugh AD, Li Y. 2018. Traffic and tillage effects on runoff and soil loss on the loess plateau of northern China. Aust J. Soil Res. 46:667–675.