MSc Thesis Report

Influence of reduced tillage and organic amendments on an organic potato production system

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Farming Systems Ecology Group,

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Preface

The current research study was conducted during my thesis at the Farming Systems Ecology group, which was part of my MSc studies 'Organic Agriculture' in Wageningen University, the Netherlands. This thesis report includes two individual scientific papers with purpose of publishing them to a scientific journal in the future.

The objective of this study was to investigate the influence of reduced tillage and organic amendments (plant- and animal-based) on crop performance and soil quality indicators in an organic potato production system in the Netherlands. Although agricultural systems are highly dependent on specific climatic and topographic conditions, they are also formed by traditions and mindsets of local farmers who need to carefully weigh potential conflicts between farm income and soil conservation goals.

This work would be impossible without the contribution of many persons. I am particularly grateful to my supervisors, Johannes Scholberg and Egbert Lantinga, who guided me throughout the thesis process with much attention and professionalism. Also, I would like to extend my gratitude to those people who generously assisted me during this study: the group of students (Lv Yanjun, Rhea Flora and Terra Bart) and Dine Volker for their great assistance on the data collection; Hennie Halm for the laboratory analysis; Andries Siepel and other support staff of Unifarm-Agros for the preparation of the experimental field and provision of research facilities with equipment for data processing. Likewise, I would like to thank my family and friends who gave me strength and encouragement to complete this study.

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A) Initial Changes in Soil Quality in an Organic Potato System as Affected by Tillage Practice and Organic Amendments

D. Drakopoulos, J. M. S. Scholberg, E. A. Lantinga, and P. A. Tittonell

Abstract

The current study aimed to assess the short-term effects of two tillage practices (Reduced Tillage up to 10 cm soil depth - RT; Standard Tillage up to 30 cm soil depth - ST) and three organic amendments (Solid Cattle Manure - SCM; Lucerne Pellets - LP; Grass/Clover Silage - GCS) on soil quality indicators in an organic potato system. Use of RT enhanced the earthworm activity in terms of biomass and number compared to ST. Total soil N_{min} values showed similar decreasing patterns over time across both tillage systems. The increased soil bulk density with RT corresponded to a linear decrease in tuber yield while potatoes responded favorably to a loose soil structure especially during initial growth. Although soil temperature and soil moisture content were not greatly affected by tillage practice, SOM_{min} was estimated to be 65 kg N ha^{-1} greater under ST than RT for the potato production period. Consequently, crop N supply was (s)lower for RT during the potato production period and this may have impacts on soil fertility management. The application of LP and GCS resulted in higher N_{min} during initial tuber formation and final harvest which in turn resulted in increased crop N accumulation compared to SCM. Farmers may face challenges during the initial adaptation of RT and need to carefully weigh potential conflicts between farm income and soil conservation goals.

Keywords: organic potato production, reduced tillage, organic amendments, sandy soil, soil bulk density, soil temperature, soil moisture, earthworms, soil N, SOM, soil pH

1. Introduction

The world population has increased rapidly during the past decades and therefore agricultural production has to evolve to enhance food security using sustainable ways that do not negatively affect the environment, which may be possible via agro-intensification (Tittonell, 2013). Soil is one of the most important components of crop production systems and it is not renewable over a human timescale (Gadermaier et al., 2011). Thus, scientists and farmers should preserve soil resources by preventing soil degradation and soil erosion.

Soil tillage is one of the oldest agricultural practices, which has been widely adopted by farmers, and refers to the soil disturbance in order to incorporate previous crop residues and inorganic or organic fertilizers; control weeds; prepare seedbed for seed germination; and create favorable physical conditions (e.g., increase aeration and porosity by loosening the soil) prior to crop establishment. The majority of farmers perceive deep ploughing to be essential, since it has become a key paradigm for increased production and thus the cornerstone of modern agriculture. However, tillage has also drawbacks in terms of soil quality parameters while it may also increase production costs and energy use, therefore contributing to GHS emissions (Hobbs, 2007). Also, excessive tillage causes increased run-off that leads to nutrient depletion and soil erosion. Conservation tillage is a broad term that contains a wide range of non-inverted tillage practices (e.g., reduced tillage and no-tillage) and has the potential to diminish soil erosion and soil degradation as well as to sustain soil quality (Holland, 2004; Carter et al., 2007; Putte et al., 2010).

Potato (*Solanum tuberosum* L.) is an important crop with production area of 19.3 million ha worldwide in 2012 (FAOSTAT). Although there is no standard tillage system for potato production, it is among the crops with the highest soil erosion risks as soil is disturbed frequently during the production period (i.e., seedbed preparation, ridging and harvesting) (Auerswald et al., 2006). Conventional tillage practices (i.e., moldboard plowing) are commonly used for potato production systems because farmers believe that it is required to ensure optimal soil structure and high yields (Ivany et al., 2007). However, several studies reported that reduced tillage could be applied successfully in potato systems by improving soil quality parameters, minimizing production cost while also sustaining potato yields (Ekeberg and Riley, 1996; Mundy et al., 1999; Carter et al., 2009a; Collins et al., 2010).

In the Netherlands, potato is a major crop since the average production of the last 10 years (i.e., 1992-2012) amounted to 7.2 million tons annually (FAOSTAT). The majority of Dutch potato producers perceive that deep ploughing is necessary for seedbed preparation, ridging and harvesting. Consequently, use of reduced tillage in high-income crops that are routinely produced on ridges, such as potato and carrot, poses major challenges and potential conflicts between farm income and soil conservation goals. Especially, organic potato producers are facing more challenges by the implementation of reduced tillage practices as there are difficulties with the incorporation of organic amendments (e.g., grass/clover silage and animal manure) and weed control (Gadermaier et al., 2011).

There is an emerging agronomic practice in Dutch organic agriculture by which crops with high nitrogen content (e.g., grass/clover and alfalfa) are harvested and applied to other fields as fertilizers (cut-and-carry fertilizers). Burgt et al. (2011) reported that cut-and-carry fertilizers had higher or similar nitrogen use efficiency compared to animal manures. Also, organic amendments are a key asset for improving inherent soil fertility via enhancement of physical, biological and chemical soil properties (Canali et al., 2012).Thus, the combination of reduced tillage with different organic amendments, such as cut-and-carry fertilizers and animal manures, could be a viable option for building sound organic potato systems.

The objective of the current research was to investigate the short-term effects of two tillage practices (i.e., reduced tillage and standard tillage) and three fertilization regimes (i.e., solid cattle manure, lucerne pellets and grass/clover silage) on soil quality indicators for an organic potato production system in the Netherlands. It was hypothesized that reduced tillage would decrease soil temperature during the first weeks compared to standard tillage. Soil bulk density was anticipated to be higher under reduced tillage than standard tillage. Moreover, it was expected that the earthworm activity would be higher for reduced tillage. Soil N_{min} was anticipated to be higher with the application of lucerne pellets in both tillage systems. Finally, total N_{min} was expected to be higher in the upper soil layer for reduced tillage compared to standard tillage.

2. Materials and Methods

2.1. Experimental site, field history and climatic data

The current study was set up in April 2013. The experimental site was located at the organic experimental farm of Droevendaal (51°59'33.68"N, 5°39'34.59"E), which is the certified organic research facility of Wageningen University in Wageningen, the Netherlands. The mean air temperature and precipitation of the last 10 years are 11 °C and 829 mm per annum, respectively. The soil had a sandy texture and contained 23.8 g soil organic matter per kg of soil (Table 1). Grass/clover was grown in the field from 2007 until 2010, while spring wheat and triticale were cultivated in 2011 and 2012, respectively, using standard tillage (i.e., moldboard plowing up to 30 cm soil depth). During the fall of 2012 white clover had volunteered spontaneously throughout the experimental field. Climatic data (i.e., minimum and maximum averaged temperatures and cumulative weekly rainfall) during the potato production period were collected from a local weather station (Fig. 1). The potato field was irrigated with a lateral moving overhead irrigation system during periods of prolonged drought, and irrigation was applied on 10 July, 12 July, 16 July and 19 July with 20 mm water each time.

2.2. Experimental design

The experimental design was a split-plot with two main-plot and four sub-plot treatment combinations, which were replicated four times in blocks. The main plot treatments consisted of different tillage systems (i.e., Reduced Tillage - RT and Standard Tillage - ST), while the sub-plot treatments included three different fertilization regimes (i.e., Solid Cattle Manure - SCM, Lucerne Pellets - LP and Grass/Clover Silage - GCS) with 170 kg N ha^{-1} application rates, which were applied before planting, and a non-fertilized treatment (i.e., Control - C). The sub-plot size was 10 × 3 m, and plots contained four rows (i.e., potato ridges) spaced 0.75 m each.

2.3. Treatments and crop management

For RT, a rotary tiller (rear-mounted full width tillage devise with 3 m working width) was employed using a tillage depth of 10 cm. For ST, a pass with the rotary tiller using 10 cm tillage depth was followed by moldboard plowing (3 m working width) up to 30 cm soil depth. Soil amendments were applied manually by spreading targeted amounts evenly across each plot area on 15 April, 2013. Materials were then incorporated superficially with a rotary tiller, and only for ST treatments this was followed by ploughing. Potato tubers (*Solanum tuberosum* L. cv. 'Frieslander') were planted on 17 April at a seeding rate of 3 Mg ha^{-1}. 'Frieslander' is an early table potato cultivar with moderate resistance to late blight (*Phytophthora infestans*). A tractor with GPS system including front and rear equipments was used for planting. Potatoes were planted at 15 cm depth using plant spacing of 30 cm within the row and 75 cm between the rows. Re-ridging occurred on 16 May, 31 May and 21 June of 2013. One week prior to final harvest, potato plants were infected by late blight. The symptoms were only observed on the lower leaves and since the infestation occurred very late during the season, it did not appear to have pronounced effects on final tuber yield. The final harvesting of potatoes occurred on 30 July.

2.4. Field and laboratory analyses

2.4.1. Pre-experimental measurements

Composite soil samples were collected per block with a soil gouge using a zigzag pattern before soil cultivation in order to measure the initial soil organic matter (SOM, g kg^{-1}), total soil mineral N (N_{min}, kg N ha^{-1}), P (kg P_2O_5 ha^{-1}), K (kg K_2O ha^{-1}) and soil pH for the 0-30 cm soil layer (Table 1). Soil available $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ were measured following the methods as described in Houba et al. (1990). Samples were extracted in 0.01 M $CaCl_2$ and analyzed using a segmented-flow system (Technicon Auto-analyzer II, Dublin, Ireland). For determination of soil available P, soil samples were extracted with 0.01 M $CaCl_2$ and analyzed spectrophotometrically using a segmented-flow system (Skalar Analytical BV. Breda, the Netherlands). For determination of soil available K, samples were extracted with 0.01 M $CaCl_2$, vaporized and analyzed by flame emission spectrophotometer at a wave length of 766.5 nm. Total SOM was determined using the loss-on-ignition (LOI) method by dry combustion of the organic material in a furnace at 500-550 °C. The loss in weight gave an indication of the organic matter content in the sample (Konare et al., 2010). The same soil samples were used to measure soil pH. The later was measured after 0.01 M $CaCl_2$ extraction using a pH/mV meter (Inolab pH/Cond Level 1, WTW, Weilheim, Germany).

Regarding the fertilization regimes, estimations were made in order to calculate the required amounts of material per plot based on target N application rates. After their application, the actual N-P-K (kg ha^{-1}), DM content and C:N ratio of each organic amendment were measured (Table 2). Total N and C contents were determined using the Dumas Method with a CHN1110 Element Analyzer (CE instruments, Milan, Italy).

2.4.2. Soil quality measurements

Soil bulk density. Soil bulk density was measured for four selected treatments (i.e., RT+GCS, RT+SCM, ST+GCS and ST+SCM) at 1, 4, 7 and 13 weeks after planting (WAP) by obtaining two soil cores (5 cm inside diameter × 5 cm long) per replicate from the 15-25 cm soil layer. A soil core (8 cm inside diameter × 10 cm long) was used to remove the upper soil layer of 0-15 cm depth. Samples were collected in the top of the ridges (vertically) between two adjacent plants from the two central rows of each plot. The soil was dried at 70 ^{o}C for 48 hours before weighing.

Soil temperature. Soil temperature was monitored for four selected treatments (i.e., RT+GCS, RT+SCM, ST+GCS and ST+SCM) and data were collected at 10 minutes intervals starting from the planting day until the potato harvesting. Thermocouples were placed at 15 cm soil depth inside the ridges and centered between two adjacent plants, and sensors were connected to a data logger (data Taker ®, Data logger DT 85 Series 3, Scoresby, VIC, Australia). Data were corrected by calibrating the sensors before the analysis.

***Soil moisture content*.** Soil moisture was measured at 1, 4, 7, 9, 11 and 13 WAP for four selected treatments (i.e., RT+GCS, RT+SCM, ST+GCS and ST+SCM). Soil cores (5 cm inside diameter × 5 cm long) were taken in the top of the ridges (vertically) between two adjacent plants from the 15-25 cm soil layer. Wet soil weights were measured directly after sampling while afterwards the soil was dried at 70 ^{o}C for 48 hours in order to record dry soil weights.

***Earthworm activity*.** Earthworm biomass (g m^{-2}) and number of earthworms (individuals m^{-2}) were determined at 4, 8 and 13 WAP. For this purpose, specific earthworm weight (i.e., weight per individual) and total earthworm number were measured by manually excavating a soil volume of 0.2 x 0.2 x 0.3 m. Two samples per replicate were taken from the two central rows of each plot while afterwards earthworms were hand-sorted, rinsed with water and stored in labeled plastic bottles. Earthworms were distinguished into two size classes: small (i.e., < 500 mg) and large (i.e., > 500 mg) earthworms.

***Soil N, SOM and pH*.** Soil N_{min} was assessed for two soil layers (i.e., 0-15 and 15-30 cm) at 4, 8 and 14 WAP. A total of 20 subsamples were collected per plot with a soil gouge following a zigzag pattern. Subsamples were mixed in order to obtain one composite sample per plot for each soil layer. Afterwards, samples were dried at 40 °C and passed through a 2-mm sieve. Soil available $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ were measured following the same methods described previously (see 2.4.1). Soil organic matter (SOM) was measured for two soil layers (i.e., 0-15 and 15-30 cm) at 14 WAP using the same sample procedures as for soil N_{min}. The same soil samples were used for the soil pH measurements. Based on crop N accumulation for the non-fertilized control treatments (Drakopoulos et al., 2014), the mineralization of soil organic matter (SOM_{min}) for both tillage systems was estimated as: SOM_{min} = total crop N accumulation - total N_{min} before planting + total N_{min} at harvest (equation 1).

2.5. Statistical analysis

Data were analyzed using Genstat 14th edition (VSN International Ltd., Hemel Hempstead, UK). Analysis of variances (ANOVA) was conducted following a Shapiro-Wilk test to assess whether the data followed a normal distribution and a Bartlett's test to assess the homogeneity of variances. Significance levels were determined for main effects and interactions while Fisher's protected LSD-test was used for mean separation.

3. Results and Discussion

3.1. Initial soil test and nutrient application

Initial soil organic matter ranged from 22.9 to 24.8 (g kg^{-1}) while soil N_{min} and P values were also relatively uniform across blocks (Table 1). However, soil K values showed pronounced differences among the different blocks. The actual nutrient application rates along with the DM content and C:N ratio of each fertilization regime are outlined in Table 2. In terms of N, actual fertilization rates were -2.9%, +7.1%, and -5.3% compared to the target value of 170 kg N ha^{-1} for SCM, LP and GCS, respectively.

3.2. Soil bulk density

Use of RT increased soil bulk density at the 15-25 cm soil layer compared to ST during the first 7 weeks after planting (WAP), while both tillage systems had similar values at the end of the growing season (13 WAP) (Table 3). This was related to soil bulk density diminishing for RT, while increasing for ST over time (Fig. 2). These findings come to agreement with reports by Carter et al. (2007) who found that soil bulk density was higher under reduced tillage (i.e., spring tillage) than conventional tillage (i.e., autumn moldboard plough or autumn chisel plough both followed by secondary spring tillage). However, use of conservation tillage in the long-term resulted in lower soil bulk density at the 0-10 cm soil layer compared to conventional tillage (Carter et al., 2009b). Ekeberg and Riley (1997) reported similar soil bulk density values under three tillage systems (i.e., plough, tine 6 cm and minimum) 10 years after the initiation of tillage treatments. Fertilization regime had no effect on soil bulk density since values were similar throughout the potato production period (Table 3).

3.3. Soil temperature and soil moisture content

Soil temperature at 15 cm depth was numerically lower for RT during the 1st and the 3rd WAP, reaching a maximum differential of -1 ^{o}C and -0.6 ^{o}C, respectively (Fig. 3). Afterwards, soil temperature was higher for RT compared to ST throughout most of the remainder of the potato production period with exceptions the 7th, 8th and 14th WAP (Fig. 3). The most extreme ΔT_{RT} values were +1 and -1 (Fig. 3). Also, Carter et al. (2005) found slight differences on soil temperature at the 2-5 cm soil layer between conservation and conventional tillage systems on a sandy soil under potato production. Soil temperature at 15 cm depth was higher for GCS than SCM during the first 3 WAP, with exception being the 1st WAP (Fig. 4). Afterwards, there were many temperature fluctuations between the two treatments without any clear or consistent differences until the 8th WAP (Fig. 4). Subsequently, GCS resulted in slightly higher soil temperatures than SCM until the end, with an exception in the beginning of the 13th WAP (Fig. 4). The most extreme ΔT_{GCS} values were +1.4 ^{o}C and -0.8 ^{o}C (Fig. 4).

Soil moisture content at the 15-30 cm soil layer was similar among the different tillage practices and fertilization regimes throughout the potato production period (Figs 5 and 6). However, in other studies soil moisture content within the same soil layer was reported to be higher under conservation tillage (i.e., tillage train up to 10 to 15 cm soil depth) than conventional tillage (i.e., mouldboard plowing up to 20 cm soil depth) (Carter et al., 2005).

3.4. Earthworm activity

Biomass and number of small-sized earthworms were 2-4 fold higher under RT compared to ST at 4, 8 and 13 WAP (Table 4). This comes to agreement with reports in the literature indicating that number and biomass of earthworms increased with more extensive tillage regimes (Peignè et al., 2007; Lahmar, 2010), since intensively tilled soils not only injure earthworms but also expose them to increased predation and desiccation risks (Boström, 1995; Holland, 2004). Ekeberg (1992) also found higher weights and numbers of earthworms under minimum tillage compared to standard plowing. Gerard and Hay (1979) reported that shallow soil cultivation had less impact on earthworm populations compared to deep plowing. Biomass and number of large-sized earthworms were twice as high under RT compared to ST at 4 WAP, whereas values were similar for both tillage systems at 8 and 13 WAP (Table 5). Fertilization regimes had no effect on biomass and number of small- or large-sized earthworms (Table 5).

3.5. Soil N_{min}

Total soil N_{min} at the 0-30 cm soil layer showed similar decline for both tillage systems throughout the potato production period (Fig. 7). Carter et al. (2009a) also reported that total N values at the 0-10 soil layer were not affected by tillage treatments. Total soil N_{min} at the 0-30 cm soil layer was lowest for the control at 4 and 8 WAP, while the different fertilization regimes had similar N_{min} values (Fig. 8). However, total soil N_{min} was lower for SCM compared to GCS and LP at 14 WAP (Fig. 8).

3.5.1. Initial crop growth - 4 WAP

There were significant interactions between tillage practice and fertilization regime in terms of soil NO_3^-, NH_4^+ and total N_{min} values at the 0-15 cm soil layer during initial crop growth (4 WAP) (Table 6). Use of RT increased soil NO_3^-, NH_4^+ and total N_{min} at the 0-15 cm layer compared to ST (Table 6). This relates to the different tillage practices, since soil amendments were incorporated into the upper soil layer using a rotary tiller (up to 10 cm soil depth) for RT and therefore nutrients were mainly concentrated in the top soil. It was earlier reported that soil organic carbon, total nitrogen, phosphorus and potassium were also more concentrated in the superficial soil layer under reduced tillage compared to conventional tillage (Kay and VandenBygaart, 2002; Peignè et al., 2007). For ST, use of different fertilization regimes did not affect N_{min}, while for RT use of SCM and LP resulted in higher soil NO_3^- and total N_{min} values at the 0-15 cm soil layer than GCS (Figs 9, 10 and 11). For the same soil layer, combination of RT with GCS resulted in the highest NH_4^+ values (Fig. 10). Soil NO_3^- and total N_{min} were higher for ST compared to RT for the 15-30 cm soil layer (Table 6), since soil amendments were displaced into higher soil depths (up to 30 cm) for ST using moldboard plowing. The displacement of soil amendments in different soil depths was found to favor initial potato growth under RT-based systems, while over time ST-based systems had better mid- and end- season crop performance as roots proliferated into deeper soil layers (Drakopoulos et al., 2014). In terms of the 0-30 cm soil layer, use of RT increased NH_4^+ compared to ST, while soil NO_3^- and total N $_{min}$ were not affected by tillage system (Table 6).

3.5.2. Initial tuber formation - 8 WAP

There were significant interactions between tillage and fertilization regime on soil NO_3^- and total N $_{min}$ during initial tuber formation (8 WAP) at the 0-15 cm soil layer (Table 7). Use of RT in combination with LP or GCS resulted in the highest soil NO_3^- and total N $_{min}$ values at the 0-15 cm soil layer, while use of ST resulted in similar values across all fertilization regimes (Figs 12 and 13). Soil NH_4^+ was higher under RT at the 0-15 cm soil layer compared to ST (Table 7). At the 0-30 cm soil layer, N $_{min}$ was similar for both tillage practices (Table 7). In terms of fertilization effects, use of GCS resulted in the highest soil NO_3^-, NH_4^+ and total N $_{min}$ values at the 0-30 cm soil layer (Table 7).

