Org. Agr. (2016) 6:75–87
DOI 10.1007/s13165-015-0110-x

Influence of reduced tillage and fertilization regime on crop performance and nitrogen utilization of organic potato

Dimitrios Drakopoulos · Johannes M. S. Scholberg · Egbert A. Lantinga · Pablo A. Tittonell

Received: 10 September 2014 / Accepted: 18 March 2015 / Published online: 15 April 2015

Abstract The majority of Dutch farmers perceive that mouldboard ploughing prior to potato planting is necessary, despite its negative impacts on inherent soil fertility and soil structure. An innovative agronomic practice in Dutch organic agriculture is the use of cut-and-carry fertilizers with which above-ground biomass of crops with high nitrogen content (e.g. grass/clover) is harvested and transferred to other fields as plant-based fertilizers. The objective of this study was to investigate the interactive effects of two tillage systems (reduced tillage (RT), standard tillage (ST)) and three organic fertilizer amendments (solid cattle manure (SCM), lucerne pellets (LP), grass/clover silage (GCS)) on crop performance and nitrogen utilization of organic potato. Use of RT decreased tuber yield by 13.4 % 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 positively affected nitrogen utilization and tuber 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 enhanced nitrogen utilization in terms of apparent nitrogen recovery compared to animal-based. Although use of LP resulted in the highest yield for both tillage systems, its high price may be cost-inhibitive. An integrated approach taking into account N release patterns, environmental conditions, final yields, and production costs is needed in order to optimize resource use efficiency and overall profitability for farmers.

Keywords Organic potato · Reduced tillage · Organic fertilizer · Crop performance · Nitrogen utilization

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, some of these measures at times have negative environmental impacts, since they may result in soil degradation, soil erosion, and water and air pollution.

One of the most common agricultural practices is soil cultivation which is commonly centred on conventional deep tillage (i.e. ploughing up to 30 cm). 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 erosion (Triplett and Dick 2008). However, conventional tillage is considered necessary in order to manage crop residues, prepare a suitable seedbed, and create favourable soil physical properties for germination and crop production, while also providing effective weed control (Grant and Epstein 1973). On the other hand, conservation tillage is a broad term which refers to a wide range of non-inversion tillage practices which

D. Drakopoulos · J. M. S. Scholberg (✉) · E. A. Lantinga · P. A. Tittonell
Farming Systems Ecology, Wageningen University,
P.O. Box 563, 6700 AN Wageningen, The Netherlands
e-mail: johannes.scholberg@wur.nl

have the potential to reduce soil degradation and preserve soil quality (Holland 2004; van den Putte et al. 2010). Organic farmers have been encouraged to implement reduced tillage practices in order to attain potential benefits while reducing negative impacts of tillage on inherent soil fertility and to enhance soil conservation (Peignè et al. 2007). However, abandoning conventional tillage might also present challenges for organic producers, since weed pressure is expected to increase and the warming of the soil in spring may be slower, thereby delaying the initial crop development. Furthermore, it may restrict the crop choice, while it is less suitable for compacted soils that are poorly drained, but also for sandy soils because no-tillage practices may increase soil compaction.

There is no standard tillage system for potato crops, but generally, potato producers perceive that deep ploughing is necessary prior to seedbed preparation and ridging to ensure an adequate volume of loose-structured soil which is required for optimal tuber formation and quality. In due course, this may be detrimental to soil structure and soil quality, while it could also increase potential soil erosion risks. It was earlier stated that the optimal level of tillage for potato crops depends on crop management, soil type, and prevailing climatic conditions, and it should just loosen the soil adequately in order to create proper potato ridges with sufficient tilth to cover the tubers (Ghazavi et al. 2010; Peigné et al. 2014). Several studies have shown 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, b).

Historically, Dutch farmers tend to increase fertilizer application rates in order to off-set soil structure losses associated with excessive intensification and heavy tractor trafficking. However, in recent years, environmental standards in the Netherlands have become more restrictive. Consequently, more sustainable tillage practices that restore inherent soil structure and meet the production objectives are required in order to minimize negative environmental impacts and optimize yield. It is well-known that use of organic fertilizer amendments is a key asset for improving inherent soil fertility via enhancement of physical, biological, and chemical soil properties (Canali et al. 2012). An innovative agronomic practice in Dutch organic agriculture is the use of cut-and-carry fertilizers (Scholberg et al. 2009). Applying this method, above-ground biomass of crops with high nitrogen content (e.g. grass/clover and alfalfa) is harvested and transferred to other fields as plant-based fertilizers. The harvested biomass is applied as mulch or may be incorporated into the soil. Nowadays, stockless farming systems gain more prominence in organic agriculture in which case nutrient inputs are mainly provided by symbiotic nitrogen fixation of leguminous crops. The use of cut-and-carry fertilizers could potentially enhance flexibility when designing crop rotations while also improving the synchronization between nutrient release and crop demand. Therefore, such systems contribute to on-farm closing of the nitrogen cycle and reducing the dependence on external inputs. In addition, it has been reported that cut-and-carry fertilizers had higher or similar nitrogen use efficiency compared to animal manures (van der Burgt et al. 2011).

