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

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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 N₂O 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
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 Skiftekar Ókologi 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 Skiftekar, 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 Skiftekar and Vostrup are given in Fig. 1. Organic management has been practised at the fields since 1998 at Skiftekar, 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 Skiftekar. 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 harvest at both Skiftekar 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 Skiftekar. 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 Skiftekar and April 2013 at Vostrup. Each field was divided into two plots: one subjected to CTF and the other to RTF. At Skiftekar, 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 Skiftekar, 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>
<thead>
<tr>
<th>Soil layer (m)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Fine sand (%)</th>
<th>Coarse sand (%)</th>
<th>Soil organic matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 0.002 mm</td>
<td>0.002-0.02 mm</td>
<td>0.02-0.2 mm</td>
<td>0.2-2.0 mm</td>
<td></td>
</tr>
<tr>
<td>Skiftekar</td>
<td>0-0.25</td>
<td>10.5</td>
<td>10.5</td>
<td>50.0</td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td>0.25-0.5</td>
<td>10.2</td>
<td>11.0</td>
<td>48.0</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td>0.5-1</td>
<td>13.2</td>
<td>11.5</td>
<td>43.0</td>
<td>31.5</td>
</tr>
<tr>
<td></td>
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<td>11.0</td>
<td>44.0</td>
<td>29.0</td>
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<tr>
<td>Vostrup</td>
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<td>3.3</td>
<td>21.0</td>
<td>69.0</td>
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<td>0.25-0.5</td>
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<td>2.1</td>
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<td></td>
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<td>2.9</td>
<td>1.6</td>
<td>8.9</td>
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</tbody>
</table>
Beta vulgaris L. convar. (Brassica oleracea L.) used as green manure, followed by white cabbage, beetroot, potato, and winter squash 'Hokkaido' (Cucurbita maxima Duch.). In 2013, onion (Allium cepa L.) was grown instead of winter squash. The crop rotation at Skiftekær was as follows: red clover (Trifolium pratense L.) in 2012, followed by carrot (Daucus carota L. var. sativus) in 2013, potato in 2014, beetroot in 2015, and winter squash in 2016. 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 2-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 (Terrano, Horsch, Germany), and a rotary tiller (Hatzenbichler, Austria) and a vision based hoeing machine (Robovator F. Poulsen Engineering APS, Denmark).

### Table 2

<table>
<thead>
<tr>
<th>Field</th>
<th>Vostrup 2015</th>
<th>Skiftekær 2015</th>
<th>Skiftekær 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-crop</td>
<td>Potato</td>
<td>Red clover</td>
<td>White cabbage</td>
</tr>
<tr>
<td>Crop</td>
<td>Beetroot</td>
<td>White cabbage</td>
<td>Potato</td>
</tr>
<tr>
<td>Cultivar</td>
<td>Wodan</td>
<td>Coronet</td>
<td>Elf</td>
</tr>
<tr>
<td>Field size (m)</td>
<td>6.54 x 100</td>
<td>6.75 x 210</td>
<td>6.75 x 210</td>
</tr>
<tr>
<td>Row distance (m)</td>
<td>0.45</td>
<td>0.466</td>
<td>0.625</td>
</tr>
<tr>
<td>Plant distance (m)</td>
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<td>0.5</td>
<td>0.18</td>
</tr>
<tr>
<td>N fertilizer (t ha⁻¹)</td>
<td>20</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Application date</td>
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<td>Aug 6</td>
<td>May 1</td>
</tr>
<tr>
<td>Transplanting</td>
<td>Jun 07</td>
<td>May 28</td>
<td>May 7</td>
</tr>
<tr>
<td>Weeding</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Harvest</td>
<td>Oct 14</td>
<td>Nov 11</td>
<td>Sep 15</td>
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### Table 3

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<th>Year</th>
<th>Treatment</th>
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<th>Field 2</th>
<th>Field 3</th>
<th>Vostrup</th>
</tr>
</thead>
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<tr>
<td>2015</td>
<td>White cabbage</td>
<td>59</td>
<td>48</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Potato</td>
<td>(50–60) a</td>
<td>49</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>P-value</td>
<td>0.0039</td>
<td>0.0009</td>
<td>0.0095</td>
<td>0.1973</td>
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</tr>
</tbody>
</table>

### Table 4

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<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Field 1</th>
<th>Field 2</th>
<th>Field 3</th>
<th>Vostrup</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>White cabbage</td>
<td>59</td>
<td>48</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Potato</td>
<td>(50–60) a</td>
<td>49</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>P-value</td>
<td>0.0039</td>
<td>0.0009</td>
<td>0.0095</td>
<td>0.1973</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Field 1</th>
<th>Field 2</th>
<th>Field 3</th>
<th>Vostrup</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>White cabbage</td>
<td>59</td>
<td>48</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Potato</td>
<td>(50–60) a</td>
<td>49</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>P-value</td>
<td>0.0039</td>
<td>0.0009</td>
<td>0.0095</td>
<td>0.1973</td>
<td></td>
</tr>
</tbody>
</table>

**CTF** = controlled traffic farming, **RTF** = random traffic farming; estimates are given with 95% confidence intervals in brackets, n = 2. Different lowercase letters indicate significant difference between treatments at a 5% significant level.
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 $N_{\text{min}}$ 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 $\pi$ indicates differences ($P < 0.1$).
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$_{\text{min}}$, 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$_{\text{min}}$ 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$_{\text{min}}$ 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 crop.
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$_{\text{min}}$ was calculated per area based on measured N$_{\text{min}}$ 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$_{\text{min}}$ from the N$_{\text{min}}$ content after incubation (Curtin and Campbell, 2007).

