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EVALUATION OF ONION PRODUCTION ON SANDY SOILS BY USE OF REDUCED TILLAGE AND CONTROLLED TRAFFIC FARMING WITH WIDE SPAN TRACTORS

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Growing of vegetables is often characterised by intensive field traffic and use of heavy machines. By implementing controlled traffic farming (CTF), compaction of the growth zone can be avoided. An experiment was established in an onion field on a coarse sandy loam. Treatments were applied in the field that for five years had been managed by seasonal CTF (SCTF), where harvest is performed by random traffic due to lack of suitable harvest machines. The main treatment was compaction with a fully loaded potato harvester. The split treatment in the crossed split plot design was mechanical loosening. Bulk density, macroporosity, penetration resistance, water retention characteristics and yield were measured. Mechanical loosening caused improvements in the physical soil measurements and more roots were found in the upper soil layers. The highest yield was however found in the CTF simulation plots (19% higher than in the SCTF simulated plots). Using wide span tractors as a harvest platform will enable CTF in vegetable production. Avoidance of compaction will enable reduced tillage intensity and productivity can be improved both through higher yield of the area that is cropped and by a larger percentage of fields can be cropped area as less area will be needed for tracks.

Keywords: soil compaction; conservation agriculture; vegetables; gantry tractors

The risk of compacting the soil profile is high in vegetable production as the production of most vegetable crops is highly mechanised and during the last decades productivity per unit of labour input has increased primarily through the use of larger and heavier agricultural machines. Furthermore, the intensity of field traffic is high in vegetable crops due to intensive plant care and transport of large volumes during harvest. In addition, vegetables are often harvested late in the season when soils are less suitable to carry heavy loads (Jackson et al., 2004).

To minimise the risk of soil compaction, harvest machines for vegetables are often designed with wheels or belts that distribute the load on a large surface area to achieve a low surface pressure. A low surface pressure reduces the soil compaction in the upper soil layers. Still intensive tillage and subsoiling down to depths of 40 cm or more is commonly used to remediate the effects of compaction (Jackson et al., 2004; Batey, 2009). In severely compacted soils mechanical loosening can cause yield increases as found in potatoes by Sojka et al. (1993) but often subsoiling does not affect yield (Parker et al., 1989; Copas et al., 2009). Stalham et al. (2005) found both positive and negative yield effects when reviewing soil loosening experiments in potatoes. No differences in yields were found by Henriksen (1986) when subsoiling was done prior to growing of onions, peas and cauliflower.

The effect of subsoiling often does not last for long as loosened soil is very susceptible to recompaction (Munkholm et al., 2005). Within a few years soils are often as

poorly structured and dense as before subsoiling (Hamilton-Manns et al., 2002; Botta et al., 2006).

In the deeper soil layers the surface pressure has little or no effect on the stresses that penetrate through to the subsoil layers (Arvidsson and Keller, 2007; Lamande and Schjonning, 2011). Van den Akker et al. (2003) concluded that European soils are more threatened by compaction than ever before in history. They point out that subsoil compaction is the most serious threat. With continuous use of heavy machines in agriculture, subsoil compaction is an ongoing cumulative process and has shown to be very persistent (Etana et al., 2013).

Conservation agriculture where tillage is omitted or reduced in intensity has been used successfully in several crops, including vegetables such as onion (Kęsik and Błażewicz-woźniak, 2009), cabbage (Übelhör et al., 2013), tomatoes (Campiglia et al., 2011; Mitchell et al., 2012; Alliaume et al., 2014) and potatoes (Young et al., 1993; Pierce and Burpee, 1995; Ekeberg and Riley, 1997; Carter et al., 2009) and in vegetable crop rotations (Wells et al., 2000; Willekens et al., 2014). However, introduction of conservation agriculture in the vegetable industry is challenged by harvest induced compaction that often requires mechanical loosening prior to establishment of a new crop.

Controlled traffic farming

Traffic induced soil compaction can be eliminated from the crop growth zone by adopting controlled traffic farming

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(CTF) that requires all implements to have the same working width or a multiple of it. Also all wheels or belts that carry the machines need to be aligned to run on permanent tracks between the growing beds.