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 vs. standard tillage) and three organic fertilizer amendments (i.e. solid cattle manure, lucerne pellets, and grass/clover silage) on crop performance and nitrogen utilization of organic potato in the Netherlands.

Materials and methods

Experimental site and design

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 (i.e. 90 % sand and 8–10 % clay and silt), and the soil contained 23.8 g organic matter per kilogram soil at the 0–30-cm soil layer. 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 practices (i.e. mouldboard ploughing up to 30-cm soil depth). During the autumn 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 occasionally with 20-mm water per irrigation during periods of prolonged drought (i.e. on 10th July, 12th July, 16th July, and 19th July).

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 organic fertilizer amendments (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 plot size was 10×3 m, and plots included four rows (i.e. potato ridges).

Treatments and crop management

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. Each soil amendment was applied manually and evenly spread across field plots on 15th April, 2013. Then, the material was incorporated into the top 10 cm of the soil with a rotary tiller throughout the whole field. Additionally, mouldboard ploughing up to 30-cm soil depth was used only for ST. Thus, soil disturbance occurred up to 10 vs. 30 cm for RT and ST, respectively. An additional sub-plot treatment (i.e. grass/clover silage mulch (GCSM)) was included only in the main plot of RT to test innovative mulching techniques that could facilitate further tillage reduction. In this case, half of the fertilizer amendment was applied before planting and incorporated as in the other treatments, while the remainder was placed as mulch after the first re-ridging (i.e. 4 weeks after planting).

Potato tubers (*Solanum tuberosum* L. cv. 'Frieslander') were planted at a seeding rate of 3 t ha^{-1} on 17th April 2013 at a 15-cm depth and using planting distances of 30 cm in the row and 75 cm between the rows. 'Frieslander' (Europotato) is an early table potato cultivar with moderate resistance to late blight (*Phytophthora infestans*). A fully automatic potato planter equipped with GPS system was used for planting. 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. The potatoes were manually harvested on 30th July 2013.

Measurements

Pre-planting soil and fertility input analyses

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 by collecting one composite soil sample per block. A total of 20 subsamples were collected with a soil auger using a zigzag pattern and mixed to obtain one composite sample. Soil available N-NO_3^- and N-NH_4^+ were measured following the methods as described in Houba et al. (1990). Samples were extracted in 0.01 M $CaCl_2$ and analysed 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 analysed spectrophotometrically using a segmented-flow system (Skalar Analytical BV, Breda, the Netherlands). For determination of soil

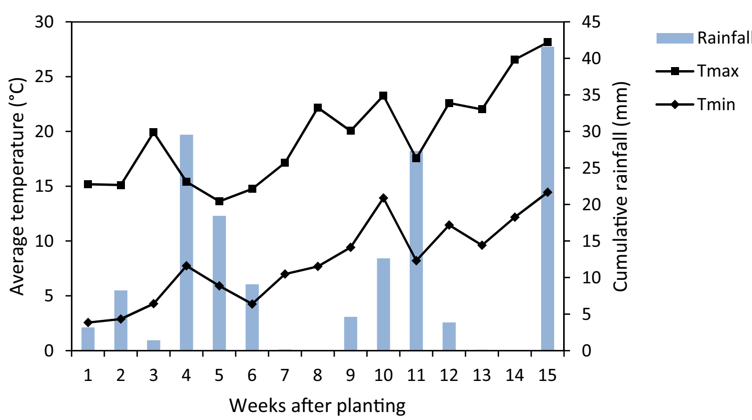

Fig. 1 Climatic data during the potato production period

available K, samples were extracted with 0.01 M $CaCl_2$, vaporized, and analysed 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 latter was measured after 0.01 M $CaCl_2$ extraction using a pH/mV meter (Inolab pH/Cond Level 1, WTW, Weilheim, Germany). In terms of fertilization regimes, application rates were based on pre-application N and moisture content analyses, and actual rates typically were within 5 % of targeted application rates. Total N and C contents were determined using the Dumas Method with a CHN1110 Element Analyzer (CE instruments, Milan, Italy).

Crop emergence, growth, tuber yield, and quality

Only the two central plant rows within each plot were used for measurements in order to avoid potential edge effects from neighbouring field plots. Also, the first and 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 fertilizer amendments.

Crop emergence was measured at 2-day intervals by recording the number of potato plants that emerged within the plot and expressed as days after planting. Plant height, plant diameter, and leaf chlorophyll index (i.e. SPAD values) 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 to the top of the plant, while plant diameter was the average of plant length and width of the canopy. 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 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, plant diameter, and leaf chlorophyll index measurements. Canopy volume (CV) was calculated as

$$CV = \pi \times D^2 \times Ht \times \frac{1}{6}$$

where Ht is plant height and D is plant diameter.

