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Crop yield response to long-term reduced tillage in a conventional and organic farming system on a sandy loam soil

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A R T I C L E I N F O

Keywords:
Reduced tillage
Marketable crop yield
Potato (*Solanum tuberosum*)
Sugar beet (*Beta vulgaris*)
Onion (*Allium cepa*)
Carrot (*Daucus carota* subsp. Sativus)
Sandy loam soil
Organic farming
Conventional farming

A B S T R A C T

This paper describes the long-term effects of practicing ten years reduced tillage on crop yields in a conventional and organic farming system context. Data were collected from the BASIS field experiment, which was established in the Netherlands in 2009 to investigate the effects of reduced tillage on crop yield and soil properties in a controlled traffic farming system on a sandy loam soil. The experiment is unique in its focus on root crops grown on ridges, planted crops and small seeded crops, including cash crops such as potato (*Solanum tuberosum*), carrot (*Daucus carota* subsp. Sativus), onion (*Allium cepa*) and sugar beet (*Beta vulgaris*). The objective of the present paper was to analyse the long-term effects of reduced tillage on the marketable yields of these crops, grown in a conventional (4-year rotation) and organic farming system (6-year rotation). Tillage treatments were conventional deep inversion tillage (CT, mouldboard plough, 23–25 cm depth), reduced tillage with sub-soiling (RTS, chisel plough, 18–20 cm depth), and reduced tillage without sub-soiling (RT). Our key finding is that the two reduced tillage systems, over a 10-year period, provided similar or even higher marketable yields than conventional tillage, for 12 (RTS) and 11 (RT) of the 13 crops grown. Reduced tillage resulted in lower yields in two crops: carrot (−13.4% in RTS and −15.2% in RT) and cabbage (−5.2% in RT). In both cases, yield losses could be partly related to negative effects of crop residues from the preceding cover crop. Our results provide evidence that yield levels of crops grown in RT in our experiment can generally compete with crop yields in ploughed systems. However, crop residue management and seedbed preparation remain a challenge in reduced tillage systems, requiring further attention in research and dissemination.

1. Introduction

Soil quality, the cornerstone of agriculture, is decreasing across the globe due to agricultural intensification (FAO, 2015). This problem has become even more urgent with the increasing frequency of weather extremes such as droughts and heavy rainfall due to climate change (Podmanicky et al., 2011). To restore soil quality and improve agricultural resilience, various mitigation and adaptation measures are being investigated, including soil organic matter and crop residue management, use of cover crops, and reduction of soil disturbance (Ten Berge et al., 2017). These measures are often combined in a systems approach, in which reduced soil tillage plays a central role (Busari et al., 2015; Prasuhn, 2020).

Reduced soil tillage is a collection of practices in which deep ploughing is replaced with shallow, non-inversion tillage methods, often with fewer tillage operations per year. Over the past decades, many studies have reported positive effects of reduced tillage on soil properties, including better soil structure (Daraghmeh et al., 2009), reduced soil and water erosion (Hoogmoed et al., 1999), increased soil biological activity (D'Hose et al., 2018), reduced greenhouse gas emissions (Tian et al., 2013), increased soil carbon stocks (Palm et al. (2014); (Cooper et al., 2016), and enhanced soil water holding capacity and water infiltration (Tebrügge and Düring, 1999). However, reduced tillage has also been reported to lead to negative effects, such as increased topsoil compaction, insufficient control of weeds, and lower crop productivity (Gruber et al., 2012; Soane et al., 2012; Bijttebier et al., 2018).

For farmers, the possible negative effects on crop productivity, in particular, form a potential hurdle to adopt reduced tillage practices. Therefore, many studies have been conducted to quantify the effect of reduced tillage on crop yield. The results of these studies have been synthesized in extensive meta-analyses in the quest to determine whether yield outcomes are affected by decreasing tillage intensity (Van

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den Putte et al., 2010; Pittelkow et al., 2015; Cooper et al., 2016). These meta-analyses show that the effect of reduced tillage on crop yield depends on many factors, particularly crop type and local environmental conditions (soil and climate), and that this effect is not necessarily negative. For example, Cooper et al., 2016) found that, compared to deep inversion tillage, reduced tillage in organic systems resulted in yield losses of 8% in the humid continental zone (16 studies), but that yield losses were negligible in the humid oceanic zone (<−1%, 3 studies). In terms of crop-specific effects, Pittelkow et al. (2015) meta-analysis of conventional tillage versus no-till systems found that yields were reduced in no-till wheat (2.6%), rice (7.5%) and maize (7.6%), but that yields of oil seed, cotton and legumes were unaffected by tillage regime. In addition, they found, for several crops, that negative yield effects tended to disappear after the first few years of abandoning conventional tillage, which emphasises the importance of long-term studies.

One important limitation of these meta-analyses is that the majority of studies available focus on cash crops grown in no-till systems in North and South America (most importantly, maize, wheat and soy). There are much fewer data on root and tuber crops, such as potato, sugar beet, carrot and onion, which are profitable crops for European arable farmers Anon (2021). For example, in Pittelkow et al. (2015) meta-analyses mentioned above, root (including tuber) crops represented only 69 out of 6005 total observations (all climate zones) and only 6 out of 4842 observations in temperate climates. Based on these limited data, they found that root crop yields were strongly reduced in no-till systems (21.4%, all climate zones). Among the few studies investigating the effects of *reduced* tillage (rather than no-tillage) in temperate zones, Arvidsson et al. (2014) found that potato yield in Swedish crop rotations was not significantly different in shallow non-inversion tillage systems than in conventional tillage systems.

Thus, to gain more insight into the effects of reduced tillage on cash crops grown in temperate zones of Europe, we conducted a long-term field experiment in the Netherlands, comparing conventional tillage (deep ploughing) with two reduced tillage treatments consisting of shallow non-inversion tillage with or without subsoiling. These treatments were applied in both conventional and organic crop rotation systems that included relevant cash crops for this region: potato, carrot, onion, and sugar beet. These crops pose specific challenges because they are grown on ridges and/or are small-seeded crops (such as carrot and onion) that are sensitive to germination conditions, which may differ between tillage regimes due to different (c0ver) crop residue management. To make the results even more relevant to farmers, we specifically quantified the effects on *marketable* yield, taking into account possible tillage effects on product size and shape.

Using the data collected from this experiment over a period of ten years (2009–2018), we addressed the following questions: (1) Compared to conventional tillage, what is the effect of reduced tillage on crop yield – specifically the *marketable* yield – of root, tuber, and small-seeded crops (potato, carrot, onion, sugar beet)? Based on the above-mentioned findings by (Arvidsson et al., 2014) and (Pittelkow et al., 2015) we expected that gross and net yields would be similar across tillage systems, but that marketable yields would be 5–10% lower in reduced tillage systems. (2) Compared to conventional tillage, what is the effect of reduced tillage on marketable yields of other crops in the rotation typical for this climate zone, such as summer and winter wheat, cabbage and pumpkin? Based on findings from (Arvidsson et al., 2014; Pittelkow et al., 2015; Martínez et al., 2016) we expected that these yields would be similar, or higher, in the reduced tillage systems compared to conventional ploughing.