3.5.3. Final harvest - 14 WAP

At final harvesting (14 WAP), interaction effects between tillage and fertilization regime were significant in terms of soil NO_3^- and total N $_{min}$ at the 0-15 cm soil layer (Table 8). For RT, application of LP and GCS resulted in the highest soil NO_3^- and total N $_{min}$ values at the 0-15 cm soil layer (Figs 14 and 15), while ST had higher soil NO_3^- values at the 15-30 cm soil layer than RT (Table 8). At the 0-30 cm soil depth, RT and ST had similar soil NO_3^-, NH_4^+ and total N $_{min}$ values, while the application of LP and GCS increased soil total N $_{min}$ compared to the use of SCM (Table 8).

3.6. Soil organic matter dynamics

The initial soil organic matter (SOM) prior to tillage was 23.8 g kg^{-1} on average (Table 1). At harvesting, SOM was similar between the two tillage practices and among different fertilization regimes for both the 0-15 cm and 15-30 cm soil layers (Table 9). According to a long-term study by Carter and Sanderson (2001), soil organic carbon was higher at the 0-8 cm soil layer under conservation tillage compared to conventional tillage after 6 years. The mineralization of soil organic matter (SOM $_{min}$) during the growth period for non-fertilized control plots (equation 1) was estimated to be 65 kg N ha^{-1} greater under ST than RT (Table 9). Thus, it could be argued that crop N supply was (s)lower with use of RT compared to ST during the potato production period, and despite the fact that initial SOM values were similar for both tillage systems, this may result in slightly higher soil carbon sequestration under RT-based systems in the long-term. Based on these results, it is evident that tillage greatly affects soil N availability.

3.7. Soil pH

At final harvesting (14 WAP) the soil pH at the 0-15 cm soil layer was 5.9 for both tillage practices. Similar findings were reported for a long-term experiment where tillage had no effect on soil pH at the 0-10 cm soil layer (Carter et al., 2009b). In terms of fertilization regime, use of LP and GCS decreased soil pH to 5.8 in the top layer, whereas values were the same (=6.0) for SCM and control. At the 15-30 cm soil layer, use of RT increased the pH values compared to ST (=6.0 and 5.8, respectively), while fertilization regime had no effect.

3.8. Regression analysis

There was a strong negative linear relationship between soil bulk density at the 15-25 soil layer and potato tuber yield (Drakopoulos et al., 2014) at 1, 3 and 7 WAP (Table 10). Soil bulk density values at 4 WAP appeared to account for 61% of the overall yield variability which is consistent with the perception that potatoes demand a loose soil structure especially during initial growth. This comes to agreement with other studies, where it was reported that potato tuber yield was reduced with an increase in soil bulk density (Blake et al., 1960; Grimes and Bishop, 1971). However, this trend was not significant at 13 WAP (Table 10).

There was a quadratic relationship between SOM at final harvest (14 WAP) and potato tuber yield (Table 11 and Fig. 16) while the same relationship was found between total soil N_{min} at the 0-30 cm soil layer (at 4 and 14 WAP) and potato tuber yield (Table 11, Figs 17 and 18). Tuber yield increased linearly with an increase in SOM until 30 g kg^{-1} where yield reached a plateau at 45 Mg ha^{-1} (Fig. 16). Tuber yield increased linearly with an increase in soil N_{min} until around 90 kg N ha^{-1} at 4 WAP and 30 kg N ha^{-1} at 14 WAP, with a yield maximum of about 41 Mg ha^{-1}. Through quantifying N_{min} at 4 WAP about 38% of the yield variability could be explained, whereas use of N_{min} or SOM values at 14 WAP only accounted for 25% and 33%, respectively, of the overall yield variation.

4. Conclusions

The current study aimed to investigate the short-term effects of two tillage systems (i.e., RT and ST) and three organic amendments (i.e., SCM, LP and GCS) on soil quality indicators under organic potato production. Use of rotary tiller up to 10 cm soil depth (i.e., RT) prior to potato planting enhanced the earthworm activity in terms of biomass and number compared to moldboard plowing (i.e., ST), while fertilization regime had no effect on earthworms. Total soil N_{min} values showed similar decreasing patterns over time across both tillage systems. However, nutrients were much more concentrated in the upper soil layer (i.e., 0-15 cm) with use of RT compared to ST during initial crop growth. This is related to displacement of surface applied soil amendments to deeper soil layers during ploughing (i.e., ST), while organic amendments were incorporated into the topsoil under RT. In terms of consequences, use of RT may promote early growth, however, it may also favor formation of shallow root systems as roots tend to proliferate in nutrient-rich soil layers. Thus, it may be argued that use of RT could render crops more sensitive to soil moisture stress which at times was also observed in the field. The application of LP and GCS resulted in higher N_{min} during initial tuber formation and final harvest which in turn resulted in increased crop N accumulation compared to SCM (Drakopoulos et al., 2014). This provides evidence that plant-based fertilizers can increase nutrient use efficiency compared to animal manures. Although soil temperature and soil moisture content were not greatly affected by tillage practice, SOM_{min} was estimated to be 65 kg N ha^{-1} greater under ST than RT for the potato production period. This implies that crop N supply will be (s)lower during the potato production period with use of RT, and this may have impacts on soil fertility management. Also, it could be speculated that soil carbon sequestration may be slightly higher with use of RT. However, initial differences appeared to be small since overall SOM values were similar across tillage treatments. The increased soil bulk density at the 15-25 cm soil layer with RT resulted in a linear decrease in tuber yield, and especially during initial growth potato plants seemed to respond favorably to a loose soil structure.

Several studies reported that RT could be applied successfully in potato systems by improving the soil quality indicators, minimizing the production costs and sustaining the potato yield. However, the current study shows that although RT improved some soil quality parameters, such as earthworm activity, it negatively affected others such as soil bulk density, which proved to be detrimental in terms of tuber bulking and final yield. Thus, use of RT in high-income crops that require a loose soil structure and are produced on ridges, such as potato, may result in decreased yield in the short-term. However, over time yield reductions may become less pronounced as soil structure is being improved due to increased depth and frequency of biopores. Thus especially during initial adaptation of RT, farmers may face major challenges and need to carefully weigh potential conflicts between farm income and soil conservation goals. Use of plant-based fertilizers (i.e., LP and GCS) appeared to be promising and may provide organic farmers with a viable alternative to the use of animal manures, enhancing nutrient use efficiency as shown in a parallel paper (Drakopoulos et al., 2014).

5. Tables and Figures

5.1. Tables

Table 1. SOM (g kg^{-1}), soil N_{min} (kg N ha^{-1}), P (g kg^{-1}), K (g kg^{-1}) and pH at the 0-30 cm soil layer prior to any cultivation practice.

	SOM (g kg^{-1})	N_{min} (kg N ha^{-1})	P (g kg^{-1})	K (g kg^{-1})	pH
Block					
1	24.8	12.2	0.94	0.67	6.94
2	23.4	11.0	0.85	3.92	6.68
3	22.9	11.1	0.86	2.10	6.50
4	24.0	11.6	0.86	0.59	6.33
Average	23.8	11.5	0.88	1.82	6.61

Table 2. Actual N-P-K (kg ha^{-1}), DM (%) and C:N ratio of each fertilization regime (solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS).

	N	P	K	DM (%)	C:N
	---------------------- kg ha^{-1}---------------------				
SCM	165	44.4	214	36.6	12
LP	182	25.6	242	92.2	16
GCS	161	35.1	231	50.2	22

Table 3. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (solid cattle manure, SCM; grass clover silage, GCS) on soil bulk density (g cm^{-3}) at 1, 4, 7 and 13 WAP at the 15-25 cm soil layer.

	Soil bulk density (g cm^{-3})			
	1 WAP[1]	4 WAP	7 WAP	13 WAP
Tillage (T)				
RT	1.43	1.43	1.41	1.36
ST	1.24	1.34	1.30	1.35
Significance[2]	**	*	*	ns
Fertilization (F)				
SCM	1.37	1.39	1.37	1.36
GCS	1.30	1.38	1.34	1.36
Significance	ns	ns	ns	ns
T × F	ns	ns	ns	ns

[1] WAP = weeks after planting.

[2] *, ** and *** refer to P values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

Table 4. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on biomass (g m^{-2}) and number (individuals m^{-2}) of small earthworms (< 500 mg) at 4, 8 and 13 WAP.

	Earthworm biomass (g m^{-2})			Earthworm number (individuals m^{-2})		
	4 WAP[1]	8 WAP	13 WAP	4 WAP	8 WAP	13 WAP
Tillage (T)						
RT	14.4	7.83	8.16	48	29	35
ST	6.7	2.60	1.82	16	12	10
Significance[2]	***	*	*	*	*	*
Fertilization (F)						
Control	10.3	4.74	3.53	36	22	16
SCM	9.4	5.02	4.16	25	17	25
LP	12.7	7.04	5.54	41	25	22
GCS	9.9	4.07	6.74	28	17	28
Significance	ns	ns	ns	ns	ns	ns
T × F	ns	ns	ns	ns	ns	ns

[1] WAP = weeks after planting.

[2] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

Table 5. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on biomass (g m^{-2}) and number (individuals m^{-2}) of large earthworms (> 500 mg) at 4, 8 and 13 WAP.

	Earthworm biomass (g m^{-2})			Earthworm number (individuals m^{-2})		
	4 WAP[1]	8 WAP	13 WAP	4 WAP	8 WAP	13 WAP
Tillage (T)						
RT	18.1	0.02	4.6	27	1	5
ST	9.1	0.17	7.1	13	5	4
Significance[2]	*	ns	ns	*	ns	ns
Fertilization (F)						
Control	13.2	0.00	3.2	19	0	3
SCM	6.4	0.17	0.8	9	6	2
LP	14.1	0.09	15.8	22	3	11
GCS	20.7	0.11	3.6	30	2	2
Significance	ns	ns	ns	ns	ns	ns
T × F	ns	ns	ns	ns	ns	ns

[1] WAP = weeks after planting.

[2] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

Table 6. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on soil NO_3^-, NH_4^+ and total N $_{min}$ (kg N ha^{-1}) at the 0-15, 15-30 and 0-30 cm soil layers during initial crop growth (4 WAP) of potato.

	0-15 cm			15-30 cm			0-30 cm		
	NO_3^-	NH_4^+	Total N $_{min}$	NO_3^-	NH_4^+	Total N $_{min}$	NO_3^-	NH_4^+	Total N $_{min}$
					Kg N ha^{-1}				
Tillage (T)									
RT	48.1	17.8	65.9	20.8	7.2	28.0	68.9	25.0	93.9
ST	17.8	7.6	25.4	53.3	9.2	62.5	71.1	16.8	87.9
Significance[1]	**	**	**	**	ns	**	ns	*	ns
Fertilization (F)[2]									
Control	25.8	10.4	36.2	30.2 a	6.5	36.7 a	56.0 a	16.9 a	72.9 a
SCM	36.9	12.5	49.4	40.3 b	8.9	49.2 b	77.2 b	21.4 b	98.6 b
LP	38.5	12.9	51.4	42.2 b	8.5	50.7 b	80.7 b	21.4 b	102.1 b
GCS	30.6	15.0	45.7	35.3 ab	8.9	44.2 ab	65.9 a	24.0 b	89.9 b
Significance	***	**	**	*	ns	*	***	**	***
T × F	**	**	**	ns	ns	ns	ns	ns	ns

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[2] No mean separation for main effects is presented whether the interaction effect was significant (*P* < 0.05); Different letters indicate significant differences according to the Fisher's protected LSD-test (*P* < 0.05).

Table 7. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on soil NO_3^-, NH_4^+ and total N_{min} (kg N ha^{-1}) at the 0-15, 15-30 and 0-30 cm soil layers during initial tuber formation (8 WAP).

	0-15 cm			15-30 cm			0-30 cm		
	NO_3^-	NH_4^+	Total N_{min}	NO_3^-	NH_4^+	Total N_{min}	NO_3^-	NH_4^+	Total N_{min}
	Kg N ha^{-1}								
Tillage (T)									
RT	28.5	8.6	37.1	13.9	5.9	19.8	42.4	14.6	56.9
ST	10.3	6.3	16.6	20.6	6.5	27.1	30.9	12.8	43.6
Significance[1]	**	*	**	ns	ns	ns	ns	ns	ns
Fertilization (F)[2]									
Control	9.0	6.8 a	15.8	9.8 a	5.2 a	15.0 a	18.8 a	12.0 a	30.8 a
SCM	16.9	6.9 a	23.8	17.6 ab	6.4 b	24.0 b	34.5 b	13.3 ab	47.8 b
LP	27.4	7.5 ab	34.9	17.9 ab	6.4 b	24.3 b	45.3 bc	13.9 b	59.2 bc
GCS	24.3	8.7 b	33.0	23.7 b	6.8 b	30.5 b	48.0 c	15.5 c	63.5 c
Significance	***	*	***	*	*	*	***	**	***
T × F	*	ns	*	ns	ns	ns	ns	ns	ns

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[2] No mean separation for main effects is presented whether the interaction effect was significant (*P* < 0.05); Different letters indicate significant differences according to the Fisher's protected LSD-test (*P* < 0.05).

Table 8. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on soil NO_3^-, NH_4^+ and total N_{min} (kg N ha^{-1}) at the 0-15, 15-30 and 0-30 cm soil layers during final harvest (14 WAP) of potato.

	0-15 cm			15-30 cm			0 - 30 cm		
	NO_3^-	NH_4^+	Total N_{min}	NO_3^-	NH_4^+	Total N_{min}	NO_3^-	NH_4^+	Total N_{min}
					Kg N ha^{-1}				
Tillage (T)									
RT	12.3	6.9	19.2	3.5	6.9	10.4	15.8	13.8	29.6
ST	4.5	7.3	11.8	9.0	8.5	17.5	13.6	15.8	29.4
Significance[1]	*	ns	ns	*	ns	ns	ns	ns	ns
Fertilization (F)[2]									
Control	4.3	5.0 a	9.3	2.8 a	5.9	8.7 a	7.1 a	10.9 a	18.0 a
SCM	5.8	7.8 b	13.6	4.1 ab	7.7	11.8 ab	9.9 a	15.5 b	25.4 b
LP	12.5	7.0 ab	19.5	10.5 c	7.9	18.4 c	23.0 b	14.9 b	37.9 c
GCS	11.1	8.7 b	19.8	7.7 bc	9.2	16.9 bc	18.8 b	17.9 b	36.7 c
Significance	***	*	***	**	ns	**	***	**	***
T × F	***	ns	**	ns	ns	ns	ns	ns	ns

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[2] No mean separation for main effects is presented whether the interaction effect was significant (*P* < 0.05); Different letters indicate significant differences according to the Fisher's protected LSD-test (*P* < 0.05).

Table 9. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on SOM (g kg^{-1}) at the 0-15 cm and 15-30 cm soil layers at final harvest (14 WAP) and estimated SOM_{min} (kg N ha^{-1}) throughout the potato production period.

	SOM (g kg^{-1}) at 14 WAP		SOM_{min} (kg N ha^{-1})
	0-15 cm	15-30 cm	
Tillage			
RT	26.2	26.3	127
ST	26.6	27.7	192
Significance[1]	ns	ns	*
Fertilization (F)			
Control	24.9	25.1	
SCM	27.1	28.3	
LP	26.3	27.0	n/a[2]
GCS	27.4	27.7	
Significance	ns	ns	
T × F	ns	ns	

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.
[2] n/a = not applicable

Table 10. Regression analysis for estimation of the relationship between soil bulk density (g cm^{-3}) at the 15-25 cm soil layer and potato tuber yield (Mg ha^{-1}). Soil bulk density is the explanatory variable (x) and potato tuber yield is the response variable (y). Y values ranged from 25.0 to 48.1 Mg ha^{-1}. Data for the potato tuber yield were obtained from Drakopoulos et al. (2014).

Explanatory variable	Equation	R^2 value	Significance[1]
Soil bulk density (g cm^{-3})			
1 WAP[2]	y = 78 - 29x	0.61	***
3 WAP	y = 86 - 33x	0.28	*
7 WAP	y = 102 - 46x	0.46	**
13 WAP	y = 90 - 37x	0.24	ns

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.
[2] WAP = weeks after planting.

Table 11. Regression analysis for estimation of the relationship among SOM (g kg^{-1}) at final harvest (14 WAP) and total soil N_{min} (Kg N ha^{-1}) throughout the production period at the 0-30 cm soil layer with potato tuber yield (Mg ha^{-1}). SOM and total N_{min} are the explanatory variables (x) and potato tuber yield is the response variable (y). Y values ranged from 25.0 to 48.1 Mg ha^{-1}. Data for the potato tuber yield were obtained from Drakopoulos et al. (2014).

Explanatory variable	Equation	R^2 value	Significance[1]
SOM (g kg^{-1})			
14 WAP - final harvest	$y = -0.11x^2 + 7.55x - 82$	0.33	**
Total N_{min} (Kg N ha^{-1})			
4 WAP[2]	$y = -0.01x^2 + 1.19x - 21$	0.38	**
8 WAP	$y = -0.01x^2 + 0.72x + 18$	0.25	ns
14 WAP	$y = -0.01x^2 + 0.96x + 22$	0.25	**

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.
[2] WAP = weeks after planting.

5.2. Figures

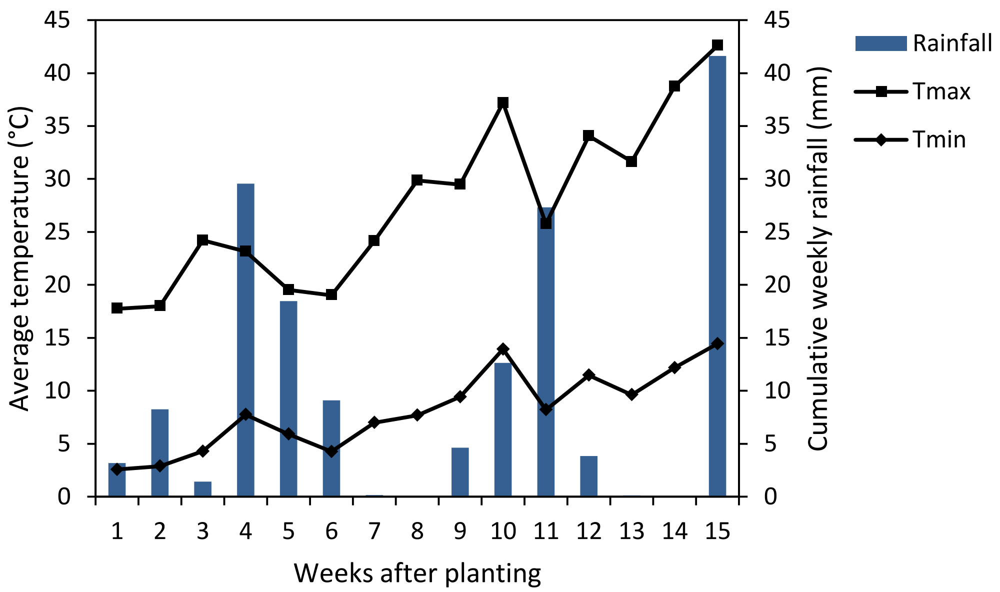

Fig. 1. Minimum (T_{min}, °C) and maximum (T_{max}, °C) averaged weekly temperatures along with cumulative weekly rainfall (mm) during the potato production period (17/4/2013 - 30/7/2013).

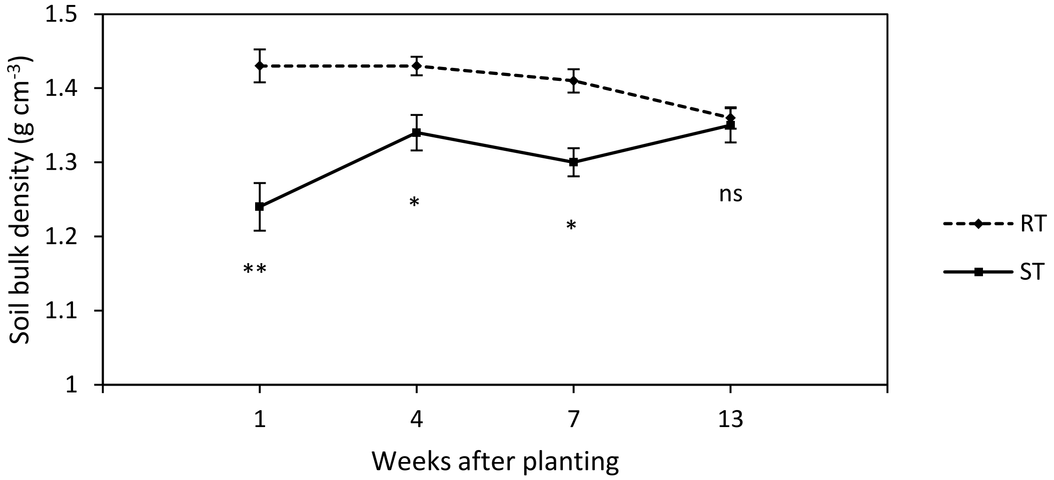

Fig. 2. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) on soil bulk density (g cm^{-3}) at the 15-25 cm soil layer during the potato production period. *P* values < 0.05, < 0.01 and < 0.001 refer to *, ** and ***, respectively; ns = not significant. The bars refer to the standard error values.