Chamen (2011) summarises numerous CTF trials. The results include increased yield in multiple crops, reduced machinery cost, as well as environmental benefits such as reduced emissions from the soil and reduced leaching of nutrients. Few CTF experiments have been done with vegetable crops other than potatoes. However, Chamen et al. (1992a) summarised experiments from several countries with different crops, including three years of Dutch experiments with onion where the yield on average was 10% higher in zero trafficked soil compared to conventional traffic. Similar increases have been found by Lamers et al. (1986) and Dickson et al. (1992). McPhee et al. (2015) demonstrated that CTF can reduce the tillage intensity and the number of passes in intensive vegetable rotations while at the same time improving the soil physical parameters. Improved crop quality of potatoes has also been documented by Dickson and Ritchie (1996) who found 3.5% more marketable potatoes in traffic free plots compared to conventional trafficked plots.

In SCTF trails with organic grown vegetables in the Netherlands, Vermeulen and Mosquera (2009) reported increased yield in 5 out of 12 experiments with vegetable crops. A yield increase of 10% was found in one year with planted onions, whereas no yield differences were found in two years of sown onion. SCTF was also found to reduce the use of fuel and emissions of greenhouse gas nitrous oxide (N_2O), whereas no difference was found in the loss of nitrogen due to leaching.

Chamen (2014a) reported on more than 50,000 ha grown under CTF management in Europe. Of these approximately 12,500 are grown on farms where solutions are used for vegetables, potatoes or sugar beet.

McPhee and Aird (2013) found a multiplicity of working widths and track gauges of the machines used in the intensive vegetable industry in

Tasmania. It was found very difficult to match up especially the harvest machines for CTF in diversified crop rotations. A wide span tractor was suggested as a suitable solution to obtain complete CTF systems.

Wide span tractors

Wide span (WS) or gantry tractors are optimal solutions for CTF (Taylor, 1994). The tractors are wide while operating in the field and long and narrow when transported on roads (Figure 1). Implements are normally operated within the span of the tractor. Track gauge in the field varies between 4 m and 12 m or even up to 21 m (Vermeulen et al., 2010). WS tractors have successfully been used in agriculture and in research in the US (Taylor, 1983; Monroe and Burt, 1989; Beard et al., 1995), in the UK (Chamen

et al., 1992b; Chamen, 2014b), in Australia (Quick, 2007; Ellis et al., 2011), in the Netherlands (Vermeulen et al., 2010) and in Israel (Hadas et al., 1990). The history of WS tractors dates back more than 150 years to a 30 feet (9.1 m) steam driven version that ran on iron tracks (Halkett, 1858).

A WS tractor has been constructed for use on the farm where the experiment reported in this paper took place. The WS tractor has been designed to perform all operations in a CTF production of onions from primary tillage to harvest (Pedersen, 2014). During harvest, a 15 t bunker on the tractor is filled and unloaded at field ends. In high yielding crops, up to 550 m of a 3.2 m wide bed can be harvested before the bunker is full (Pedersen, 2011).

Figure 1

ASA WS9000 wide span tractor mounted with an onion harvester, upper in position for field operation and lower in position for road transport

The objective of the research was to assess the impact on soil and crop parameters of the CTF production system for onion growing on a sandy soil. The case used was a 9.6 m WS CTF production system that is planned established on the farm. The WS system was compared with the 3.2 m SCTF system that was used on the farm. The hypothesis was that it is possible to obtain improved crop growth conditions when harvest induced soil compaction prior to establishment of the onion crops was avoided. In addition, it was expected that mechanical subsoil loosening was needed in case of harvest induced soil compaction but otherwise not.

Material and methods

The experiment was established in autumn 2011 on a commercial vegetable farm on the island of Samsø, Denmark (55° 57' N, 10° 33' E) on a loamy coarse sand with 5% clay, 18% silt (2–63 µm), 27% fine sand (63–200 µm) and 49% coarse sand (200–2,000 µm). The soil organic matter was 1.5%. The crops grown in the three years preceding the experiment were white cabbage (*Brassica oleracea* var. *alba*) and two years of early harvested potatoes (*Solanum tuberosum*). Only minor textural variability was observed within the trial area.

