Soil & Tillage Research 191 (2019) 117–130

Contents lists available at ScienceDirect

Soil & Tillage Research

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

Controlled traffic farming increased crop yield, root growth, and nitrogen supply at two organic vegetable farms

Margita Hefner[a], Rodrigo Labouriau[b], Michael Nørremark[c], Hanne Lakkenborg Kristensen[a,*]

[a] Department of Food Science, Aarhus University, 5792 Aarslev, Denmark
[b] Department of Mathematics, Aarhus University, 9000 Aarhus, Denmark
[c] Department of Engineering, Aarhus University, 8830 Tjele, Denmark

ARTICLE INFO

Keywords:
Beetroot
Potato
Root density
Soil mineral nitrogen
White cabbage
Winter squash

ABSTRACT

Increased farm machinery weight in agricultural production results in soil compaction. Controlled traffic farming (CTF) restricts traffic to permanent lanes, thereby creating traffic free beds for crop production. Field experiments were conducted at two organic vegetable farms in Denmark, on a sandy loam (2013–2016) and on coarse sand (2013–2015) to investigate CTF effects compared with random traffic farming (RTF) on vegetable yield, root growth, and soil mineral nitrogen (N). Root growth was measured using minirhizotrons. White cabbage, potato, and beetroot yield increased by 27%, 70% and 42%, respectively, in CTF compared with RTF in 2015 and winter squash indicated a yield increase of 43% on sandy loam in 2016. White cabbage (2015) and potato, beetroot and winter squash (2016) grew 2–25 times more roots and beetroot grew deeper roots under CTF compared with RTF on sandy loam in 2016. On coarse sandy soil, beetroot root frequency was 1.4 times greater under CTF than under RTF and beetroot roots grew deeper than 1.5 m under both treatments in 2015. Soil mineral N and potential net N mineralization were equal between treatments or higher in CTF by 2–41 kg ha^{-1} and 11 mg kg^{-1} 35 days^{-1}, respectively, indicating N supply was maintained or increased in this system. Despite the variability in crop and root growth responses to traffic between years and crops, the effects were always equal or positive for CTF following treatment implementation. Therefore, our results encourage the use of CTF for organic vegetable production under temperate conditions.

1. Introduction

The increasing machinery weight in agriculture degrades soil and leads to soil compaction (Raper, 2005). Soil particles are rearranged via the weight and driving force of tractors, which reduces soil porosity and increases soil bulk density (Hamza and Anderson, 2005; Wolkowski, 1990). Raper (2005) reported soil compaction exhibited negative impacts on water infiltration, root development, and crop production, among other factors. Potato root penetration was halved at a soil strength of 1.5 MPa (Stalham et al., 2007). Root growth was restricted in compacted soils, due to increased mechanical impedance or decreased oxygen availability, which depended on precipitation levels during the growing season (Lipiec and Hakansson, 2000). Batey and McKenzie (2006) suggested nutrient uptake in plants might be reduced by restricted root growth and reduced nitrate availability in compacted soils. Decreased yields were observed as a result of soil compaction in several studies (Chan et al., 2006; Nevens and Reheul, 2003).

Reducing trafficked areas using controlled traffic farming (CTF) is a potential management tool to alleviate the problems associated with soil compaction (Johansen et al., 2015). The Australian Controlled Traffic Farming Association Inc. (http://actfa.net/) defines CTF as a system where machinery traffic with the same or modular working width is used to keep field traffic confined to permanent traffic lanes, which is achieved through precise guidance (Antille et al., 2015). CTF adoption increases soil porosity, water infiltration, and saturated hydraulic conductivity (Antille et al., 2015), thereby decreasing N_2O emissions compared with trafficked soil (Tullberg et al., 2018).

Despite improved water infiltration, N leaching is not increased under CTF (Vermeulen and Mosquera, 2009), because improved crop root growth, for example to deeper soil layers, increases N uptake by the crop (Kristensen and Thorup-Kristensen, 2007).

CTF effects in vegetable production systems have been studied to a

Abbreviations: CTF, controlled traffic farming; N, nitrogen; N_{acc}, nitrogen accumulation; Root intensity$_{mod}$, modified root intensity; RTF, random traffic farming; Soil N_{min}, soil mineral nitrogen

* Corresponding author.
E-mail address: hanne.kristensen@food.au.dk (H.L. Kristensen).

https://doi.org/10.1016/j.still.2019.03.011
Received 12 July 2018; Received in revised form 30 January 2019; Accepted 19 March 2019
Available online 09 April 2019

limited degree. Beneficial changes in soil bulk density, infiltration, and soil resistance with CTF were observed in Australian vegetable production, but yield impacts were variable, with increased yield reported only in onions (McPhee et al., 2015). Yield increases in a seasonal CTF were observed in the Netherlands in organic green pea, spinach, and planted onion production, whereas carrots and sown onions showed no yield difference compared with random traffic farming (RTF) (Vermeulen and Mosquera, 2009). CTF's influence on root growth for different crops has received little attention to date. In the Netherlands, potato root proliferation was better under CTF compared with RTF (Lamers et al., 1986).

Effects of CTF to RTF were compared in organic vegetable production systems across two soil types in Denmark three years after study establishment. The hypotheses were that CTF, in contrast to RTF, will (1) increase crop yield; (2) improve soil N supply; and (3) improve root growth. The research objective was to confirm if CTF compared with RTF is a viable management system for organic vegetable farms in Denmark in terms of crop performance and soil fertility. The following variables were examined: soil N_{min} content, vegetable yield, plant N accumulation (N_{acc}) and root growth.

2. Material and methods

2.1. Experimental sites

Two field experiments were conducted at two commercial organic vegetable farms in Denmark, at Skiftekær Økologi on the island of Tåsinge (2013–2016), and at Vostrup Øko in Western Jutland (2013–2015). The geographical locations of the experimental sites were 54°97′N, 10°53′E on fine sandy loam at Skiftekær, and 55°89′N, 8°45′E on coarse sand at Vostrup. Table 1 indicates the soil properties of the two sites, which were determined by a combined sieve/sedimentation analysis after destruction of soil organic matter. Precipitation and average air temperature at Skiftekær and Vostrup are given in Fig. 1. Organic management has been practised at the fields since 1998 at Skiftekær, and 1996 at Vostrup. Fertilization and irrigation schemes were maintained slightly below optimum according to the farmer's visual evaluation to determine the best treatment (CTF or RTF) under these limiting conditions at both farms. White cabbage was used as the reference for irrigation and all fields were irrigated directly after white cabbage transplanting, and whenever white cabbage showed clear signs of water deficit at Skiftekær. Beetroot received no irrigation at Vostrup.

2.2. Experimental design

Two traffic treatments, CTF and RTF, were applied at both farms. CTF was conducted with vehicles fitted with auto-steering, based on highly accurate Real Time Kinematic Global Positioning System (RTK-GPS) guidance. The CTF plot machinery traffic was restricted to these permanent traffic lanes throughout the entire experiment, with the exception of a 2.5 Mg row-by-row harvester (ASA-Lift, Denmark) with 0.6-m wide wheels and 1.5-bar inflation pressure for the beetroot

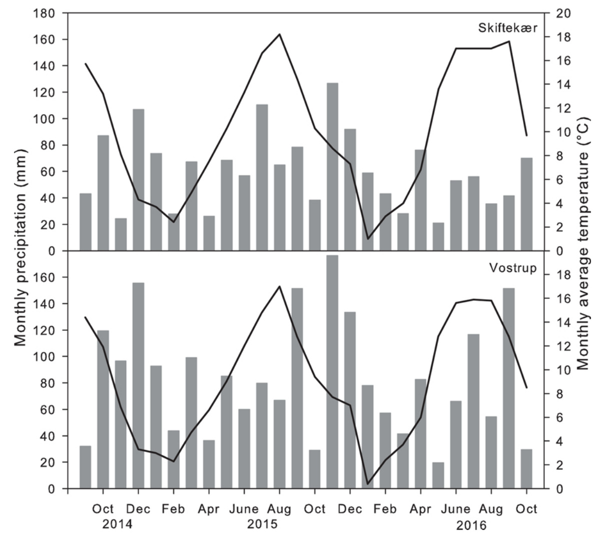

Fig. 1. Monthly precipitation and average monthly temperature from Sep 2014 until Oct 2016 at Skiftekær and Vostrup. Precipitation data was taken from the nearest relevant meteorological station located at Bøjden (55°10′N, 10°10′E) for Skiftekær and at Outrup (55°72′N, 8°43′E) for Vostrup. Temperature data was taken from Assens (55°27′N, 9°90′E) for Skiftekær and from Borris (55°96′N, 8°65′E) for Vostrup.
Data was obtained from DMI (2018).

harvest at both Skiftekær and Vostrup, and one wheel of a 7 Mg potato harvester (Grimme, UK) with 0.7-m wide wheels and 2.5-bar inflation pressure driving in the beds at Skiftekær. According to CTF Europe Ltd. (http://www.controlledtrafficfarming.com/), this CTF system translates to a Tier 1 system, where 30–40 % of the area was trafficked. In the RTF treatment, machinery traffic at harvest and soil tillage in the spring occurred randomly, without the use of auto-steering. Non-inversion tillage to 0.25 m depth in both treatments was done using a stubble cultivator, which replaced the plough, from May 2013 at Skiftekær and April 2013 at Vostrup. Each field was divided into two plots: one subjected to CTF and the other to RTF. At Skiftekær, each plot was split into five different fields in which a different crop was grown each year. At Vostrup, only one crop was grown each year under both treatments. Each field had a total size of 6.75 m × 210 m at Skiftekær, and 6.54 m × 100 m at Vostrup. Soil surface digital elevation attributes and electrical conductivity were mapped to cluster homogenous areas covering the experimental plots. Experimental sampling points were randomly placed inside the established homogeneous subplots and within intermediate areas between wheel tracks. The sampling points served as replicates for each treatment and were kept as fixed points throughout the experiment for soil N_{min}, potential net N mineralization, visual evaluation of soil structure evaluation, and crop yield sampling. Two replicates were randomly assigned to each field.