2. Materials and methods

2.1. Experimental site and design

For this study we used data from the BASIS field experiment (*Broekemahoeve Applied Soil Innovation Systems*). This long-term farming systems experiment was established in 2009 by Wageningen University and Research in Lelystad (52°32’38.01"N, 5°34’36.37"E), the Netherlands. The aim of BASIS (ongoing) is to investigate measures to mitigate the effects of climate change induced droughts and heavy rainfall on soil quality and crop yield in arable farming on a sandy loam soil. The field experiment, which includes both conventional and organic farming systems, is situated on land reclaimed from the sea in 1957. The characteristic soil Cambisol (WRB 2014) is related to Entisols and Inceptisols and a homogeneous sandy loam composed of 61% sand, 22% silt and 17% clay, with a soil pH-KCl (NEN-ISO 10390) of 7.2–7.4. Soil organic matter (LOI) ranges from 3.4% to 3.8% in the organic fields and 3.2–3.5% in the conventional fields in the 0–25 cm soil layer. The climate is classified as a marine west coast climate (Cfb, Köppen climate classification); average total annual precipitation is 833 mm and mean annual temperature is 10.3 °C.

The BASIS experiment consisted of three organic (ORG) and two conventional (CONV) trial fields (Fig. 1). The ORG fields were converted to organic management in 2003, well before the start of the BASIS experiment (2009). Management of the ORG fields is presented in paragraph 2.2.2. Each field was split into three subfields, of which only two were used for the study described in this paper (Fig. 2). These two subfields were each divided into two blocks of three plots each, with three tillage treatments randomly assigned to each block: conventional tillage with mouldboard plough (CT), reduced tillage with sub-soiling (RTS), and reduced tillage without sub-soiling (RT) (details, see 2.2.1). This way a randomised complete block design was achieved resulting in four replicates per tillage treatment per trial field. To grasp the full potential of reduced tillage, all crops were managed using controlled traffic lanes (CTF) to prevent soil compaction caused by driving machinery. To this end, all plots (12.6 m by 85 m) were split into four CTF strips of 3.15 m wide (including a 15 cm wheel track), which allowed to execute all management practices with use of standard agricultural equipment. All plots had been annually ploughed with a mouldboard plough until the start of the BASIS experiment in 2009.

2.2. Management practices

2.2.1. Crop rotation and cultivation practices

The farming systems investigated in the BASIS experiment were developed and optimised via a methodical way of prototyping, in which regional farming systems are re-designed and improved stepwise towards sustainability (Vereijken, 1997; Prost et al., 2016). In this approach, farming systems were evaluated based on their ability to meet certain goals in terms of production of ecosystem services, taking into account trade-offs and dynamic interactions between services (Power, 2010). The re-designed systems may not produce the highest possible

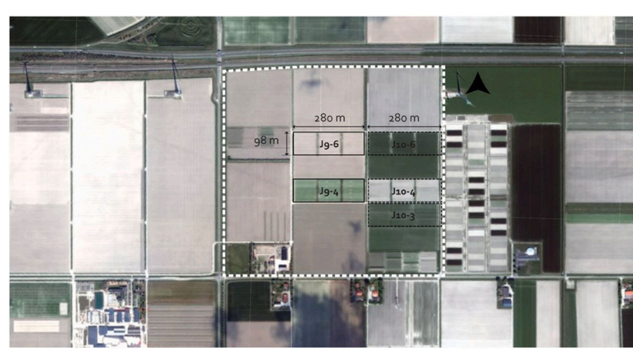

Fig. 1. Aerial view of the Wageningen University experimental farm (dashed white lines), showing the BASIS long-term experiment field with two conventional trial fields (J9–4 and J9–6; solid black lines) and three organic trial fields (J10–3, J10–4 and J10–6; dashed black lines) Photo: Satelietdataportaal.nl; accessed: May 2020.

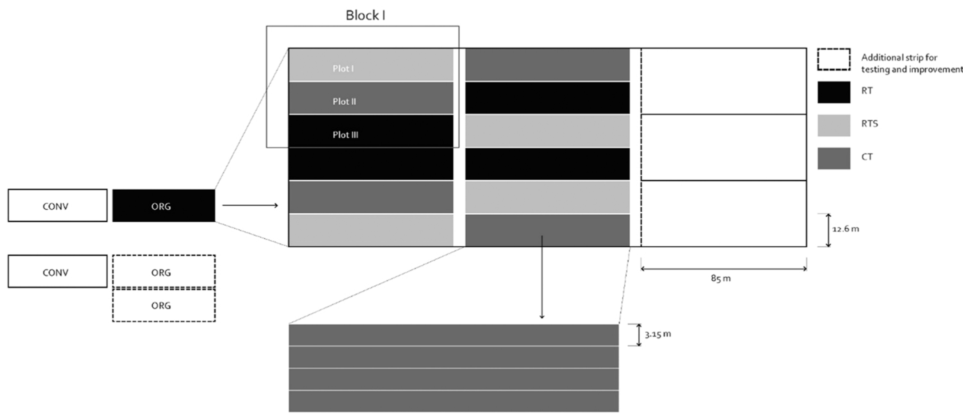

Fig. 2. BASIS experimental design.
The scheme on the left reflects the layout of the five trial fields shown in Fig. 1. On the right, the upper scheme presents the design of each trial field in detail. As shown, each trial field is divided in three subfields separated by permanent grass lanes. Two of these subfields are divided into two blocks each, with each block split into three plots randomly assigned to one of the tillage treatments: RT (reduced tillage), RTS (reduced tillage with sub-soiling) and CT (conventional tillage), resulting in total of four replicates per tillage treatment per trial field. The third sub-field (white with dashed black lines) was used for testing and improving of farm management techniques, hence no samples were taken there. The lower scheme details how each plot consisted of four beds, each 3.00 m wide and separated by wheel tracks of 15 cm wide.

yields (ecosystem service of crop production) but will provide an overall gain, based on improvements in other important ecosystem services such as climate resilience and biodiversity (Schipanski et al., 2014).

The BASIS experiment is purposefully designed as a farming systems experiment (Drinkwater, 2002). In BASIS, certain management practices are intrinsically linked to the compared tillage treatments, such as cover crop choice and cover crop management. Therefore, attributes besides the factor of interest (in BASIS: tillage) such as cover crop management, have been modified in each tillage treatment to fully optimize each treatment (Figure A.1, Appendix A). Besides, by following the prototyping method, management practices have been slightly modified for each tillage treatment each year, to respond to weather and soil conditions (Vereijken, 1997). Together, this results in three tillage treatments which are each evolving throughout the length of the experiment. Tillage therefore, is seen as main factor of interest however should be viewed in the complex of attributes that have been modified around it.