For LAI and above-ground dry weight measurements, a total number of two plants per replicate was sampled. First, composite leaves were collected, and fresh weights were recorded before determining LAI by feeding individual leaves through a leaf area meter (LI3100, Li-Cor, Lincoln, NE, USA). Afterwards, the samples were dried at 105 °C for 48 h in order to determine the above-ground dry matter accumulation. Exceptionally, at 15 WAP, a second set of samples was dried at 70 °C, since this is standard procedure for N content measurements to avoid N losses. Afterwards, the samples were ground 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 was monitored at 6-day 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 30th July 2013 (15 WAP) by manually harvesting the two central rows within each plot over a length of 5.4 m. Tubers were graded 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). Thereafter, fresh weights of each category were measured. Tuber specific gravity (SG) as an important quality indicator for the crisp industry was determined on the basis of a representative subsample of 5 kg as

$$SG = \frac{Wa}{(Wa-Ww)}$$

where Wa and Ww are the tuber fresh weights in air and water, respectively.

Subsequently, two sub-subsamples of about 0.5 kg tubers were collected to determine tuber DM and N contents. Tubers were dried at 105 °C for 48 h for DM content analysis and at 70 °C for 72 h for N determination. Samples used for N analysis were first ground to pass through a 2-mm sieve. The starch content (S) of potato tubers was calculated according to Simmonds (1977) as

$$S = -1.39 + 0.196 \times [1000 \times (\mathrm{SG}-1)]$$

N accumulation, apparent N recovery, and partial factor productivity

Crop N accumulation (Nacc) was calculated as

$$\mathrm{Nacc} = (\mathrm{DMab{\cdot}gr} \times \mathrm{Nab{\cdot}gr}) + (\mathrm{DMtu} \times \mathrm{Ntu})$$

where DMab·gr and Nab·gr are dry matter and N contents of above-ground biomass, respectively; DMtu and Ntu are dry matter and N contents of tuber, respectively.

Apparent N recovery (ANR) was calculated as

$$\mathrm{ANR} = 100 \times \frac{(\mathrm{Nacc{\cdot}tr} - \mathrm{Nacc{\cdot}c})}{\mathrm{Na}}$$

where Nacc·tr and Nacc·c are N accumulation of treatment and control, respectively; Na is N applied. Nacc·c corresponds to the average value of four replicates 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

$$\mathrm{PFP} = \frac{(\mathrm{Ytr} - \mathrm{Yc})}{\mathrm{Na}}$$

where Ytr and Yc are yield of treatment and control, respectively. Yc was taken as the average value of four replicates of each tillage system.

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, and mean separation was conducted using Fisher's protected LSD test.

Results

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 (Table 1). The actual nutrient application rates, fresh weight, 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.

Crop emergence and growth

Use of RT led to 3 days faster crop emergence than ST; however, there was a significant interaction between tillage system and fertilization treatment on crop emergence time (Table 3). For RT, fertilization with LP resulted in faster crop emergence compared to GCS, with other treatments showing intermediate values (data not shown). In contrast, use of ST in combination with GCS led to a somewhat quicker potato crop emergence compared to the other two soil amendments (data not shown).

SPAD values (i.e. leaf chlorophyll index) were similar for both tillage systems at 6 WAP but were slightly higher for RT at 8 WAP compared to ST (Table 3). At 10 and 12 WAP, SPAD values were substantially higher for ST (Table 3). Plants amended with GCS had the lowest leaf chlorophyll index at 8, 10, and 12 WAP compared to all other fertilization treatments (Table 3).

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}), fresh weight (FW, t ha^{-1}), DM (%), and C/N ratio of each fertilization regime

	N kg ha^{-1}	P	K	FW t ha^{-1}	DM (%)	C/N
SCM	165	44.4	214	26.9	36.6	12
LP	182	25.6	242	7.9	92.2	16
GCS	161	35.1	231	17.5	50.2	22

SCM solid cattle manure, *LP* lucerne pellets, *GCS* grass/clover silage

At 6 WAP, RT resulted in slightly taller plants on average for all fertilization treatments compared to the corresponding ST treatments except for GCS in which case the effect was reversed (data not shown). Tillage had no effect on plant height at 8 WAP, while plants were taller for ST compared to RT at 10 and 12 WAP (Table 4). In terms of fertilization, the control plots had the shortest plants throughout the entire trial, while LP had the tallest even though differences were only significant at 12 WAP (Table 4).

