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Research article

Differences in N uptake and fruit quality between organically and conventionally grown greenhouse tomatoes

Valérie GRAVEL[1,7]*, Wim BLOK[1], Ewelina HALLMANN[2], Carmen CARMONA-TORRES[3], Hongyan WANG[4], Arjen VAN DE PEPPEL[5], Aníbal Franco CÓNDOR GOLEC[6], Martine DORAIS[7], Uulke VAN MEETEREN[5], Ep HEUVELINK[5], Ewa REMBIALKOWSKA[2], Ariena H.C. VAN BRUGGEN[1,8]

[1] Wageningen University, Department of Plant Sciences, Biological Farming Systems Group, Marijkeweg 22, 6709 PG Wageningen, The Netherlands
[2] Organic Foodstuffs Division, Faculty of Human Nutrition and Consumer Sciences, 02-776 Warszawa, Nowoursynowska 159c, Poland
[3] Department of Agricultural Economics and Sociology. Andalusian Institute of Agricultural Research, IFAPA. P.O. Box 2027, 18080 Granada, Spain
[4] North-East Agricultural University, College of Resource and environment, No. 59 Mucai Street, Xiangfang District, Harbin Heilongjiang Province, P.R. China
[5] Wageningen University, Department of Plant Sciences, Horticultural Supply Chains Group, Marijkeweg 22, 6709 PG Wageningen, The Netherlands
[6] Calle Francisco de Cuellar 451 casa 18 Monterrico, Santiago de Surco, Lima 33, Lima, Peru
[7] Agriculture and Agri-Food Canada, Centre de recherche en horticulture, Pavillon Envirotron, Université Laval, Québec, QC G1V 0A6, Canada
[8] Department of Plant Pathology and Emerging Pathogens Institute, University of Florida, Gainesville, FL32611, USA

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Abstract – Soil-bound intensive greenhouse production has been scrutinized for its sustainability due to contamination of ground water by over-fertilization resulting in leaching of nutrients. As environmental guidelines are becoming more restrictive worldwide, and especially in Europe, many greenhouse growers have converted to more sustainable production systems including rockwool culture with recycled water and organic cropping systems in soil. The increase in popularity of organic production systems has amplified the debate whether organically grown produce is healthier than conventional produce. So far, little is known about the variations in fruit quality associated with production systems for greenhouse grown tomatoes. Thus, two organic (organic fertilization with and without straw amendment) and three conventional tomato cropping systems (regular and increased nutrient solution in rockwool and regular fertilization in soil) were compared in order to evaluate differences in nutrient availability and effects on fruit quality over a three-year period. Three modern medium-sized round tomato cultivars and one old cultivar were compared. There were no significant interactions between cropping systems and cultivars, so that main effects of systems and cultivars could be evaluated. Fruit yields in the organic systems were similar to those obtained in the conventional soil-bound system, but 15% lower than in the regular rockwool system, even though nitrogen concentrations in soil were not limiting in any of the production systems. Frequent organic amendments resulted in higher soil NO_3^{2-} contents in the organic system without straw than in the other soil-bound systems, indicating that the organic systems were not yet stable in terms of nutrient availability after three years. A fruit quality index, based on the contents of compounds such as lycopene, β-carotene and vitamin C, was similar in all cropping systems. The old cultivar had a significantly higher quality index, but a lower yield than the other cultivars. According to this study, high quality tomatoes can be obtained through proper adjustment of the quantity and the source of nitrogen fertilizers in organic and conventional cropping systems and the use of selected cultivars with a high nutrient use efficiency for organic systems.

greenhouse tomato / organic / conventional / nitrogen uptake / xylem sap / fruit quality

1. INTRODUCTION

In certified organic greenhouses in the Netherlands, vegetable production must take place in natural soil. Nutrients need to be supplied from the soil amended with organic materials such as cover crops, composted manure or green waste. Organic methods of production have long been recognised as friendly to the environment. However, questions still remain about the possible effect of organic management on fruit quality (Brandt and Mølgaard, 2001; Magkos et al., 2003; Williams, 2002). Numerous investigations have proven that organic plant products contain fewer nitrates, nitrites and pesticide residues but more vitamin C, phosphorus and potassium (Bourn and Prescott, 2002; Rembialkowska, 2000). Nevertheless, knowledge about the nutritive value and the antioxidant contents, such as lycopene, β-carotene and flavonols,

* Corresponding author: gravelv@agr.gc.ca

of organic crops is still insufficient, especially in the case of organic greenhouse crops.