The CONV farming system was designed as a four-year crop rotation with (1) seed potato (*Solanum tuberosum*), (2) sugar beet (*Beta vulgaris*), (3) spring barley (*Hordeum vulgare*) or winter wheat (*Triticum aestivum*), and (4) onion (*Allium cepa*). The ORG system was a six-year crop rotation with (1) potato (*Solanum tuberosum*), (2) grass clover (*Trifolium-Lolium* perenne), (3) white or red cabbage (*Brassica oleracea*) or pumpkin (*Cucurbita maxima*), (4) spring wheat *(Triticum aestivum)* or oats (*Avena sativa*), (5) carrot (*Daucus carota* subsp. Sativus), and (6) spring wheat/faba bean (*Triticum aestivum - Vicia faba*). The crop rotation described was the template however, due to changes in market and soil conditions, slight changes in crop and cultivar choice were made over the course of the years (Table 1). With two CONV fields and three ORG fields, not every crop could be grown each year. Potato and carrot were grown on ridges. Potatoes grown in the ORG system were cultivated for human consumption, potatoes in the CONV system were cultivated for seed.

The three tillage systems compared in this experiment mainly differed in the cultivation method practiced in autumn (November), after harvesting the main crop of that year: (i) mouldboard ploughing down to 23–25 cm in the conventional tillage (CT) system; (ii) chisel ploughing down to 18–20 cm in the reduced tillage with sub-soiling (RTS) system; and (iii) no autumn cultivation in the reduced tillage (RT) system, except for sub-soiling after harvesting carrots (ORG), to reduce soil compaction for the next crop in that rotation (faba bean/spring wheat). In that case, the soil was chisel-ploughed to 18–20 cm depth, like in RTS (Table A.1, Appendix A). Differences in timing of soil cultivation operations resulted in variations of soil cover and cover crop management between tillage systems (Table A.1 & Table A.2, Fig. A.1, Appendix A). Cover crops were sown after each harvest of the cash crop in all tillage systems, when time and weather conditions allowed. Seedbed preparation for the main crops (March/April) as well as for the cover crops (August/September) was done in the same way in all three tillage systems (Table A.1 & Table A.2, Appendix A). For details on the tillage equipment used, see Table A.3, Appendix A.

2.2.2. Soil fertilization and crop protection

Fertilization schemes (fertilizer type, rate and timing of application) did not differ among tillage systems (CT, RTS, and RT), but did differ between organic (ORG) and conventional (CONV) farming systems because of different crop rotations and crop demands (see Tables A.4 and A.5, Appendix A). In the ORG fields, soils were fertilized with a combination of animal manure and other organic fertilizer types, following standard organic practices as prescribed in EU organic regulations (EG Nr.834.2007, IFOAM-eu.org, 2018). In the CONV fields, only mineral fertilizers were used, based on the leading fertilization recommendations for arable crops (Commissie Bemesting Akkerbouw en Vollegrondsgroenteteelt (CBAV)). For both ORG and CONV crops, fertilization rates were based on crop demand, soil properties and legislation. This resulted in average rates (averaged over 2009–2018) of 111 N, 57 P_2O_5 and 144 K_2O kg/ha/yr in the ORG farming system and 108 N, 61 P_2O_5 and 139 K_2O kg/ha/yr in the CONV farming system.

Use of crop protection in the ORG fields was limited to incidental use of *Bacillus thuringiensis* in cabbage for control of diamondback moth (*Plutella xylostella*). Usage of this insecticide is allowed in organic fields and was performed according to Dutch organic regulations which in turn are based on EU organic regulations (EG Nr.834.2007, IFOAM-eu.org, 2018). Weed control was performed by mechanical and hand weeding. In CONV fields, crop protection and weed control was performed according best practices in the local area, using a combination of mechanical and chemical weed control.

2.3. Data collection and analysis

2.3.1. Sampling procedure

To determine the effect of tillage system on crop yield, we took yield samples of the main crops each year, at harvest time. Yield sampling methods ranged from hand sampling in small plots to machine sampling for larger plots. Sampling methods and dimensions differed between crops and feasibility (Table A.6, Appendix A). In addition, depending on crop type, we measured plant density before or at harvest time (Table A.7, Appendix A). Yield was categorised into three classes: marketable yield, net yield, and gross yield. Marketable yield was defined as crop yield suitable for sale; net yield as marketable yield plus the yield not meeting the size grading criteria; and gross yield as net yield plus rotten and deformed products (see Table A.8, Appendix A, for the inclusion criteria per crop and yield category). In the case of potato, carrots and onion, yield was also assessed in terms of size classes

Table 1
Crop and cover crop (including cultivars) grown per year per parcel of the BASIS experiment. Crop sequence per column.

	Organic farming system			Conventional farming system	
Year	Field J10-3	Field J10-4	Field J10-6	Field J9-4	Field J9-6
2009	Potato[1], *Ditta* (grass clover)	Carrot, *Nerac* (Winter rye)	Spring wheat, *Lavett* (White clover)	Spring barley, *Tipple* (Italian rye grass)	Sugar beet, *Emilia*
2010	Grass clover, *	Faba bean/ spring wheat, *Imposa/Lavett*	Carrot, *Nerac*	Onion[2], *Summit*	Winter wheat, *Tabasco*
2011	White cabbage *Hinova*	Potato, *Ditta* (grass clover)	Faba bean/ spring wheat, *Imposa/Lavett* (Yellow mustard)	Seed potato[3], *Agria* (Winter rye)	Onion, *Summit* (Yellow mustard)
2012	Spring wheat, *Lavett* (common vetch)	Grass clover *	Potato, *Ditta* (grass clover)	Sugar beet, *Rhino*	Seed potato, *Agria* (Winter rye)
2013	Carrot, *Nerac*	White cabbage, *Attraction*	Grass clover *	Spring barley, *Jennifer* (Yellow mustard, common vetch, phacelia)	Sugar beet, *Coyote*
2014	Faba bean/ spring wheat *Imposa, Lavett* (Yellow mustard)	Spring wheat, *Lavett* (Hairy fetch)	White cabbage, *Reaction*	Onion, *Dormo* (Yellow mustard)	Spring barley, *Tipple*
2015	Potato, *Ditta* (grass clover)	Carrot, *Norway*	Spring wheat, *Lennox* (White clover)	Seed potato, *Milva* (Oats)	Onion, *Summit* (Yellow mustard)
2016	Grass clover *	Spring wheat, *Lennox* (Mixture 1**)	Carrot, *Nerac* (Oats)	Sugar beet, *Annelaura*	Seed potato *Milva* (Mixture 2**)
2017	Pumpkin *Amoro* (Yellow mustard)	Potato *Carolus* (grass clover)	Spring wheat *Lennox* (Mixture 3**)	Spring Barley *Irina* (Mixture 4**)	Sugar Beet *Florena*
2018	Oats, Dominik (Mixture 3**)	Grass clover *	Potato *Carolus* (grass clover)	Onion *Hybelle* (Mixture 3**)	Spring Barley *Irina* (Mixture 4**)

[1]Potato cultivar grown in organic system is a cultivar specifically selected and grown for human consumption
[2]Onion is a sowed onion (grown from seed), opposed to a planted onion
[3]Potato cultivar grown in conventional system is a cultivar specifically selected and grown for seed
*Trivos, Astorga, Sultano, Lucrem, Klondik
* *Mixture 1: White clover, red clover, Persian clover, English rye grass
Mixture 2: Oats, pea, common vetch, phacelia, Alexandrian clover, gingelli, flax, tillage radish, black oats
Mixture 3: Yellow mustard, common vetch, phacelia, Alexandrian clover, gingelli, flax, tillage radish
Mixture 4: Yellow mustard, common vetch, phacelia, Alexandrian clover, gingelli, flax
( ) Crop sequence differs from template. Further specified in 2.2.1.