Both tillage systems resulted in similar LAI values during initial growth, but ST had higher values at 9 and 13 WAP compared to RT. There was a significant interaction between tillage system and fertilization treatment on canopy volume at 6 WAP (Table 4), with interaction effects being similar to those described previously for plant height at 6 WAP (data not shown). 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 4). At 12 WAP, canopy volume was highest for SCM and LP and lowest for the control, with GCS having intermediate values (Table 4).

Starting at 9 WAP, above-ground dry matter (DM) accumulation was greater with use of ST compared to RT, while values were similar for both tillage systems during initial growth (Table 5). The above-ground DM accumulation was similar among the different fertilization treatments (Table 5).

Tuber yield, number, size, and quality

Total tuber yield and marketable yield were higher for ST compared to RT, and yields were highest for LP and lowest for the control, with SCM and GCS having intermediate values (Table 6). Use of ST increased the yield of large tubers compared to RT, while the yield of small tubers and culls was similar for both tillage systems (Table 6). The yield of large tubers was highest for LP and lowest for the control, with SCM and GCS

Table 3 Effect of tillage system (reduced tillage (RT), standard tillage (ST)) and fertilization treatment (control (C), solid cattle manure (SCM), lucerne pellets (LP), grass/clover silage (GCS)) on crop emergence (days after planting (DAP)) and leaf chlorophyll index (SPAD values) of potato

	Crop emergence (DAP)	Leaf chlorophyll index (−)			
		6 WAP	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	***	ns	*	*	*
Fertilization (F)[a]					
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

WAP weeks after planting, *ns* not significant

*$P<0.05$; **$P<0.01$; ***$P<0.001$

[a] 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 4 Effect of tillage system (reduced tillage (RT), standard tillage (ST)) and fertilization treatment (control (C), solid cattle manure (SCM), lucerne pellets (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	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	ns	ns	**	*	ns	**	**	ns	ns	*	*
Fertilization (F)[a]											
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

WAP weeks after planting, *ns* not significant

*$P<0.05$; **$P<0.01$; ***$P<0.001$

[a] 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 5 Effect of tillage system (reduced tillage (RT), standard tillage (ST)) and fertilization treatment (control (C), solid cattle manure (SCM), lucerne pellets (LP), grass/clover silage (GCS)) on above-ground DM accumulation (t ha^{-1}) of potato

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

WAP weeks after planting, *ns* not significant

*$P<0.05$; **$P<0.01$; ***$P<0.001$

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

having intermediate values (Table 6). The yield of small tubers was higher for the control compared to the fertilized treatments, while the opposite occurred for culls (Table 6). One-way comparison among different treatments showed that the two tillage systems resulted in similar total tuber yields when LP and SCM were used as fertilization; however, use of GCS combined with RT performed poorly (Fig. 2). The combination of GCSM and RT had similar yield to SCM (Fig. 2).

Tillage did not affect the number of tubers for any of the grading classes (i.e. small, large, and culls); however, there was a significant interaction effect on large tubers (Table 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 (data not shown). 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 6).

Use of RT increased specific gravity, DM content, and starch content of potato tubers compared to ST (Table 6), while a strong correlation between specific gravity and tuber DM content was found (data not shown). In terms of fertilization, specific gravity, DM content, and starch content were highest for the control and lowest for LP and GCS, with SCM taking an intermediate position (Table 6).

Table 6 Effect of tillage system (reduced tillage (RT), standard tillage (ST)) and fertilization treatment (control (C), solid cattle manure (SCM), lucerne pellets (LP), grass/clover silage (GCS)) on yield (t ha^{-1}), tuber number (10^{3} ha^{-1}) and average tuber size (g) per tuber category, and tuber quality parameters, i.e. specific gravity (−), dry matter (%) and starch content (%) of potato

	Yield per tuber category[a]					Tuber number			Average tuber size		Tuber quality parameters		
	Small	Large	Culls	Marketable	Total	Small	Large	Culls	Total	Marketable	Specific gravity	Dry matter	Starch content[c]
	t ha^{-1}					10^{3} ha^{-1}			g		-	%	
Tillage (T)													
RT	8.4	27.2	0.7	35.6	36.3	290	339	19	56.8	57.4	1.087	25.0	15.7
ST	7.5	33.1	1.3	40.6	41.9	299	341	57	61.2	64.3	1.073	24.1	13.0
Significance	ns	**	ns	*	**	ns	ns	ns	ns	*	**	**	**
Fertilization (F)[b]													
Control	10.3 b	22.4 a	0.5 a	32.6 a	33.1 a	325	255	24	55.9	57.6	1.091 ab	26.4 b	16.5 b
SCM	7.7 a	30.5 b	1.4 b	38.1 b	39.5 b	304	354	35	57.9	58.8	1.081 ab	24.0 a	14.6 ab
LP	6.6 a	36.2 c	0.9 ab	42.9 c	43.8 c	254	387	56	63.9	67.2	1.071 a	24.0 a	12.5 a
GCS	7.2 a	31.5 bc	1.2 b	38.8 b	40.0 b	296	364	35	58.5	59.9	1.078 a	23.7 a	13.9 a
Significance	**	***	*	***	***	ns	***	ns	ns	ns	*	***	*
T×F	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns

ns not significant

*$P<0.05$; **$P<0.01$; ***$P<0.001$

[a] 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

[b] 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 ($P<0.05$)