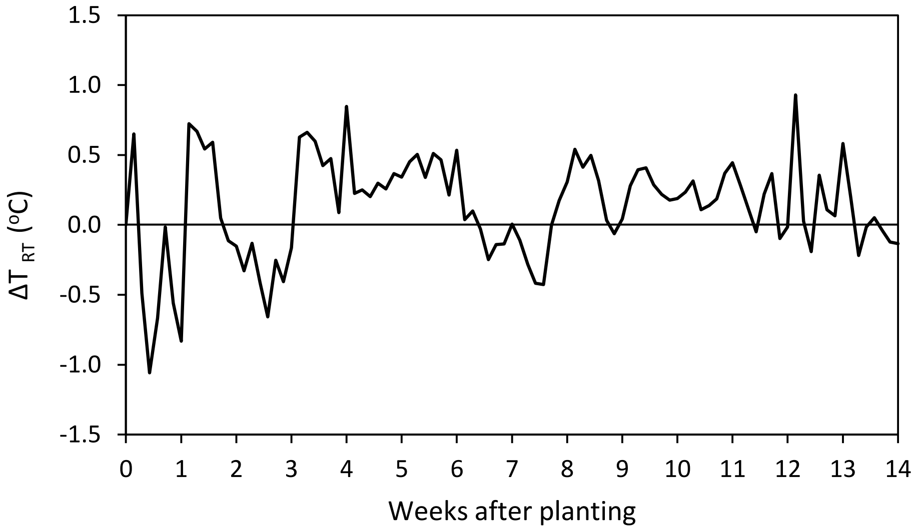

Fig. 3. Soil temperature (^{o}C) differential ($\Delta T_{RT} = T_{RT} - T_{ST}$) at 15 cm depth between reduced tillage (RT) and standard tillage (ST) during the potato production period. Daily data were recorded at 10 minutes intervals.

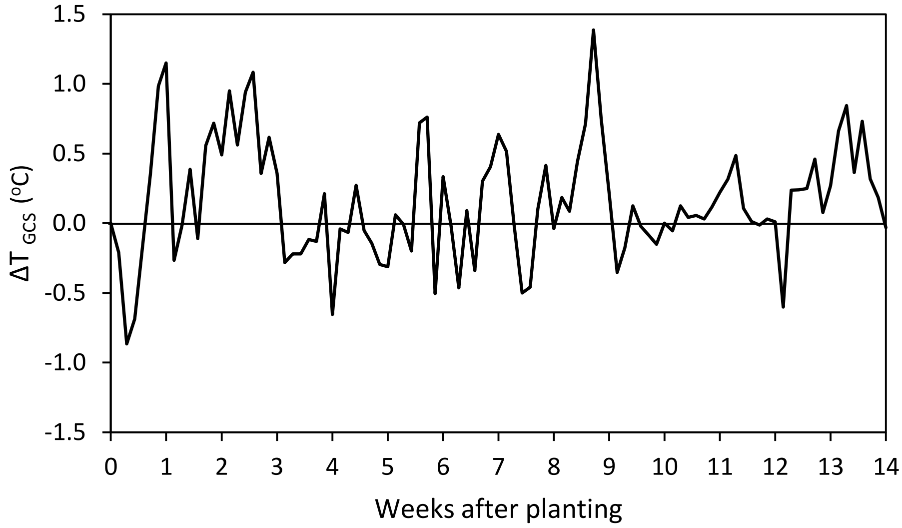

Fig. 4. Soil temperature (^{o}C) differential ($\Delta T_{GCS} = T_{GCS} - T_{SCM}$) at 15 cm depth between grass clover silage (GCS) and solid cattle manure (SCM) during the potato production period. Daily data were recorder at 10 minutes intervals.

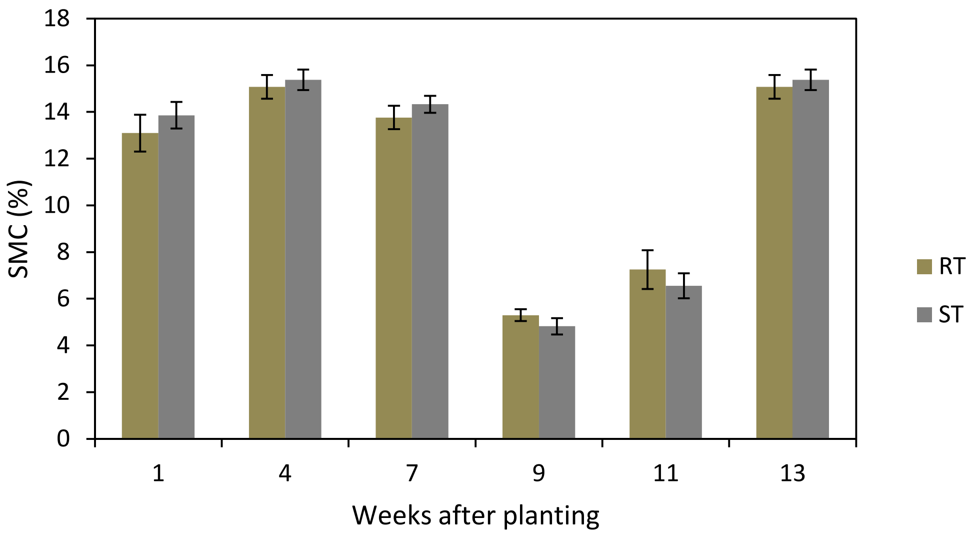

Fig. 5. Effect of tillage practice (reduced tillage, RT; standard tillage, ST) on soil moisture content (SMC) at the 15-25 cm soil layer during the potato production period. *P* values < 0.05, < 0.01 and < 0.001 refer to *, ** and ***, respectively; ns = not significant. The bars refer to the standard error values.

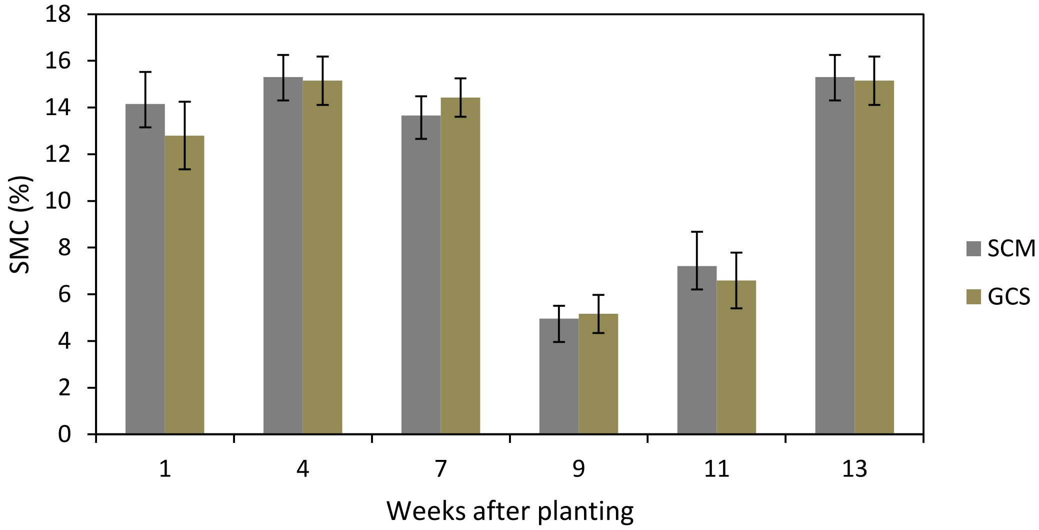

Fig. 6. Effect of fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on soil moisture content (SMC) at the 15-25 cm soil layer during the potato production period. *P* values < 0.05, < 0.01 and < 0.001 refer to *, ** and ***, respectively; ns = not significant. The bars refer to the standard error values.

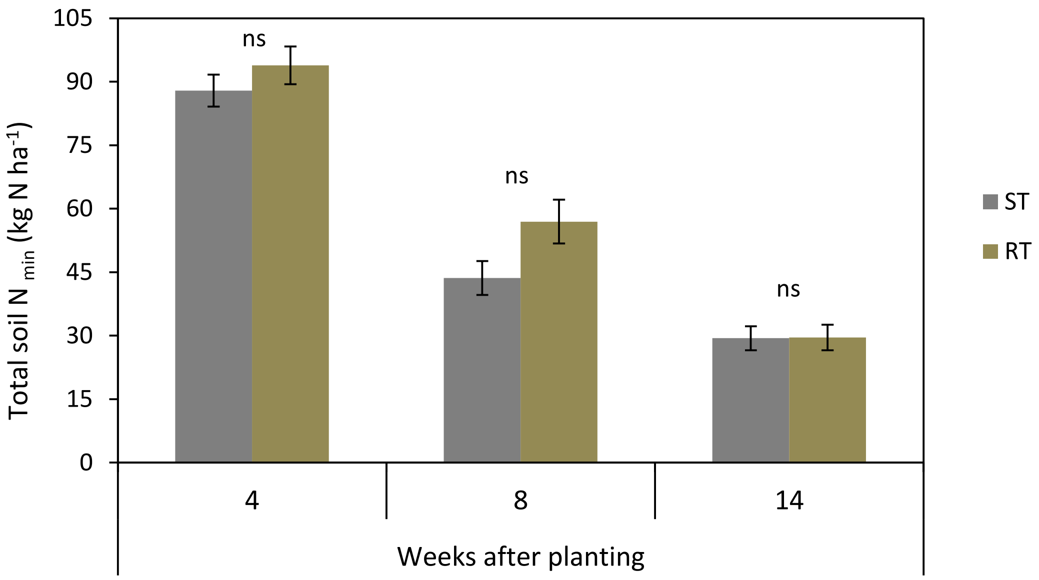

Fig. 7. Total soil N_{min} (kg N ha^{-1}) at the 0-30 cm soil layer as influenced by tillage practice (reduced tillage, RT; standard tillage, ST) at 4, 8 and 14 weeks after planting. *P* values < 0.05, < 0.01 and < 0.001 refer to *, ** and ***, respectively; ns = not significant. The bars refer to the standard error values.

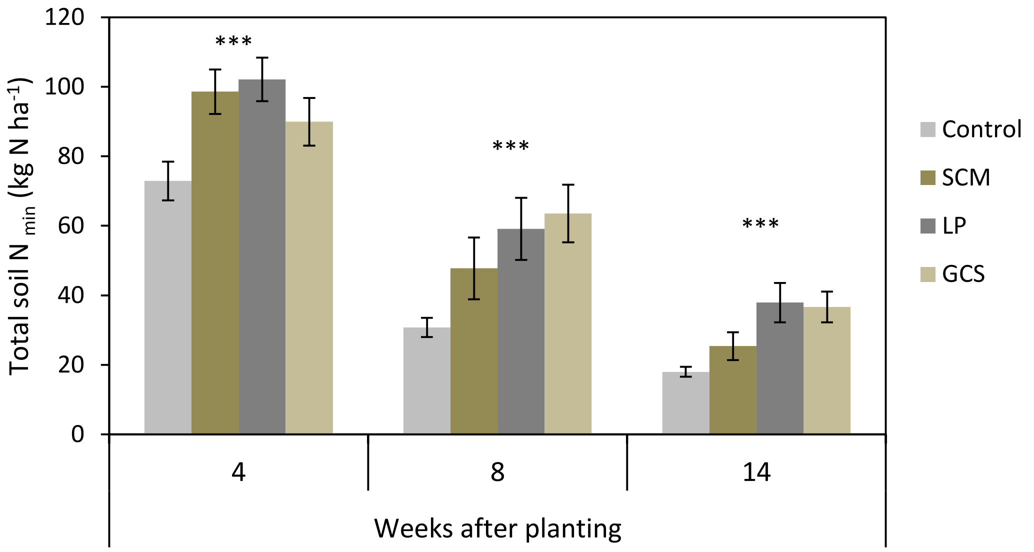

Fig. 8. Total soil N $_{min}$ (kg N ha^{-1}) at the 0-30 cm soil layer as influenced by fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) at 4, 8 and 14 weeks after planting. *P* values < 0.05, < 0.01 and < 0.001 refer to *, ** and ***, respectively; ns = not significant. The bars refer to the standard error values.

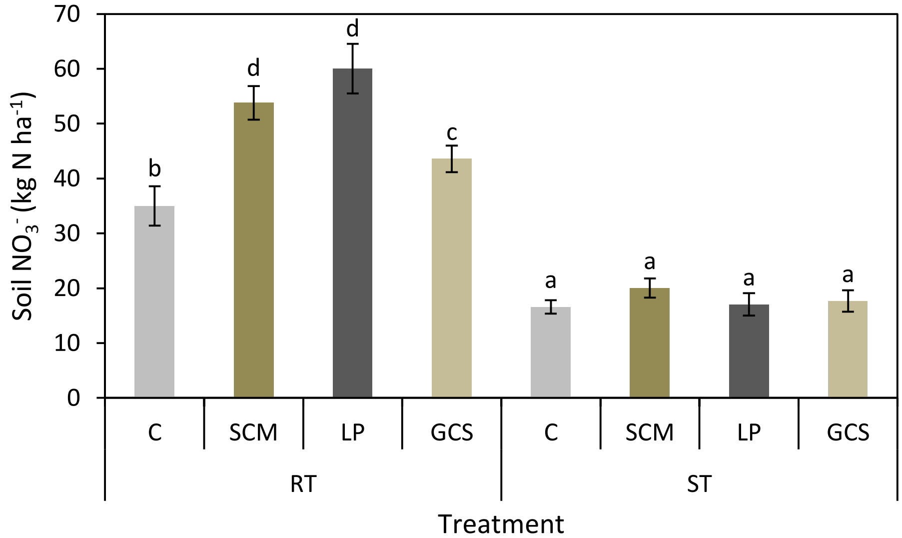

Fig. 9. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on soil NO_3^- (kg N ha^{-1}) at the 0-15 cm soil layer during initial crop growth (4 WAP) of potato. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$). The bars refer to the standard error values.

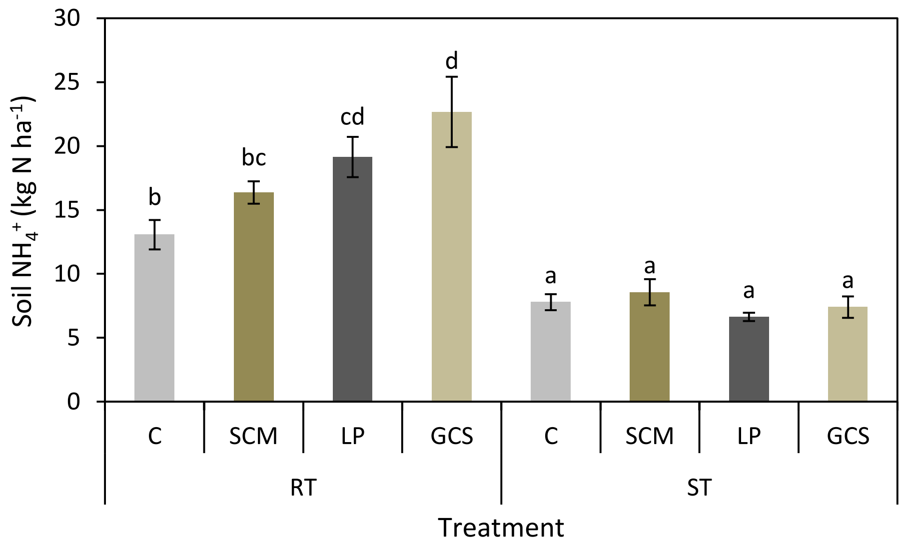

Fig. 10. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on soil NH_4^+ (kg N ha^{-1}) at the 0-15 cm soil layer during the initial crop growth (4 WAP) of potato. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$). The bars refer to the standard error values.

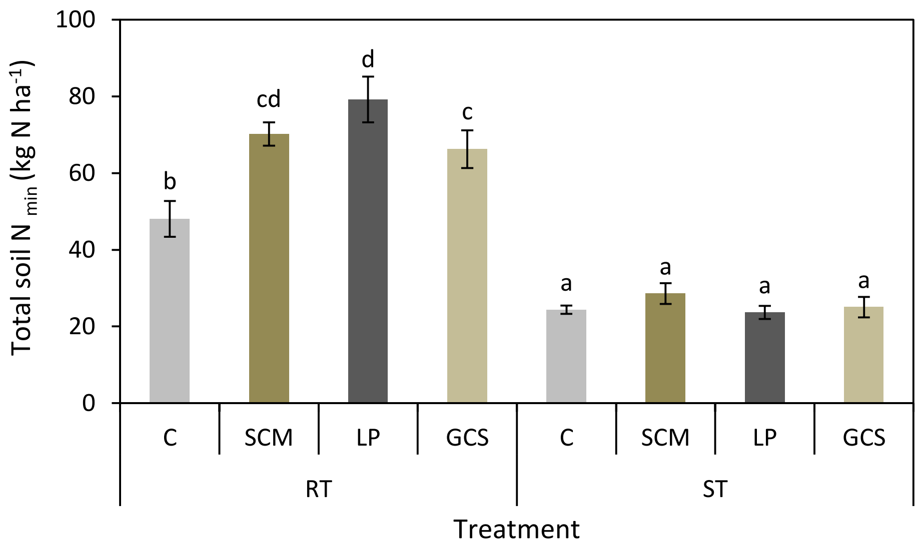

Fig. 11. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on total soil N $_{min}$ (kg N ha^{-1}) at the 0-15 cm soil layer during initial crop growth (4 WAP) of potato. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$). The bars refer to the standard error values.

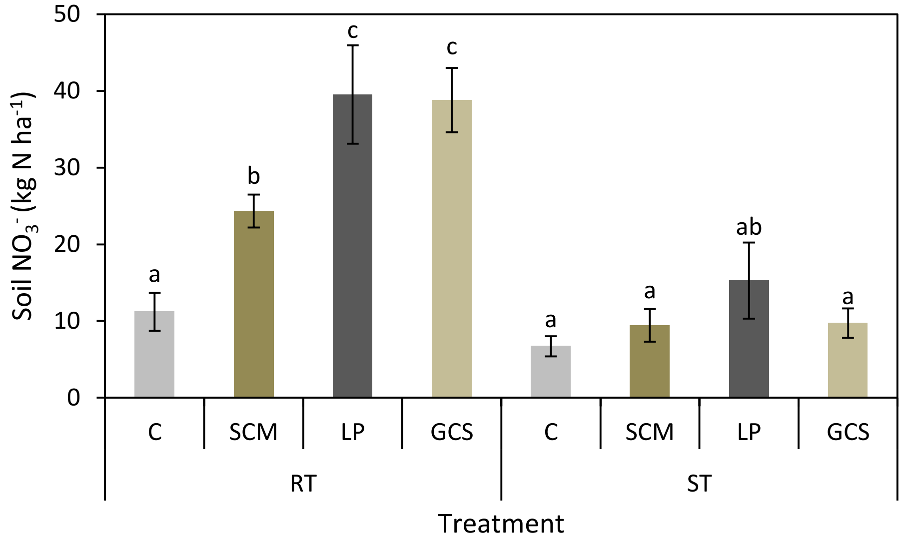

Fig. 12. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on soil NO_3^- (kg N ha^{-1}) at the 0-15 cm soil layer during initial tuber formation (8 WAP). Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$). The bars refer to the standard error values.

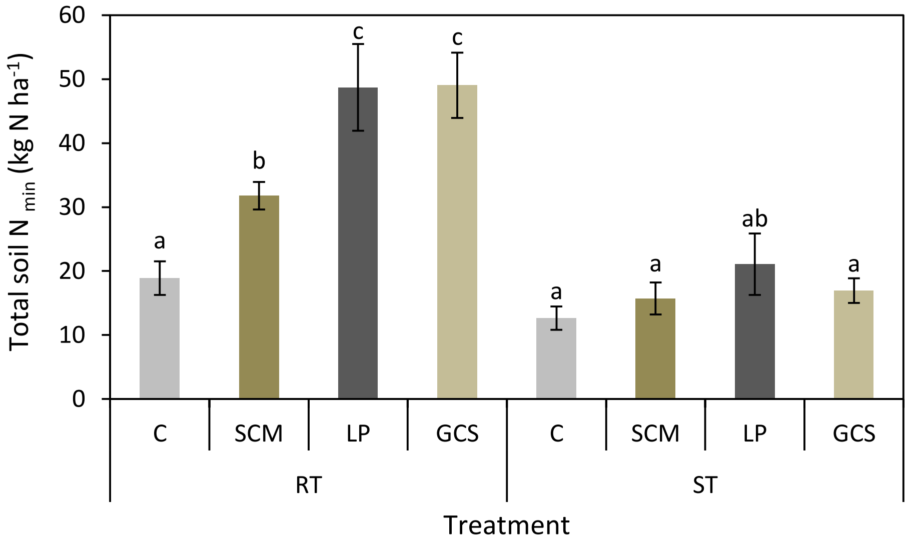

Fig. 13. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on total soil N_{min} (kg N ha^{-1}) at the 0-15 cm soil layer during initial tuber formation (8 WAP). Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$). The bars refer to the standard error values.

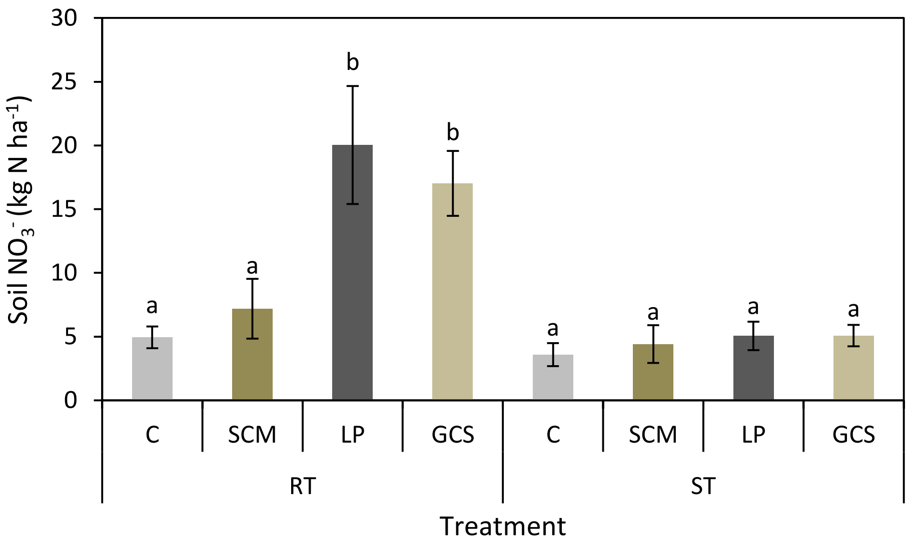

Fig. 14. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on soil NO_3^- (kg N ha^{-1}) at the 0-15 cm soil layer during final harvest (14 WAP) of potato. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$). The bars refer to the standard error values.