SCTF and non-inversion tillage had been practised for five years prior to the establishment of the experiment in November 2011. All field traffic had been restricted to the traffic lanes that were 3.2 m apart. Only harvest of onions, potatoes and celeriac did not take place from the traffic lanes, due to lack of CTF compatible harvest machines. After harvest of these crops, the growing beds were subsoiled down to a maximum depth of 60 cm. Cover crops had been used yearly to improve the soil structure.

The operations prior to and during the growing season were: 20 May 2011: Harvest of potatoes by a two-row potato harvester (as treatment C+, Figure 2); 15 June: Subsoiling by use of a three-coulter subsoil loosener to the depth of 50 cm; 22 June: Establishment of a blue bell cover with a disc drill; 20 October: Tilling of cover crop; 1 November: Compaction treatment (C+) (half of the plots, Figure 2); 2 November: Loosening treatment (L+) (half of the plots, Figure 2); 2 November: Winter tillage "Ridging of soil", four ridges 250 mm high, 750 mm between ridges; 22 March 2012: Tillage with a tine cultivator; 23 March: Drilling of seed onions, 12 row, 230 mm row distance in 3.2 m beds;

1 May: Soil measurements; 8 August: Root measurements; 28 August: Mulching top of onions; 28 August: Hand harvest of 1.5 m of each row (12 rows in each plot). Onions were stored in an indoor cool store until 1 November when they were sorted and weighed.

The experiment received the same base treatments as the surrounding field. The total application of fertiliser per ha was 141 kg N, 68 kg P and 232 kg K. Plant care included five herbicide, four fungicide treatments and a total of 115 mm irrigation in five treatments.

The experiment was arranged as a crossed split plot trial with four replicates (Table 1). The two factors were compaction (C+ and C-) and subsoiling (loosening: L+ and L-). The experiment covered nine 3.2 m wide beds. Bed no 2 was not used as the spray tractor spanned this bed and wheels of the irrigation boom ran through the bed. The 10 m long and 3.2 m wide plots were located along two rows perpendicular to the direction of field traffic. The rows were placed 20 m apart to allow the change of bed for the tractor used for subsoiling.

Compaction treatment

For the compaction treatment (C+) a two-row Grimme SE 150-60 fully loaded potato harvester pulled by a Fendt 818 tractor was used to simulate machinery induced compaction during a harvest event (Figure 2). The harvester drove four times through the two 6.4 m strips that each covered two growing beds (beds 3–4 and 7–8). This was equal to normal traffic intensity for harvesting the total of eight rows in the two beds. The wheels on the tractor and on the harvester were positioned to ensure that all parts of the 6.4 m strip were covered by a wheel at least once. The tractor was steered by a high precision steering system that was encoded with the predefined driving pattern. As can be seen in Table 2, the two wheels of the harvester exceeded the weight of the tractor wheels.

Subsoiling treatment

For the subsoiling treatment (L+) an Amazone TL 302 four-leg subsoiler was used. It was mounted with 40 cm wide blades working at the depth of 40 cm. The distance between the legs was 72 cm. The tractor was mounted with 40 cm wide tyres that ran in the permanent tracks between the beds, i.e. this operation led to no further compaction of the growing beds. The speed of operation was measured by time and distance measurements. Draught forces were measured in the three-point linkages of the tractor by use of

Figure 2 Machines used. Left: the compaction treatment (C+) by use of a tractor and a fully loaded potato harvester. Right: the subsoiling treatment (L+) with a four-leg subsoiler working to the depth of 40 cm

Table 1 Layout of the crossed split plot experiment. The main factor was compaction (C+ and C-). The split factor was subsoiling (L+ and L-)