[c] According to Simmonds (1977), starch content=−1.39+0.196×[1000×(specific gravity−1)]

Crop N accumulation, ANR, and PFP

Use of ST resulted in higher tuber and total crop Nacc compared to RT, while Nacc in the above-ground biomass was not affected by tillage system (Table 7). In terms of fertilization effects, total Nacc was highest for LP and GCS and lowest for the control, with SCM having intermediate values (Table 7). The Nacc in the above-ground biomass was highest for GCS, intermediate for LP, and lowest for the control and SCM (Table 7). The 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 for tubers was not influenced by fertilization, while total

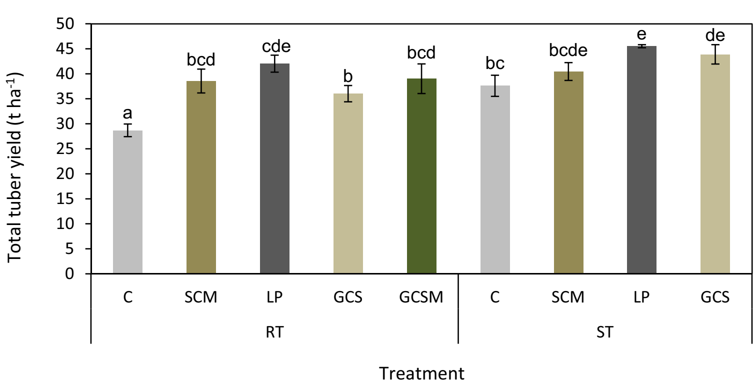

Fig. 2 One-way comparison among different treatments (reduced tillage (*RT*), standard tillage (*ST*), control (*C*), solid cattle manure (*SCM*), lucerne pellets (*LP*), grass/clover silage (*GCS*), grass/clover silage mulch (*GCSM*)). *Different letters* indicate significant differences according to Fisher's protected LSD test ($P<0.05$)

ANR was lower in SCM than LP and GCS (Table 7). With use of RT, the efficiency of N use in terms of tuber productivity increased by 44.1 % (Table 7).

Regression analysis

Correlations between crop growth parameters and final tuber yield and quality were examined for this particular potato variety (data not shown). Starting at 8 WAP, linear relationships expressing yield as a function of plant height and canopy volume were significant. At 5 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. Contrarily, there was no significant relationship between leaf chlorophyll index and total yield. Finally, there was an inverse linear relationship between tuber DM content and total tuber yield.

Discussion

Crop emergence was faster for RT despite the fact that ST resulted in slightly higher soil temperatures (≈1 °C) in the upper 15-cm soil layer during the first 3 WAP (Drakopoulos 2014). It was observed that the use of mouldboard plough (i.e. ST) prior to potato planting resulted in the development of approximately 4-cm higher ridges compared to RT. Therefore, 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 addition, use of RT resulted in higher N concentration in the 0–15-cm soil layer compared to ST, which may increase initial nutrient uptake (Drakopoulos 2014). Whereas, N concentration was higher in the 15–30-cm soil layer with use of ST due to soil inversion practices (Drakopoulos 2014). Consequently, it was evident that RT favoured crop emergence and initial crop growth. Similar results were obtained for cereal crops at the same research location (Hofmeijer 2010). However, over time, ST-based systems gradually caught up as roots may have reached deeper soil layers, thus resulting in similar mid-season (i.e. 8 WAP) performance in terms of plant height and canopy volume. During tuber bulking stage (i.e. 10 and 12 WAP), plant height, LAI, and canopy volume were remarkably higher for ST compared to RT. Since tuber number was the same

Table 7 Effect of tillage system (reduced tillage (RT), standard tillage (ST)) and fertilization treatment (control (C), solid cattle manure (SCM), lucerne pellets (LP), grass/clover silage (GCS)) on crop N accumulation (kg N ha^{-1}), Apparent N recovery (ANR, %) and partial factor productivity (PFP, kg yield kg N applied^{-1}) of potato

	Crop N accumulation (kg N ha^{-1})			ANR (%)			PFP (kg yield kg N applied^{-1})
	Above-ground	Tubers	Total	Above-ground	Tubers	Total	
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	ns	**	**	ns	**	***	*
Fertilization (F)[a]							
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

ns not significant

*$P<0.05$; **$P<0.01$; ***$P<0.001$

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

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. 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) also resulted in the same number of potato tubers (Carter and Sanderson 2001). Hence, use of RT did not appear to suppress tuber initiation, whereas the decrease in tuber bulking did account for most of the 13.4 % yield reduction for RT compared to ST. Presumably, it was the rate of tuber bulking that was affected rather than the duration of tuber bulking.