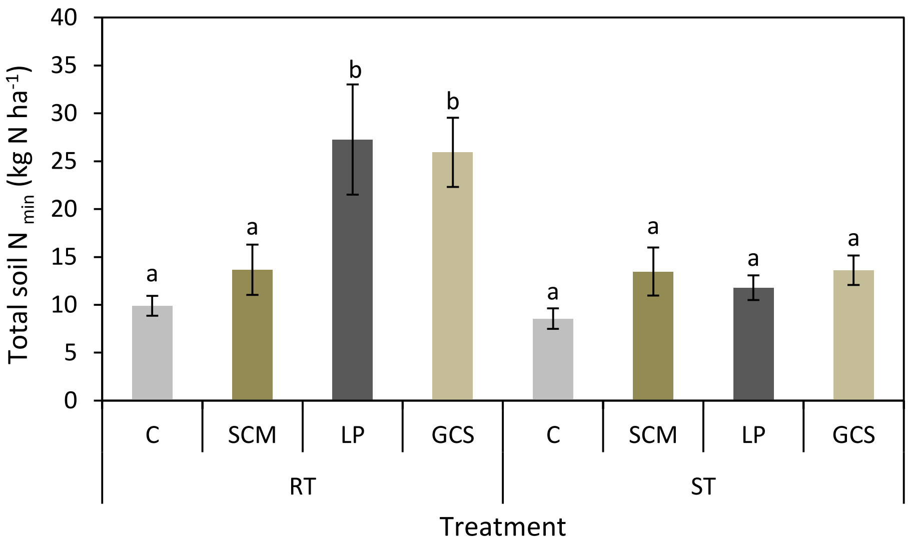

Fig. 15. Influence of tillage practice (reduced tillage, RT; standard tillage, ST) and fertilization regime (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on total soil N_{min} (kg N ha^{-1}) at the 0-15 cm soil layer during final harvest (14 WAP) of potato. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$). The bars refer to the standard error values.

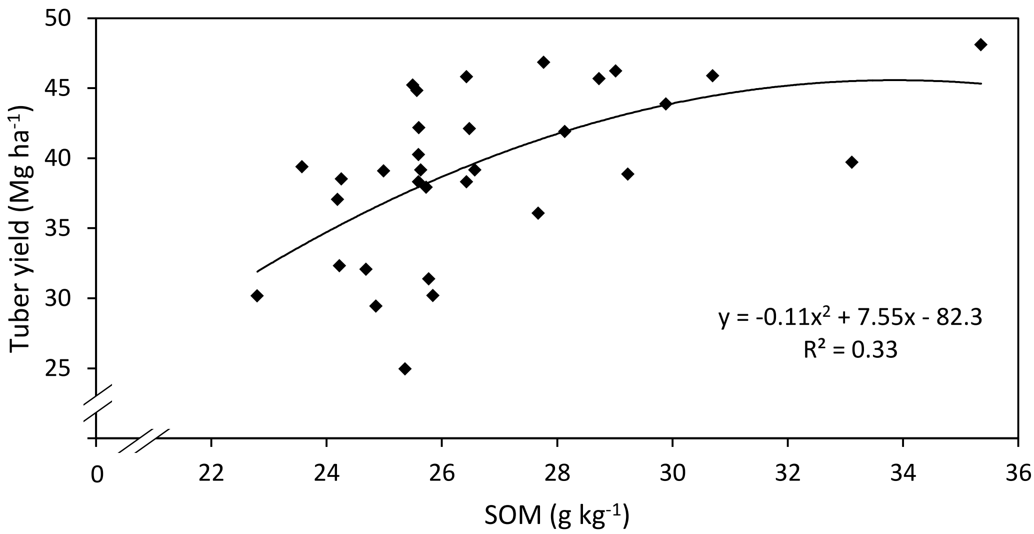

Fig. 16. Quadratic relationship between SOM (g kg^{-1}) at final harvest at the 0-30 cm soil layer and potato tuber yield (Mg ha^{-1}). Data for the potato tuber yield were obtained from Drakopoulos et al. (2014).

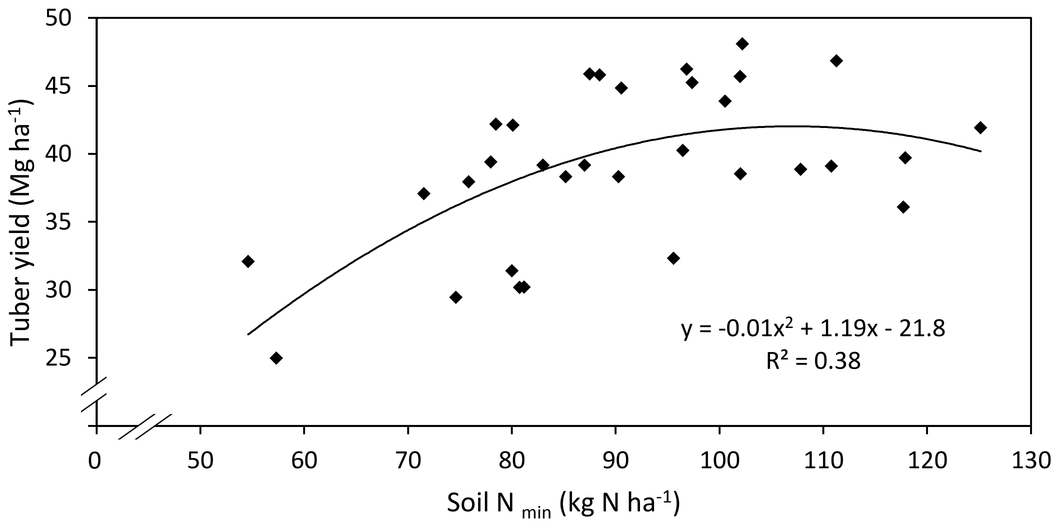

Fig. 17. Quadratic relationship between total soil N_{min} (kg N ha^{-1}) at 4 WAP at the 0-30 cm soil layer and potato tuber yield (Mg ha^{-1}). Data for the potato tuber yield were obtained from Drakopoulos et al. (2014).

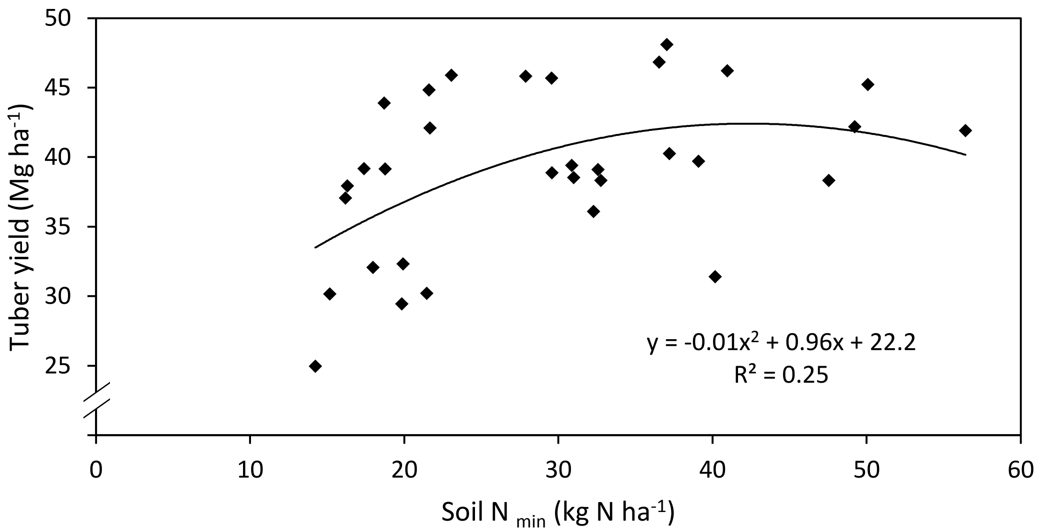

Fig. 18. Quadratic relationship between total soil N_{min} (kg N ha^{-1}) at 14 WAP at the 0-30 cm soil layer and potato tuber yield (Mg ha^{-1}). Data for the potato tuber yield were obtained from Drakopoulos et al. (2014).

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B) Influence of Reduced Tillage and Fertilization Regime on Crop Performance and Nutrient Utilization of Organic Potato in the Netherlands

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Abstract

The majority of Dutch farmers perceive that continuous moldboard plowing is necessary for potato production systems, despite its negative impacts on inherent soil fertility and soil structure while it may also increase potential soil erosion risks. The objective of this study was to investigate the interactive effects of two tillage systems (Reduced Tillage up to 10 cm soil depth - RT; Standard Tillage up to 30 cm soil depth - ST) and three organic amendments (Solid Cattle Manure - SCM; Lucerne Pellets - LP; Grass/Clover Silage - GCS) on crop performance and nutrient utilization of organic potato. Use of RT decreased tuber yield compared to ST due to lower average tuber size which was related to higher soil bulk density and increased vulnerability to drought stress during tuber bulking. On the other hand, use of RT also generated positive effects as nutrient utilization was improved and tubers had a better quality in terms of specific gravity, dry matter and starch contents. However, the price premium associated with enhanced tuber quality may not offset the observed yield gap between RT and ST. Plant-based fertilizers were found to enhance nutrient utilization in terms of ANR compared to animal-based. Use of LP showed great potentials for both tillage systems since it improved most of the crop growth parameters, while GCS may be used with a higher clover to grass ratio and/or N content to promote faster N release. Alternatively, GCS may be applied fresh or dried several weeks before planting to enhance synchronization between N release and crop demand.

Keywords: organic potato, reduced tillage, organic amendments, crop growth, tuber yield, tuber quality, nutrient utilization

1. Introduction

During the past decades, agricultural production has increased rapidly mainly because of breeding, greater nutrient inputs, more effective crop protection measures and innovative soil cultivation practices (Tilman et al., 2002). Nevertheless, such measures at times negatively impact the environment since they may also result in soil degradation, soil erosion as well as water and air pollution (Ludwig et al., 2011).

One of the most common agricultural practices is soil cultivation which is commonly centered on inverted tillage (i.e., conventional deep plowing). Over time this may result in a decline of soil organic matter and inherent soil fertility in the topsoil along with increased risk of soil compaction at greater soil depth (Holland, 2004). However, conventional tillage (i.e., up to 30 cm plowing) is considered necessary in order to manage crop residues, prepare a suitable seedbed, create favorable soil physical properties for germination and crop production as well as to control weeds (Grant and Epstein, 1973; Peignè et al. 2007). On the other hand, conservation tillage is a broad term which refers to a wide range of non-inverted tillage practices and has the potential to reduce soil degradation and preserve soil quality (Holland, 2004; Carter et al., 2007; Putte et al., 2010). Conservation tillage aims to reduce soil disturbance as much as possible using special equipment (e.g., no-till planting drills, disks, chisels) as integral part of innovative tillage techniques. Organic farmers have been encouraged to implement conservation tillage practices in order to attain potential benefits while reducing negative impacts of tillage on inherent soil fertility and to enhance soil conservation (IFOAM, 2009). However, abandoning conventional tillage might also present challenges for organic producers since weed pressure is expected to increase, while the warming of the soil in spring may be slower thereby delaying the initial crop development. Moreover, it is less suitable for compacted soils that are poorly drained and it may restrict the crop choice.

World-wide, potato (*Solanum tuberosum* L.) is the fourth most important crop species after rice, corn and wheat. Global potato production amounted to 368 million tons in 2012 and continues to increase each year (FAOSTAT). There is no standard tillage system for potato crops, but generally soil is intensely tilled for seedbed preparation, repeated ridging and harvesting. This may be detrimental to soil structure and soil quality while it could also increase potential soil erosion risks (Ghazavi et al., 2010). However, many potato producers believe that conservation tillage may result in soil compaction and slower initial plant growth due to lower soil temperature, while soil residues may hamper bed formation as well as harvest operation and thereby reducing yields. On the other hand, some potato growers may opt to implement reduced tillage for two main reasons: a) to improve soil quality and b) to increase profits through cost minimization (Collins et al., 2010). It was stated that the optimal level of tillage depends on soil type and prevailing climatic conditions, and it should just loosen the soil adequately in order to create proper potato ridges (Ghazavi et al., 2010). Several other studies also underlined that reduced tillage could provide a viable alternative to conventional tillage in potato crops (Carter and Sanderson, 2001; Holmstrom et al., 2006; Carter et al., 2009a; Carter et al., 2009b).

In the Netherlands, only 0.8% of the total potato production was certified organic in 2008 (Canali et al., 2012). Except that organic products target a niche market, there is also high yield risk due to infection by *Phytophthora infestans*, high production costs (e.g., seed tubers and fuel costs) and low inherent soil fertility that hamper wide-scale transition to organic potato production. The majority of Dutch farmers perceive that deep plowing is necessary prior to seedbed preparation, ridging and harvesting, thus resulting in soil structure loss. Historically, Dutch farmers tend to increase fertilizer application rates, to off-set decline in soil structure associated with excessive intensification and heavy tractor trafficking which is causing shallow rooting and low fertilizer use efficiencies (Triplett and Dick, 2008). However, during the past decades environmental standards in the Netherlands are becoming more restrictive. So, currently more sustainable tillage practices that restore inherent soil structure and meet the production demand are more acceptable in order to minimize negative environmental impacts.

An innovative agronomic practice in Dutch organic agriculture is the use of cut-and-carry fertilizers (Scholberg et al., 2009). Applying this method, crops with high nitrogen content (e.g., grass-clover and alfalfa) are harvested and transferred to other fields as plant-based fertilizers. The harvested biomass is applied as mulch or may be incorporated into the soil. It may be argued that the combination of cut-and-carry fertilizers and reduced tillage practices could afford organic potato producers in the Netherlands with a viable alternative to enhance resource use efficiency and soil quality while sustaining or even improving crop yield. However, there is limited information on how these strategies may complement and reinforce each other.

The aim of the current study was to investigate the interactive effects of two tillage systems (i.e., Reduced Tillage - RT and Standard Tillage - ST) and three organic amendments (i.e., Solid Cattle Manure - SCM, Lucerne Pellets - LP and Grass/Clover Silage - GCS) on crop performance and nutrient utilization for an organic potato production system. It was hypothesized that initial plant growth would be enhanced using ST compared to RT because of lower soil temperature expected in the latter treatment. Furthermore, it was expected that potato yield and tuber quality would not be affected by tillage system, whereas use of plant-based materials may increase yields due to enhanced nutrient utilization as compared to the use of cattle manure.

2. Materials and Methods

2.1. Experimental site, field history and climatic data

A field experiment was carried out during the spring and summer of 2013 in the organic experimental farm Droevendaal of Wageningen University (51°59'33.68"N, 5°39'34.59"E), Wageningen, the Netherlands. The soil texture was sandy and the soil contained 23.8 g organic matter per kg of soil at the 0-30 cm soil layer. The potato field was irrigated occasionally with 20 mm water during periods of prolonged drought (i.e., on 10th July, 12th July, 16th July and 19th July). More details about the experimental site, the field history and the climatic data during the potato production period are provided in Drakopoulos et al. (2014).

2.2. Experimental design

The experiment had a split-plot design with main- and sub-plot treatments two tillage practices (i.e., Reduced Tillage - RT and Standard Tillage - ST) and four fertilization regimes (i.e., Control - C , Solid Cattle Manure - SCM, Lucerne Pellets - LP and Grass/Clover Silage-GCS), respectively. All treatment combinations were replicated four times in blocks. The target N-application rate was 170 kg N ha^{-1} for each fertilization regime, except for the unamended control plots, and soil amendments were applied prior to planting. The plot size was 10 × 3 m and plots included four rows (i.e., potato ridges). An additional sub-plot treatment (i.e., Grass/Clover Silage Mulch - GCSM) was also included only in the main plot of the RT to test innovative mulching techniques that could facilitate further tillage reduction. In this case only half of the GCSM was applied before planting, while the remainder was placed as mulch four weeks after planting. A paired comparison of GCSM in the main plot of the ST was not included because the treatment was only pertinent in the context of reduced tillage systems.

2.3. Treatments and crop management

Each soil amendment was applied manually and evenly spread across field plots. Then, the material was incorporated into the top 10 cm of the soil with a rotary tiller. Additionally, moldboard plowing up to 30 cm soil depth was used for ST. Thus, soil disturbance occurred up to 10- vs. 30-cm for RT and ST, respectively. Potato tubers (*Solanum tuberosum* L. cv. 'Frieslander') were planted on 17 April 2013 at a depth of 15 cm and using planting distances of 30 cm in the row and 75 cm between the rows. Re-ridging occurred at 29, 44 and 65 days after planting for all treatments except GCSM where it was undertaken only once just before mulch application. Further details about the treatments and crop management practices are provided in Drakopoulos et al. (2014).

2.4. Field and laboratory analyses

2.4.1. Pre-experimental measurements

Total soil mineral nitrogen (N_{min}, kg N ha^{-1}), P (kg P_2O_5 ha^{-1}), K (kg K_2O ha^{-1}) content, initial soil organic matter content (SOM, g kg^{-1}) and soil pH for the 0-30 cm soil layer were determined prior to soil cultivation as described in Drakopoulos et al. (2014). In terms of soil amendments, application rates were based on pre-application N and moisture content analyses, and actual rates typically were within 5% of targeted application rates (Drakopoulos et al., 2014).

2.4.2. Crop performance measurements

The two central plant rows within each plot were used for crop performance measurements in order to avoid potential edge effects from neighboring field plots. Similarly, the first and the last 1.2 m from each row were not included in any measurements collected to avoid displacement effects due to mechanical incorporation of the organic amendments. The overall net plot consisted of 2 rows with 19 plants each.

Plant emergence. Plant emergence counts were collected at 2 days intervals by measuring the number of potato plants that emerged within the net plot. When ≥ 50% plants within a net plot had emerged, the emergence day (expressed as days after planting, DAP) was calculated as: $ED = T_1 + (T_2 - T_1) \times [(19 - M_1) / (M_2 - M_1)]$; where ED is the emergence day; T_1 is DAP when < 50% plants within the net plot had emerged; T_2 is DAP when ≥ 50% plants within the net plot had emerged; 19 refers to 50% of the total plant number (i.e., 38) in the net plot having emerged and is used as reference value; M_1 is the number of plants measured at T_1; M_2 is the number of plants measured at T_2.

Crop growth measurements. Plant height, plant diameter and SPAD values (i.e., leaf chlorophyll index) were recorded at 6, 8, 10 and 12 weeks after planting (WAP). LAI and above-ground dry weight were measured at 7, 9 and 13 WAP. Additionally, the above-ground dry weight and N content were measured at 15 WAP.

Plant height was the distance from the soil surface until the top of the plant, while plant diameter was the average of plant length and width. The leaf chlorophyll index was measured using a SPAD meter (SPAD 502, Konica Minolta Sensing, Inc, Osaka, Japan). A total of four readings was taken using the most recently matured leaflet for which typically translates into the 4th or 5th youngest leaf counting from the upper growing tip of the plant. For consistency, measurements were always made on the terminal leaflet of each composite leaf. Five representative plants per replicate were used for plant height and diameter as well as leaf chlorophyll index measurements. Canopy volume (CV) was calculated based on plant height (Ht) and the plant diameter (D) measurements as: $CV = \pi \times D^2 \times Ht \times 1/6$.

For LAI and above-ground dry weight measurements, a total number of two plants was sampled per replicate within the net plot. First, composite leaves were collected and fresh weights were recorded before determining LAI by feeding individuals leaves through a leaf area meter (LI3100, Li-Cor, Lincoln, NE, USA). Afterwards, the samples were dried at 105^{o}C for 48 hours in order to determine the above-ground dry matter accumulation.

Exceptionally, at 15 WAP a second set of samples was dried at 70^{o}C since this is standard procedure for N content measurements to avoid N losses. Afterwards, the samples were grinded to pass through a 2-mm sieve and transferred for laboratory analysis. Plant samples were digested with a mixture of H_2SO_4-Se and salicylic acid (Novozamsky et al., 1983). Total nitrogen (N_{total}) was measured spectrophotometrically with a segmented-flow system (Technicon Auto-analyzer II, Dublin, Ireland)

Potato tuber yield, number and quality measurements. Potato tuber yield was monitored at 6 days intervals from 12 WAP onwards in order to estimate when the increase in tuber weight would approach zero. To this end, a quadratic regression equation was used (data not shown). Potato tuber yield and tuber number per size category were determined on 30 July 2013 (15 WAP) by manual harvesting the two central rows within each plot over a length of 5.4 m. Tubers were graded and categorized in three categories: a) Small (i.e., 15 - 40 mm), b) Large (i.e., >40 mm) and c) Culls (i.e., tubers with damage and/or infestations regardless of their size). Hereafter, fresh weights of each size category were measured. Tuber specific gravity (SG) was determined on the basis of a representative subsample of 5 kg: SG = W_{air} / (W_{air} - W_{water}); where W_{air} is the tuber fresh weight in air; W_{water} is the tuber fresh weight in water. Subsequently, two sub-subsamples of about 0.5 kg tubers were collected for determining tuber DM and N content. Tubers were sliced in small pieces and dried at 105^{o}C for 48 hours for DM content analysis and at 70^{o}C for 72 hours for N determination. Samples used for N analysis were first grinded to pass through a 2-mm sieve. The starch content of potato tubers was calculated as: Starch content = -1.39 + 0.196 [1000 × (specific gravity - 1)] (Simmonds, 1977).