(Table A.9, Appendix A).

2.3.2. Statistics

All statistical analysis was performed using Genstat 20 (VSN International, 2019). First, the effect of tillage on crop yield was tested per year, for each crop and each farming system (CONV, ORG) using ANOVA based on a randomized block design with three tillage treatments (CT, RTS and RT) and four replicates. The interaction between effects of farming system (CONV and ORG) and tillage treatments could not be tested because the ORG and CONV fields were not randomized over tillage treatments (CT, RTS, RT). Second, we assessed the effect of tillage on crop yield of crops with a variation in pre-crop (organic potato, organic spring wheat and conventional onion, Table 2) with an ANOVA model that adjusted for block, tillage and year. Third, we tested the long-term effect of tillage system on crop yield by combining data across the years (2009–2018) and across farming system (CONV or ORG) per crop. This analysis was performed using a linear mixed model (LMM), with the annual yield data as repeated measurements per plot. In this analysis, the fixed effects were tillage, year, and tillage x year interaction, while the random effects were field, block within field, and plot within block. In ANOVA treatment effects were tested with F-tests, in LMM treatment effects were tested the Wald test. If a significant treatment effect was found ($P < 0.05$), pairwise differences between means were tested using the Student's t-test.

3. Results and discussion

For the majority of crops grown in this 10-year field experiment, reduced soil tillage (RTS and RT) provided a viable alternative for conventional deep inversion tillage (CT). Compared to CT, average marketable yields in RTS and RT were similar, or higher, in 12 (RTS) and 11 (RT) of the 13 crops grown (Table 2, Fig. 3). Among these crops, yields were significantly higher in grass clover and oats (in both RTS and RT). Negative yield effects were observed in only two crops: carrot (in both RTS and RT) and cabbage (RT). The latter was the only crop showing significantly lower yields in RT than in RTS.

Table 2
Effect of tillage system (CT, RTS and RT) on absolute marketable yield of crops grown in organic (ORG) and conventional (CONV) farming systems (2009–2018). N = number of experimental years in which the crop was grown (with 4 replicate plots per year); CT: mouldboard ploughing; RTS: reduced tillage with subsoiling; RT: reduced tillage without subsoiling. Mean values followed by different letters are significantly different according to the Student t-test ($P < 0.05$).

Average absolute marketable crop yield ton ha-1							
Crop	*N*	CT	RTS	RT	s.e.m.[c]	F.probability[d]	
Potato (ORG)	6	34.2	33.2	33.8	0.44	0.191	ns
Grass clover (ORG)[a]	5	12.7[a]	13.9[b]	14.1[b]	0.23	0.001	* *
Cabbage (ORG)	3	58.8[b]	59.7[b]	55.8[a]	1.28	0.012	*
Pumpkin (ORG)	1	53.4	54.1	54.6	*1.28*	*0.832*	ns
Spring wheat (ORG)	6	5.0	5.1	5.1	0.08	0.623	ns
Oats (ORG)	1	6.5[a]	7.5[b]	7.3[b]	*0.16*	*0.011*	*
Carrot (ORG)	5	58.6[b]	50.8[a]	49.7[a]	3.65	0.00002	* **
Wheat/faba bean (ORG)[b]	3	5.0	5.3	5.0	0.10	0.104	ns
Seed potato (CONV)	4	40.9	41.3	41.4	0.34	0.414	ns
Sugar beet (CONV)	5	18.2	18.2	18.1	0.16	0.922	ns
Spring barley (CONV)	5	7.6	7.6	7.8	0.09	0.207	ns
Winter wheat (CONV)	1	11.4	12.0	11.9	0.19	0.648	ns
Onion (CONV)	3	70.9	69.1	67.4	1.12	0.086	ns

[a] In 2010 the grass clover yield was not sampled in the RTS fields.
[b] Wheat/faba bean yield in RT not sampled in 2010.
[c] S.e.m. values represent the standard error of the mean.
[d] F. probability values show the overall significance of the tillage treatment effect.

In the following paragraphs (3.2–3.5), we focus our discussion on potato, carrot, onion and sugar beet, i.e. the main cash crops, which pose specific tillage challenges because they are grown on ridges and/or are small-seeded crops. The remaining crops are briefly discussed in 3.6. For all crops, we discuss yields in RTS and RT as relative yields (CT=100%), averaged over the N years (four replicate plots per year) in which the crop was grown during 2009–2018. The full data set, including marketable, net and gross yield per crop, per year, is presented in Appendix B, Tables B.1-B.3.

3.1. Potato yield

Marketable yield of potato (grown in the ORG rotation) was slightly lower in RTS (96.9%) and RT (98.6%) compared to CT (100%) but this difference was not significant (Table 2, Fig. 3). Net and gross yield also showed no significant difference between tillage systems (Tables B.2 & B.3, Appendix B). These findings differ from (Cooper et al., 2016), who in a metanalysis of 11 studies found a 6% yield reduction (marketable or total yield) in root crops (combined number for potato and carrots) in reduced tillage systems. In addition, (Martínez et al., 2016) found a 15% average yield reduction in potato in a no-till system compared to conventional deep inversion tillage, in a 20-year experiment on a sandy loam soil. The yield per size class per year is presented in Fig. 4. In our experiment we also measured average tuber size, but again found no significant difference between tillage systems, except for year one in which both RTS and RT had a significantly smaller tuber size than CT (Table B.4, Appendix B). The latter effect may have been caused by the larger soil aggregate size in the potato ridges in the first years after establishment of the reduced tillage systems: in 2011 (year 3), soil aggregates in the ridges were larger and less homogeneously distributed in RT than in CT (Fig. 5A-B), but in 2017 (year 9) this difference had disappeared (Fig. 5C-D).

Marketable yield of seed potato (grown in the CONV rotation) was slightly higher in RTS (101.1%) and RT (101.3%) compared to CT, but this difference was not significant (Table 2). However, gross yield was significantly higher (RT, RTS > CT) in two of the four years that this crop was grown (Table B.3, Appendix B). This can be explained by the significantly ($P = 0.009$) larger average tuber size in RTS (48.1 mm) and RT (47.9 mm) compared to CT (47.1 mm), leading to an increase in non-marketable seed tubers. Fig. 6 presents yield per size class per year. The larger tuber size in RTS and RT, in some years, might be related to a higher moisture availability in the potato ridges in these systems, resulting in faster plant emergence and plant growth. However, this hypothesis remains to be explored as no data were collected on soil moisture content in the potato ridges.

3.2. Carrot yield

Marketable yield of carrot (grown in the ORG rotation) was significantly lower in RTS (84.8%) and RT (86.6%), compared to CT (Table 2, Fig. 3). These results contradict the results of (Willekens et al., 2014), who did not find a significant effect of reduced tillage on marketable carrot yield. The 14–16% reduction in marketable yield in our experiment was also larger than the percentage reported by (Cooper et al., 2016), who found an average 6% yield reduction in root crops (combined number for potato and carrot) in a meta-analysis of 11 studies on reduced tillage effects in organic production systems.