Prior to treatment onset in 2013, soil N_{min} content, potential net N mineralization, and visual evaluation of soil structure pre-

Table 1
Experimental field soil properties at the two farms Skiftekær and Vostrup.

	Soil layer (m)	Clay (%) < 0.002 mm	Silt (%) 0.002–0.02 mm	Fine sand (%) 0.02–0.2 mm	Coarse sand (%) 0.2–2.0 mm	Soil organic matter (%)
Skiftekær	0–0.25	10.5	10.5	50.0	26.5	1.9
	0.25–0.5	10.2	11.0	48.0	30.0	1.1
	0.5–1	13.2	11.5	43.0	31.5	0.7
	1–1.5	15.5	11.0	44.0	29.0	0.6
Vostrup	0–0.25	4.7	3.3	21.0	69.0	2.8
	0.25–0.5	4.3	2.1	14.0	79.0	0.8
	0.5–1	3.8	1.6	8.2	86.0	0.3
	1–1.5	2.9	1.6	8.9	86.0	0.1

Table 2
Agricultural management practices at the two farms in 2015 and at Skiftekær in 2016.

Field	Unit	Vostrup 2015	Skiftekær 2015 1	2	3	Skiftekær 2016 1	2	3
Pre-crop		Potato	Red clover	White cabbage	Potato			
Crop		Beetroot	White cabbage	Potato	Beetroot	Potato	Beetroot	Winter squash
Cultivar		Wodan	Coronet	Elfe	Wodan	Marabel	Wodan	Amoro
Field size	(m)	6.54 × 100	6.75 × 210	6.75 × 210	6.75 × 210	6.75 × 210	6.75 × 210	6.75 × 210
Row distance	(m)	0.45	0.466	0.625	0.466	0.625	0.466	1
Plant distance	(m)	0.04	0.5	0.18	0.25	0.18	0.25	0.6
N fertilizer	Type	Cow slurry	Pig slurry	Pig slurry	Pig slurry	Cow slurry	Cow slurry	Cow slurry
	(t ha^{-1})	20	18	30	18	35	30	30
	N (kg ha^{-1})	60	34.	57	34.	67	57	57
	Application date	Oct 2014	Aug 6	May 1	Aug 6	May 6	May 4	May 4
Harrowing	Stubble	Oct 2014	May 21	Apr 25	Apr 25	Apr 20	Apr 20	Jan 03, Apr 20
	Seedbed		May 28	May 7	May 7	May 7	May 5	May 5
Transplanting		Jun 07	Jun 19	May 10	Jun 8	May 8	May 26	May 29
Weeding		–	–	–	–	–	May 31	Jul 28
Harvest		Oct 14	Nov 11	Sep 15	Sep 28	Sep 15	Sep 21	Sep 21

Table 3
Timetable of measurements recorded at Skiftekær and Vostrup in 2015 and at Skiftekær in 2016.

	Year	Skiftekær	Vostrup
Soil sampling for soil N_{min} and potential net N mineralisation	2015	Mar 25, Nov 26/27	Mar 27, Nov 5/6
	2016	Apr 5/6, Oct 26/27 (only soil N_{min})	–
Visual evaluation of soil structure	2015	Mar 25, Nov 26	Nov 18
	2016	Apr 5	–
Root filming	2015	Jul 21 (all), Aug 19 (all), Sep 28 (beetroot and white cabbage), Nov 11 (white cabbage)	Aug 12, Sep 8, Oct 14
	2016	Jul 19 (all), Aug 18 (all), Sep 21 (beetroot and winter squash)	–

measurements were performed. After two years (in 2015), these measurements were repeated at both farms and in 2016 at Skiftekær only, as well as additional measurements including crop yield, crop N content, and root growth.

The 5-year crop rotation implemented at Skiftekær was red clover (*Trifolium pratense* L.) used as green manure, followed by white cabbage (*Brassica oleracea* L. convar. *capitata* (L.) Alef. var. *alba* DC), potato (*Solanum tuberosum* L.) with hairy vetch (*Vicia* villosa Roth) as a winter cover crop, beetroot (*Beta vulgaris* L. ssp. *vulgaris* var. *conditiva* Alef.), and winter squash ‘Hokkaido’ (*Cucurbita maxima* Duch.). In 2013, onion (*Allium cepa* L.) was grown instead of winter squash. The crop rotation was applied in a time scale, but also in a spatial scale, so that each crop was grown each year in the different fields. Three out of five fields per treatment were sampled each year. They are hereafter referred to as field one, two, and three. White cabbage, potato, and beetroot were sampled in 2015, and potato, beetroot, and winter squash in 2016. At Vostrup, the 5-year crop rotation included a grass-clover mixture grown as a green manure in 2012, followed by carrot (*Daucus carota* L. ssp. *sativus*) in 2013, potato in 2014, beetroot in 2015, and winter squash in 2016. Beetroot was sampled in 2015. All details of crop management are given in Table 2. Tractors used for farm management operations were a 80 kW tractor (Fendt, Germany) with 0.3-m wide wheels and 3-bar inflation pressure at Skiftekær and a 90 kW tractor (John Deere, USA) with 0.24-m wide wheels and 3-bar inflation pressure at Vostrup. Fertilization was applied with a customized 6 Mg (at Skiftekær) or 8 Mg (at Vostrup) row injector with flowmeter, 0.3-m wide wheels and 2-bar inflation pressure. Stubble cultivation was conducted with a cultivator

Table 4
Total and marketable crop yield (Mg ha^{-1}) in the three Skiftekær fields in 2015 and 2016 and one Vostrup field in 2015.

Total yield

Year	Treatment	Field 1	Field 2	Field 3	Vostrup
2015		White cabbage	Potato	Beetroot	Beetroot
	CTF	57(52–61) [a]	59 (51–67) [a]	48 (43–54) [a]	47 (41–53) [a]
	RTF	44 (40–49) [b]	35 (27–43) [b]	37 (31–42) [b]	41 (35–47) [a]
	P-value	0.0015	0.0006	0.0099	0.2231
2016		Potato	Beetroot	Winter squash	
	CTF	22 (14–31) [a]	50 (42–59) [a]	37 (29–46) [a]	
	RTF	22 (13–30) [a]	43 (35–52) [a]	25 (17–34) [a]	
	P-value	0.9066	0.2842	0.064	

Marketable yield

Year	Treatment	Field 1	Field 2	Field 3	Vostrup
2015		White cabbage	Potato	Beetroot	Beetroot
	CTF	55 (50–60) [a]	59 (50–67) [a]	42 (36–48) [a]	44 (38–51) [a]
	RTF	44 (39–48) [b]	35 (26–43) [b]	30 (24–36) [b]	38 (31–44) [a]
	P-value	0.0039	0.0009	0.0095	0.1973
2016		Potato	Beetroot	Winter squash	
	CTF	21 (12–30) [a]	49 (40–58) [a]	33 (24–42) [a]	
	RTF	21 (12–30) [a]	41 (32–50) [a]	23 (14–32) [a]	
	P-value	0.9483	0.2623	0.1424	

CTF = controlled traffic farming, RTF = random traffic farming; estimates are given with 95% confidence intervals in brackets, n = 2. Different lower-case letters indicate significant difference between treatments at a 5% significant level.

Terrano (Horsch, Germany), and a rotary hiller (Grimme, UK) at Skiftekær, and a stubble cultivator Vibro Flex (Kongskilde, Denmark) at Vostrup. The harrow Terra-Dan (HE-VA, Denmark) was used for seedbed preparation at Skiftekær, whereas a spader (Imants, Netherlands) was used at Vostrup. Crops were either planted with a pneumatic planter (Monosem, France) at Skiftekær and Vostrup, or transplanted with a pneumatic planting machine (CM Regero industries, France) at Skiftekær. Weed control was carried out with an interrow cultivator (Hatzenbichler, Austria) and a vision based hoeing machine Robovator (F. Poulsen Engineering APS, Denmark) at Skiftekær.

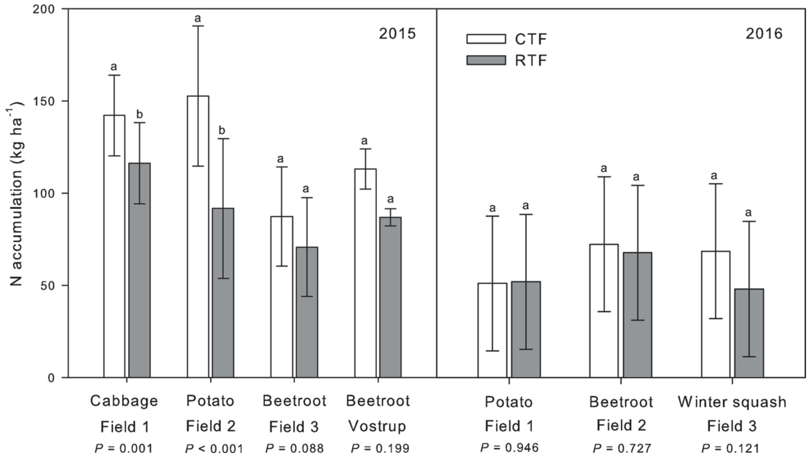

Fig. 2. Tubers and above ground plant material N accumulation of three crops at Skiftekær in 2015 and 2016 and beetroot at Vostrup in 2015. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 2. Different lower case letters represent significant differences between treatments ($P < 0.05$).