Bed	1	2	3	4	5	6	7	8	9
Repetition	1			2		3		4	
Row A	C-; L-		C+; L-	C+; L+	C-; L+	C-; L-	C+; L-	C+; L+	C-; L+
Shield area (20 m)									
Row B	C-; L+		C+; L+	C+; L-	C-; L-	C-; L+	C+; L+	C+; L-	C-; L-

Table 2 Dimensions and loads of the tractor, potato harvester combinations used for the compaction treatment. Loads were measured on a scale installed at the farm

Wheel	Tyre dimension	Tyre air pressure, kPa	Wheel weight, t
Tractor front wheels	600/60 R 28	100	2.0
Tractor back wheels	710/60 R 38	110	4.8
Harvester right	600/55 R 26.5	380	7.3
Harvester left	600/55 R 26.5	350	5.2
Total weight			28.0

three extended octagonal ring transducers as described by Godwin (1975).

Soil measurements

Undisturbed soil cores (6.1 cm diameter, 3.4 cm height, 100 cm³ volume) were collected in stainless steel cylinders from the depths of 10 cm and 25 cm. Six soil samples were collected from each plot in each of the two layers (192 samples in total). Two disturbed soil samples from 0–20 cm depth for each repetition were taken for -1,500 kPa water potential analysis. All samples were stored field moist at 2 °C.

Laboratory measurements were conducted. The undisturbed soil cores were adjusted at 20 °C to -1 kPa, -3 kPa and -10 kPa matric potential using tension tables and to -30 kPa and -100 kPa using ceramic plates. The bulk density of the samples was measured after 24 hours oven drying at 110 °C. The matric potential at -1,500 kPa was adjusted by draining disturbed soil samples on -1,500 kPa ceramic plates for one month.

Penetration resistance was measured on 1 May 2012 after crop establishment at approximately field capacity with an automated cone penetrometer (Olsen, 1988). A 30° semiangle 20.27 mm diameter cone was used. Eleven measurements per bed were made in the interrow sections (176 measurements in total) at a strain rate of 3 cm/s, with recording for each 1 cm increment to a maximum depth of 50 cm. The dataset included outliers with high resistance primarily caused by stones. The outliers were deleted from the dataset. If more than 5 of the 11 measurements in a plot and in a given depth were outliers, then no average value for the plot was calculated. Results are only presented if an average value was found in all four repetitions.

Root measurements

Root development was assessed on 8 August 2012. A cylinder with an inner diameter of 5 cm was forced down to a depth of 35 cm. The number of growing roots was assessed at the 30 cm, 20 cm and 10 cm depth using the

core-break method (Drew and Saker, 1980; Bennie et al., 1987). Samples were taken between the plant rows. In each plot six cores were taken from an outer row in one side and to the centre of the bed (106 cores in total). The number of fresh roots, visually observable with the naked eye, was counted on both opposite breakage planes. The average of the two observations was used to calculate the roots per cm² in the horizontal plane.

Yield and quality measurements

In all plots, 1.5 m of each row was hand harvested and all onions, including under-sized and disease infected onions, were placed in a box. The boxes were stored and dried in the indoor onion store for 65 days. After drying, all the onions were sorted in the sizes <40 mm (undersized); 40–60 mm; 60–80 mm and >80 mm. Onions infected by diseases (*Botrytis allii* and *Fusarium oxysporum* f. sp. *cepae* onion) were sorted in separate portions. Each of the portions was weighed and the number of onions was counted. The outer rows of the beds were in some plots (independent of treatment) hindered by heavy weed infestation or imprecise driving. So only 10 rows from each plot were used for the yield measurements.

Statistical analyses

The penetration resistance data were fitted using a log-normal distribution and transformed to yield normality. Other data were fitted using a normal distribution. Averages were calculated for each plot and used in the calculation of mean and standard error. The averages were also used as an input in general linear models for testing treatment effects. We used the Fit Linear Mixed-Effects Models (lmer) procedure of the statistical software R (R Core Team, 2014). Treatment effects were considered significant when $P < 0.05$ for least square means.