Yield losses in reduced tillage systems are often linked to reduced seed germination and seedling emergence (Lamichhane et al., 2018); however, in our experiment no significant difference was observed in carrot plant density (Table B.5, Appendix B). In our case, the lower marketable carrot yield in RT and RTS appears partly due to the greater amount of non-marketable, large sized carrots (>250 gr) harvested from these systems (Fig. 7 C & D). As a result, yield reductions in *gross* carrot yield (8.1% in RTS and 7.6% in RT) are smaller than in the *marketable*

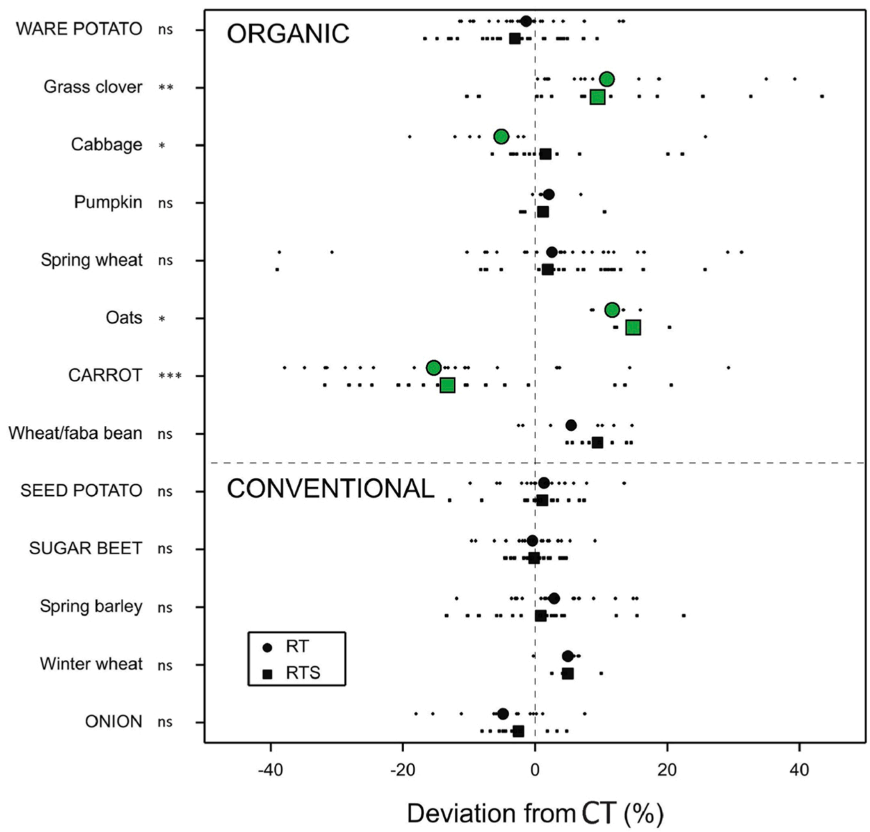

Fig. 3. Relative marketable crop yields in RT (reduced tillage) and RTS (reduced tillage with subsoiling) compared to CT (conventional tillage = 100%). The large symbols represent marketable yields in RT (circles) and RTS (squares) relative to CT, averaged over the N years that the crop was grown in the period 2009–2018 (N see Table 2). Small symbols (RT= circles and RTS = squares) represent observations per individual year and block. Crops in capital letters are the main cash crops. Green circles and squares indicate significant yield differences between reduced tillage systems (RT and/or RTS) and CT. Significances next to crop names, indicate treatment effect.

yield (Table B.3, Appendix B). RT yielded significantly more large-sized, non-marketable carrots (250–400 gr) than CT and RTS (Fig. 7 C). In addition, both RT and RTS had significantly more deformed and rotten carrots (product tare) than CT (Fig. 7 E). Thus, reduced tillage resulted in a greater number of carrots of non-marketable size and quality. This may be explained, firstly, by the larger soil aggregate size in the RT and RTS plots (Crittenden et al., 2015). He et al. (2009) also found larger soil aggregates up to 30 cm depth in a no-till system, compared to a conventional tillage system. Soil aggregates may have had an effect on plant growth and carrot size. Secondly, whereas in CT the soil was ploughed in the autumn and then left bare until sowing carrot the next spring, the RT and RTS systems had white clover or vetch as a preceding crop up till 4 – 6 weeks before sowing carrots. (Bradow and Connick, 1990) found that Berseem clover (*Trifolium alexandrinum*), Crimson clover (*Trifolium incarnatum*) and Hairy vetch (*Vicia villosa*) had an allelopathic effect on onion and carrot. In our experiment, this allelopathic effect, combined with an increase of plant residues in and on the ridges, may have led to growth disturbance of carrot plants and an increase in branched, unmarketable carrots.

3.3. Onion yield

Marketable yield of onion (CONV rotation) was lower but not significantly different in RT (95.1%) and RTS (97.5%) compared to CT (Table 2, Fig. 3). This finding contrasts with Kesik and Marzena (2009), who found marketable yield reductions of − 30.7% in a conservation tillage system, but is similar to reports of other authors who found no significant effect of reduced tillage on marketable onion yield (Jardẽnia et al., 2020). In these studies a range of tillage systems were tested, from direct sowing into untilled soil combined with cover crop treatments (Kesik and Marzena, 2009) to different levels of reduced tillage (Jardẽnia et al., 2020). In general, the diversity of tillage systems calls for careful interpretation of results and caution in comparisons of findings.

Reduced seed germination has been mentioned as a potential cause of lower onion yields in conservation tillage systems (Kesik and Marzena, 2009). Physical seedbed factors such as seedbed structure and seedbed water content probably play a major role. In our field experiment, average soil aggregate size was significantly larger in reduced tillage (Crittenden et al., 2015) and this may have contributed to reduced seed germination, as reflected in the significantly lower plant densities in RTS (59.0 plants per m^2) and RT (61.0 per m^2), compared to CT (67.1 plants per m^2) (Table B.5, Appendix B). However, probably as a result of reduced competition for resources, the lower plant densities in RTS and RT translated into significantly bigger average bulb size in RTS (60.2 mm) and RT(61.1 mm), compared to CT (57.6 mm) (Table B.4, Appendix B). Specifically, yields of the larger bulb size classes (60–80 mm, and the non-marketable 80 + mm) were significantly higher in RTS and RT. However, despite these significant differences in bulb sizes and plant densities, reduced tillage in our experiment did not result in significant changes (gains or losses) in marketable, gross, or net yield (Tables B1- B.3, Appendix B).