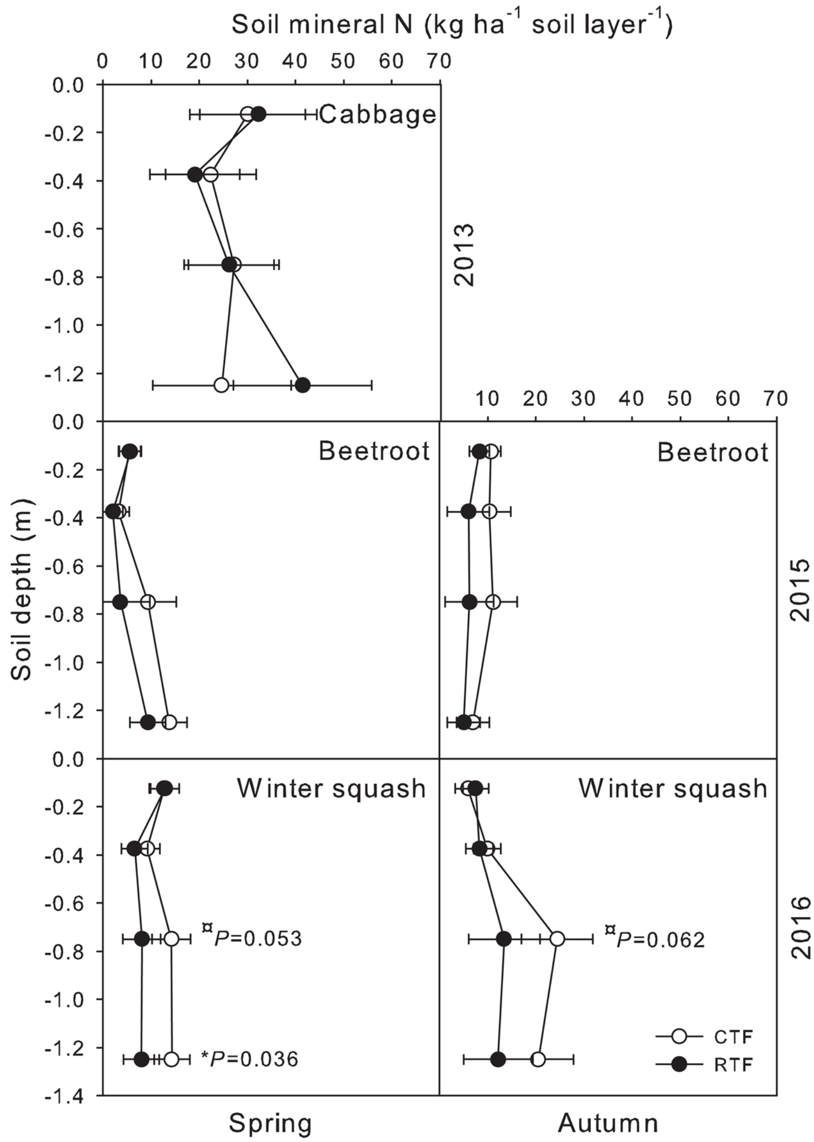

Fig. 3. Distribution of soil N_{min} in field 1 in 0–1.5 m soil depth under CTF and RTF at Skiftekær in 2013, 2015, and 2016. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 2. * represents significant differences between treatments ($P < 0.05$) and ¤ indicates differences ($P < 0.1$).

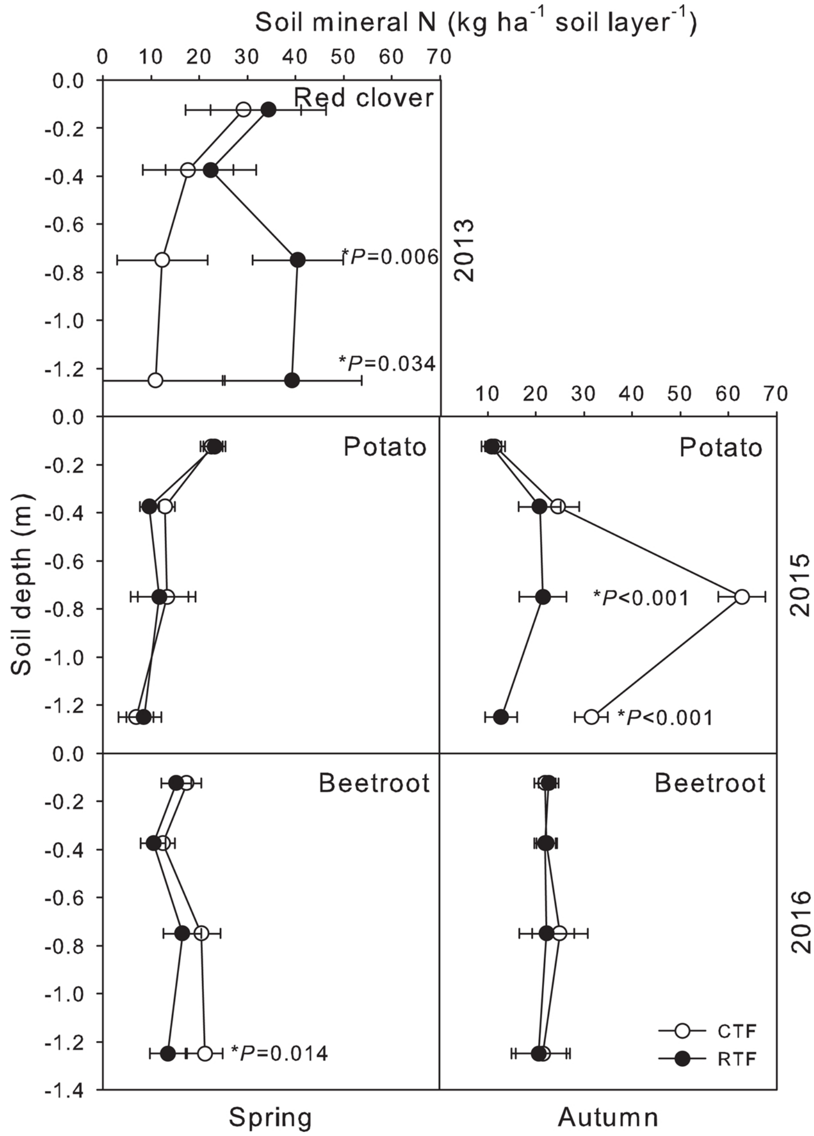

Fig. 4. Distribution of soil N_{min} in field 2 in 0–1.5 m depths under CTF and RTF at Skiftekær in 2013, 2015, and 2016. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 2. * represents significant difference between treatments ($P < 0.05$).

2.3. Measurements

2.3.1. Soil, root and plant sampling

The measurement sampling times during 2015 and 2016 are provided in Table 3. The 0–0.25 m topsoil layer structure at Skiftekær was assessed with the visual evaluation of soil structure method as described by Ball et al. (2007) prior to soil tillage after several months without soil disturbance. The soil from each permanent sampling point was graded from 1–5, where 1 is best, based on aggregation, porosity, and roots present. The same person visually conducted the evaluations for all samples.

For soil N_{min}, ten replicates were obtained at each permanent sampling point by a machine driven soil piston auger with a 14 mm inner-diameter. The machine had a wheel load of 0.375 Mg and was considered light enough to drive in the beds. The N_{min} content was determined for soil from 0–0.25 m, 0.25–0.5 m, 0.5–1 m, and 1–1.5 m depth layers and mixed into a composite sample for each depth and permanent sampling point. Soil samples were kept cool, transferred to the laboratory, and frozen until analysis. Analysis of soil N_{min} was performed according to the Plant Directorate of the Danish Ministry of Agriculture (1994), where samples were thawed and 100 g fresh weight subsamples were extracted in 1 M KCl for 1 h (1 soil: 2 solution). The soil extract was centrifuged and the supernatant was analysed for NH_4^+ and NO_3^- by standard colorimetric methods using AutoAnalyzer 3 (Bran + Luebbe, Germany).

Potential net N mineralization was determined according to Hart et al. (1994) using field-moist soil from the 0–0.25 m layer. The soil was mixed, sieved (5 mm), put into 500 ml containers, covered with polyethylene (30 µm), and incubated under aerobic conditions at 25 °C for 35 days (Curtin and Campbell, 2007). The water content was adjusted once a week by spraying samples with deionized water to keep the sample moist. Samples were frozen until analysis and subsequently thawed and extracted by the procedure described above.

Root growth was measured in minirhizotron tubes (four per field), installed close to the edge of the fields shortly after crop planting to avoid traffic in the crop beds, and traffic effects on root growth measurements. The minirhizotron tubes were prepared by drawing observation windows (0.04 × 0.04 m crosses) along the tube surface as described by Kristensen and Thorup-Kristensen (2004). Perpendicular to the direction of the crop rows, holes were drilled into the soil with a spiral auger at a 30° angle and tubes were inserted into the soil reaching depths of 1.5 to or 2.5 m, depending on the expected root depth of the

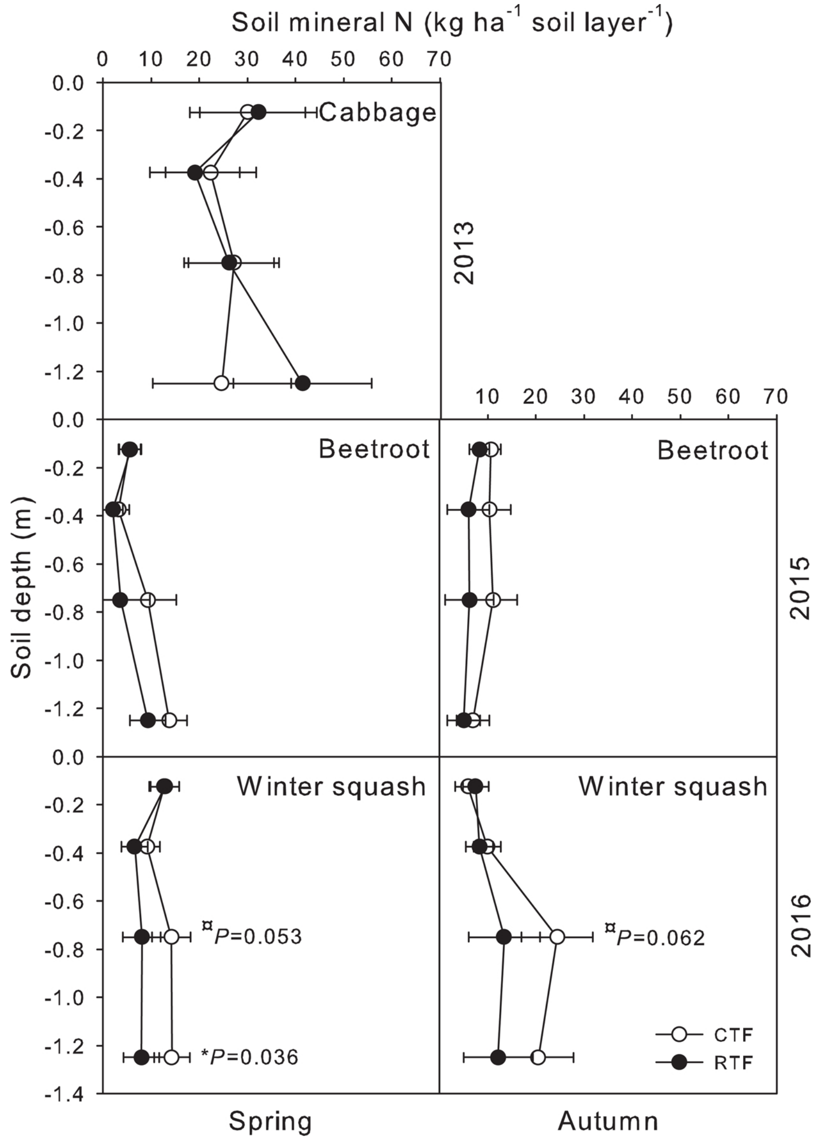

Fig. 5. Distribution of soil N_{min} in field 3 in 0–1.5 m soil depth under CTF and RTF at Skiftekær in 2013, 2015, and 2016. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 2. * represents significant differences between treatments ($P < 0.05$) and ¤ indicates differences ($P < 0.1$).