***N accumulation, Apparent N-Recovery (ANR) and Partial Factor Productivity (PFP*).** Total crop N accumulation was calculated as: ($DM_{above\text{-}ground}$ × N $content_{above\text{-}ground}$) + ($DM_{tuber}$ × N $content_{tuber}$). Apparent N-Recovery (ANR) was calculated as: 100 × (N $accumulation_{treatment}$ - N $accumulation_{control}$) / $N_{applied}$, where N $accumulation_{control}$ corresponds to the average value of each tillage system. It was assumed that indigenous soil N transformations were similar for the fertilized treatments and the control (Cambouris et al., 2008). Partial Factor Productivity (PFP) was calculated as: ($Yield_{treatment}$ - $Yield_{control}$) / $N_{applied}$, where $Yield_{control}$ was taken as the average value for each tillage system.

2.5. Statistical analysis

Data analysis was conducted with analysis of variances (ANOVA) using Genstat 14th edition (VSN International Ltd., Hemel Hempstead, UK). Shapiro-Wilk and Bartlett's tests were used to verify that data showed a normal distribution and variations were constant. Main effects and interactions were assessed for significance levels while mean separation was conducted using Fisher's protected LSD-test.

3. Results and Discussion

3.1. Nutrient application and initial soil measurements

The actual nutrient application rates for each fertilization treatment as well as the initial soil organic matter, total mineral soil N, P, K and pH values are provided in Drakopoulos et al. (2014).

3.2. Plant emergence and leaf chlorophyll index

On average, use of RT led to 3 days faster plant emergence than ST (Table 1). However, there was a significant interaction between tillage system and fertilization treatment on plant emergence time, which is presented in Fig. 2. For RT, fertilization with LP resulted in faster plant emergence compared to GCS, with other treatments showing intermediate values. In contrast, use of ST in combination with GCS led to a somewhat quicker potato plant emergence compared to the other two organic amendments. Overall, plant emergence was faster for RT despite the fact that ST resulted in higher soil temperatures in the upper 15 cm soil layer during the first 3 weeks after planting (WAP) (Drakopoulos et al., 2014). It was observed that the use of moldboard plow (i.e., ST) prior to potato planting resulted in the development of approximately 4 cm higher ridges compared to RT. This could be related to a greater soil volume as reflected by lower soil bulk density values (Drakopoulos et al., 2014). Thus, potato plants may have emerged sooner under RT because the seed tubers were closer to the soil surface. Similarly, Holmstrom et al. (2006) reported more shallow seed depth with use of reduced tillage compared to conventional tillage in a potato production system. In case of GCS, plants emerged at the same time under both tillage systems (Fig. 2).

SPAD values (i.e., leaf chlorophyll index) were similar for both tillage systems at 6 WAP, but slightly higher for RT at 8 WAP compared to ST (Table 1). At 10 and 12 WAP, SPAD values were substantially higher for ST (Table 1). This may be related to the fact that with RT nutrients were mainly concentrated in the upper soil layer (Drakopoulos et al., 2014) and this might have promoted initial crop growth. Over time, as plants exploited deeper soil layers, they may have been benefited from higher nutrient levels at the 15-30 cm soil layer with ST, since this soil layer had nearly three times higher total N_{min} values compared to RT. Alternatively, it may also be argued that higher concentration of nutrients in the top soil under RT may have favored formation of more shallow rooting system. From a resource utilization perspective, this may have resulted in less effective utilization of nutrients and residual soil moisture from the deeper soil layers. This is consistent with field observations, where plants in RT plots appeared to be more vulnerable to soil water stress during a dry spell that occurred at 7 and 8 WAP (Fig. 1).

Plants amended with GCS had the lowest leaf chlorophyll index at 8, 10 and 12 WAP compared to all other fertilization treatments (Table 1). SPAD measurement did not prove to be a reliable tool of assessing either mineral soil N stocks or final yields since the control had similar or higher leaf chlorophyll index compared to GCS. However, it clearly pointed out the nitrogen immobilization that occurred in GCS mainly during initial plant growth resulting in lower SPAD values for this treatment throughout most of the potato production period

(Table 1). Minotti et al. (1994) also reported that SPAD measurement may be used to identify severe nitrogen deficiencies in potatoes, while it cannot be used to detect marginal deficiencies. This may be related to plants tending to keep equilibrium between N uptake and growth, so growth increases proportionally as N supply increases. It is only at extreme low or high supply levels that plants either show a sharp decrease in N content or hyper accumulation as nitrate is stored in the vacuole or in N-rich compounds (luxurious uptake). These compounds may be remobilized later on as N supply declines.

Especially under RT, use of GCS led to obvious nitrogen immobilization as the majority of the leaves were light green. This could be attributed to the fact that the GCS biomass was incorporated into the upper soil layer (i.e., 10 cm) and the soil microbial activity increased rapidly due to the high availability of organic carbon resulting in accumulation of the available nitrogen. Collins et al. (2010) suspected a build-up of soil microorganism under reduced tillage that caused nitrogen immobilization because of more surface residues compared to standard tillage systems. Also, part of this may be related to the changes in microbial communities. Application of material which has higher cellulose and lower N concentrations (e.g., GCS compared to LP) closer to the soil surface would promote more fungal-based decomposition. As a result, the derived microbial biomass may have a wider C:N ratio which in turn affects crop N availability, since the C:N ratio of GCS was 22 and materials with higher values than 20 were reported to cause temporary N immobilization (Canali et al., 2012).

3.3. Plant height, LAI and canopy volume

There was a significant interaction between tillage system and fertilization treatment on plant height at 6 WAP (Table 2), which is presented in Fig. 3. At 6 WAP, RT resulted in about 1 cm taller plants on average for all fertilization treatments compared to the corresponding ST treatments except for GCS in which case the effect was reverse (Fig. 3). This may be related to the observed trends for emergence as discussed earlier. Tillage had no effect on plant height at 8 WAP, whereas plants were taller for ST compared to RT at 10 and 12 WAP (Table 2). In terms of fertilization regime, the control plots had the shortest plants throughout the entire trial, while LP had the tallest although differences were only significant at 12 WAP (Table 2).

Overall LAI values were not affected by tillage during initial growth, but ST had higher LAI values at 9 and 13 WAP than RT, while LAI was not affected by fertilization treatments (Table 2). There was a significant interaction between tillage system and fertilization treatment on canopy volume at 6 WAP (Table 2), and interaction effects are presented in Fig. 4. The interaction effects are similar to those which were described previously for plant height at 6 WAP. Canopy volume was lower under RT compared to ST at 10 and 12 WAP, but there was no clear tillage effect at 6 and 8 WAP (Table 2). At 8, 10 and 12 WAP, canopy volume was highest for SCM and LP and lowest for the control, with GCS having intermediate values (Table 2).

During tuber bulking stage (10 and 12 WAP), plant height, LAI and canopy volume thus were remarkably higher for ST compared to RT. There was a long period of drought at 7 and 8 WAP, while average air temperature increased rapidly, which may explain these differences between the two tillage systems (Fig. 1). Organic amendments were incorporated into deeper soil layer (i.e., up to 30 cm) for ST than RT (i.e., up to 10 cm). As a consequence, with RT roots may have proliferated closer to the soil surface because nutrients were more concentrated in the top soil. These findings are consistent with a field study in an irrigated sweet corn system on a sandy soil in Florida (Cherr et al., 2006; Cherr et al., 2007) where roots did not proliferate to deeper soil layers when RT was applied. So, RT-based systems may be more vulnerable to drought stress especially on sandy soils which have limited water storage capacity. Also, the higher soil bulk density that was found under RT possibly hampered root elongation in deeper soil layers (Drakopoulos et al., 2014).

It was evident that RT tillage appeared to favor early emergence and initial growth. Over time ST-based systems were able to gradually catch-up as roots reached deeper soil layers, thus resulting in similar mid-season (8 WAP) performance in terms of plant height and canopy volume. Towards the end, ST system clearly out-performed RT, which was probably related to the short drought-stress induced growth-lag after 8 WAP, resulting in a decrease in plant height and LAI of 10.9 and 15.6%, respectively. In terms of soil amendments, there was a clear benefit of their application on plant growth (i.e., plant height and canopy volume) starting at 8 WAP.

3.4. Dry matter yield, above-ground DM accumulation and tuber yield

Use of ST resulted in 10% higher tuber dry matter (DM) yield compared to RT (Table 3). In terms of soil amendments, DM yield was highest for LP and lowest for the control, with SCM and GCS having intermediate values (Table 3). Starting at 9 WAP, above-ground DM accumulation was greater with ST compared to RT, while values were similar for both tillage systems during initial growth (Table 3). The above-ground DM accumulation did not differ among different fertilization treatments (Table 3).

In terms of tuber yield, use of ST increased the yield of large tubers compared to RT, while the yield of small tubers and culls was not influenced by tillage (Table 4). The yield of large tubers was highest for LP and lowest for the control, with SCM and GCS having intermediate values (Table 4). The yield of small tubers was higher in the control than the fertilized treatments, while the opposite occurred for culls (Table 4). Total tuber yield and marketable yield were higher for ST compared to RT (Table 4). These findings are in contrast with those by Carter and Sanderson (2001) who reported that reduced-shallow tillage (i.e., chisel plough up to 15 cm) prior to potato planting had similar potato yields compared to conventional tillage. Similarly, Alva et al. (2009) found that reduced tillage sustained tuber yield under an irrigated potato production system. However, based on field observations, potato plants in RT plots were more susceptible to water stress during initial tuber formation (8 WAP) and positive correlation between yield and soil moisture supply have been shown during that period (Saue et al., 2010). Costa et al. (1997) also reported that the greatest reductions of photosynthesis, total biomass and final yield of potatoes occurred when drought was imposed during tuber initiation. Furthermore, potatoes have in general a relatively shallow root system compared to other crops such as legumes and therefore require irrigation during drought periods, especially when soils have low water holding capacity (e.g., sandy soils) (Loon,1981). Thus, it is presumed that the drought period at 7 and 8 WAP may have negatively impacted initial tuber formation and tuber bulking of potato plants under RT impairing also plant growth parameters as described above (i.e., canopy volume and above-ground DM accumulation). Total yield and marketable yield were highest for LP and lowest for the control, with SCM and GCS taking intermediate positions (Table 4).

One-way comparison among different treatments showed that yield differences were most pronounced for RT treatments while yield for the non-fertilized control was also lower with use of RT compared to ST (Fig. 5). Combined use of ST with LP resulted in highest yields, whereas among fertilized plots use of GCS combined with RT performed relatively poor mainly because of nitrogen immobilization during initial crop growth, as indicated by the reductions in leaf chlorophyll index (Fig. 5, Table 1). The combination of GCSM with RT appeared to be a promising treatment, since it yielded similarly with GCS and SCM under ST (Fig. 5).

3.5. Tuber number and average tuber size

Tillage did not affect the number of tubers for any of the grading classes (i.e., small, large, culls and marketable) (Table 5). However, there was a significant interaction effect on large tubers, which is presented in Fig. 6. The number of large tubers was similar for RT and ST for each corresponding fertilization treatment, except GCS where ST had higher number than RT (Fig. 6). The number of small, cull, and marketable tubers was not affected by fertilization treatment (Table 5). The average marketable tuber size was 10.7% larger for ST compared to RT, while N source had no effect on average tuber size (Table 5). So, RT did not appear to hamper tuber initiation, whereas the reduction in tuber bulking did account for most of the 13.4% yield reduction for RT system. This may have been caused because water was a limiting factor for the RT treatments, as discussed earlier. Also, the increased soil bulk density under RT was found to affect negatively tuber bulking (Drakopoulos et al, 2014). Similarly in another study, use of conservation tillage (i.e., shifting the primary tillage from autumn to spring and apply reduced shallow tillage prior to potato planting) resulted in the same number of potato tubers, but decreased average tuber size, compared to conventional tillage (Carter and Sanderson, 2001).

3.6. Potato tuber quality

Use of RT increased the specific gravity, dry matter and starch content of potato tubers compared to ST (Table 6) while strong positive correlation between dry matter content and specific gravity was found (data not shown). This again points towards potential water stress effects as dry matter content of potato tubers tends to increase under water-limited conditions (Heuer and Nadler, 1995; Sharma et al., 2011), since water stress promotes accumulation of assimilates in the tubers (Munns and Pearson 1974). It was also reported that larger potato tubers may result in lower dry matter and starch contents compared to smaller tubers (Tein et al., 2014), and the average tuber size was lower for RT compared to ST.

In terms of fertilization regime, specific gravity and starch content were highest for the control and lowest for LP and GCS, with SCM taking an intermediate position (Table 6). Ojala et al. (1990) reported that specific gravity decreased with increased nitrogen availability, while it was not affected by different tillage (i.e., conventional-primary tillage with chisel plowing vs. reduced-no primary tillage) and nitrogen management practices on a fine sandy soil (Alva et al., 2009). Hajšlová et al. (2005) reported that the amount of nitrogen applied was negatively correlated with tuber dry matter and starch contents.

3.7. N accumulation, ANR and PFP

Use of ST resulted in higher tuber and total N accumulation compared to RT, while N accumulation in the above-ground biomass was not affected by tillage system (Table 7). Ekeberg and Riley (1996), on the other hand, found higher nitrogen content in both haulm and potato tubers under no till system (i.e., direct planting into untilled soil) compared to conventional tillage (i.e., autumn ploughing up to 20-25 cm depth). In another study, tuber concentration of macro- and micro-nutrients was not affected by tillage treatment when measured each year from 2000 to 2005 (Carter et al., 2009c). In terms of fertilization effects, tuber and total N accumulation were highest for LP and GCS and lowest for the control, with SCM having intermediate values (Table 7). The N accumulation in the above-ground biomass was highest for GCS, intermediate for LP and lowest for the control and SCM (Table 7).

The Apparent N-Recovery (ANR) for above-ground biomass was not influenced by tillage, while tuber and total ANR values were higher for RT compared to ST (Table 7). The ANR value for above-ground biomass was higher for GCS than SCM and LP, which had similar values (Table 7). The ANR values for tubers were not influenced by fertilization, whilst total ANR was lower in SCM than LP and GCS (Table 7). The relatively high N accumulation in GCS stands in sharp contrast with the low leaf chlorophyll index (Table 1). It may be argued that GCS material caused N immobilization earlier in the season and net N released late during final growth. Consequently, this did not contribute to increased chlorophyll content since leaf formation had already ceased, but instead the extra N was partitioned directly to the tubers.

Although GCS performed well from a N recovery perspective, poor synchronization of N supply and crop demand hampered optimal growth and efficient N utilization from a production perspective. This is supported by the results for Partial Factor Productivity (PFP) where numeric PFP values were highest for LP compared to SCM and GCS, however the differences were not significant (Table 7). It should be noted that with RT the efficiency of N-use in terms of tuber productivity increased by 44.1% (Table 7). This finding is related to a sharp decrease in estimated SOM mineralization rate (i.e., 127 vs. 192 kg N ha^{-1} for RT and ST, respectively) in non-amended control plots (Drakopoulos et al., 2014).

Thus, it is evident that the optimal material choice and/or timing of application greatly differ among tillage systems. More specifically, mineralization of both soil amendments and SOM may be greatly delayed and/or reduced under RT. Therefore, in order to minimize yield reductions either materials that mineralize more readily (e.g., LP) should be used or materials may be applied earlier (e.g., GCS).

3.8. Regression analysis

In terms of resource management and marketing logistics, it may be desirable to develop simple indicators that correlate well with the final yield. Linear regression equations and corresponding r-squared and p-values for potato yield as a function of selected plant growth parameters are outlined in Table 8. Starting at 8 WAP, linear relationships expressing yield as a function of plant height and canopy volume appeared to be significant (Table 8). At 4 weeks before final harvesting, use of plant height and canopy volume measurements accounted for 68% and 61% of the observed yield variability, respectively. In general, total yield increased with higher values of plant height, LAI and canopy volume at 8, 10 and 12 WAP (Table 8). Similarly, other research studies showed that LAI was strongly correlated with light interception while potato tuber yield increased linearly with an increase in these parameters (MacKerron and Waister, 1985; Oijen, 1991; Boyd et al., 2002). Contrarily, there was no significant relationship between leaf chlorophyll index and total yield (Table 8). There were inverse linear relationships between tuber dry matter content and total tuber yield (Table 9). Thus, as yield and/or total N accumulation increased, tuber dry matter content and to some extend the tuber quality decreased (Table 9). White et al. (2009) reported that higher-yielding genotypes occasionally resulted in lower concentrations of some mineral elements compared to lower-yielding genotypes of potatoes while Westermann et al. (1994) found that the highest specific gravity was associated with the lowest nitrogen and potassium application rates.

4. Conclusions

The aim of the current research was to investigate the influence of reduced tillage and different fertilization regimes on crop performance and nutrient utilization of organic potato on a sandy soil in the Netherlands. Although long-term studies reported that conservation tillage can sustain potato yield and tuber quality compared to conventional moldboard plowing by simultaneously lowering the production costs and enhancing soil quality, we found that RT (i.e., rotary tiller up to 10 cm tillage depth) before planting decreased tuber yield compared to ST (i.e., moldboard plowing up to 30 cm tillage depth). Since tuber number was the same between the two tillage systems and average tuber size was higher for ST, it could be argued that tuber bulking was hampered under RT mainly because of higher soil bulk density and increased vulnerability to drought stress (7 and 8 WAP). Thus, as potato plants appeared to be more susceptible to drought with the use of RT due to root proliferation mainly in the top soil layer, supplemental irrigation may be required earlier in the season if prolonged drought occurs. These findings are in contrast with the prevailing notion that RT results in more effective use of limited water resources. So, it is more relevant to understand the specific context of resource management systems in terms of what, where and how system works, rather than trying to perpetuate preconceived notions. On the other hand, use of RT also generated positive effects as tubers had a better quality in terms of specific gravity, dry matter and starch content. However, the price premium associated with enhanced tuber quality may not offset the observed yield gap between RT and ST. Although use of RT appeared to improve nutrient utilization, since ANR and PFP values were higher compared to ST, N synchronization dynamics may still be enhanced to improve further N use efficiency.

Plant-based fertilizers were found to enhance nutrient utilization compared to animal-based, since LP and GCS had higher ANR percentages than SCM. The combination of RT with GCS as fertilization performed poor because of N immobilization, pointing out the importance of C:N ratio for different soil amendments along with optimal synchronization. Applying half of the grass clover silage prior to planting and the remainder after the first re-ridging (i.e., GCSM) under RT performed relatively well in terms of tuber yield. This may be a viable practice, since it allows producers to further reduce field trafficking and production costs while sustaining final yields. Thus, this fertilization technique along with reduced tillage should be further investigated in potato systems to confirm these positive preliminary results. SPAD measurement did not prove to be a useful predictor for final yield, however it did point out potential risks of N immobilization (e.g., RT+GCS treatment). Use of LP under organic potato production showed great potentials for both tillage systems, since it improved most of the crop growth parameters compared to all other fertilization treatments. Nevertheless, its high cost may be restrictive and therefore it could be combined with other cheaper soil amendments. Use of grass-clover material with a higher clover to grass ratio and/or N content may result in faster N release or alternatively, the material could be applied fresh or dried several weeks before planting.

5. Tables and Figures

5.1. Tables

Table 1. Effect of tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on plant emergence (days after planting, DAP) and leaf chlorophyll index (-) of potato.

	Plant emergence (DAP)	Leaf chlorophyll index (-)			
		6 WAP[1]	8 WAP	10 WAP	12 WAP
Tillage (T)					
RT	23	34.5	46.8	43.4	41.6
ST	26	35.7	46.3	47.2	46.8
Significance[2]	***	ns	*	*	*
Fertilization (F)[3]					
Control	25	35.6	47.7 bc	47.3 b	45.3 bc
SCM	25	35.1	46.5 b	46.7 b	45.1 b
LP	24	34.8	48.5 c	46.9 b	47.7 c
GCS	25	34.9	43.6 a	40.3 a	38.7 a
Significance	ns	ns	***	***	***
T × F	*	ns	ns	ns	ns

[1] WAP = weeks after planting.

[2] *, ** and *** refer to P values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[3] No mean separation for main effects is presented whether interaction effect was significant (P < 0.05); Different letters indicate significant differences according to Fisher's protected LSD-test (P < 0.05).

Table 2. Effect of tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on plant height (cm), LAI ($m^2\ m^{-2}$) and canopy volume ($cm^3 \times 10^3$) of potato.

	Plant height (cm)				LAI ($m^2\ m^{-2}$)			Canopy volume ($cm^3 \times 10^3$)			
	6 WAP[1]	8 WAP	10 WAP	12 WAP	7 WAP	9 WAP	13 WAP	6 WAP	8 WAP	10 WAP	12 WAP
Tillage (T)											
RT	7.51	26.1	39.0	40.9	0.61	1.98	2.76	1.01	22.5	50.9	54.2
ST	7.03	26.0	43.4	45.9	0.58	2.54	3.27	0.87	24.5	64.6	84.4
Significance[2]	ns	ns	**	*	ns	**	**	ns	ns	*	*
Fertilization (F)[3]											
Control	6.57	22.9 a	37.3 a	37.5 a	0.61	1.86	2.43	0.75	17.5 a	45.6 a	51.7 a
SCM	7.53	26.3 b	42.9 b	44.3 b	0.56	2.48	3.01	1.06	24.9 b	63.1 b	74.7 bc
LP	8.00	28.5 b	43.9 b	47.6 c	0.64	2.41	3.38	1.09	27.9 b	64.0 b	81.4 c
GCS	6.97	26.5 b	40.7 ab	44.0 b	0.58	2.30	3.24	0.87	23.6 b	58.5 ab	69.3 b
Significance	*	***	*	***	ns	ns	ns	ns	**	*	***
T × F	*	ns	ns	ns	ns	ns	ns	*	ns	ns	ns

[1] WAP = weeks after planting.