3.4. Sugar beet yield

Marketable yield of sugar beet (CONV rotation) was not significantly affected by tillage system (Table 2, Fig. 3). Several other studies show similar results, finding no significant effect on sugar beet yield in no-till, reduced tillage or shallow tillage systems, compared to conventional ploughing (Jabro et al., 2010; Van den Putte et al., 2010; Afshar et al., 2019). However, Arvidsson et al. (2014) reported significantly reduced sugar beet yield (−5.2%) in shallow tillage systems. Various authors have attributed sugar beet yield reduction in no-till and reduced tillage systems to poor crop establishment, caused by limited embedding of seeds due to inadequate crop residue management in these systems (Pringas and Märländer, 2004; Arvidsson et al., 2014; Lamichhane et al., 2018). This is reflected in our results, as both RTS and RT had

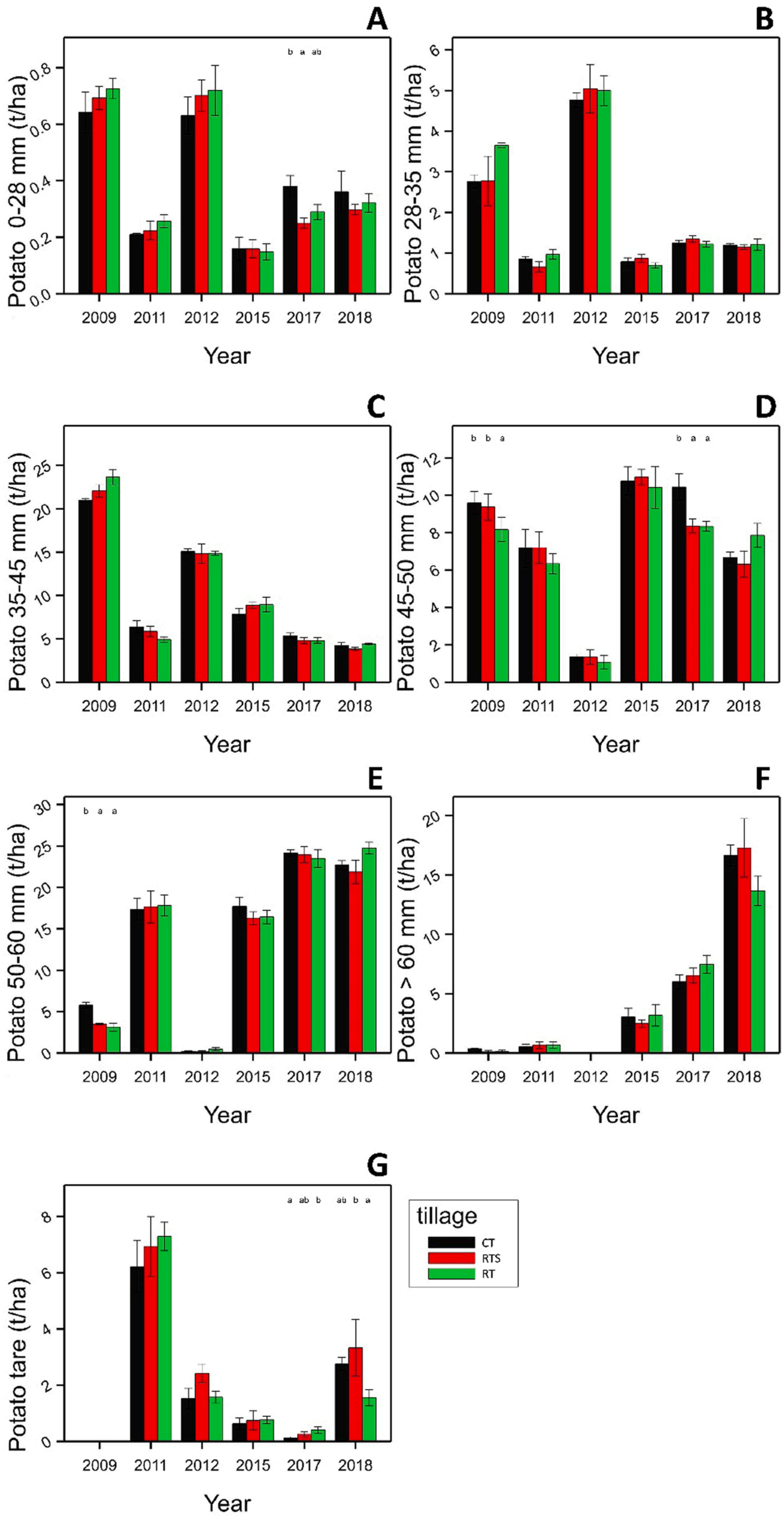

Fig. 4. Absolute mean potato yield (t/ha) per size class (A-F) and product tare (G) for different tillage treatments including: in CT (conventional tillage), RTS (reduced with subsoiling tillage) and RT (reduced tillage without subsoiling). Fig. B presents marketable tuber size. Error bars indicate standard errors. Letters above bars indicate significant ($p < 0.05$) differences between tillage treatments.

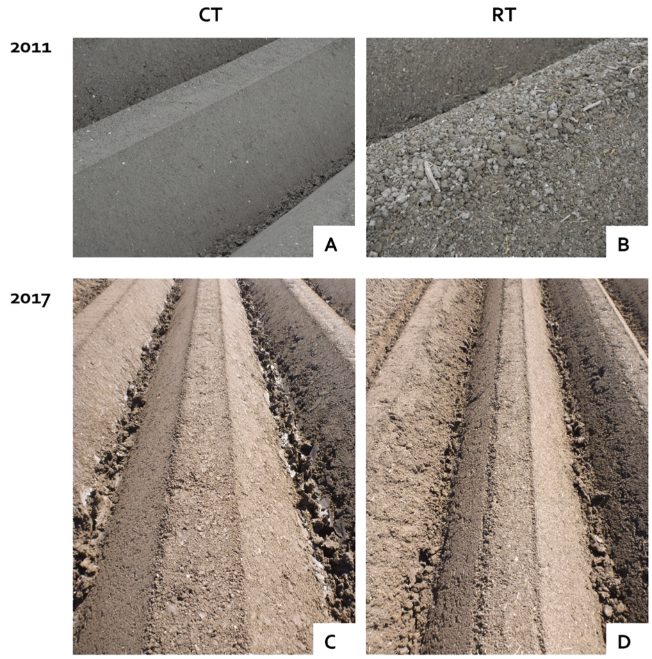

Fig. 5. Visual impression of soil aggregation in potato ridges in CT (photos A and C) versus RT (photos B and D). Photos A and B were taken on 29 April 2011; photos C and D were taken on 15 May 2017. Photos: Wageningen University and Research, D. van Balen and W. Haagsma.

significantly reduced beet plant density (85%) compared to CT (Table B.5, Appendix B). We hypothesize that limited seed-soil contact (Blunk et al., 2021) caused by surface residues in the seed furrow, and non-optimal closing of the seed furrow at time of sowing, are the main causes of the reduced plant density in these systems. Averaged over the two years in which sugar beets were grown in the rotation (2009 and 2013), this reduced plant density did not result in reduced sugar beet yield. However, in the year in which plant density in RTS and RT fell below 7 plants per m^2 (2013), the net yield in these systems was significantly lower than in CT (Tables B.2 & B.5, Appendix B). This finding is in line with (Westerdijk et al., 1994), who reported that yield is not affected within a density range of 7–10 plants per m^2, due to compensation in the form of larger sized beets.