Figure 3 Measurements from undisturbed soil samples from the depths of 10 cm and 25 cm. Graph A and B: Bulk density (BD). Graph C and D: Portion of soil with pores >30 μ m (macroporosity, MP). In each graph, values marked with the same letter are not significantly different ($p < 0.05$)

Figure 4 Penetration resistance of the four treatments. The depth of measurements varied across the treatment due to the number of valid measurements achieved. Bars show the standard error between average values of the four repetitions

Results

Mechanical loosening of the soil

The tractor speed was measured to 1.05 m/s in the non-compacted plots and 0.98 m/s in the compacted plots. The average pulling force was measured to respectively 34.6 kN and 44.3 kN. By multiplying the force and speed, this gives an average 35.4 kW power used from the tractor in the non-compacted compared to 45.4 kW (+28%) in the compacted plots. Assuming a field efficiency of 85%, the capacity of the operation was 1.0 ha/h ($3.2 \text{ m} \times 1 \text{ m/s} \times 3,600 \text{ s/h} \times 0.0001 \text{ ha/m}^2 \times 85\%$).

Soil measurements

Compaction of the soil (C+, L-) caused an increase in bulk density (BD) in both 10 cm and 25 cm, as can be seen in Figure 3 (A and B). The difference was only significant when comparing to the treatment C-, L+. As average in both depths, subsoiling (C+, L+) resulted in

the recovery of bulk density to the level of the non-compacted plots (C-, L-).

The increase in BD followed compaction was due to a decrease in the fraction of macropores ($>30\ \mu\text{m}$), as can be seen in Figure 3 (C and D). There was a tendency to reduced macroporosity when the soil was compacted (C+, L-) in both depths. Mechanical loosening (C+, L+) restored the macroporosity to the level of the non-treated plots (C-, L-).

There were no significant differences found in the average water content between the -10 kPa and -100 kPa matric potential. Available water in this range varied between 7.0% and 7.5%, with a tendency to a larger fraction of such smaller pores ($<30\ \mu\text{m}$) in the compacted plots.

As can be seen in Figure 4, the penetration resistance measurements at depths below 9 cm were highly influenced by the subsoiling treatment (L+). The resistance of the soil in the treatment C+, L- was significantly higher than all the other treatments. In addition, the measured resistance in the treatment C-, L- was higher than in the two subsoiled treatments from 13 cm to 38 cm when comparing to C+, L+ and from 12 cm to 42 cm when comparing to C-, L+. Below the depth of subsoiling (40 cm), resistance in C+, L+ was significantly higher than in C-, L+ at the depths of 47 cm and 48 cm. It shows that the compaction treatment influenced the soil deeper than the depth of the subsoiling treatment.

Root measurements

The number of roots found at the depths of 20 cm and 30 cm was highly influenced by the subsoiling treatment (Figure 5). More roots were found in the subsoiled plots (L+). For the plots that had not been loosened, more roots were found in C-, L- than in C+, L- at the depth of 20 cm and 30 cm. At the depth of 10 cm, no significant differences were found.

Yield measurements

The average yield of marketable onions was significantly higher in the plots that were neither compacted nor subsoiled (C-, L-) compared to the plots with both treatments (C+, L+) (Figure 6). No significant yield differences were found between the other treatments. No significant differences were found in the percentage of onions

Figure 5 Number of roots crossing the horizontal plane at the depths of 10 cm, 20 cm and 30 cm. Bars show the standard error between average values of the four repetitions

in the different size classes, also the percentage of non-marketable onions due to size or disease infections was not different between the treatments.

Discussion

The hypotheses were that improved crop growth conditions could be achieved if harvest induced soil compaction prior to establishment of the onion crops was avoided. Considering the compaction treatment (C+), the only significant differences found were higher penetration resistances below the depth of seedbed preparation. There were also clear tendencies that C+ caused lower yield, higher bulk density and lower macroporosity compared to C-.

However, the soil physical conditions in the experiment were much influenced by the treatment subsoiling (L+). So the second part of the hypotheses has to be addressed. Does subsoiling remediate the effect of soil compaction and is it needed where the soil was not compacted?