At 7 and 8 WAP, an increase of average air temperature coincided with a pronounced drought period, which may explain the observed differences between tillage systems. As mentioned above, organic fertilizer amendments were incorporated into deeper soil layers (i.e. up to 30 cm) for ST than RT (i.e. up to 10 cm). As a consequence, roots may have proliferated closer to the soil surface with RT because nutrients were more concentrated in the top soil. Therefore, 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 2014). Thus, potato plants in RT plots were more susceptible to water stress during initial tuber formation (i.e. 8 WAP), since positive correlation between yield and soil moisture supply has been shown during that period (Saue et al. 2010). Costa et al. (1997) reported that the greatest reductions of fresh and dry matter 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 and therefore require irrigation during drought periods, especially when soils have low water holding capacity (e.g. sandy soils) (van Loon 1981). So, it is presumed that the drought period at 7 and 8 WAP may have decreased tuber bulking of potato plants under RT impairing crop growth parameters (i.e. canopy volume and above-ground DM accumulation). Several studies have showed that LAI is strongly correlated with solar radiation interception, while there is a well-established linear relationship between tuber yield and light interception (MacKerron and Waister 1985; van Oijen 1991; Boyd et al. 2002). Total tuber and marketable yields were higher for ST than RT within a season despite the fact that several studies have underlined that reduced tillage could provide a viable alternative to conventional tillage in potato crops sustaining final yields in the long-term (Carter and Sanderson 2001; Holmstrom et al. 2006; Alva et al. 2009; Carter et al. 2009a, b). Our findings are in contrast with the prevailing notion that RT results in more effective use of limited water resources. Thus, it is relevant to understand the specific context of resource management systems in terms of underlying processes governing yield in order to be able to understand what works, where, and why.

The higher tuber quality that was found under RT points again towards potential water stress effects, since DM content of potato tubers tends to increase under water-limited conditions (Heuer and Nadler 1995; Sharma et al. 2011). Other studies also showed that the ratio of below-ground dry mass to total biomass increased under these conditions (Fleisher et al. 2008). It was earlier reported that larger tuber size may result in lower DM and starch contents (Tein et al. 2014), and in this context, the average tuber size in the current study was lower for RT compared to ST.

Use of RT appeared to improve nitrogen utilization, since ANR and PFP values were higher compared to ST. This finding is related to the lower Nacc of non-amended control plots that was found under RT compared to ST (i.e. 121 vs. 185 kg N ha^{-1} for RT and ST, respectively). Also, this is connected to a sharp decrease in the estimated SOM mineralization rate (i.e. 127 vs. 192 kg N ha^{-1} for RT and ST, respectively) in control plots (Drakopoulos 2014). As a consequence, the efficiency of N use in terms of tuber productivity was 44.1 % higher for RT compared to ST.

Application of LP as organic fertilizer amendment improved most crop performance parameters (i.e., plant height, canopy volume, and total tuber yield) compared to the other fertilization types, while the unfertilized plots performed poorly. However, tuber quality (i.e. specific gravity and starch content) was highest for control and lowest for LP and GCS, with SCM taking an intermediate position. Ojala et al. (1990) reported that specific gravity decreased with increased nitrogen availability, while it was not affected by different tillage and nitrogen management practices on a fine sandy soil (Alva et al. 2009). 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.

SPAD measurement did not prove to be a reliable tool for assessing either mineral soil N stocks or final yields in the field, since the control had similar or higher leaf chlorophyll index compared to GCS. However, it clearly indicated the nitrogen immobilization that was observed with GCS which mainly occurred during initial plant growth resulting in lower SPAD values for this treatment throughout most of the potato production period. Minotti et al. (1994) also reported that SPAD measurement may be used to identify severe nitrogen deficiencies in potatoes, while it may be less effective in detecting marginal deficiencies. Especially under RT, use of GCS led to obvious nitrogen immobilization during the period of rapid canopy expansion 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. Similarly, Collins et al. (2010) suspected a build-up of soil microorganisms under reduced tillage that caused nitrogen immobilization because of more surface applied residues compared to standard tillage systems. Also, the C/N ratio of GCS was 22, and soil amendments with C/N ratio above 20 were reported to cause temporary N immobilization (Canali et al. 2012). However, the low leaf chlorophyll index with use of GCS stands in sharp contrast with the relatively high N accumulation. Hence, it may be argued that GCS material caused N immobilization earlier in the season, and net N released late during final crop growth.