[2] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[3] No mean separation for main effects is presented whether interaction effect was significant (*P* < 0.05); Different letters indicate significant differences according to Fisher's protected LSD-test (*P* < 0.05).

Table 3. Effect of tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on tuber dry matter (DM) yield (Mg ha^{-1}) and above-ground DM accumulation (Mg ha^{-1}) of potato.

	Tuber DM yield (Mg ha^{-1})	Above-ground DM accumulation (Mg ha^{-1})			
		7 WAP[1]	9 WAP	13 WAP	15 WAP
Tillage (T)					
RT	9.06	0.45	1.13	1.71	1.75
ST	10.04	0.42	1.36	2.25	2.00
Significance[2]	**	ns	*	***	*
Fertilization (F)[3]					
Control	8.71 a	0.46	1.05	1.68	1.58
SCM	9.49 ab	0.39	1.34	1.96	1.74
LP	10.50 b	0.46	1.38	2.20	2.01
GCS	9.49 ab	0.43	1.22	2.08	2.17
Significance	*	ns	ns	ns	ns
T × F	ns	ns	ns	ns	ns

[1] WAP = weeks after planting.

[2] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[3] Different letters indicate significant differences according to Fisher's protected LSD-test (*P* < 0.05).

Table 4. Effect of tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on yield of three tuber categories (Mg ha^{-1}), marketable yield (Mg ha^{-1}) and total yield (Mg ha^{-1}) of potato.

	Yield per tuber category[1]			Marketable yield	Total yield
	Small	Large	Culls		
	------------	------------	Mg ha^{-1}	------------	------------
Tillage (T)					
RT	8.43	27.2	0.70	35.6	36.3
ST	7.46	33.1	1.31	40.6	41.9
Significance[2]	ns	**	ns	*	**
Fertilization (F)[3]					
Control	10.25 b	22.4 a	0.53 a	32.6 a	33.1 a
SCM	7.67 a	30.5 b	1.37 b	38.1 b	39.5 b
LP	6.63 a	36.2 c	0.91 ab	42.9 c	43.8 c
GCS	7.23 a	31.5 bc	1.20 b	38.8 b	40.0 b
Significance	**	***	*	***	***
T × F	ns	ns	ns	ns	ns

[1] Tuber categories: Small = 15-40 mm; Large = >40 mm; Culls = tubers with damages and/or infestations regardless of their size. Marketable yield = Small and large tubers. Total = Small, large and culls tubers.

[2] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[3] Different letters indicate significant differences according to Fisher's protected LSD-test (*P*

< 0.05).

Table 5. Effect of tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on tuber number (10^3 ha^{-1}) of three tuber categories and average tuber size (g) of total and marketable tubers of potato.

	Potato tuber number (10^3 ha^{-1})				Average tuber size (g)	
	Small[1]	Large	Culls	Marketable	Total	Marketable
Tillage (T)						
RT	290	339	19	629	56.8	57.4
ST	299	341	57	640	61.2	64.3
Significance[2]	ns	ns	ns	ns	ns	*
Fertilization (F)[3]						
Control	325	255	24	581	55.9	57.6
SCM	304	354	35	658	57.9	58.8
LP	254	387	56	641	63.9	67.2
GCS	296	364	35	659	58.5	59.9
Significance	ns	***	ns	ns	ns	ns
T × F	ns	*	ns	ns	ns	ns

[1] Tuber categories: Small = 15-40 mm; Large = >40 mm; Culls = tubers with damages and/or infestations regardless of their size. Marketable = Small and large tubers. Total = Small, large and culls tubers.

[2] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[3] No mean separation for main effects is presented whether interaction effect was significant ($P < 0.05$).

Table 6. Effect of tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on tuber quality parameters, i.e. specific gravity (-), dry matter content (%) and starch content (%) of potato tubers.

	Specific gravity (-)	Dry matter (%)	Starch content (%)[1]
Tillage (T)			
RT	1.087	25.03	15.71
ST	1.073	24.05	13.00
Significance[2]	**	**	**
Fertilization (F)[3]			
Control	1.091 b	26.37 b	16.47 b
SCM	1.081 ab	24.04 a	14.57 ab
LP	1.071 a	24.03 a	12.52 a
GCS	1.078 a	23.73 a	13.87 a
Significance	*	***	*
T × F	ns	ns	ns

[1] According to Simmonds, 1977: Starch content = -1.39 + 0.196 [1000 (specific gravity - 1)].

[2] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[3] Different letters indicate significant differences according to Fisher's protected LSD-test ($P < 0.05$).

Table 7. Effect of tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS) on N accumulation (kg N ha^{-1}), Apparent N-Recovery (ANR, %) and Partial Factor Productivity (PFP, kg yield kg N $applied^{-1}$) of potato.

	N accumulation (kg N ha^{-1})			ANR (%)			PFP
	Above-ground	Tubers	Total	Above-ground	Tubers	Total	(kg yield kg N $applied^{-1}$)
Tillage (T)							
RT	35.6	140	176	9.5	33.4	42.9	59.7
ST	44.8	163	208	6.3	12.3	18.6	33.4
Significance[1]	ns	**	**	ns	**	***	*
Fertilization (F)[2]							
Control	30.3 a	123 a	153 a	-	-	-	-
SCM	32.3 a	150 b	182 b	1.2 a	16.8	18.0 a	38.6
LP	42.4 b	174 c	216 c	6.7 a	28.6	35.3 b	58.5
GCS	55.7 c	160 bc	216 c	15.8 b	23.3	39.1 b	42.4
Significance	***	***	***	***	ns	**	ns
T × F	ns	ns	ns	ns	ns	ns	ns

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[2] Different letters indicate significant differences according to Fisher's protected LSD-test (*P* < 0.05).

Table 8. Outline of regression analysis for plant growth parameters vs. potato tuber yield (i.e., tuber yield is expressed as a function of plant height, LAI, canopy volume and leaf chlorophyll index). The plant growth parameters are the explanatory variables (x), and the potato tuber yield is the response variable (y). Y values ranged from 25.0 to 48.1 Mg ha^{-1}.

Explanatory variable	Equation	R^2 value	Significance[1]
Plant height (cm)			
6 WAP[2]	y = 30.2 + 1.22x	0.06	ns
8 WAP	y = 9.42 + 1.14x	0.33	***
10 WAP	y = -3.03 + 1.02x	0.68	***
12 WAP	y = -1.66 + 0.94x	0.72	***
LAI (m^2 m^{-2})			
7 WAP	y = 42.2 - 5.20x	0.01	ns
9 WAP	y = 26.8 + 5.44x	0.34	***
13 WAP	y = 27.5 + 3.85x	0.28	**
Canopy volume ($cm^3 \times 10^3$)			
6 WAP	y = 37.1 + 1.45x	0.03	ns
8 WAP	y = 26.3 + 0.36x	0.32	***
10 WAP	y = 21.9 + 0.20x	0.61	***
12 WAP	y = 26.0 + 0.13x	0.52	***
Leaf chlorophyll index (-)			
6 WAP	y = 47.4 - 0.24x	0.00	ns
8 WAP	y = 53.2 - 0.30x	0.02	ns
10 WAP	y = 23.5 + 0.34x	0.06	ns
12 WAP	y = 23.0 + 0.36x	0.10	ns

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[2] WAP = weeks after planting.

Table 9. Outline of regression analysis for crop productivity parameters vs. tuber dry matter content (i.e., tuber dry matter content is expressed as a function of total crop N accumulation and tuber yield). The total crop N accumulation and tuber yield are the explanatory variables (x), and the tuber dry matter content is the response variable (y). Y values ranged from 22.3 to 27.3 %.

Explanatory variable	Equation	R^2 value	Significance[1]
Total N accumulation[2] (kg N ha^{-1})	y = 28.5 - 0.021x	0.31	**
Tuber yield (Mg ha^{-1})	y = 29.9 - 0.139x	0.32	***

[1] *, ** and *** refer to *P* values < 0.05, < 0.01 and < 0.001, respectively; ns = not significant.

[2] Total N accumulation = N accumulation of tubers + N accumulation of above-ground biomass at harvest.

5.2. Figures

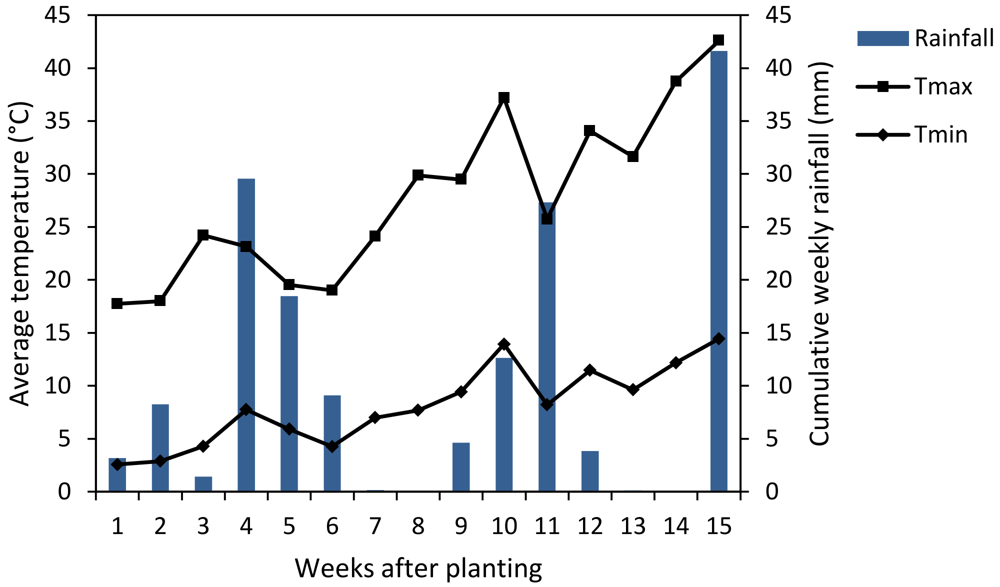

Fig. 1. Minimum (T_{min}, °C) and maximum (T_{max}, °C) averaged weekly temperatures along with cumulative weekly rainfall (mm) during the potato production period (17/4/2013 - 30/7/2013).

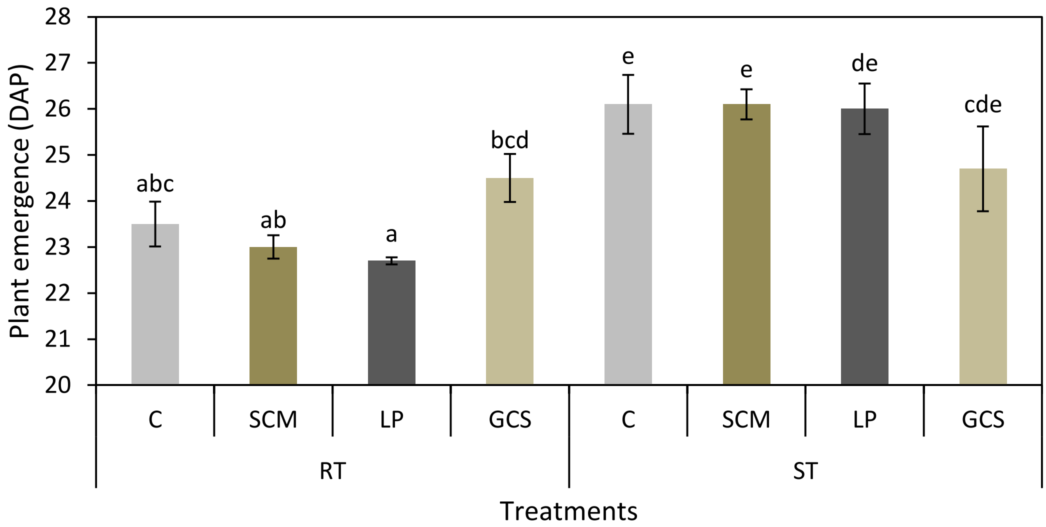

Fig. 2. Plant emergence (days after planting, DAP) as influenced by tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS). The bars stand for the standard error values. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$).

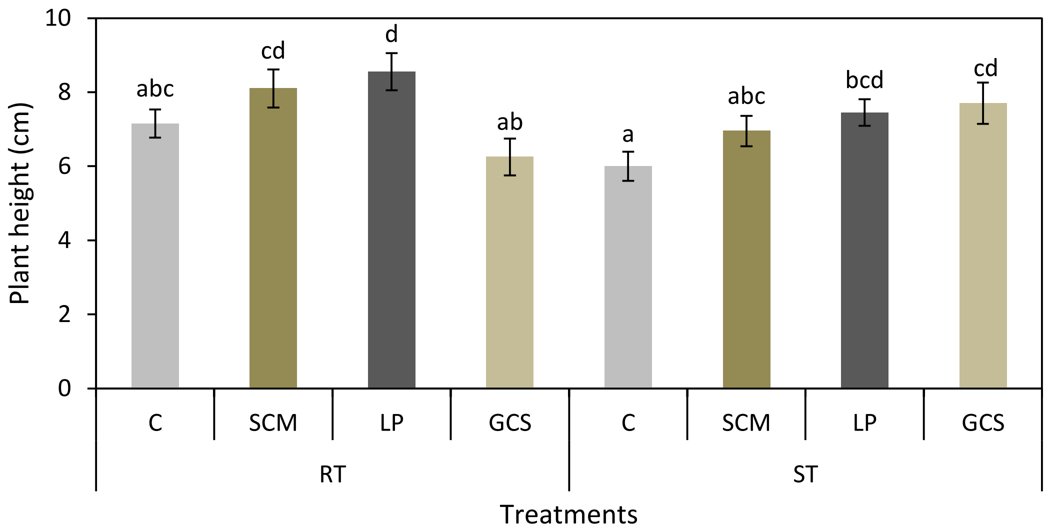

Fig. 3 Plant height (cm) of potato at 6 WAP as influenced by tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS). The bars stand for the standard error values. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$).

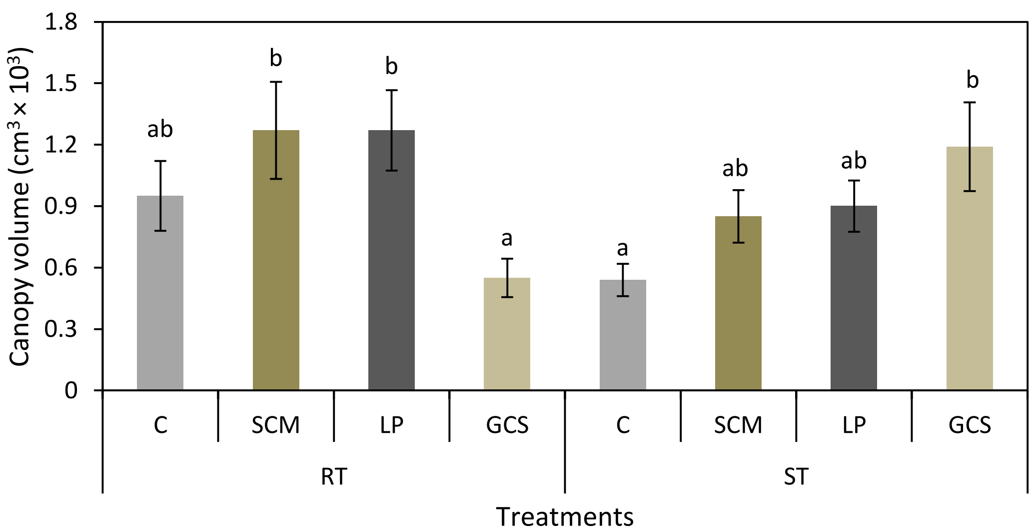

Fig. 4 Canopy volume ($cm^3 \times 10^3$) of potato at 6 WAP as influenced by tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS). The bars stand for the standard error values. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$).

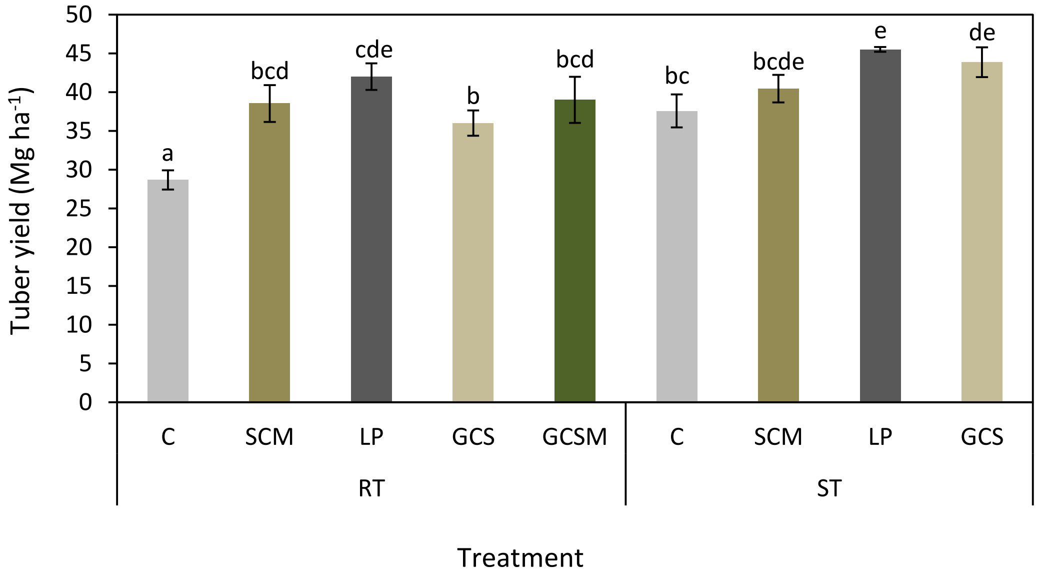

Fig. 5. Tuber yield (Mg ha^{-1}) of potato as influenced by tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS). The bars stand for the standard error values. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$).

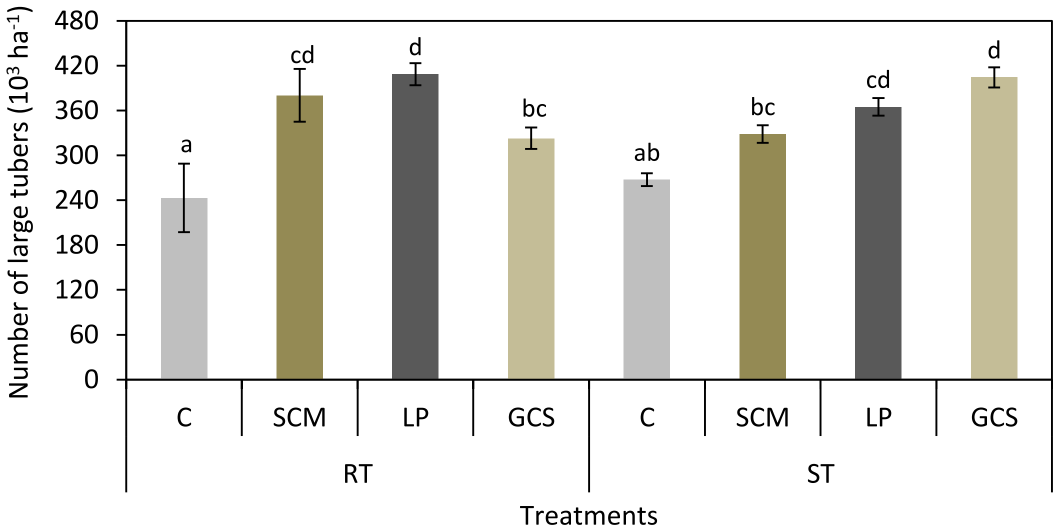

Fig. 6. Number of large potato tubers (10^3 ha^{-1}) as influenced by tillage system (reduced tillage, RT; standard tillage, ST) and fertilization treatment (control, C; solid cattle manure, SCM; lucerne pellet, LP; grass clover silage, GCS). The bars stand for the standard error values. Different letters indicate significant differences according to the Fisher's protected LSD-test ($P < 0.05$).