Although average marketable yield of sugar beet thus was not affected by reduced tillage, we did observe that soil tare was significantly higher in RTS (135%) and RT (129%) compared to CT (Table B.6, Appendix B). Soil tare is the soil that adheres to the beets after harvest (Vermeulen et al., 2003), which is undesirable for farmers and sugar beet processing. Most likely, the higher soil tare in beets harvested from RT and RTS resulted from increased bifurcation of sugar beet roots in these systems (Vandergeten and Roisin, 2004; Koch et al., 2009).

3.5. Other crops

Among the various cereal crops grown in our field experiment, average marketable yields were all similar or higher in RT and RTS, compared to CT. For example, yields of spring wheat (ORG rotation) in RTS (101.9%) and RT (102.5%), and yields of spring barley (CONV rotation) in RTS (100.8%) and RT (102.9%) were statistically similar to yields in CT (Table 2, Fig. 3). This finding is in line with Arvidsson et al. (2014), who found comparable results for spring wheat and spring barley in a meta-analysis of 918 experimental years, comparing results from multiple Swedish experiments with shallow tillage versus conventional tillage. For winter wheat (CONV), we also found that yields in RTS (105.3%) and RT (104.4%) were not significantly different from CT. This is in line with findings by (Büchi et al., 2017), who found that winter wheat yield was not affected by reduced tillage in a conventional winter wheat, winter rape and maize rotation. Peigné et al. (2014) found an overall comparable wheat yield between a RT and CT system in an organic farming system and different soil types. However, the aforementioned meta-analysis of Arvidsson et al. (2014) found that winter wheat yields were generally significantly lower in shallow and no-tillage, compared to conventional tillage. As for oats (ORG rotation), we found that yields in RTS (115%) and RT (112.1%) were significantly higher than in CT, while (Arvidsson et al., 2014) for this crop found no significant yield differences between reduced versus conventional tillage systems. Finally, we found that the average yield of a mixed crop of wheat and faba bean (ORG) was significantly higher in RTS (106%) and similar in RT (98.7%), compared to CT.

For these cereal crops, we also analysed the effect of reduced tillage on plant density, by counting the number of haulms per m^2 and averaging this number across the years in which the crop was grown (see Table B.5, Appendix B; Note: winter wheat not counted). While we found no differences between tillage systems with regard to spring wheat, the average number of haulms of spring barley was significantly higher in RTS (840 m^{-2}) and RT (749 m^{-2}) than in CT (713 m^{-2}). Similarly, oats had a significantly higher number of haulms in RTS (361 m^{-2}) and RT (334 m^{-2}) than in CT (275 m^{-2}). These findings differ from Arvidsson et al. (2014), who found that cereal plant establishment (plants m^{-2}) was less in shallow and no-till systems and attributed this to poor germination due to larger soil aggregates and more plant residues in reduced tillage systems. In our experiment, the lower number of oat haulms in CT may be due to the looser topsoil, resulting in greater plant loss during harrowing (mechanical weed control).

Grass clover yield (ORG rotation) was significantly higher in RTS (109.3%) and RT (111%), compared to CT (Table21, Fig. 3). The lower yields in CT were mainly due to slaking after heavy rainfall in autumn 2012, which required a re-sowing of grass clover in CT plots in spring 2013. This problem did not occur in RTS and RT, most likely because of the greater soil aggregate size and stability in these plots (Crittenden et al., 2015), which lessened the risk of slaking (Barthès and Roose, 2002; Daraghmeh et al., 2009).

Cabbage yield (ORG rotation) was significantly lower in RT (94.9%) compared to RTS (101.6%) and CT (Table 2, Fig. 3). The statistical significance of the lower cabbage yield in RT (averaged over 3 years) is mainly driven by significantly lower yields from RT plots in 2013. In that year, termination of the preceding grass-clover crop was more superficial than in 2011 and 2014, due to soil and weather conditions. This may have led to hampered crop growth in RT plots, as reflected in the significantly lower weight of the cabbage heads harvested that year in RT, compared to CT and RTS (Table B.4, Appendix B). Similarly, Hefner et al. (2020) found that cabbage yields were lower in cropping systems where the preceding cover crop was incompletely terminated or not fully incorporated into the soil.

Pumpkin yield (ORG) in RTS (101.3%) and RT (102.2%) was not significantly different from yield in CT (Table 2, Fig. 3). Similarly, O'Rourke and Petersen (2016) found no yield effects of reduced tillage when comparing average pumpkin yields between no-till, strip-till and conventional tillage systems across two cropping seasons. However, when they analysed the two years separately, they found marginally significant yield differences between tillage systems in one of these years, and referred to weed management as one of the main causes behind these differences (Walters et al., 2008; O'Rourke and Petersen, 2016). In our experiment, pumpkin was only grown in the ninth cropping season (2017). It may be assumed that, by that time, weed management practices were fully optimized and that the effect of weed competition on pumpkin yield was thus limited.

4. Conclusions

This study explored the long-term effects of reduced tillage on arable crop yield with a specific focus on root crops and small-seeded crops in a