Plant-based fertilizers were found to enhance nitrogen utilization compared to animal-based, since LP and GCS had higher ANR values than SCM. However, the optimal choice and/or application time of soil amendments may greatly differ among tillage systems. More specifically, N mineralization of both soil amendments and SOM may be greatly delayed and/or reduced under RT. Therefore, in order to minimize yield reductions in RT systems, either materials that mineralize more readily (e.g., LP) should be used or materials may be applied earlier (e.g., GCS). 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. 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 because it allows producers to further reduce field trafficking and production costs, since mechanical weed control is conducted only once during the growing season instead of three times, which is common in organic potato production systems.

Conclusions

Although several long-term studies reported that use of RT can sustain potato yield and tuber quality while lowering production costs, our findings showed that on a sandy soil, RT may decrease tuber yield during initial adaptation. Moreover, use of RT appeared to render potato plants to be more susceptible to drought due to increased root proliferation in the top soil layer. Therefore, for RT systems, supplemental irrigation may be required if prolonged drought occurs during tuber bulking. On the other hand, use of RT also generated positive effects including improved nitrogen utilization while potato tubers also had a better quality in terms of specific gravity, DM, and starch contents. However, the price premium associated with enhanced tuber quality may not offset the observed yield gap between RT and ST, since a price premium of at least 10.7 % for higher tuber dry matter of about 1 % would be required to compensate for the lower tuber yield. In terms of soil amendments, use of LP improved crop growth and had the highest yield in both tillage systems. Nevertheless, its high price may be cost-inhibitive in terms of using high application rates. Therefore, LP may be combined with more affordable and locally available soil amendments (e.g. chicken manure). Having a higher clover to grass ratio and/or a lower C/N ratio for GCS would speed up its mineralization and subsequent net N release. Moreover, to improve early season N availability from locally available grass/clover pastures, either fresh material may be used or dried material may be applied several weeks before planting. Applying half of the grass/clover prior to planting and the remainder after the first re-ridging (i.e. GCSM) combined with RT appears to hold promise and should be explored in subsequent studies as well as use of animal manures other than SCM (e.g. pig and poultry manures).

Although the current study was for a single field season, it included a detailed in-season monitoring of underlying crop and soil related processes in an integrative manner providing evidence on what factors may govern yield reductions during initial transition to reduced tillage systems. An integrated approach taking into account N release patterns, environmental conditions, final yields, and production costs (e.g. labour and fertilization costs) is needed in order to optimize resource use efficiency and overall profitability for farmers.

Acknowledgments The authors gratefully acknowledge those people who assisted for this study: the group of students (i.e. Lv Yanjun, Rhea Flora, and Terra Bart), Hennie Halm, Andries Siepel, and Dine Volker. The completion of this study was done in the context of the MSc programme 'Organic Agriculture' which was funded by Greek State Scholarships Foundation (IKY) with individualized assessment process for the academic year 2011–2012 with funds from Education and Lifelong Learning European Social Fund and NSRF, 2007–2013.

References

Alva AK, Collins HP, Boydston RA (2009) Nitrogen management for irrigated potato production under conventional and reduced tillage. Soil Sci Soc Am J 73:1496–1503

Boyd NS, Gordon R, Martin RC (2002) Relationship between leaf area index and ground cover in potato under different management conditions. Potato Res 45:117–129

Cambouris AN, Zebarth BJ, Nolin MC, Laverdière MR (2008) Apparent fertilizer nitrogen recovery and residual soil nitrate under continuous potato cropping: effect of N fertilization rate and timing. Can J Soil Sci 88:813–825

Canali S, Ciaccia C, Tittarelli F (2012) Soil fertility management in organic potato: the role of green manure and amendment applications. In: He Z, Larkin R, Honeycutt W (eds) Sustainable potato production: global case studies, pp 453–469

Carter MR, Sanderson JB (2001) Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. Soil Tillage Res 63:1–13

Carter MR, Noronha C, Peters RD, Kimpinski J (2009a) Influence of conservation tillage and crop rotation on the resilience of an intensive long-term potato cropping system: restoration of soil biological properties after the potato phase. Agric Ecosyst Environ 133:32–39

Carter MR, Peters RD, Noronha C, Kimpinski J (2009b) Influence of 10 years of conservation tillage on some biological properties of a fine sandy loam in the potato phase of two crop rotations in Atlantic Canada. Can J Soil Sci 89:391–402

Collins HP, Alva AK, Boydston R (2010) Reduced tillage in an irrigated potato rotation. In: Chen S et al (eds) CSANR research report 2010–001 Clim Friendly Farming 20:1–18

Costa LD, Vedove GD, Gianquintoi G, Giovanardi R, Peressotti A (1997) Yield, water use efficiency and nitrogen uptake in potato: influence of drought stress. Potato Res 40:19–34

Drakopoulos D (2014) Influence of reduced tillage and organic amendments on an organic potato production system. Master Thesis, Farming Systems Ecology, Wageningen University, The Netherlands