crop under investigation. The roots growing along the tube margins were filmed two to four times during the crop growth period (Table 3) and root frequency, root intensity, and root depth were recorded. For root frequency, the presence or absence of roots crossing each observation window grid was recorded measuring the soil volume occupied by the root system, whereas the total number of roots crossing each observation window grid was counted to measure root intensity, characterizing the intensity of root colonization. Root frequency and intensity were summed for each 0.25 m depth interval. The root depth was considered the deepest root in the observation window.

At harvest, two vegetable rows of 3 m lengths per permanent sampling point were harvested by hand. One row was located at the bed's centre, whereas the second row was located next to the wheel track, to account for yield differences within beds. Plant materials were sorted into yield and crop residues for all crops, except potatoes (2015 and 2016) and beetroot (2016) at Skiftekær and beetroot at Vostrup (2015), as above ground biomass of these crops was not present at harvest. Total yields included crop yields and crop residues, whereas marketable yields were defined as cabbage heads ≥ 0.5 kg, beetroots with a diameter of 4–8 cm, and winter squash with a ≥ 12.5-cm diameter. Crops with a fungal infection were further discarded from marketable yields. Plant materials were chopped, mixed well, weighed, oven-dried at 80 °C for 20 h, weighed again, combusted, and analysed for total plant N content by the VDLUFA method (VDLUFA, 1991). Plant materials were first burnt at 900 °C and molecular N was then determined by use of LECO TruSpec CN (St. Joseph, Michigan).

2.3.2. Data and statistical analyses

Yield was calculated as fresh weight per area. Nitrogen accumulation in plant material at harvest was calculated per area using dry matter, total tuber (potato, beetroot) N concentration and above ground plant biomass. Soil N_{min} was calculated per area based on measured N_{min} concentrations from 0–0.25 m, 0.25–0.5 m, 0.5–1 m, and 1–1.5 m depth layers and corresponding soil bulk density. Potential net N mineralization was calculated by subtracting the initial N_{min} from the N_{min} content after incubation (Curtin and Campbell, 2007).

Yield, N_{acc}, soil N_{min}, and potential net N mineralization were analysed separately for each farm, year, and crop using a Gaussian linear mixed model containing a fixed effect indicating the treatment (RTF or CTF) and a Gaussian random component representing the

Table 5

Potential net soil N mineralization (mg kg^{-1} 35 days^{-1}) from 0 to 0.25 m depth from the three Skiftekær fields and Vostrup following incubation at 25 °C for a period of 35 days in spring 2013, spring 2015, autumn 2015, and spring 2016.

Time	Treatment	Field 1	Field 2	Field 3	Vostrup
Spring 2013		Onion	Green manure	White cabbage	Carrot
	CTF	14	13	19	17
		(12–16) [a]	(11–15) [b]	(17–21) [a]	(10–23) [a]
	RTF	14	18	12	20
		(12–16) [a]	(16–20) [a]	(10–14) [b]	(13–26) [a]
	P-value	0.9751	0.0134	0.0043	0.3019
Spring 2015		White cabbage	Potato	Beetroot	Beetroot
	CTF	16	25	16	18
		(11–21) [a]	(20–30) [a]	(11–21) [a]	(16–20) [a]
	RTF	16	22	18	23
		(11–21) [a]	(17–27) [a]	(13–23) [a]	(21–25) [a]
	P-value	0.9569	0.4306	0.5758	0.6341
Autumn 2015		White cabbage	Potato	Beetroot	Beetroot
	CTF	17	24	21	12
		(13–20) [a]	(20–27) [a]	(17–25) [a]	(9–15) [a]
	RTF	18	24	21	14
		(15–22) [a]	(21–28) [a]	(17–25) [a]	(11–17) [a]
	P-value	0.5424	0.7449	0.9863	0.9923
Spring 2016		Potato	Beetroot	Winter squash	
	CTF	31	22	20	
		(26–36) [a]	(17–27) [a]	(15–26) [a]	
	RTF	20	22	23	
		(14–25) [b]	(17–27) [a]	(18–28) [a]	
	P-value	0.0255	0.9696	0.5647	

CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; estimates are given with 95% confidence intervals in brackets, n = 2. Different lower case letters indicate significant differences at a 5% significant level between treatments.

sampling points. The models also included electrical conductivity as a continuous explanatory variable introduced to exclude possible biases caused by local soil irregularities. Analyses of soil N_{min} content were performed for each 0–0.25 m, 0.25–0.5 m, 0.5–1 m, and 1–1.5 m soil layer separately.

Two root system aspects, root frequency and intensity, were considered in parallel in the analysis of the minirhizotron determinations. Root frequency was analysed by creating a dichotomous variable, indicating the presence or absence of roots in an observation window of the minirhizotron. This variable was modelled as a Bernoulli distributed response variable in a generalized linear mixed model (GLMM) defined with a logistic link function, a fixed effect given by the combination of factors representing the traffic treatment type (RTF or CTF), date, and soil depth. The root intensity was analysed by creating a variable counting the number of roots crossing the reference lines of the minirhizotron observation window in a pre-defined soil depth range of 0.25 m. These counts were modelled as the response variable of a GLMM defined with a Poisson distribution, a logarithmic link function, and the logarithm of the number of roots as an offset, which improved the analyses observed in earlier studies e.g. Kristensen and Thorup-Kristensen (2004) and Xie and Kristensen (2017), and was therefore called modified root intensity (root intensity_{mod}). Details of the analysis are given in Appendix A. The modelled estimates of the root intensity resulted in an arbitrary number, explaining the lack of a unit. The fixed effects of the model described above were given by the combination of factors representing the traffic treatment type (RTF or CTF), date, and soil depth. According to this model, the expected values of the counts were given by the expected number of crosses divided by the observed number of roots (see details in Appendix A). Since the expected number of crosses is proportional to the root system length, the parameters of this model describe the root intensities, i.e. the length of each root branch. The models for root intensity and root frequency included two Gaussian random components, introduced to account for the dependency and intrinsic variability induced by the experimental design: one random component taking the same value for each observation arising from the same minirhizotron and one random component taking the same value for each observation from the same minirhizotron and obtained at the same date.

All the statistical analyses were performed using the freeware software R version 3.2 (R Core Team, 2016). The mixed models were adjusted using the R-package “lme4” (Bates et al., 2015). Post-hoc analyses, including the determination of statistical significance grouping and the construction of confidence intervals were conducted using the R-package “pairwiseComparisons” (available at http://home.math.au.dk/astatlab/software/pairwisecomparisons). Tests with *P*-values $<$ 0.10 and $\geqq$ 0.05 were considered an indication for significant differences, while tests with *P*-values $<$ 0.05 were reported as statistically significant. When simultaneous tests were employed, the *P*-values were adjusted for multiple comparisons using the false discovery rate (FDR) method (Benjamini and Yekutieli, 2001).

3. Results

3.1. Crop biomass yield and N accumulation

Significantly higher total yields were obtained for all three crops in CTF, compared to RTF, at Skiftekær in 2015, whereas no significant differences between treatments were observed in 2016 (Table 4), although a higher yield was indicated for winter squash (P = 0.064). Marketable yield followed the same pattern as the total yield, with higher marketable yields under CTF for all crops in 2015, but not 2016. Marketable yield increased by 27% for white cabbage, 42% for beetroot, and 70% for potato under CTF compared with RTF in 2015. As a percentage of total yield, marketable yield ranged from 81% for beetroot in 2015 to 100% for potato in 2015. At Vostrup, both total and marketable beetroot yields were similar between treatments in 2015 (Table 4).

Nitrogen accumulation in tubers and above ground plant material at Skiftekær was higher under CTF than RTF for white cabbage and potato in 2015, and a higher N_{acc} was indicated for beetroot in 2015 (P = 0.088). Nitrogen accumulation did not significantly differ between treatments at Vostrup in 2015 or for all three crops at Skiftekær in 2016 (Fig. 2).

3.2. Soil N_{min} distribution, potential net N mineralization, and visual soil structure

At Skiftekær field 1, onion was grown at the start of the experiment in 2013, followed by red clover as green manure in 2014, white cabbage in 2015, and potato in 2016. Before the start of the experiment, i.e. spring 2013, the soil N_{min} content was similar among treatments in the top 0.5 m, but it was 20–37 kg ha^{-1} higher under RTF than CTF in 0.5–1.5 m depths (Fig. 3). At the beginning of the third experimental year, i.e. spring 2015, soil N_{min} content was 4 kg ha^{-1} higher under CTF than RTF in 0–0.5 m depths, whereas differences disappeared below 0.5 m. In autumn 2015, soil N_{min} was similar under both treatments. Soil N_{min} content was 10 kg ha^{-1} higher under CTF than RTF in 0–0.25 m in spring 2016, but equal among treatments in the deeper soil layers. In autumn 2016, 4 kg ha^{-1} more soil N_{min} remained in CTF compared with RTF in 0.25–0.5 m, whereas there were no differences in the 0–0.25 m soil layers and below 0.5 m depth. Potato left 76 kg N ha^{-1} in the 0.5–1.5 m soil layers after harvest under both treatments.