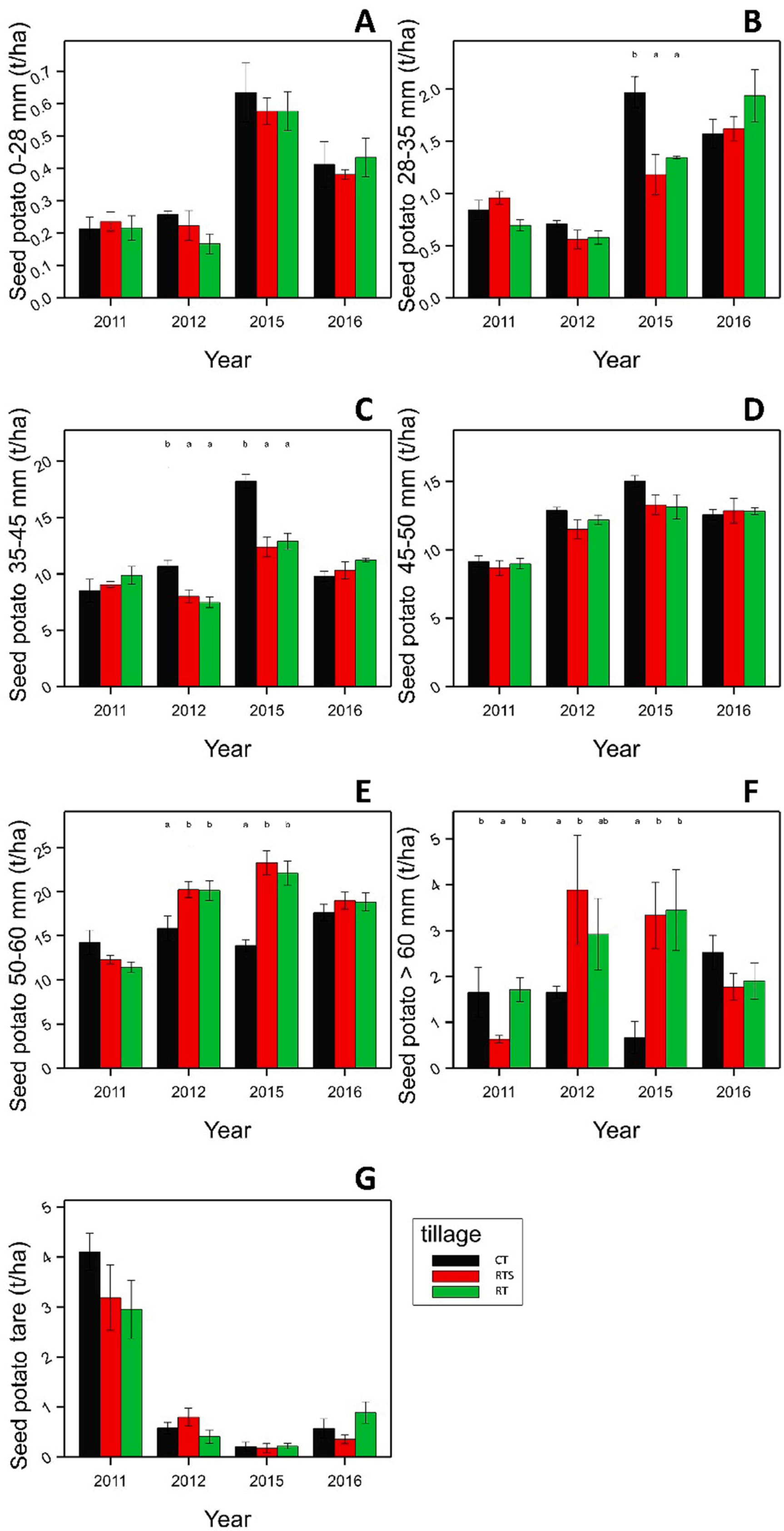

Fig. 6. Absolute mean seed potato yield (t/ha) per size class (A-F) and product tare (G) for different tillage treatments including: in CT (conventional tillage), RTS (reduced with subsoiling tillage) and RT (reduced tillage without subsoiling). Fig. B presents marketable tuber size. Error bars indicate standard errors. Letters above bars indicate significant ($p < 0.05$) differences between tillage treatments.

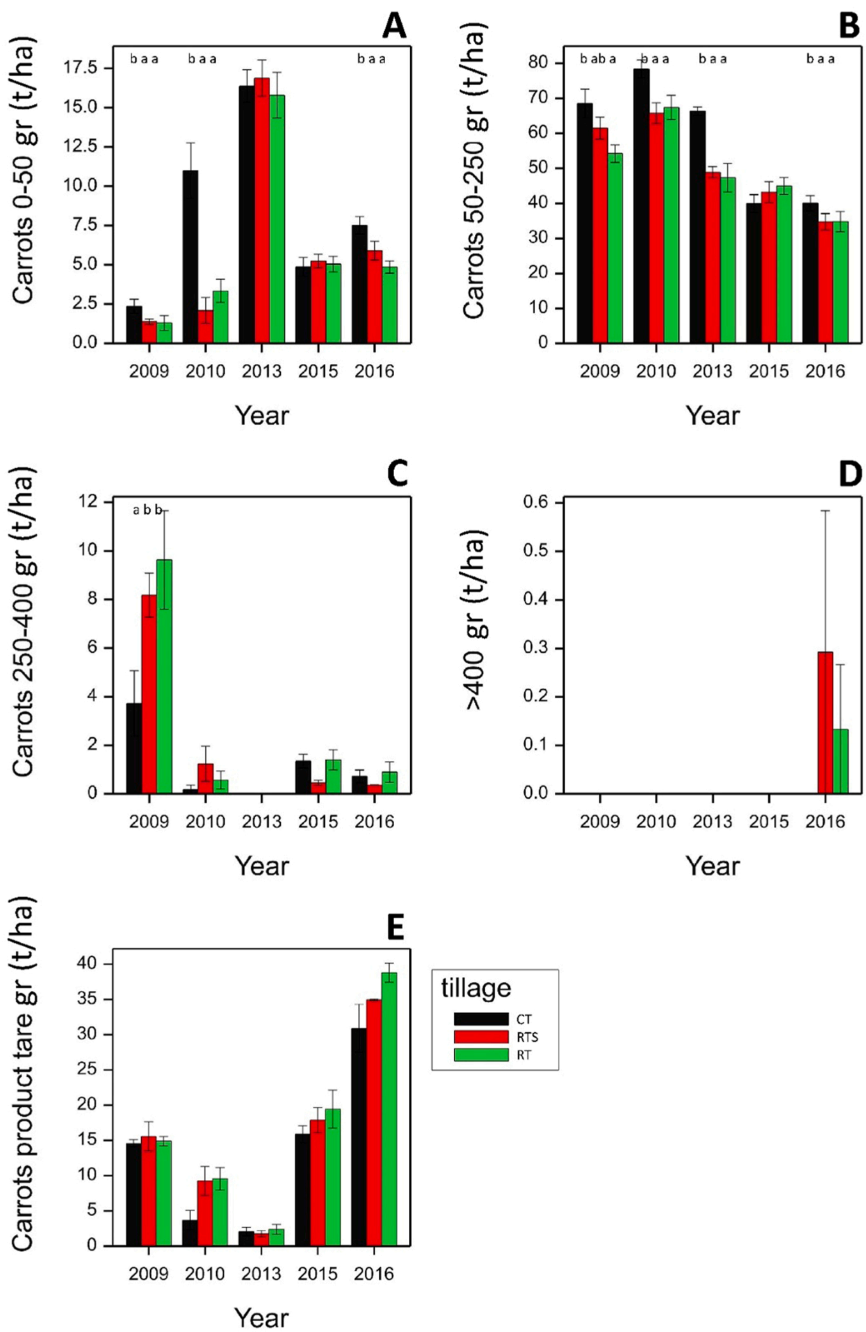

Fig. 7. Absolute mean carrot yield (t/ha) per size class (A-D) and product tare (E) for different tillage treatments including: in CT (conventional tillage), RTS (reduced with subsoiling tillage) and RT (reduced tillage without subsoiling). Fig. B presents marketable carrot size. Error bars indicate standard errors. Letters above bars indicate significant ($p < 0.05$) differences between tillage treatments.

conventional and organic crop rotation. Our main result reveals that marketable yield of 11 (RT) and 12 (RTS) of the 13 crops studied is sustained in reduced tillage systems. The only crops showing significantly reduced yields were carrot (RT&RTS < CT) and cabbage (RT < RTS&CT). Our findings imply that reduced tillage is a viable option to sustain competitive crop yields as compared to conventional tillage. However, outside experimental settings, maintaining competitive yields with reduced tillage is often perceived as challenging in everyday farming practice. Thus, in order to promote the adoption of reduced tillage, we need to optimize research and knowledge exchange with farmers, especially for financially profitable crops such as carrot and onion. For these small-seeded crops, it is essential to further improve seedbed management to prevent poor seed germination and hampered crop development. To solve the real and perceived challenges in growing these crops under reduced tillage, more research is needed on the yield effects of cover crop residue management and the mechanisms of water and nutrient supply in reduced tillage systems. Only with these answers to hand, we can minimize potential yield losses and make reduced tillage a viable and realistic option for farmers to adopt.

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Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A-B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2022.105553.

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