Europotato http://www.europotato.org/menu.php. Accessed 7 Mar 2015

Fleisher DH, Timlin DJ, Reddy VR (2008) Interactive effects of carbon dioxide and water stress on potato canopy growth and development. Agron J 100:711–719

Ghazavi MA, Hosseinzadeh B, Lotfalian A (2010) Evaluating physical properties of potato by a combined tillage machine. Nat Sci 8:66–70

Grant WJ, Epstein E (1973) Minimum tillage for potatoes. Am Potato J 50:193–203

Heuer B, Nadler A (1995) Growth and development of potatoes under salinity and water deficit. Aust J Agric Res 46:1477–1486

Hofmeijer M (2010) The effects of non-inverted tillage on weed diversity and nutrient cycling in organic agriculture on sandy soil. Bachelor Thesis, Farming Systems Ecology, Wageningen University, Wageningen, The Netherlands

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosyst Environ 103:1–25

Holmstrom D, Arsenault W, Ivany J, Sanderson JB, Campbell AJ (2006) Effect of pre-plant tillage systems for potatoes in Prince Edward Island, Canada, on soil properties, weed control and potato yield. J Soil Water Conserv 61:370–380

Houba VJG, Novozamsky I, Lexmond TM, van der Lee JJ (1990) Applicability of 0.01 M $CaCl_2$ as a single extraction solution for the assessment of the nutrient status of soils and other diagnostic purposes. Commun Soil Sci Plant Anal 21:2281–2290

Konare H, Yost RS, Doumbia M, McCarty GW, Jarju A, Kablan R (2010) Loss on ignition: measuring soil organic carbon in soils of the Sahel, West Africa. Afr J Agric Res 5:3088–3095

MacKerron DKL, Waister PD (1985) A simple model of potato growth and yield: part I. Model development and sensitivity analysis. Agric For Meteorol 34:241–252

Minotti PL, Halseth DE, Sieczka JB (1994) Field chlorophyll measurements to assess the nitrogen status of potato varieties. Hortscience 29:1497–1500

Novozamsky I, Houba VJG, van Eck R, van Vark W (1983) A novel digestion technique for multi-element plant analysis. Commun Soil Sci Plant Anal 14:239–248

Ojala JC, Stark JC, Kleinkopf GE (1990) Influence of irrigation and nitrogen management on potato yield and quality. Am Potato J 67:29–43

Peignè J, Ball BC, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? A review. Soil Use Manag 23:129–144

Peigné J, Messmer M, Aveline A, Berner A, Mäder P, Carcea M, Narducci V, Samson MF, Thomsen IK, Celette F, David C

(2014) Wheat yield and quality as influenced by reduced tillage in organic farming. Org Agric 4:1–13

Saue T, Viil P, Kadaja J (2010) Do different tillage and fertilization methods influence weather risks on potato yield? Agron Res 8:427–432

Scholberg JMS, ter Berg C, Staps S, van Strien J (2009) Minder en anders bemesten: voordelen van maaimeststoffen voor de teelt van najaarsspinazie: resultaten veldproef bij Joost van Strien in Ens. Louis Bolk Intituut (Rapport / Louis Bolk Instituut nr. 2010–007 LbP), 51 p

Sharma N, Kumar P, Kadian MS, Pandey SK, Singh SV, Luthra SK (2011) Performance of potato (*Solanum tuberosum*) clones under water stress. Indian J Agric Sci 81:39–43

Simmonds NW (1977) Relations between specific gravity, dry matter content and starch content of potatoes. Potato Res 20:137–140

Tein B, Kauer K, Eremeev V, Luik A, Selge A, Loit E (2014) Farming systems affect potato (*Solanum tuberosum* L.) tuber and soil quality. Field Crop Res 156:1–11

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418:671–677

Triplett GB, Dick WA (2008) No-tillage crop production: a revolution in agriculture! Agron J 100:153–165

van den Putte A, Goversa G, Dielsa J, Gillijns K, Demuzerea M (2010) Assessing the effect of soil tillage on crop growth: a meta-regression analysis on European crop yields under conservation agriculture. Eur J Agron 33:231–241

van der Burgt GJHM, Scholberg JMS, Koopmans CJ (2011) Developing novel farming systems: effective use of nutrients from cover crops in intensive organic farming. In: Organic is life—knowledge for tomorrow, pp 32–35

van Loon CD (1981) The effect of water stress on potato growth, development, and yield. Am Potato J 58:51–69

van Oijen M (1991) Light use efficiencies of potato cultivars with late blight (*Phytophthora infestans*). Potato Res 34:123–132

Westermann DT, James DW, Tindall TA, Hurst RL (1994) Nitrogen and potassium fertilization of potatoes: sugars and starch. Am Potato J 71:433–453

White PJ, Bradshaw JE, Finlay M, Dale B, Ramsay G, Hammond JP, Broadley MR (2009) Relationships between yield and mineral concentrations in potato tubers. Hortscience 44:6–11