At Skiftekær field 2, red clover was grown as a green manure in 2013, followed by white cabbage in 2014, potato in 2015, and beetroot in 2016. Similar to field 1, soil N_{min} was 28 kg ha^{-1} higher in RTF than in CTF in field 2 below 0.5 m in spring 2013 (Fig. 4). No differences between treatments were observed in soil N_{min} in spring 2015, but in autumn 2015, 19–41 kg ha^{-1} more soil N_{min} remained under CTF compared with RTF in 0.5–1.5 m depths. Potato left 94 kg N ha^{-1} under

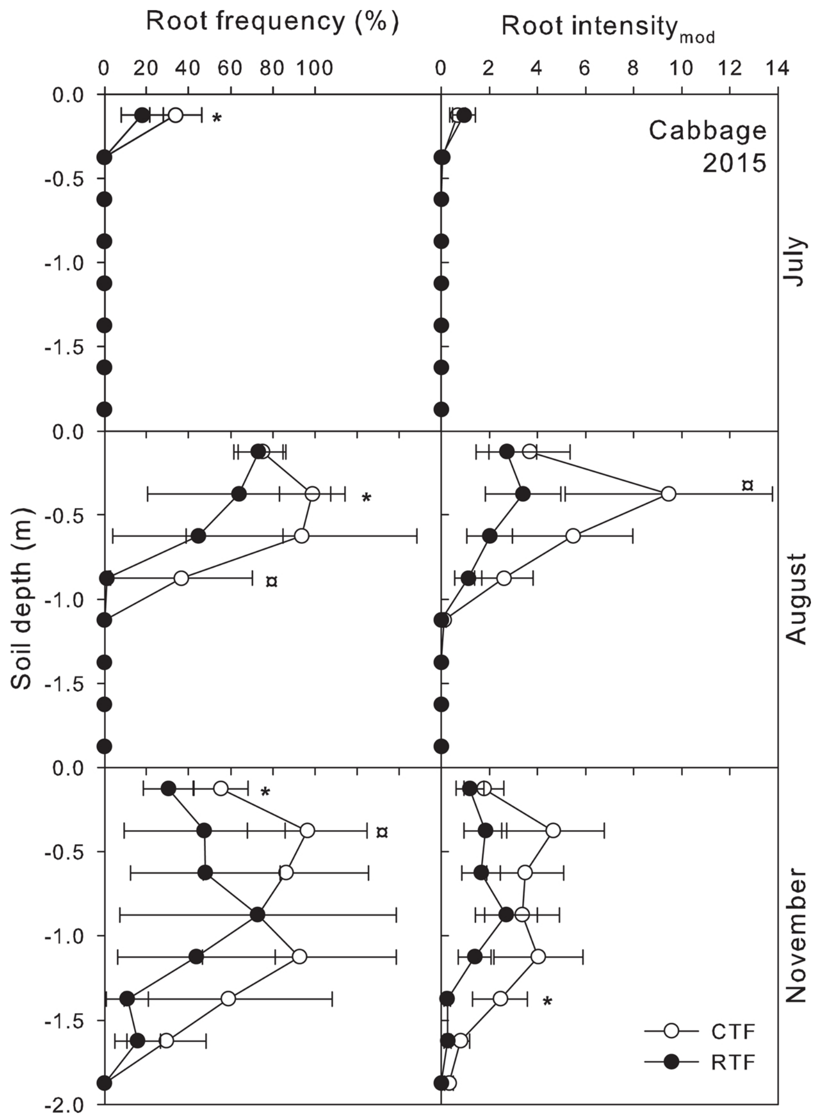

Fig. 6. White cabbage root frequency and intensity$_{mod}$ at Skiftekær field 1 in 0–2 m soil depth under CTF and RTF at three times in 2015. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 4. * represents significant differences between treatments ($P < 0.05$) and ¤ indicates differences ($P < 0.1$).

CTF and 34 kg N ha^{-1} under RTF in 0–1.5 m soil depths. In the subsequent spring, the differences between treatments appeared only at a soil depth of 1–1.5 m, and it disappeared in autumn 2016, where the soil N_{min} content was the same in both treatments in the entire soil profile to 1.5 m depth.

At Skiftekær field 3, white cabbage was grown in 2013, followed by potato in 2014, beetroot in 2015, and winter squash in 2016. Soil N_{min} was similar between treatments in spring 2013, spring 2015, and autumn 2015, but it was 6 kg ha^{-1} higher under CTF compared with RTF in 1–1.5 m soil depth in spring 2016 (Fig. 5). Higher soil N_{min} levels were indicated under CTF than RTF ($P = 0.053$) in 0.5–1 m soil depth in the spring 2016 and 0.5–1 m soil depth in autumn 2016 ($P = 0.062$).

At Vostrup, soil N_{min} levels did not differ between treatments and ranged from 1.5–27 kg ha^{-1} soil layer^{-1} during the measurement period (data not shown). Values were as high as 106 kg ha^{-1} soil layer^{-1} before treatment implementation in spring 2013 (data not shown).

Potential net N mineralization at Skiftekær was similar between treatments in spring 2013 in field 1, higher under CTF than RTF in field 2, but lower under CTF compared with RTF in field 3 (Table 5). No differences between treatments were found in 2015, in spring and autumn. In spring 2016, potential net N mineralization was higher under CTF than RTF treatments in field 1, but not in fields 2 and 3. Potential net N mineralization did not differ between traffic treatments at Vostrup.

Soil structure, estimated using the visual evaluation of soil structure method, was similar between traffic treatments: a value of 2.5 was given in spring 2013 prior to implementation of the experiment and a score of 1.6 in spring 2015. Values of 1.6–1.8 under CTF were scored in autumn 2015 and spring 2016 and suggest improved soil structures compared to scored values of 2–2.3 under RTF. Vostrup soil structure was similar between treatments (results not shown).

3.3. Root growth

3.3.1. White cabbage at Skiftekær

White cabbage root frequency and root intensity$_{mod}$ at Skiftekær were either equal between treatments or higher under CTF than RTF during the 2015 growth period. The root frequency was 1.7–1.9 times higher under CTF in 0–0.25 m or 0.25–0.5 m soil depths over all three months (Fig. 6). Higher root frequency under CTF compared with RTF was indicated in deeper soil layers of 0.75–1 m in August ($P = 0.0997$).

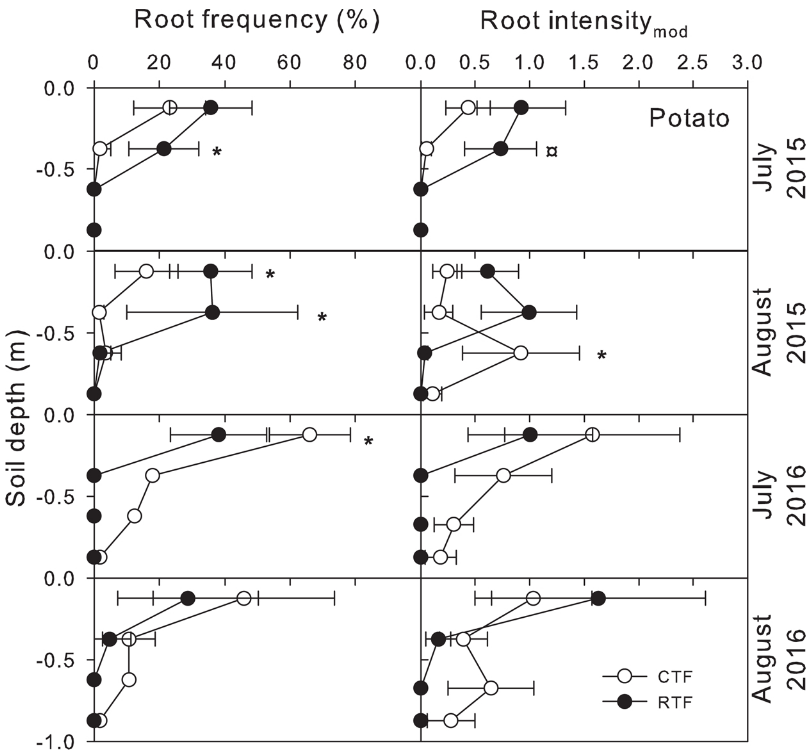

Fig. 7. Potato root frequency and intensity$_{mod}$ at Skiftekær in field 2 (2015) and field 1 (2016) in 0–2 m soil depths under CTF and RTF treatments at two times each year. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 4. * represents significant differences between treatments ($P < 0.05$) and ¤ indicates differences ($P < 0.1$).

White cabbage root intensity$_{mod}$ was 10 times higher under CTF than RTF in deeper soil layers (1.25–1.5 m) in November. White cabbage root depth did not differ between treatments and was on average 1.65 m in November 2015 (results not shown).

3.3.2. Potato at Skiftekær

Potato root frequency and intensity$_{mod}$ at Skiftekær in 2015 showed divergent results. Potato root frequency was 2–12 times higher under RTF than CTF in the upper soil layers in July and August 2015 (Fig. 7). Similarly, a higher root intensity$_{mod}$ was indicated ($P = 0.0704$) under RTF than CTF at 0.25–0.5 m depths in July 2015. In contrast, root intensity$_{mod}$ was 25 times higher under CTF compared with RTF in 0.5–0.75 m soil depths in August 2015. Potato root depth did not differ between treatments and reached on average 0.40 m in August 2015 (results not shown). In 2016, potato root frequency and intensity$_{mod}$ were similar between treatments, except for a 1.7 times higher root frequency under CTF than RTF in 0–0.25 m soil depths in July 2016. A statistical comparison between treatments was not possible below 0.25 m in July and 0.5 m depths in August 2016, due to the absence of roots under RTF. Roots were present in CTF down to 1 m depths at both time periods. Potato root depth did not differ between treatments and reached on average 0.29 m in August 2016 (results not shown).