Yield, N$_{\text{accr}}$, soil N$_{\text{min}}$, 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
sampling points. The models also included electrical conductivity as a
effect. Different lowercase

Table 5

<table>
<thead>
<tr>
<th>Time</th>
<th>Treatment</th>
<th>Field 1</th>
<th>Field 2</th>
<th>Field 3</th>
<th>Vostrup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring 2013</td>
<td>Onion</td>
<td>CTF 14</td>
<td>13</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Green manure</td>
<td>(12–16) a</td>
<td>(11–15) b</td>
<td>(17–21) a</td>
<td>(10–23) a</td>
</tr>
<tr>
<td></td>
<td>White cabbage</td>
<td>18</td>
<td>12</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carrot</td>
<td>P-value</td>
<td>0.9751</td>
<td>0.0134</td>
<td>0.0043</td>
</tr>
<tr>
<td>Spring 2015</td>
<td>White cabbage</td>
<td>CTF 16</td>
<td>25</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>(11–21) a</td>
<td>(20–30) a</td>
<td>(11–21) a</td>
<td>(16–20) a</td>
</tr>
<tr>
<td></td>
<td>Beetroot</td>
<td>RSA 20</td>
<td>22</td>
<td>18</td>
<td>23</td>
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<td></td>
<td>Beetroot</td>
<td>P-value</td>
<td>0.9569</td>
<td>0.4306</td>
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<td>Autumn 2015</td>
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<td>24</td>
<td>21</td>
<td>12</td>
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<tr>
<td></td>
<td>Potato</td>
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<td>(20–27) a</td>
<td>(17–25) a</td>
<td>(9–15) a</td>
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<td>21</td>
<td>14</td>
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<td></td>
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<td>0.7449</td>
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<td>(15–26) a</td>
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<td>Winter squash</td>
<td>RSA 20</td>
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<td>P-value</td>
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<td>0.9696</td>
<td>0.5647</td>
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</table>

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.

soil depth. The root intensity was analysed by creating a dichotomous variable, indicating the presence or absence of roots in an observation window of 215 mm × 21 mm × 215 mm. 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. The root intensity was analysed by creating a dichotomous variable, in-

dependency and intrinsic variability induced by the experimental de-

sign: one random component taking the same value for each observa-
tion arising from the same minirhizotron and one random component
taking the same value for each observation from the same mini-

rhizotron and obtained at the same date.

All the statistical analyses were performed using the freeware soft-
ware R version 3.2 (R Core Team, 2016). The mixed models were ad-
justed using the R-package "lme4" (Bates et al., 2015). Post-hoc ana-
lyses, including the determination of statistical significance grouping
and the construction of confidence intervals were conducted using the
dk/atstatlab/software/pairwisecomparisons). Tests with P-values <
0.10 and ≥ 0.05 were considered an indication for significant differ-
ences, 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 Skifterkær in 2015, whereas no significant
differences between treatments were observed in 2016 (Table 4), al-
though 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 than RTF for all crops in 2015, but not 2016. Marketable yield increased by 27% for white cabbage, 42% for beet-
root, and 70% for potato under CTF compared with RTF in 2015. As a
percentage of total yield, marketable yield ranged from 81% for beet-
root 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
Skifterkær was higher under CTF than RTF for white cabbage and potato
in 2015, and a higher Nacc 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 Skifterkær in 2016 (Fig. 2).

3.2. Soil Nmin distribution, potential net N mineralization, and visual soil structure

At Skifterkær field 1, onion was grown at the start of the experiment in
2013, followed by red clover as green manure in 2014, white cab-
bage in 2015, and potato in 2016. Before the start of the experiment, i.e. spring 2013, the soil Nmin content was similar among treatments in the
top 0.5 m, but it was 20–37 kg ha−1 higher under RTF than CTF at 0.5–1.5 m depths (Fig. 3). At the beginning of the third experimental
year, i.e. spring 2015, soil Nmin 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 Nmin was similar under both treatments.
Soil Nmin 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 Nmin 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 Skifterkær 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 Nmin 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 Nmin in spring 2015, but in
autumn 2015, 19–41 kg ha−1 more soil Nmin remained under CTF
compared with RTF in 0.5–1.5 m depths. Potato left 94 kg N ha−1 under
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$_{\text{min}}$ 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$_{\text{min}}$ 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$_{\text{min}}$ 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$_{\text{min}}$ 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$_{\text{mod}}$ 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 ($P = 0.0997$).
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 RTF than CTF in 0.5–0.75 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 in September 2015. 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. 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.
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.

The relationship between crop yield and root growth under CTF relative to RTF for Skiftekær and Vostrup is depicted in Fig. 8. Beetroot root frequency and intensity 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).

3.4. Relationship between crop yield and root growth

The relationship between increased yield and root intensity at harvest under CTF relative to RTF for Skiftekær and Vostrup is depicted in Fig. 8.
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 $N_{\text{min}}$ 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 $N_{\text{min}}$ 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 $N_{\text{min}}$ 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 $N_{\text{min}}$ 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 $N_{\text{min}}$ uptake by potato was limited due to its shallow root system (Fig. 7) and due to late blight ($\text{Phytophthora infestans}$) infestation in 2016 (visual observation), hampering crop
development. The otherwise similar soil N\textsubscript{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\textsubscript{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\textsubscript{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 Skiftekar 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 Skiftekar 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 $N_{\text{min}}$ 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 $N_{\text{acc}}$ was not higher.

Beetroot root growth on coarse sand at Vostrup exhibited similar root frequency and intensity levels as on sandy loam at Skiftekar. 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 minihizotron 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 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 improved 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 $N_{\text{min}}$ 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 $N_{\text{acc}}$ 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.

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Appendix A. Supplementary material

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Ramankutty, N., 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.