Secondary plant metabolites such as lycopene and phenolic compounds may function as defence mechanisms against plant pathogens and pests, but may also function as provitamins and antioxidants in humans and are considered as anti-carcinogenic substances. The contents of these metabolites are currently suboptimal for human health (Brandt and Mølgaard, 2001). Organic vegetables and fruits may contain more of these compounds than conventional ones, as organically produced plants may be exposed to more pests, diseases and other stress factors (Brandt and Mølgaard, 2001).

Two different theories have been put forward to describe the physiological mechanisms involved in the possibly higher content of secondary plant metabolites in organic plant products. The C/N balance theory states that when nitrogen is readily available, plants will primarily make compounds with high N content whereas when N-availability is limiting for growth, plant metabolism changes towards carbon containing compounds, such as lycopene or β-carotene which are present in relatively high amounts in greenhouse tomatoes (Bryant et al., 1983; Coley et al., 1985). The GDBH theory (growth-differentiation balance hypothesis) states that a plant will assess the resources available to it and optimise its investment in processes directed towards growth or differentiation (Herms and Mattson, 1992; Lorio, 1986). Based on this theory, Lundegårdh and Mårtensson (2003) suggested that organically produced plant foods could be more health-promoting than conventional foods due to enhanced activation of plant resistance mechanisms in the absence of pesticides, enhanced interactions between plant roots and a variety of microbes and more balanced mineral nutrient availability and uptake.

The types of fertilizers used and the N form available for plant uptake play a major role in plant development and fruit quality of tomato plants (Heeb et al., 2005; Toor et al., 2006). When using organic nitrogen sources, the organic material is mineralized to amino-compounds and ammonium, which is subsequently converted to nitrate, depending largely on oxygen availability and the activity of microorganisms in the rhizosphere (Clarholm, 1985). While nitrate is the preferred N-form for plant uptake, ammonium and organic N compounds can also be taken up by the plant and its associated mycorrhizal fungi under low nitrate conditions (Hodge et al., 2001; Näsholm et al., 1998, 2000). So far, little is known about the forms of N taken up by tomato plants in organic versus conventional greenhouse systems, and the relation between N uptake and fruit quality.

Our research hypotheses based on the theories presented above were that organically produced tomatoes would contain more dry matter, vitamin C and more flavonoids than conventionally grown tomatoes, assuming that the available nitrogen would be lower in organic systems. The level of carotenoids was expected to be higher in systems with more available nitrogen (Brandt and Mølgaard, 2001).

The objective of this experiment was therefore to compare, over a 3 year period, organic and conventional greenhouse tomato cropping systems in terms of nutrient availability and uptake by the plant, and their effects on plant growth and fruit quality, especially in relation to the contents of antioxidant compounds.

2. MATERIALS AND METHODS

2.1. Location and experimental design

Greenhouse experiments were carried out over a period of 3 years (January 2004 to December 2006) in two adjacent compartments (each 150 m^2) at the Unifarm glasshouse of Wageningen University in The Netherlands. The soil was a sandy soil that had been overlaid with plastic until the start of the experiment. Soil pH ranged from 5.5 and to 5.9 whereas soil electrical conductivity (EC) was between 1.6 and 1.9 dS/m. Climate conditions were similar in the two compartments. The organic matter content was between 8.6 and 10% at the beginning of the experiment. Natural daylight was supplemented with HPS lamps (100 μmol m^{-2} s^{-1} PAR) to maintain a photoperiod of 14 h. A ground heating system was used to maintain adequate temperature. The average temperatures were 21.0 °C (day) and 17.4 °C (night). The average relative humidities were 79.2% (day) and 85.4% (night).