In the compacted plots, subsoiling did cause lower penetration resistance and more root development. However, the 3% yield increase found was not significant. Where the soil had not been compacted, subsoiling also led to more roots at the depths of 20 cm and 30 cm (C-, L+, Figure 5) but a tendency to lower yield was observed when the non-compacted soil was loosened. So if soil had been compacted, then mechanical loosening remediated the compaction as measured by the

Figure 6 Yield after drying of marketable onions of the four treatments. Values followed by the same letters are not significantly different ($p < 0.05$). Bars show the standard error

Figure 7 Increase in plant population caused by wider beds. Onions are grown with 230 mm row distance. Tyre width is 400 mm for conventional and CTF and 600 mm for WS

soil physical parameters, but no yield increase resulted from loosening in neither the compacted nor the non-compacted plots.

CTF and SCTF

The treatment C+, L+ simulated the SCTF management that had been practised on the farm for five years. This was compared with the CTF simulated treatment (C-, L-) where harvest induced compaction was avoided. In the SCTF simulation, more roots were found at 20 cm and 30 cm compared to CTF (Figure 5) and less penetration resistance was measured in more depths. These measures did however not cause a positive yield effect as the yield on average was 19.3% higher in the CTF compared to the SCTF treatment.

Compared to other crops, roots on onions grow slowly and only to the depth of around 30 cm (Burns, 1980; Thorup-Kristensen, 2006). Also, onion is a crop that is known to be sensitive to compacted soil, as shown by Whalley et al. (2004). Although penetration resistance is often used to characterise soils for their ability to support root and plant growth, then it may not be a good measure when comparing soils with different management history. Ehlers et al. (1983) found that in non-tilled soils roots were able to grow at a higher penetration resistance than in tilled soils. Also more roots were found in the deeper soil layers due to lack of a hard pan and as there were more earthworm and root channels in the untilled soils. Abdollahi et al. (2014) also found that biopores alleviated the effect of a higher penetration

resistance in direct drilled soils. In the experiment reported here, tillage was performed, but still the soil below the depth of seedbed preparation had not been disturbed, which may have favoured the CTF simulated plots.

Assessment of wide span growing of onions

Tracks between vegetable beds or ridges are not cropped. The tyres of tractors do not fit between rows in onions and other crops grown on narrow row spacing. Assuming the width of tyres is kept the same, then an increase in bed width will enable more plant to be grown per ha of land. Figure 7 shows an example where 30% more plants can be grown in a 9.6 m WS system compared to a conventional system where beds are typically between 1.8 m and 2.0 m wide. The 3.2 m beds, as used on the farm of the experiment, is a common standard for the SCTF production of vegetables (Bernaerts, 2014). A change from the 3.2 m to the 9.6 m wide beds can increase plant population by 8% (from 36 to 39 rows for each 9.6 m).

The positive effect of growing in beds free from traffic should be achievable independent of how wide the crop beds are, so with a WS cropping system we can expect the yield effect both from plants growing in traffic free beds (19% measured in this experiment) and from additional plants grown per ha (up to 30%), depending of the original bed width.

Conclusion

The simulated controlled traffic farming system (i.e. the system with

no harvest induced soil compaction and no subsoiling) produced adequate crop growth conditions and the highest marketable yield of onions. As compared to the simulated seasonal controlled traffic system, 10.6 t/ha (equal to 19.3%) more marketable onions were measured. Interestingly, the treatment with the lowest penetration resistance and highest root intensity (i.e. the non-compacted and loosened treatment) resulted in lower marketable yields than the simulated CTF system, although the difference was not significant. Apparently, moderate mechanical impedance to root growth benefited crop yield. Wide bed CTF growing systems with reduced tillage intensity have the potential to improve productivity both through higher yield per area cropped but also through a larger percentage of cropped area as less area is used for tracks.

Abbreviations

C+: compaction treatment, C-: no compaction treatment, CA: conservation agriculture, BD: bulk density, CTF: controlled traffic farming, L+: subsoiling (loosening) treatment, L-: no subsoiling treatment, MP: macroporosity (>30 µm), SCTF: seasonal controlled traffic farming, WS: wide span

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