3.3.3. Beetroot at Skiftekær

Beetroot root frequency and intensity$_{mod}$ at Skiftekær were similar between treatments in 2015, except for an indication ($P = 0.0527$) of a lower root frequency under CTF compared with RTF in 0.5–0.75 m depth (Fig. 8). Beetroot root depth was 1.7 m in September 2015 and did not differ between treatments (results not shown). Beetroot root frequency was 1.3 times higher under CTF in 0–0.25 m soil depths in July 2016. In September 2016, beetroot root frequency was 2–4 times higher under CTF in 1.5–2 m soil depths. Root intensity$_{mod}$ was 3–14 times higher under CTF than RTF in 0.25–0.75 m depths in July and 3 times higher in 1–1.25 m depths in September 2016, with several indications of improved root intensity$_{mod}$ under CTF in several soil layers in September. Beetroot roots grew deeper under CTF treatment (1.6 m) than RTF (1.33 m) in August 2016 and the same tendency ($P = 0.058$) was observed in September 2016, with root depths of 2.07 m in CTF and 1.84 m in RTF (results not shown).

3.3.4. Winter squash at Skiftekær

The winter squash root frequency at Skiftekær was similar among treatments in July 2016, but was 6 times higher under CTF compared with RTF in 1.5–2 m depths in September 2016, and by indication ($P = 0.0968$) in 1.5–1.75 m (Fig. 9). Winter squash roots were present in all observations (100% root frequency) under CTF at 0.5–1.5 m depths in September 2016, which prevented statistical comparison between treatments, but a higher root frequency under CTF than RTF in this soil layer was assumed.[1] The winter squash root intensity$_{mod}$ was lower under CTF than RTF in 1–1.25 m depths in July 2016. This changed, however, in the following two months, where root intensity$_{mod}$ was 2–16 times higher under CTF than RTF in 1.25–2 m depths in August (results not shown) and in 0.5–2 m in September 2016, with an indicated increase ($P = 0.0585$) in 1–1.25 m depths. The winter squash root depths were deeper under CTF (1.93 m) compared with RTF (1.73 m) treatments in August 2016 (results not shown). No differences in root depth were observed in September, where the average root depth was 1.92 m (results not shown).

3.3.5. Beetroot at Vostrup

Beetroot showed a 1.4 times higher root frequency under CTF compared with RTF in 0.25–0.5 m depths at Vostrup in September 2015

[1] Since all the observation windows of the minirhizotron presented roots under CTF, the use of the logistic-binomial model for comparing the root frequency between RTF and CTF was made impossible. Note, however, that the following alternative informal argument can be used to conclude that there were differences between the root frequencies observed under RTF and CTF: since the probability of observing a root in an observation window is estimated as 0.67 under RTF and since 56 windows were observed under CTF, then assuming the probability of finding a root under CTF to be equal to the probability of finding a root under RTF (i.e., estimated as 0.67), one concludes that the probability of observing all the 56 observation windows containing at least one root is estimated as $0.67^{56} \approx 1.8\,10^{-10}$, which is very low.

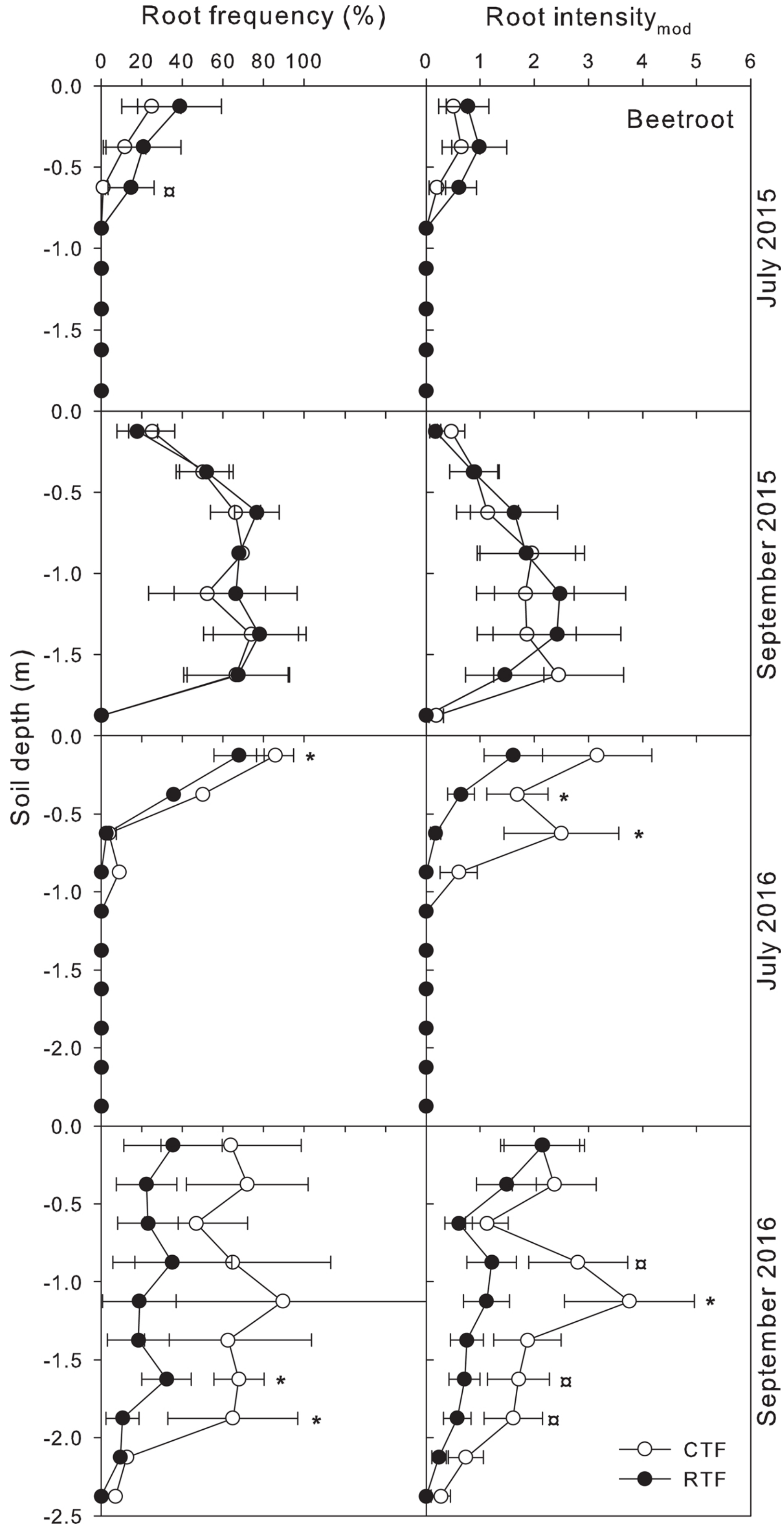

Fig. 8. Beetroot root frequency and intensity$_{mod}$ at Skiftekær in field 3 (2015) and field 2 (2016) in 0–2 m soil depths under CTF and RTF treatments at two times each year. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 4. * represents significant differences between treatments ($P < 0.05$) and ¤ indicates differences ($P < 0.1$).

(Fig. 10). Beetroot root depths did not significantly differ between treatments in August and could not be estimated in September and October because roots grew below the minirhizotron measuring depth of 1.5 m.

3.4. Relationship between crop yield and root growth

The relationship between increased yield and root intensity$_{mod}$ at harvest under CTF relative to RTF for Skiftekær and Vostrup is depicted

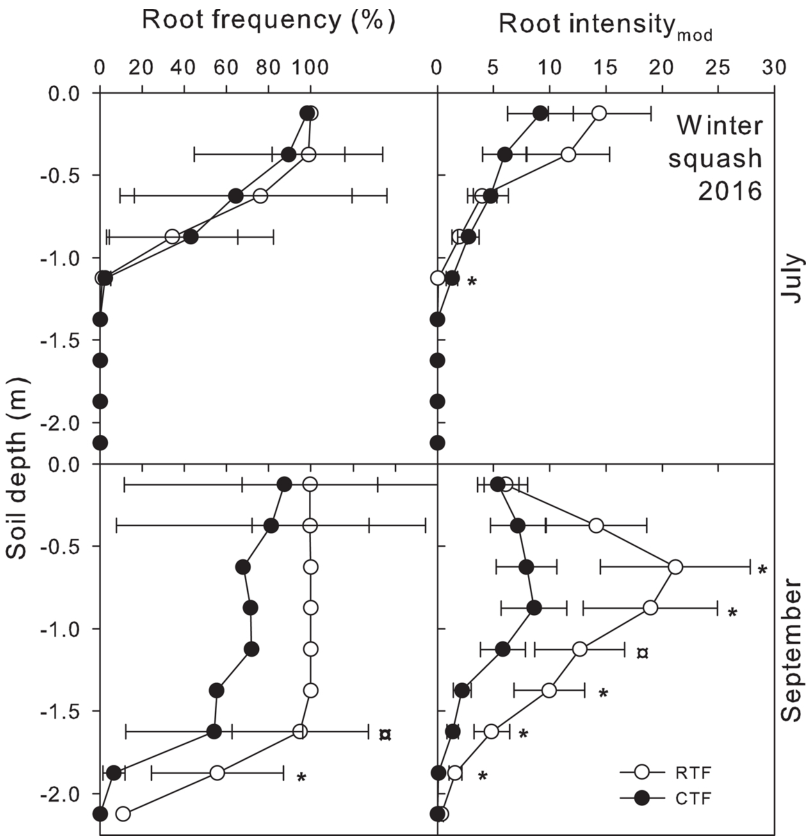

Fig. 9. Winter squash root frequency and intensity$_{mod}$ at Skiftekær field 3 in 0–2 m soil depths under CTF and RTF treatments at two times in 2016. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 4. * represents significant differences between treatments ($P < 0.05$) and ¤ indicates differences ($P < 0.1$).

in Fig. 11. Five of the seven crops showed increased yield and root growth under CTF, whereas two crops (potato and beetroot in 2015) exhibited increased yield under CTF, without increased root growth compared to RTF.