Three consecutive tomato crops, starting in March or April and ending in December, were cultivated in 4 different growing systems. There were two conventional systems with tomato plants grown in rockwool at two nutrient concentrations (CONV-RWL and CONV-RWH) and two soil-based growing systems: an organic (ORG) system and a conventional soil-based (CONV-S) system. All CONV systems were located in one greenhouse compartment (each 50 m^2) and the ORG systems were in the adjacent compartment. After the first year, the initial ORG system was divided into two subsystems by incorporating 200 kg of straw into half of the organic plots (75 m^2) creating 2 treatments: with (ORGWS) or without straw (ORG).

There were three blocks per system with four plots each containing four indeterminate tomato (*Lycopersicon esculentum* Mill.) hybrid cultivars (cv15, cv40, cv45, cv93; De Ruiter Seeds) with medium-size round fruits. Cv40 was an old cultivar, while the others were modern cultivars. In the CONV-S and ORG systems, a plot consisted of 2 rows of 5 plants. In the CONV-RWL and CONV-RWH systems, a plot consisted of 1 row of 5 plants each. The plant density was 2.5 plants m^{-2}. Because of limitations in the number of greenhouse compartments available, repetitions were done in time (3 years considered as 3 repetitions). Cultivars (experimental unit) were randomized within each of 3 blocks every year. Within each plot, three plants were evaluated and border plants were excluded from measurements.

2.2. Soil fertilisation relative to planting time

Before every crop and during the growing season, soil samples were sent for analysis to the Blgg laboratory in Naaldwijk

Table I. Initial fertilization and subsequent amendments for soil-bound growing systems.

	Application rates (ton ha^{-1})		
	2004	2005	2006
ORG			
Initial fertilisation			
Green waste compost	156.7	156.7	156.7
Cow manure	109.3	27.3	27.3
Amendments			
Culterra manure pellets (N-P-K: 10-4-6)	2.3	1.5	1.5
Magnesium sulphate	1.2	0.6	0.6
ORGWS			
Initial fertilisation			
Green waste compost	156.7	156.7	156.7
Cow manure	109.3	27.3	27.3
Amendments			
Culterra manure pellets (N-P-K: 10-4-6)	2.3	0.9	0.9
Magnesium sulphate	1.2	0.6	0.6
CONV-S			
Amendments			
23-23-0 (N-P-K)	0.9		
12-10-18 (N-P-K)	1.2		
Magnesium sulphate	2.25	2.0	2.0
Magnesamon® (22% N, 7% MgO)		1.3	1.3
Potassium nitrate		1.3	1.3

Crop systems were: organic system in soil with (ORG) or without straw (ORGWS), and conventional system in soil (CONV-S).

(see below), and fertilisation in all systems was adjusted according to the recommendations following the analysis in order to remain as close as possible to the reality of commercial growers.

Initial fertilization and subsequent amendments in soil-bound systems are presented in Table I. The organic plots received the following organic amendments before planting. In October 2003, 3 m^3 (2350 kg) of green-waste compost and 2 m^3 (1640 kg) of cow manure were added to the organic greenhouse compartment (150 m^2) and incorporated to a depth of 25 cm. A cover crop consisting of vetch and rye was then sown and 4 months later turned under in the soil. On March 18th 2004, tomato plants were transplanted. In January 2005, 3 m^3 (2350 kg) of green-waste compost and 1/2 m^3 (410 kg) of cow manure were added to the organic greenhouse compartment and once again incorporated to a depth of 25 cm. A cover crop of rye only was then sown and incorporated 2 months later. On April 28th 2005, tomato plants were transplanted. In January of 2006, the same amount of compost and manure as in 2005 was added but no cover crop was planted. On March 20th 2006, tomato plants were transplanted. Each year, crop cycles ended in December at which point plants were removed and cover crops sown.