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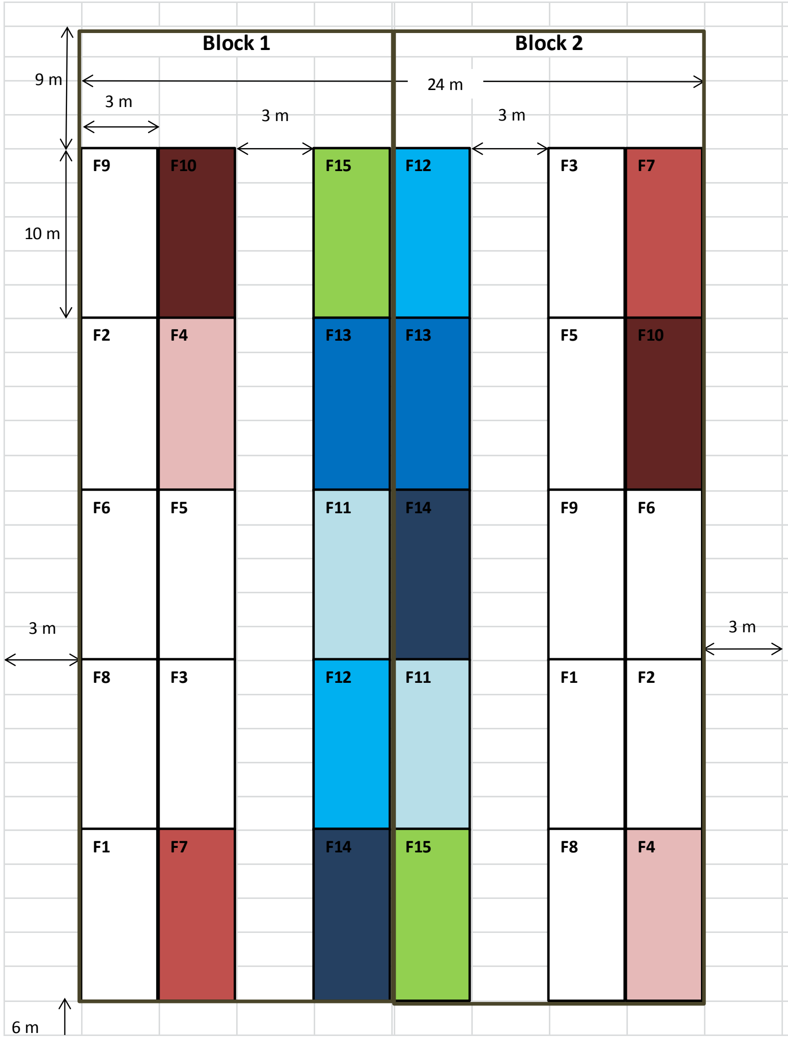
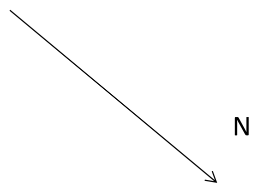
Appendixes

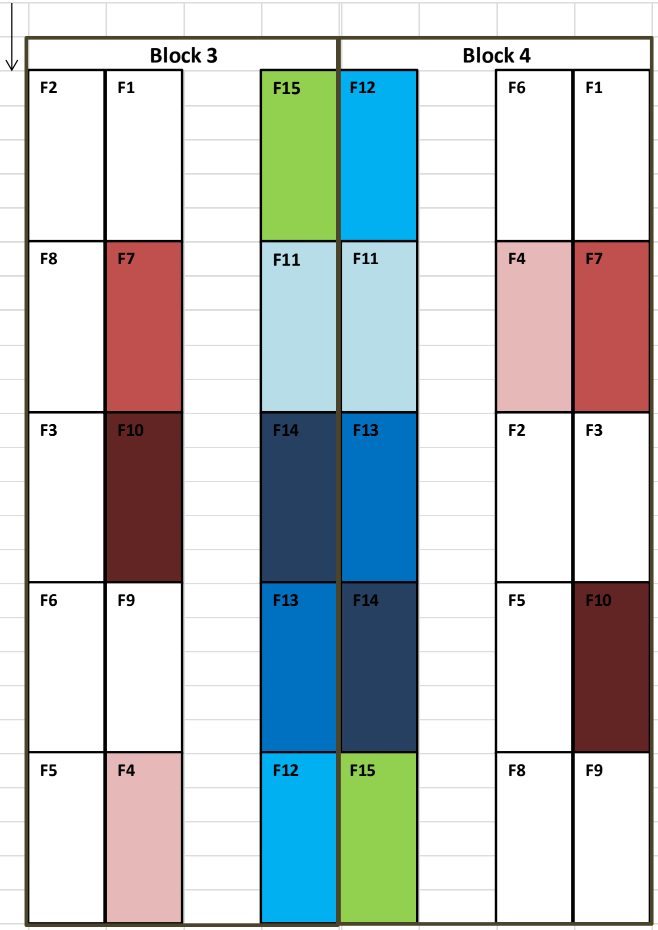
Appendix I. Experimental field-layout





Legend

Treatment	Fertilization	Kg N ha^{-1}	Tillage
F1	C	0	ST
F2	SCM	57	ST
F3	SCM	114	ST
F4	SCM	170	ST
F5	LP	57	ST
F6	LP	114	ST
F7	LP	170	ST
F8	GCS	57	ST
F9	GCS	114	ST
F10	GCS	170	ST
F11	C	0	RT
F12	SCM	170	RT
F13	LP	170	RT
F14	GCS	170	RT
F15	GCSM	170	RT



C: Control
SCM: Solid Cattle Manure
LP: Lucerne Pellets
GCS: Grass Clover Sillage
GCS-M: Grass Clover Silage - Mulch
ST: Standard Tillage
RT: Reduced Tillage

Appendix II. Experimental data

Experimental data on number (individuals m^{-2}) and biomass (g m^{-2}) of earthworms.

			Earthworm number (individuals m^{-2})						Earthworm biomass (g m^{-2})					
			4WAP		8WAP		13WAP		4WAP		8WAP		13WAP	
Blocks	**Tillage**	**Fertilization**	<500 mg	>500 mg	<500 mg	>500 mg	<500 mg	>500 mg	<500 mg	>500 mg	<500 mg	>500 mg	<500 mg	>500 mg
1	**ST**	**C**	13	13	0	0	13	13	5.4	15.0	0.0	0.0	0.4	17.4
2	**ST**	**C**	25	0	25	0	0	0	9.0	0.0	3.4	0.0	0.0	0.0
3	**ST**	**C**	13	0	0	0	38	0	2.2	8.3	0.0	0.0	6.6	0.0
4	**ST**	**C**	0	25	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
1	**ST**	**SCM**	13	0	13	13	0	0	13.8	0.0	2.7	0.6	0.0	0.0
2	**ST**	**SCM**	0	38	25	0	13	0	3.2	29.3	4.2	0.0	2.4	0.0
3	**ST**	**SCM**	25	0	0	25	13	0	10.7	0.0	0.0	0.6	0.3	0.0
4	**ST**	**SCM**	25	0	50	0	0	0	5.1	0.0	10.5	0.0	0.0	0.0
1	**ST**	**LP**	25	38	13	25	0	25	0.0	23.5	2.8	0.7	0.0	56.0
2	**ST**	**LP**	25	0	13	0	13	0	9.4	16.8	1.9	0.0	4.3	0.0
3	**ST**	**LP**	0	0	25	0	50	13	11.3	0.0	8.4	0.0	9.6	11.6
4	**ST**	**LP**	38	25	13	0	0	0	11.6	0.0	1.9	0.0	0.0	0.0
1	**ST**	**GCS**	25	13	0	0	13	0	10.5	13.0	0.0	0.0	2.7	0.0
2	**ST**	**GCS**	25	0	0	0	13	13	0.0	0.0	0.0	0.0	2.9	29.0
3	**ST**	**GCS**	0	25	13	0	0	0	9.7	24.6	5.9	0.0	0.0	0.0
4	**ST**	**GCS**	13	38	0	13	0	0	6.1	14.8	0.0	0.9	0.0	0.0
1	**RT**	**C**	25	0	25	0	25	13	20.7	49.4	3.3	0.0	8.7	8.3
2	**RT**	**C**	63	75	63	0	13	0	1.0	32.7	17.6	0.0	1.1	0.0
3	**RT**	**C**	75	0	25	0	38	0	27.7	0.0	8.5	0.0	11.6	0.0
4	**RT**	**C**	75	38	38	0	0	0	16.5	0.0	5.2	0.0	0.0	0.0
1	**RT**	**SCM**	38	25	25	13	50	0	19.6	0.0	7.5	0.3	6.6	0.0
2	**RT**	**SCM**	13	0	0	0	13	13	11.0	15.3	0.0	0.0	3.3	6.8
3	**RT**	**SCM**	63	0	13	0	63	0	3.8	6.5	3.1	0.0	10.8	0.0

4	**RT**	**SCM**	25	13	13	0	50	0	8.2	0.0	4.6	0.0	9.9	0.0
1	**RT**	**LP**	63	25	63	0	25	0	17.2	0.0	14.1	0.0	3.0	0.0
2	**RT**	**LP**	50	0	25	0	25	13	20.7	23.3	8.0	0.0	6.7	7.6
3	**RT**	**LP**	63	38	25	0	13	25	13.8	19.0	11.2	0.0	3.8	44.3
4	**RT**	**LP**	63	50	25	0	50	13	17.2	29.8	8.1	0.0	17.1	6.7
1	**RT**	**GCS**	13	38	25	0	88	0	1.9	22.7	7.7	0.0	22.3	0.0
2	**RT**	**GCS**	63	50	38	0	25	0	24.5	22.5	11.9	0.0	7.1	0.0
3	**RT**	**GCS**	38	38	25	0	38	0	14.3	36.7	6.0	0.0	4.6	0.0
4	**RT**	**GCS**	50	38	38	0	50	0	12.1	31.6	8.7	0.0	14.2	0.0

Experimental data on soil pH, SOM (g kg^{-1}) and SOM min (kg N ha^{-1}).

			Soil pH		**SOM (g kg^{-1}) - 14 WAP**			**SOM min (kg N ha^{-1})**
Blocks	**Tillage**	**Fertilization**	**0 - 15 cm**	**15 - 30 cm**	**0 - 15 cm**	**15 - 30 cm**	**0 - 30 cm**	
1	**ST**	**C**	6.14	6.31	27.6	25.4	26.5	205
2	**ST**	**C**	6.08	6.01	23.8	24.5	24.2	211
3	**ST**	**C**	6.02	5.95	24.7	24.7	24.7	154
4	**ST**	**C**	5.91	5.79	25.1	26.2	25.6	196
1	**ST**	**SCM**	5.83	5.92	27.9	29.5	28.7	na
2	**ST**	**SCM**	5.89	5.85	32.9	33.3	33.1	na
3	**ST**	**SCM**	5.98	5.92	24.1	24.4	24.3	na
4	**ST**	**SCM**	6.03	6.02	24.5	27.0	25.7	na
1	**ST**	**LP**	5.66	5.49	25.6	25.4	25.5	na
2	**ST**	**LP**	5.77	5.74	25.5	27.4	26.4	na
3	**ST**	**LP**	5.83	5.71	26.7	31.3	29.0	na
4	**ST**	**LP**	5.95	5.99	24.7	26.4	25.6	na
1	**ST**	**GCS**	5.75	5.54	25.6	25.6	25.6	na
2	**ST**	**GCS**	5.79	5.67	34.7	36.0	35.4	na
3	**ST**	**GCS**	5.82	5.76	29.6	31.8	30.7	na
4	**ST**	**GCS**	5.77	5.7	22.8	24.4	23.6	na
1	**RT**	**C**	5.7	5.86	24.5	25.3	24.9	139
2	**RT**	**C**	5.91	5.97	25.5	25.2	25.4	97

3	**RT**	**C**	5.9	6	23.0	22.6	22.8	134
4	**RT**	**C**	5.93	6.1	25.1	26.6	25.8	139
1	**RT**	**SCM**	5.9	6.13	29.5	28.9	29.2	na
2	**RT**	**SCM**	6.06	6.13	25.6	27.5	26.6	na
3	**RT**	**SCM**	6	6.13	23.6	24.8	24.2	na
4	**RT**	**SCM**	6.04	6.14	28.9	30.9	29.9	na
1	**RT**	**LP**	5.8	5.99	28.4	27.9	28.1	na
2	**RT**	**LP**	5.91	6.11	28.4	27.1	27.8	na
3	**RT**	**LP**	5.89	6	24.6	25.4	25.0	na
4	**RT**	**LP**	5.82	6.06	26.1	25.1	25.6	na
1	**RT**	**GCS**	5.79	6.07	25.7	25.5	25.6	na
2	**RT**	**GCS**	5.94	6.14	26.9	26.0	26.4	na
3	**RT**	**GCS**	5.93	6.06	27.5	27.8	27.7	na
4	**RT**	**GCS**	5.88	6.09	26.7	24.8	25.8	na

Experimental data on soil NO_3^-, NH_4^+ and total N_{min} (kg N ha^{-1}) for the 0-15 cm and 15-30 cm soil layers.

			N_{min} (Kg N ha^{-1}) for the 0-15 cm soil layer									**N_{min} (Kg N ha^{-1}) for the 15-30 cm soil layer**								
			NO_3^-			**NH_4^+**			**Total N_{min}**			**NO_3^-**			**NH_4^+**			**Total N_{min}**		
Blocks	**Tillage**	**Fertilization**	**4 WAP**	**8 WAP**	**14 WAP**	**4 WAP**	**8 WAP**	**14 WAP**	**4 WAP**	**8 WAP**	**14 WAP**	**4 WAP**	**8 WAP**	**14 WAP**	**4 WAP**	**8 WAP**	**14 WAP**	**4 WAP**	**8 WAP**	**14 WAP**
1	**ST**	**C**	15.5	6.6	6.0	7.5	7.3	5.5	22.9	14.0	11.5	49.8	15.4	4.7	7.4	5.7	5.5	57.2	21.1	10.2
2	**ST**	**C**	14.9	4.0	2.2	9.6	5.1	4.7	24.5	9.1	6.8	41.2	7.0	4.4	5.8	5.8	5.0	47.0	12.8	9.4
3	**ST**	**C**	15.8	6.0	3.9	6.9	4.4	4.8	22.7	10.4	8.7	27.0	11.1	3.0	4.9	6.8	6.2	31.9	17.9	9.3
4	**ST**	**C**	20.2	10.3	2.2	7.1	6.8	5.0	27.3	17.1	7.2	47.4	8.9	2.5	8.3	5.3	7.7	55.7	14.2	10.2
1	**ST**	**SCM**	17.0	6.3	5.2	7.2	5.4	11.8	24.2	11.8	17.0	67.5	18.5	4.3	10.3	8.0	8.3	77.8	26.5	12.6
2	**ST**	**SCM**	25.1	15.5	8.2	11.5	7.2	8.3	36.6	22.8	16.4	68.8	52.9	10.9	12.5	8.2	11.8	81.3	61.0	22.7
3	**ST**	**SCM**	18.4	6.9	1.4	8.4	5.6	12.9	26.7	12.5	14.3	64.4	11.1	4.1	10.9	6.1	12.6	75.3	17.2	16.7
4	**ST**	**SCM**	19.7	9.0	2.8	7.1	6.8	3.3	26.9	15.8	6.1	40.9	8.6	3.3	8.1	5.6	6.8	49.0	14.1	10.2
1	**ST**	**LP**	16.0	30.1	8.0	7.0	5.3	7.3	23.1	35.5	15.3	62.6	13.3	28.4	11.7	6.8	6.3	74.3	20.0	34.8
2	**ST**	**LP**	11.9	11.4	3.9	7.3	5.1	5.6	19.2	16.5	9.5	61.1	21.0	9.0	8.2	5.7	9.3	69.2	26.7	18.3

3	**ST**	**LP**	21.1	9.6	5.4	6.0	7.1	6.7	27.1	16.6	12.2	62.6	22.4	19.4	7.1	6.7	9.4	69.7	29.1	28.8
4	**ST**	**LP**	19.2	9.9	2.9	6.2	5.7	7.3	25.4	15.6	10.2	57.9	23.3	5.9	7.3	5.6	5.5	65.2	28.9	11.4
1	**ST**	**GCS**	14.0	5.4	4.8	7.1	7.6	11.7	21.1	13.0	16.5	41.9	23.8	18.2	15.4	6.7	14.5	57.3	30.4	32.7
2	**ST**	**GCS**	23.2	10.2	7.4	9.3	9.8	8.6	32.5	20.0	16.0	60.5	41.9	9.5	9.2	7.3	11.5	69.7	49.2	21.0
3	**ST**	**GCS**	15.9	14.7	3.3	5.3	5.9	7.4	21.2	20.5	10.7	57.9	27.8	5.3	8.4	5.9	7.1	66.3	33.7	12.3
4	**ST**	**GCS**	17.5	8.6	4.8	7.9	5.7	6.4	25.5	14.2	11.2	40.9	21.8	11.6	11.6	7.9	8.1	52.5	29.7	19.7
1	**RT**	**C**	38.2	9.5	5.9	12.7	7.3	4.3	50.9	16.8	10.2	17.0	10.2	3.2	6.8	5.3	6.4	23.7	15.5	9.6
2	**RT**	**C**	24.4	5.5	2.4	10.0	7.6	5.0	34.4	13.1	7.4	16.7	6.4	1.5	6.3	4.9	5.3	22.9	11.2	6.8
3	**RT**	**C**	40.3	12.5	6.0	15.3	7.8	3.5	55.7	20.3	9.5	18.9	9.4	1.5	6.1	4.9	4.2	25.1	14.3	5.7
4	**RT**	**C**	37.1	17.3	5.5	14.2	8.2	7.0	51.3	25.4	12.5	23.7	9.6	1.8	6.3	3.1	7.1	29.9	12.7	9.0
1	**RT**	**SCM**	60.2	26.6	13.7	17.9	8.4	7.2	78.1	35.0	20.9	20.4	15.2	2.6	9.4	6.8	6.1	29.7	22.0	8.7
2	**RT**	**SCM**	48.6	25.8	4.1	16.5	6.1	5.8	65.0	31.9	9.8	16.6	15.7	4.1	5.4	6.4	4.8	22.0	22.1	8.9
3	**RT**	**SCM**	48.6	18.0	7.5	17.2	7.7	6.7	65.8	25.6	14.2	21.0	8.0	0.4	8.8	5.9	5.3	29.8	14.0	5.8
4	**RT**	**SCM**	57.8	27.0	3.5	13.9	7.6	6.2	71.7	34.6	9.7	22.9	10.7	3.3	6.0	4.3	5.7	28.8	15.0	9.0
1	**RT**	**LP**	72.1	57.4	33.0	23.7	10.0	10.8	95.8	67.4	43.8	23.8	22.0	5.9	5.5	6.0	6.7	29.3	28.1	12.6
2	**RT**	**LP**	58.1	33.5	12.8	18.7	8.4	5.3	76.8	41.9	18.0	22.9	14.3	4.7	11.6	8.2	13.8	34.5	22.4	18.5
3	**RT**	**LP**	59.7	39.5	14.0	16.7	9.9	7.2	76.3	49.4	21.2	25.1	16.0	4.7	9.4	7.3	6.7	34.4	23.3	11.3
4	**RT**	**LP**	50.2	27.7	20.3	17.5	8.4	5.6	67.7	36.1	25.9	21.9	10.8	6.0	6.9	4.8	5.3	28.8	15.6	11.3
1	**RT**	**GCS**	40.4	50.4	23.9	24.1	13.0	12.8	64.5	63.4	36.7	15.6	20.3	4.7	5.0	7.5	6.2	20.7	27.7	10.9
2	**RT**	**GCS**	42.2	37.6	11.8	20.4	9.5	9.7	62.6	47.2	21.5	21.9	18.6	4.1	5.7	5.7	7.2	27.7	24.3	11.3
3	**RT**	**GCS**	50.8	36.8	15.4	29.5	9.4	6.6	80.3	46.2	21.9	26.5	22.7	4.1	10.9	7.7	6.3	37.4	30.5	10.4
4	**RT**	**GCS**	40.9	30.4	17.1	16.6	9.0	6.5	57.6	39.4	23.6	17.3	12.8	3.9	5.1	6.0	12.8	22.5	18.8	16.6

Experimental data on soil moisture content and soil bulk density (g cm^{-3}).

			Soil moisture content						Soil bulk density (g cm^{-3})			
Blocks	**Tillage**	**Fertilization**	**1 WAP**	**4 WAP**	**7 WAP**	**9 WAP**	**11 WAP**	**13 WAP**	**1 WAP**	**4 WAP**	**7 WAP**	**13 WAP**
1	**ST**	**SCM**	15.5	17.2	16.2	5.3	8.7	17.2	1.13	1.32	1.25	1.23
2	**ST**	**SCM**	12.0	17.1	14.7	4.3	5.3	17.1	1.32	1.27	1.25	1.36
3	**ST**	**SCM**	17.8	14.3	13.8	5.2	8.6	14.3	1.42	1.34	1.33	1.42
4	**ST**	**SCM**	11.7	14.4	14.6	5.1	7.8	14.4	1.32	1.40	1.35	1.45
1	**ST**	**GCS**	13.0	14.9	14.4	5.3	5.7	14.9	1.20	1.36	1.32	1.42
2	**ST**	**GCS**	13.4	13.1	13.6	4.8	5.3	13.1	1.17	1.21	1.31	1.24
3	**ST**	**GCS**	14.1	15.5	14.4	3.7	5.5	15.5	1.11	1.42	1.28	1.36
4	**ST**	**GCS**	13.5	16.5	13.0	4.9	5.5	16.5	1.27	1.36	1.32	1.36
1	**RT**	**SCM**	14.8	14.5	10.8	4.8	5.1	14.5	1.42	1.41	1.46	1.36
2	**RT**	**SCM**	17.3	17.1	14.6	5.2	11.0	17.1	1.47	1.44	1.36	1.36
3	**RT**	**SCM**	11.0	15.0	11.8	4.2	6.5	15.0	1.48	1.48	1.40	1.35
4	**RT**	**SCM**	13.1	12.8	12.8	5.5	4.7	12.8	1.41	1.46	1.33	1.36
1	**RT**	**GCS**	11.5	14.3	14.0	4.6	9.0	14.3	1.39	1.40	1.43	1.30
2	**RT**	**GCS**	11.0	16.7	15.7	7.0	11.2	16.7	1.38	1.38	1.43	1.41
3	**RT**	**GCS**	9.6	13.1	13.8	4.9	5.4	13.1	1.45	1.47	1.38	1.36
4	**RT**	**GCS**	16.3	17.2	16.6	6.2	5.1	17.2	1.43	1.42	1.46	1.39

Experimental data on average daily soil temperature (°C).