4. Discussion

4.1. Crop yield

Compared with RTF, the CTF system showed increased yields in several crops on fine sandy loam at Skiftekær three to four years after CTF implementation. White cabbage marketable yield increased by 28% under CTF in 2015, which was consistent with an experiment in New York, USA on silt loam, where marketable cabbage yield was 41% higher in uncompacted compared to compacted soil (Wolfe et al., 1995). We recorded increased potato yield of 70% and increased beetroot yield of 42% under CTF in 2015, which were notably higher than the increased marketable yield of 7% in seed potato and 6% in sugar beet in CTF on light clay in the Netherlands (Lamers et al., 1986). In general, Skiftekær and Vostrup yields were lower or similar to yields obtained in another Danish study (Kristensen and Thorup-Kristensen, 2007) and they were within the range of white cabbage and beetroot yields found in a German study (Katroschan and Stutzel, 2017).

Year-to-year variability in crop yields appeared to dominate over differences observed among crops in our study. Higher yields under CTF at Skiftekær in 2015, but not 2016, were associated with a higher precipitation in 2015 (830 mm) than 2016 (569 mm). This is in contrast to a study by Galambosova et al. (2017), who found greater cereal yield increase under CTF in a dry year. Improved crop yield under CTF can be ascribed to improved top-soil structure (Vermeulen and Mosquera, 2009) and increased plant available water, as non-wheeled soil showed a higher water infiltration rate than wheeled soil (Li et al., 2001). However, limited water availability under RTF might not reduce yields in irrigated vegetable production to the same extent as in non-irrigated cereal production, explaining the smaller yield differences based on traffic treatments observed in the more dry year of 2016. Further, variable vegetable yield response to CTF was found in other studies, where yield increases under CTF occurred only in some crops or in some years (McPhee et al., 2015; Vermeulen and Mosquera, 2009).

Moreover, crop yield response seemed to depend on soil type, as beetroot yield increased under CTF on fine sandy loam at Skiftekær in 2015, but not on a coarse sand at Vostrup the same year. Coarse sands are only slightly susceptible to soil compaction and the soil physical properties do not deteriorate, even at high compactness levels (Horn et al., 1995). We confirmed the first hypothesis that CTF improved crop yield on fine sandy loam at Skiftekær in one out of two years, indicating that CTF is a promising production system for vegetable growers due to maintained or improved yields.

4.2. Nitrogen dynamics

Soil N_{min} was equal or higher under CTF in the years after traffic treatments were implemented (2015–2016), indicating CTF was a viable system for improving N supply. Incorporation of more cabbage and beetroot residues under CTF in Skiftekær in 2015 resulted in higher soil N_{min} levels in spring 2016 (Figs. 3 and 5) and higher potential net N mineralization in field 1 in spring 2016 (Table 5). Vegetable residues show a narrow C/N-ratio range between 9 and 24 (Rahn and Lillywhite, 2002) resulting in fast mineralization. In conclusion, soil N_{min} in spring was either maintained or raised under CTF compared with RTF, indicating increased soil fertility due to mineralization of higher crop residue levels.

Soil N_{min} content in autumn was higher under CTF than RTF at three sampling times in Skiftekær (Figs. 3–5), which were most likely residual effects of white cabbage residue mineralization from the previous year. At the same time soil N_{min} uptake by potato was limited due to its shallow root system (Fig. 7) and due to late blight (*Phytophthora infestans*) infestation in 2016 (visual observation), hampering crop

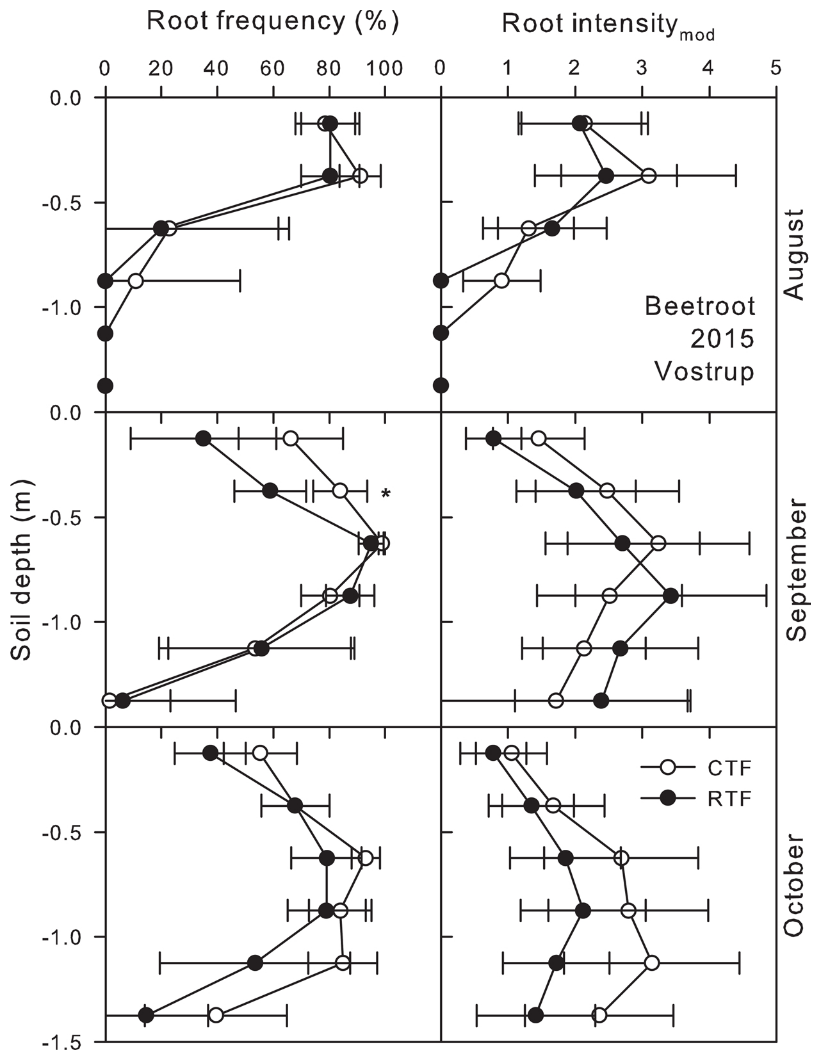

Fig. 10. Beetroot root frequency and intensity$_{mod}$ at Vostrup in 0–1.5 m soil depths under CTF and RTF treatments at three times in 2015. CTF = Controlled Traffic Farming, RTF = Random Traffic Farming; bars indicate 95% confidence intervals, n = 4. * represents significant differences between treatments ($P < 0.05$).

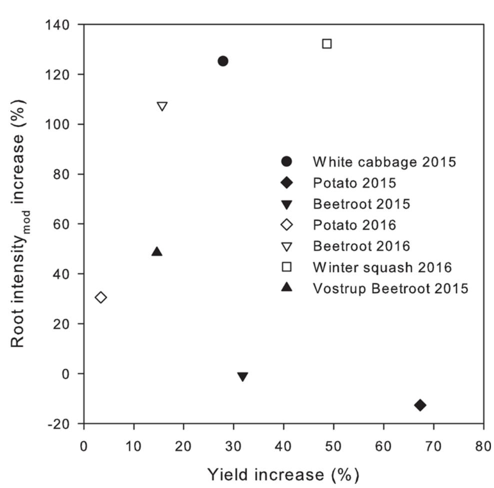

Fig. 11. Total increased yield and root intensity$_{mod}$ at harvest under CTF relative to RTF at three Skiftekær fields in 2015 and 2016 and at one Vostrup field in 2015. Increased yield = (CTF yield/ RTF yield) and increased root intensity$_{mod}$ = (Σ CTF root intensity$_{mod}$/ Σ RTF root intensity$_{mod}$), where root intensity$_{mod}$ was summed for the entire root zone.

development. The otherwise similar soil N_{min} levels in autumn suggest that despite better water infiltration (Li et al., 2001), N leaching was not higher under CTF due to more N_{acc} by the crop (Fig. 2), when at the same time denitrification loss was higher under RTF (Tullberg et al., 2018). Likewise, Vermeulen and Mosquera (2009) found similar soil N_{min} levels between traffic systems in winter. We concluded that soil N supply was either equal between treatments or increased under CTF, supporting our second hypothesis.

4.3. Root growth

Crop root growth was significantly increased in a majority of cases when CTF was applied compared with RTF. Root growth differed among crop species and years with more differences in 2016 than 2015.

Beetroot roots reached 2.07 m depth under CTF at Skiftekær in 2016, which was deeper than beetroot roots reaching 1.84 m depth under RTF and 1.85 m depth in a Danish study on sandy loam (Kristensen and Thorup-Kristensen, 2007). Potato root growth at Skiftekær was shallow, reaching a maximum 0.4 m depth, which was less than the 0.67 m root depth reported in the Danish study. Both beetroot and potato root growth were improved under CTF in 2016, but not in 2015, probably owing to an enhanced soil structure, as indicated by the visual evaluation of soil structure. Soil porosity and water infiltration were improved in CTF (Antille et al., 2015; Bai et al., 2009), creating better root growth conditions. In addition, differences between treatments were more likely in the fourth year (2016) after traffic implementation. Further, more soil N_{min} was available for potato under CTF in spring 2016 (Fig. 3), suggesting increased N uptake by potato due to higher root frequencies under CTF, although N_{acc} was not higher.

Beetroot root growth on coarse sand at Vostrup exhibited similar root frequency and intensity levels as on sandy loam at Skiftekær. Higher beetroot root frequency in the top-soil layer under CTF at Vostrup in September (Fig. 10) indicated traffic might affect crop growth parameters on coarse sand, even though beetroot yields were not affected by traffic (Table 4). Beetroot root depth of 0.68 m in August was comparable to rocket root depth range, i.e. 0.68–0.90 m, on coarse sand (Kristensen and Stavridou, 2017). At harvest, beetroot roots exceeded the minirhizotron measuring depth of 1.5 m at Vostrup, showing that annual crops on coarse sandy soils can grow deep roots in contrast to the general expectation of shallow root growth on sandy soil, as observed by Andersen and Aremu (1991) with peas.

The greatest root growth differences between treatments were seen for winter squash, where root $intensity_{mod}$ was higher under CTF than RTF, especially in deeper soil layers in September (Fig. 9), indicating a restriction in root growth under RTF. The deeper maximum root depth of winter squash under CTF compared with RTF in September was within the maximum root depth range observed for summer squash in another Danish study (Kristensen and Thorup-Kristensen, 2007). The decreased root depth under RTF likely resulted from delayed root growth in compacted soil, indicated by the visual evaluation of soil structure measurement. Lipiec et al. (1991) reported barley root depth also decreased with increased degree of soil compactness.