In addition to these initial amendments, ORG plots (6.25 m^2 each) were fertilized 6 times during the growing cycles with 4 to 7.5 kg of Culterra manure pellets (N-P-K:10-4-6) and 2 to 4 kg of magnesium sulphate in 2004. In that year, CONV-S plots were fertilized 3 times with 1.58 kg of 23-23-0 (N-P-K) and 2.25 kg of magnesium sulphate followed by 2 applications of 3 kg of 12-10-18 (N-P-K) with 2.25 kg of magnesium sulphate. In 2005 and 2006, ORG plots were fertilized 3 times with 3.76 kg of Culterra manure pellets (N-P-K:10-4-6) and 1.41 kg of magnesium sulphate. ORGWS plots were fertilized twice with 3.76 and 2.82 kg of Culterra manure pellets (N-P-K:10-4-6) and 3 times with 1.4 kg of magnesium sulphate. CONV-S plots were fertilized 7 times per season with 0.94 kg of Magnesamon® (magnesium ammonium nitrate; 22% N and 7% MgO), 0.94 kg of potassium nitrate and 1.41 kg of magnesium sulphate. In all cases, solid fertilizers were applied in the first 10 cm on the soil surface.

The compositions of the nutrient solutions, supplied through fertigation, in the rockwool systems were the same in all years, namely for the high EC system (per 100 000 L): $Ca(NO_3)_2{\cdot}4H_2O$ (296.1 L), NH_4NO_3(15.1 L), HNO_3 (77.8 L), H_3PO_4 (34.0 L), H_2SO_4 (81.7 L), $MgSO_4$(244.3 L), K_2O (140.3 L), chelated iron DTPA 6% (2325.0 g), chelated iron DTPA 3% (3.6 L), $MnSO_4{\cdot}H_2O$ 32% (210.0 g), $ZnSO_4{\cdot}7H_2O$ 23% (215.0 g), Borax (285 g), $CuSO_4{\cdot}5H_2O$ (23 g) and Na_2MoO_4 (12 g) (as recommended by Blgg laboratory). For the low EC system, the nutrient solution contained (per 100 000 L): $Ca(NO_3)_2{\cdot}4H_2O$ (146.6 L), NH_4NO_3(15.1 L), HNO_3 (46.6 L), H_3PO_4 (20.3 L), H_2SO_4 (33.1 L), $MgSO_4$(120.8 L), K_2O (69.5 L), chelated iron DTPA 6% (2325.0 g), chelated iron DTPA 3% (3.6 L), $MnSO_4{\cdot}H_2O$ 32% (210.0 g), $ZnSO_4{\cdot}7H_2O$ 23% (215.0 g), Borax (285 g), $CuSO_4{\cdot}5H_2O$ (28 g) and Na_2MoO_4 (12 g) (as recommended by Blgg laboratory).

2.3. Plant growth

For the ORG and ORGWS treatments and the CONV-S treatment, seeds were sown in sowing flats containing an organic potting mixture. After 10 days, seedlings were transplanted into 1-litre pots containing the same mixture. Six weeks later, plants were transplanted into the soil of each production system. For the CONV-RWL and -RWH treatments, plants were sown and raised in rockwool plugs. For the ORG and CONV-S treatments, sprinklers were used to irrigate the plants whereas drip fertigation was used for the CONV-RW systems. In the CONV-RW systems, plants were irrigated with either a nutrient solution of low EC (RWL, 2 dS m^{-1}) or with a solution of high EC (RWH, 5.3 dS m^{-1}). The compositions of the nutrient solutions are outlined above.

Plants were grown using the high wire system. Axillary shoots were removed and plants were lowered on a weekly basis. Biological control was used to control pests such as white flies and red mites. Sulphur dust was used to control powdery mildew in all systems.

Fruits were harvested on a weekly basis. The numbers of fruits and their weights were recorded. Numbers of leaves and trusses were counted on a weekly basis and the growth rate was calculated. Bottom leaves were removed as needed. At every leaf removal time, the surface area and the dry weight of the leaves were measured. Specific leaf area (SLA) was calculated as the surface area per g of dry weight. Relative growth rates (RGR) for leaves, trusses and SLA were obtained by fitting a logistic curve to the collected data using the statistical software SAS (SAS Institute Inc.).