Average daily soil temperature (°C)														
DAP	**GCS**	**SCM**	**RT**	**ST**	**DAP**	**GCS**	**SCM**	**RT**	**ST**	**DAP**	**GCS**	**SCM**	**RT**	**ST**
1st	10.2	10.5	10.7	10.0	**34th**	9.8	10.1	10.1	9.8	**67th**	14.5	14.6	14.7	14.4
2nd	9.3	10.2	9.5	10.0	**35th**	8.8	9.1	9.1	8.8	**68th**	13.8	13.9	14.0	13.7
3rd	10.7	11.4	10.5	11.6	**36th**	9.5	9.5	9.7	9.3	**69th**	15.0	15.2	15.2	15.0

4th	11.8	11.9	11.5	12.2	**37th**	11.0	11.0	11.2	10.7	**70th**	15.0	15.0	15.1	14.9
5th	12.0	11.6	11.8	11.8	**38th**	10.5	10.7	10.8	10.4	**71st**	16.8	16.9	16.9	16.7
6th	14.4	13.5	13.7	14.2	**39th**	14.9	14.1	14.8	14.2	**72nd**	17.0	16.8	17.1	16.8
7th	17.0	15.9	16.0	16.9	**40th**	18.1	17.3	17.9	17.5	**73rd**	17.4	17.3	17.4	17.3
8th	12.0	12.3	12.5	11.8	**41st**	14.0	14.5	14.4	14.2	**74th**	18.0	17.9	18.0	17.9
9th	10.1	10.1	10.4	9.7	**42nd**	15.0	14.7	15.1	14.6	**75th**	18.5	18.5	18.6	18.4
10th	11.1	10.7	11.1	10.6	**43rd**	16.5	16.6	16.6	16.5	**76th**	19.2	19.0	19.3	18.9
11th	9.8	10.0	10.2	9.6	**44th**	14.3	14.7	14.6	14.5	**77th**	20.3	20.1	20.4	20.0
12th	11.8	11.3	11.6	11.5	**45th**	14.7	14.6	14.6	14.7	**78th**	21.3	21.0	21.3	21.0
13th	14.0	13.3	13.6	13.7	**46th**	14.2	14.6	14.3	14.5	**79th**	21.2	20.7	21.0	20.9
14th	14.3	13.8	14.0	14.1	**47th**	16.5	16.2	16.3	16.4	**80th**	19.0	18.9	18.9	19.0
15th	15.7	14.8	15.1	15.4	**48th**	18.4	18.0	18.1	18.3	**81st**	16.0	16.0	16.1	15.9
16th	15.5	15.0	15.2	15.3	**49th**	20.1	19.4	19.8	19.8	**82nd**	15.5	15.5	15.7	15.3
17th	17.0	16.1	16.4	16.8	**50th**	20.7	20.2	20.4	20.5	**83rd**	16.3	16.3	16.3	16.4
18th	18.9	17.8	18.1	18.7	**51st**	19.8	19.9	19.7	20.0	**84th**	16.7	16.7	16.7	16.7
19th	17.5	17.2	17.2	17.5	**52nd**	18.0	18.5	18.1	18.5	**85th**	17.7	18.3	18.5	17.5
20th	17.7	17.1	17.2	17.6	**53rd**	17.0	17.4	17.0	17.4	**86th**	19.1	18.9	19.0	19.0
21st	17.4	17.1	17.2	17.3	**54th**	17.7	17.6	17.7	17.7	**87th**	19.5	19.3	19.3	19.5
22nd	13.9	14.2	14.4	13.7	**55th**	19.3	18.9	19.2	19.0	**88th**	20.8	20.5	20.8	20.5
23rd	12.3	12.5	12.8	12.1	**56th**	17.5	17.6	17.7	17.4	**89th**	19.7	19.3	19.5	19.4
24th	12.0	12.2	12.4	11.8	**57th**	16.3	16.2	16.5	16.0	**90th**	18.2	18.1	18.2	18.1
25th	11.8	11.9	12.1	11.7	**58th**	16.3	16.3	16.5	16.1	**91st**	20.2	19.9	20.3	19.7
26th	11.2	11.3	11.5	11.0	**59th**	17.5	17.1	17.5	17.0	**92nd**	22.6	22.0	22.4	22.2
27th	12.6	12.4	12.6	12.5	**60th**	18.6	17.9	18.4	18.1	**93rd**	23.8	23.0	23.3	23.5
28th	10.4	11.1	11.2	10.3	**61st**	22.3	20.9	21.6	21.6	**94th**	22.3	21.9	22.1	22.1
29th	11.2	11.3	11.3	11.1	**62nd**	22.0	21.3	21.6	21.7	**95th**	21.9	21.2	21.6	21.5
30th	10.6	10.6	10.7	10.5	**63rd**	20.0	19.7	19.9	19.8					
31st	13.2	12.9	13.2	13.0	**64th**	15.8	16.2	16.2	15.9					
32nd	13.3	13.3	13.4	13.2	**65th**	15.1	15.2	15.3	14.9					
33rd	11.9	12.0	12.1	11.8	**66th**	14.6	14.5	14.7	14.3					

Experimental data on plant emergence (DAP), leaf chlorophyll index (-), plant height (cm), LAI (m^2 m^{-2}) and canopy volume (cm^3).

				Leaf chlorophyll index (-)				Plant height (cm)				LAI (m^2 m^{-2})			Canopy volume (cm^3)			
Blocks	Tillage	Fertilization	Plant emergence (DAP)	6 WAP	8 WAP	10 WAP	12 WAP	6 WAP	8 WAP	10 WAP	12 WAP	7 WAP	9 WAP	13 WAP	6 WAP	8 WAP	10 WAP	12 WAP
1	ST	C	26.6	35.0	44.8	49.2	48.8	6	26	42	45	0.84	2.92	2.30	614	25172	66197	76618
2	ST	C	26.7	37.5	46.3	50.6	46.5	6	21	39	42	0.58	1.72	2.46	794	14152	37664	60805
3	ST	C	27.0	34.1	49.3	50.5	49.0	7	25	36	35	0.54	2.50	2.07	433	19683	63174	60223
4	ST	C	24.2	36.3	47.5	49.2	48.7	5	22	44	41	0.42	1.77	3.89	327	15694	58502	78476
1	ST	SCM	25.8	35.1	46.9	48.1	47.0	9	26	47	47	0.44	3.11	4.20	1409	26923	63516	88369
2	ST	SCM	25.3	36.9	47.0	46.2	49.8	6	28	42	48	0.46	3.13	3.92	467	26064	66220	65642
3	ST	SCM	26.6	34.7	45.8	46.8	44.0	7	27	42	46	0.54	2.02	1.68	960	12746	55154	104182
4	ST	SCM	26.6	37.2	45.2	49.3	46.8	6	20	45	43	0.57	3.34	3.72	550	29369	70478	97140
1	ST	LP	24.8	35.9	44.9	48.9	45.9	8	29	47	49	0.60	1.71	5.18	1325	30565	71002	80192
2	ST	LP	25.2	35.8	49.3	48.6	52.5	8	26	45	51	0.63	1.96	3.34	1117	29216	63771	81212
3	ST	LP	26.8	36.4	45.2	43.2	47.7	7	28	46	46	0.75	3.09	3.30	627	30883	62887	105741
4	ST	LP	27.0	36.4	49.9	49.7	49.2	7	28	43	49	0.60	3.09	2.82	546	23829	64812	112938
1	ST	GCS	23.3	33.5	46.1	40.6	48.2	8	30	42	50	0.68	2.00	3.33	1372	23008	70837	71102
2	ST	GCS	23.0	36.5	43.4	50.6	44.0	9	27	43	47	0.61	3.35	3.43	1827	35253	68628	69777
3	ST	GCS	26.8	34.6	44.6	42.7	39.2	7	27	52	51	0.67	3.25	3.99	878	26714	102667	117286
4	ST	GCS	25.8	36.3	44.8	41.5	41.4	7	26	38	42	0.37	1.75	2.63	669	22511	48697	80875
1	RT	C	22.6	36.8	48.4	46.8	38.8	7	21	35	37	0.51	1.45	2.36	689	19133	35744	35671
2	RT	C	23.6	35.5	49.1	44.0	46.2	7	23	32	29	0.66	1.42	2.03	966	12580	31720	25269
3	RT	C	24.9	33.6	47.4	44.5	39.6	7	23	37	35	0.65	1.14	2.09	778	15329	38939	35801
4	RT	C	23.0	36.0	48.9	43.5	45.1	7	22	32	35	0.69	1.92	2.21	1357	18635	32577	40558
1	RT	SCM	22.7	34.2	47.0	46.2	43.5	7	26	43	46	0.42	1.96	4.05	788	19816	60115	63153
2	RT	SCM	23.6	33.6	45.4	48.8	43.1	7	31	42	42	0.56	2.16	2.32	854	26277	67950	58315
3	RT	SCM	22.5	34.7	48.4	44.5	43.2	10	26	39	42	0.93	2.00	1.89	2139	21532	46939	58306
4	RT	SCM	23.3	34.2	46.4	43.8	43.7	8	26	44	41	0.53	2.15	2.31	1311	36767	74247	62857
1	RT	LP	22.6	33.4	48.2	48.0	43.6	8	30	41	46	0.61	1.97	2.97	1343	21388	54012	73636
2	RT	LP	22.9	33.1	51.6	45.3	46.8	9	29	44	45	0.51	2.74	3.05	1580	27109	68765	77500
3	RT	LP	22.6	33.4	49.9	45.7	47.6	9	26	44	49	0.75	2.49	3.31	1174	31927	69669	65802
4	RT	LP	22.6	34.0	49.0	45.6	48.1	8	31	42	45	0.63	2.24	3.08	996	27996	56838	54360

1	**RT**	**GCS**	26.0	34.9	40.7	38.6	31.0	5	28	38	39	0.56	1.48	2.84	509	18402	61625	63001
2	**RT**	**GCS**	24.3	32.9	41.7	34.8	35.6	6	24	38	40	0.61	2.12	3.66	601	18560	27032	40135
3	**RT**	**GCS**	23.8	35.2	42.4	40.2	34.3	6	25	44	44	0.32	2.75	2.53	317	19315	45475	52441
4	**RT**	**GCS**	23.8	35.7	45.0	33.7	36.2	7	23	30	38	0.77	1.70	3.50	772	25334	42986	60061

Experimental data on above-ground DM accumulation (Mg ha^{-1}), DM tuber yield (Mg ha^{-1}), tuber number (10^3 ha^{-1}) and average tuber size (g).

			Above-ground DM accumulation (Mg ha^{-1})				**DM tuber yield (Mg ha^{-1})**	**Tuber number (10^3 ha^{-1})**				**Average tuber size (g)**	
Blocks	**Tillage**	**Fertilization**	**7 WAP**	**9 WAP**	**13 WAP**	**15 WAP**		**Large**	**Small**	**Culls**	**Marketable**	**Total**	**Marketable**
1	**ST**	**C**	0.59	1.49	1.7	1.92	10.2	286	210	25	496	80.8	84.3
2	**ST**	**C**	0.38	0.99	1.7	2.01	9.7	257	296	27	553	63.9	65.7
3	**ST**	**C**	0.44	1.39	1.5	1.35	8.5	277	336	42	612	49.0	50.3
4	**ST**	**C**	0.29	0.94	2.6	1.90	10.5	249	272	57	521	67.8	73.3
1	**ST**	**SCM**	0.29	1.55	2.6	1.88	10.9	346	259	17	605	73.4	74.4
2	**ST**	**SCM**	0.32	1.37	2.9	1.74	9.0	294	291	27	585	64.8	65.3
3	**ST**	**SCM**	0.37	1.22	1.4	2.52	8.6	341	321	35	662	55.3	55.7
4	**ST**	**SCM**	0.41	1.91	2.5	1.44	9.5	333	358	96	691	48.2	50.8
1	**ST**	**LP**	0.43	0.98	3.3	1.65	10.3	360	341	54	701	59.9	63.2
2	**ST**	**LP**	0.41	1.06	2.2	1.99	10.3	388	225	15	612	73.0	72.7
3	**ST**	**LP**	0.61	1.67	2.2	1.52	10.8	333	254	67	588	70.6	76.3
4	**ST**	**LP**	0.43	1.89	2.2	2.62	10.6	378	296	249	674	48.6	64.4
1	**ST**	**GCS**	0.40	0.99	2.1	2.40	10.0	410	415	47	825	48.4	49.4
2	**ST**	**GCS**	0.51	1.68	2.5	2.89	12.0	415	395	52	810	55.8	57.9
3	**ST**	**GCS**	0.49	1.71	2.5	1.60	10.8	427	257	42	684	63.2	65.6
4	**ST**	**GCS**	0.34	0.92	2.1	2.50	8.9	365	262	62	627	57.2	59.2
1	**RT**	**C**	0.43	0.87	1.5	1.92	7.7	227	343	17	570	50.1	51.2
2	**RT**	**C**	0.60	0.87	1.5	0.85	6.8	156	375	12	531	45.9	46.3
3	**RT**	**C**	0.45	0.72	1.3	1.26	7.9	306	462	10	768	38.8	39.0
4	**RT**	**C**	0.48	1.09	1.6	1.45	8.2	284	309	5	593	50.5	50.7
1	**RT**	**SCM**	0.30	1.22	2.2	1.26	9.8	462	316	40	778	47.5	47.7

2	**RT**	**SCM**	0.45	1.15	1.4	2.04	9.3	380	272	25	652	57.9	58.6
3	**RT**	**SCM**	0.61	1.08	1.2	1.43	7.9	289	415	20	704	44.7	44.8
4	**RT**	**SCM**	0.35	1.20	1.5	1.62	10.9	390	200	22	590	71.6	73.1
1	**RT**	**LP**	0.44	1.12	1.7	1.90	10.4	437	269	40	706	56.2	58.2
2	**RT**	**LP**	0.41	1.58	2.0	2.81	11.4	430	247	15	677	67.7	68.8
3	**RT**	**LP**	0.48	1.49	1.9	1.71	9.8	393	205	0	598	65.4	65.4
4	**RT**	**LP**	0.44	1.27	2.1	1.86	10.3	375	195	10	570	69.4	68.6
1	**RT**	**GCS**	0.48	0.83	1.7	2.26	8.9	333	136	27	469	77.2	80.0
2	**RT**	**GCS**	0.45	1.15	2.2	2.05	9.2	358	257	12	615	61.1	60.9
3	**RT**	**GCS**	0.27	1.47	1.5	1.87	9.0	294	291	35	585	58.2	58.8
4	**RT**	**GCS**	0.50	1.01	2.1	1.76	7.2	306	353	7	659	47.1	47.2

Experimental data on yield per tuber category (Mg ha^{-1}), tuber specific gravity (-), tuber DM content and starch content.

			Yield per tuber category (Mg ha^{-1})					Specific gravity (-)	Tuber DM content	Starch content
Blocks	**Tillage**	**Fertilization**	**Large**	**Small**	**Culls**	**Marketable**	**Total**			
1	**ST**	**C**	34.6	7.3	0.26	41.8	42.1	1.083	24.3	14.9
2	**ST**	**C**	28.0	8.4	0.71	36.3	37.1	1.085	26.2	15.3
3	**ST**	**C**	22.7	8.2	1.24	30.8	32.1	1.083	26.6	15.0
4	**ST**	**C**	28.0	10.1	0.99	38.2	39.2	1.086	26.7	15.5
1	**ST**	**SCM**	37.8	7.1	0.70	45.0	45.7	1.089	23.9	16.0
2	**ST**	**SCM**	32.0	6.2	1.51	38.2	39.7	1.073	22.6	12.9
3	**ST**	**SCM**	28.2	8.6	1.66	36.9	38.5	1.087	22.3	15.7
4	**ST**	**SCM**	27.4	7.7	2.82	35.1	37.9	1.054	25.2	9.2
1	**ST**	**LP**	35.5	8.8	0.93	44.3	45.2	1.042	22.8	6.8
2	**ST**	**LP**	38.9	5.6	1.32	44.5	45.8	1.075	22.4	13.4
3	**ST**	**LP**	38.1	6.7	1.36	44.9	46.2	1.038	23.4	6.0
4	**ST**	**LP**	37.6	5.7	1.44	43.4	44.8	1.075	23.6	13.4
1	**ST**	**GCS**	31.1	9.7	1.45	40.7	42.2	1.075	23.7	13.3
2	**ST**	**GCS**	39.4	7.5	1.21	46.9	48.1	1.071	24.9	12.6
3	**ST**	**GCS**	38.6	6.3	0.98	44.9	45.9	1.080	23.5	14.3
4	**ST**	**GCS**	31.6	5.5	2.28	37.1	39.4	1.078	22.7	13.9
1	**RT**	**C**	16.3	12.9	0.25	29.2	29.4	1.102	26.2	18.6
2	**RT**	**C**	12.3	12.3	0.37	24.6	25.0	1.107	27.3	19.6
3	**RT**	**C**	17.1	12.8	0.21	30.0	30.2	1.090	26.3	16.2
4	**RT**	**C**	20.1	10.0	0.18	30.0	30.2	1.092	27.2	16.7
1	**RT**	**SCM**	30.4	6.7	1.76	37.1	38.9	1.093	25.1	16.8
2	**RT**	**SCM**	31.2	7.0	0.97	38.2	39.2	1.079	23.8	14.2
3	**RT**	**SCM**	20.1	11.4	0.81	31.5	32.3	1.083	24.6	14.8
4	**RT**	**SCM**	36.5	6.6	0.76	43.1	43.9	1.094	24.8	17.0
1	**RT**	**LP**	35.0	6.1	0.83	41.1	41.9	1.094	24.9	17.0
2	**RT**	**LP**	39.1	7.5	0.30	46.5	46.8	1.081	24.4	14.6
3	**RT**	**LP**	32.8	6.3	0.00	39.1	39.1	1.081	25.1	14.6

4	**RT**	**LP**	32.8	6.3	1.12	39.1	40.2	1.081	25.6	14.5
1	**RT**	**GCS**	33.5	4.0	0.80	37.5	38.3	1.077	23.1	13.7
2	**RT**	**GCS**	30.2	7.3	0.85	37.5	38.3	1.086	24.0	15.6
3	**RT**	**GCS**	26.4	8.0	1.70	34.4	36.1	1.080	24.9	14.2
4	**RT**	**GCS**	21.5	9.6	0.29	31.1	31.4	1.075	23.0	13.4
1	**RT**	**GCSM**	22.1	9.9	0.2	32.0	32.1	na	na	na
2	**RT**	**GCSM**	38.8	6.9	0.9	45.8	46.6	na	na	na
3	**RT**	**GCSM**	28.8	8.6	1.4	37.4	38.8	na	na	na
4	**RT**	**GCSM**	28.2	10.1	0.2	38.3	38.5	na	na	na

Experimental data on N accumulation (kg N ha^{-1}), ANR (%) and PFP (kg yield per kg N applied).

			N accumulation (kg N ha^{-1})			**ANR (%)**			**PFP (kg yield per kg N applied)**
Blocks	**Tillage**	**Fertilization**	**Above-ground**	**Tubers**	**Total**	**Above-ground**	**Tubers**	**Total**	
1	**ST**	**C**	37.2	158	195	na	na	na	na
2	**ST**	**C**	42.5	164	206	na	na	na	na
3	**ST**	**C**	29.1	118	147	na	na	na	na
4	**ST**	**C**	39.4	151	190	na	na	na	na
1	**ST**	**SCM**	37.6	169	206	0.3	12.7	13.0	49.1
2	**ST**	**SCM**	40.1	158	198	1.8	6.2	8.1	12.8
3	**ST**	**SCM**	43.9	135	179	4.2	-7.5	-3.4	5.6
4	**ST**	**SCM**	31.2	146	177	-3.6	-1.0	-4.6	2.0
1	**ST**	**LP**	37.2	181	218	0.1	18.1	18.2	42.0
2	**ST**	**LP**	47.5	178	226	5.8	16.8	22.6	45.2
3	**ST**	**LP**	35.7	180	216	-0.8	17.9	17.2	47.5
4	**ST**	**LP**	59.5	175	235	12.4	15.3	27.7	39.9

1	**ST**	**GCS**	57.3	165	222	12.6	10.5	23.1	28.5
2	**ST**	**GCS**	77.4	211	289	25.1	39.6	64.8	65.3
3	**ST**	**GCS**	37.6	182	220	0.3	21.4	21.8	51.5
4	**ST**	**GCS**	64.0	144	208	16.8	-2.0	14.8	11.2
1	**RT**	**C**	32.4	99	131	na	na	na	na
2	**RT**	**C**	15.3	79	94	na	na	na	na
3	**RT**	**C**	24.2	106	130	na	na	na	na
4	**RT**	**C**	22.4	106	129	na	na	na	na
1	**RT**	**SCM**	21.5	153	175	-1.3	33.9	32.6	61.8
2	**RT**	**SCM**	33.2	160	193	5.9	37.8	43.6	63.6
3	**RT**	**SCM**	24.5	119	143	0.6	13.1	13.7	22.0
4	**RT**	**SCM**	26.9	161	188	2.0	38.8	40.8	92.2
1	**RT**	**LP**	42.2	178	220	10.3	44.1	54.4	72.8
2	**RT**	**LP**	44.6	187	232	11.6	49.5	61.1	100.0
3	**RT**	**LP**	34.7	159	193	6.1	33.8	39.9	57.3
4	**RT**	**LP**	37.8	157	195	7.8	32.8	40.6	63.7
1	**RT**	**GCS**	64.2	146	210	25.3	30.0	55.3	59.9
2	**RT**	**GCS**	52.2	166	219	17.8	43.0	60.8	59.9
3	**RT**	**GCS**	45.8	149	195	13.8	32.1	45.9	46.0
4	**RT**	**GCS**	47.3	117	164	14.7	12.0	26.7	16.8