Machine traffic can also exhibit deteriorating effects on root growth in wet seasons, consistent with 2015, where white cabbage root growth was reduced under RTF (Fig. 6). Wolkowski (1990) showed traffic reduced air-filled pore spaces in wet seasons, which resulted in oxygen deficiency. We found white cabbage reached an average 1.65 m root depth under both treatments, which was < 2.5 m found by Kristensen and Thorup-Kristensen (2007) and might be the result of higher precipitation (830 mm vs. 624 mm). We confirmed our third hypothesis that root development was improved under CTF on sandy loam and coarse sand.

Results showed substantial annual variation in CTF effects on yield and root growth, but yield and root differences were consistently around zero (in two cases) or positive (in five cases) under CTF relative to RTF (Fig. 11). These generally positive responses indicated the CTF management system was an overall improvement, although the specific plant physiological and agronomic responses might differ from year to year. It appears the cropping system resilience, defined as the same production level achieved over a longer time frame (Seufert and Ramankutty, 2017), was increased under the CTF system. For vegetable producers, these are important findings, because the CTF system might provide improved production stability over time compared with RTF.

5. Conclusion

Vegetable yields increased by 27–70% under CTF on fine sandy loam in Denmark in the third year after treatment implementation, possibly caused by the detrimental effects of traffic under high precipitation conditions. Soil N_{min} content in spring was similar or higher in CTF compared with RTF on sandy loam, which might have been the result of a build-up of soil fertility through the incorporation and subsequent release of mineral N from greater crop residue amounts. This indicated that CTF was a viable system for improving soil N supply and N_{acc} by the crops. Differences in climatic conditions between years, and the longer time period since implementation, might explain the improved root growth under CTF compared with RTF in 2016. Although vegetable root growth and yield responses differed from year to year, they were generally positive under CTF, indicating an increased resilience of the system. These results show that CTF maintained or improved vegetable yield and root growth, and increased soil N supply compared with RTF, making it a promising upcoming production system for organic vegetable growers.

Declarations of interest

None.

Acknowledgements

The project was funded by the Green Growth and Development programme (GUDP) under the Danish Ministry of Environment and Food and participants in the project ORGANICS IN THE TRAIL [grant number 34009-12-0489]. We thank the farmers Peter Bay Knudsen, Skiftekær Økologi, and Niels Christian Nielsen, Vostrup Øko, as well as their staff, especially Jesper Mortensen, Skiftekær Økologi, for providing the experimental areas and conducting the field management; Richard de Visser, HortiAdvice, for knowledge exchange, and Astrid Bergmann, Lasse Vesterholt, Jens Barfod and Bjarne Egedal, Aarhus University for skilful technical assistance.

Appendix A. Supplementary material

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2019.03.011.

References

Andersen, M.N., Aremu, J.A., 1991. Drought sensitivity, root development and osmotic adjustment in field-grown peas. Irrig. Sci. 12, 45–51.

Antille, D.L., Chamen, W.C.T., Tullberg, J.N., Lal, R., 2015. The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in arable land: a critical review. Trans. ASABE 58, 707–731.

Bai, Y.H., He, J., Li, H.W., Wang, Q.J., Chen, H., Kuhn, N.J., Hikel, H., Chen, F., Gong, Y.S., 2009. Soil structure and crop performance after 10 years of controlled traffic and traditional tillage cropping in the dryland loess plateau in China. Soil Sci. 174, 113–119.

Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality - a development of the Peerlkamp test. Soil Use Manage. 23, 329–337.

Bates, D., Machler, M., Bolker, B.M., Walker, S.C., 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67, 1–48.

Batey, T., McKenzie, D.C., 2006. Soil compaction: identification directly in the field. Soil Use Manage. 22, 123–131.

Benjamini, Y., Yekutieli, D., 2001. The control of the false discovery rate in multiple testing under dependency. Ann. Stat. 29, 1165–1188.

Chan, K.Y., Oates, A., Swan, A.D., Hayes, R.C., Dear, B.S., Peoples, M.B., 2006. Agronomic consequences of tractor wheel compaction on a clay soil. Soil Till. Res. 89, 13–21.

Curtin, D., Campbell, C.A., 2007. Mineralizable nitrogen. In: Carter, M.R., Gregorich, E.G. (Eds.), Soil Sampling and Methods of Analysis, second ed. Canadian Society of Soil Science, Canada, pp. 602–603.

DMI, 2018. Danish Meteorological Institution, Copenhagen. URL. Last accessed 19.10.2018. www.dmi.dk.

Galambosova, J., Macak, M., Rataj, V., Antille, D.L., Godwin, R.J., Chamen, W.C.T., Zitnak, M., Vitazkova, B., Dudak, J., Chlpik, J., 2017. Field evaluation of controlled traffic farming in central europe using commercially available machinery. Trans. ASABE 60, 657–669.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems - A review of the nature, causes and possible solutions. Soil Till. Res. 82, 121–145.

Hart, S.C., Stark, J.M., Davidson, E.A., Firestone, M.K., 1994. Nitrogen mineralization, immobilization and nitrification, methods of soil analysis, part 2. Microbiolocial and Biochemical Properties. Soil Science Society of America, Madison, WI 53711, USA, pp. 985–1018.

Horn, R., Domzal, H., Slowinskajurkiewicz, A., Vanouwerkerk, C., 1995. Soil compaction processes and their effect on the structure of arable soils and the environment. Soil Till. Res. 35, 23–36.

Johansen, T.J., Thomsen, M.G., Loes, A.-K., Riley, H., 2015. Root development in potato and carrot crops - influences of soil compaction. Acta Agric. Scand. 65, 182–192.

Katroschan, K.U., Stutzel, H., 2017. Narrow-leaved lupine as an N source alternative to grass-clover swards in organic vegetable rotations. Biol. Agric. Hortic. 33, 125–142.

Kristensen, H.L., Stavridou, E., 2017. Deep root growth and nitrogen uptake by rocket (*Diplotaxis tenuifolia* L.) as affected by nitrogen fertilizer, plant density and leaf harvesting on a coarse sandy soil. Soil Use Manage. 33, 62–71.

Kristensen, H.L., Thorup-Kristensen, K., 2004. Root growth and nitrate uptake of three different catch crops in deep soil layers. Soil Sci. Soc. Am. J. 68, 529–537.

Kristensen, H.L., Thorup-Kristensen, K., 2007. Effects of vertical distribution of soil inorganic nitrogen on root growth and subsequent nitrogen uptake by field vegetable crops. Soil Use Manage. 23, 338–347.
Lamers, J.G., Perdok, U.D., Lumkes, L.M., Klooster, J.J., 1986. Controlled traffic farming systems in the Netherlands. Soil Till. Res. 8, 65–76.
Li, Y.X., Tullberg, J.N., Freebairn, D.M., 2001. Traffic and residue cover effects on infiltration. Aust. J. Soil Res. 39, 239–247.
Lipiec, J., Hakansson, I., 2000. Influences of degree of compactness and matric water tension on some important plant growth factors. Soil Till. Res. 53, 87–94.
Lipiec, J., Hakansson, I., Tarkiewicz, S., Kossowski, J., 1991. Soil physical properties and growth of spring barley as related to the degree of compactness of two soils. Soil Till. Res. 19, 307–317.
McPhee, J.E., Aird, P.L., Hardie, M.A., Corkrey, S.R., 2015. The effect of controlled traffic on soil physical properties and tillage requirements for vegetable production. Soil Till. Res. 149, 33–45.
Nevens, F., Reheul, D., 2003. The consequences of wheel-induced soil compaction and subsoiling for silage maize on a sandy loam soil in Belgium. Soil Till. Res. 70, 175–184.
Plant Directorate of the Danish Ministry of Agriculture (Landbrugsministeriet), 1994. Fælles arbejdsmetoder for jordbundsanalyser III. 22, Lyngby, Denmark. .
R Core Team, 2016. R: a Language and Environment for Statistical Computing. URL. R Foundation for Statistical Computing, Vienna, Austria Last accessed: 10.07.2018. https://www.R-project.org/.
Rahn, C.R., Lillywhite, R.D., 2002. A study of the quality factors affecting the short-term decomposition of field vegetable residues. J. Sci. Food Agric. 82, 19–26.
Raper, R.L., 2005. Agricultural traffic impacts on soil. J. Terramech. 42, 259–280.
Seufert, V., Ramankutty, N., 2017. Many shades of gray -the context-dependent performance of organic agriculture. Sci. Adv. 3.
Stalham, M.A., Allen, E.J., Rosenfeld, A.B., Herry, F.X., 2007. Effects of soil compaction in potato (*Solanum tuberosum*) crops. J. Agric. Sci. 145, 295–312.
Tullberg, J., Antille, D.L., Bluett, C., Eberhard, J., Scheer, C., 2018. Controlled traffic farming effects on soil emissions of nitrous oxide and methane. Soil Till. Res. 176, 18–25.
VDLUFA, 1991. Bestimmung von leicht löslichen (pflanzenverfügbaren) Haupt- und Spurennährstoffen. In: Die Untersuchung von Böden, fourth ed. VDLUFA Verlag, Darmstadt, Germany.
Vermeulen, G.D., Mosquera, J., 2009. Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. Soil Till. Res. 102, 126–134.
Wolfe, D.W., Topoleski, D.T., Gundersheim, N.A., Ingall, B.A., 1995. Growth and yield sensitivity of 4 vegetable crops to soil compaction. J. Am. Soc. Hortic. Sci. 120, 956–963.
Wolkowski, R.P., 1990. Relationship between wheel-traffic-induced soil compaction, nutrient availabilty, and crop growth – a review. J. Prod. Agric. 3, 460–469.
Xie, Y., Kristensen, H.L., 2017. Intercropping leek (*Allium porrum* L.) with dyer's woad (*Isatis tinctoria* L.) increases rooted zone and agro-ecosystem retention of nitrogen. Eur. J. Agron. 82, 21–32.