2.4. Soil and solution nutrient analyses

Soil samples were collected (4 times in 2004 and every month in 2005 and 2006) from each plot of the ORG and CONV-S systems at two depths (0–25 cm and 25–50 cm). Soil samples were dried at 40 °C and then sieved through a 2 mm mesh. To determine the NO_3^- and NH_4^+ content at the laboratory of the Biological Farming Systems Group, 3 g of soil were mixed with 30 mL of a 0.01 M calcium chloride solution. Samples were shaken for 2 h at room temperature and the mixture was then centrifuged (1800 g) for 10 min. Subsequently, 10 mL of the supernatant were mixed with 0.1 mL of 1 M hydrochloric acid. Samples were then analyzed for NO_3^- and NH_4^+ using a segmented-flow analyzer. For total nutrient analyses, soil samples (depth of 0–25 cm) and solution samples from the rockwool slabs were collected and sent to the Blgg Naaldwijk Laboratory (Naaldwijk, The Netherlands). In 2004, soil and rockwool were sampled 6 times whereas in 2005 and 2006, they were sampled 3 times.

2.5. Xylem sap analyses

The amounts of NO_3^-, NH_4^+ and total amino acids were measured in the xylem sap of leaves in October of 2004 and of 2005. Both times, the 5th leaf from the top was removed from each sampled plant early in the morning. Each petiole was put through a stopper and the leaf was placed inside of a pressure bomb (10 bars for 15 to 20 min). The sap collected with a syringe (150–350 μL) was kept at –19 °C until analysis. Samples were analyzed directly for NO_3^- and NH_4^+ with a segmented flow analyzer. Malate dehydrogenase activity in the xylem sap samples was measured in order to detect contamination with cell compounds or phloem sap (Yu et al., 1999). Contaminated samples were not used in the analyses. Amino acid concentration was evaluated in the sap using the Ninhydrin procedure as described by Jones et al. (2002). Briefly, 100 μL of xylem sap sample was mixed with 50 μL of Ninhydrin color reagent and heated for 25 min at 100 °C. After cooling, 1 mL of 50% ethanol was added. The absorbance at 570 nm was measured using a spectrophotometer. The amino acid standard consisted of a mixture of methionine, alanine, lysine, arginine, glutaminic acid, serine, valine, phenylalanine, leucine, isoleucine, tyrosine, cysteine, glycine, asparagine nonhydrate, proline, histidine and treonine (L-isomeres; each at 0.4 μmol/mL in 0.1 M HCl). The amino acid content was calculated using the following equation: Amino acids (μM) = $((O_N - B_N - A_N)/S_N) \times 100$ [O_N: absorbance of the sample mixed with the ninhydrin reagent; B_N: absorbance of the blank; S_N: spectrometer reading of 100 μM amino acid standard; $A_N = AC_N \times AR_N/AS_N$($AC_N$: ammonium concentration in the sample (μM); AS_N: ammonium concentration of standard (μM); AR_N: absorbance of the ammonium standard using the ninhydrin colorimetric procedure)].

2.6. Chemical analyses of leaves, stems and fruits

At the end of each crop, leaves and stems were collected and dried at 40 ∘C. Total N and total C contents were determined using the Dumas Method with a CHN1110 Element Analyzer (CE instruments, Milan, Italy). Fruit samples were harvested three times during each crop at the same growth stage of the plant. Five fruits per plot were collected from the sampling plants. Tomato fruits were cut into 8 pieces and 2 pieces from each fruit from a same plot were pooled and quickly frozen in liquid nitrogen in order to stop enzymatic processes. Samples were freeze-dried and stored at –80 °C. Just before quality analysis, samples were stored in a dessicator at –5 °C in the dark.

Ascorbic acid content was evaluated according to the method described by Helsper et al. (2003). Carotenoid content was determined according to the methods described by Konings and Roomans (1997) and by Helsper et al. (2003). Flavonoid content was evaluated according to the method described by Hertog et al. (1992). Carbohydrates and anion contents were determined according to the methods described by Hajjaj et al. (1998).

2.7. Fruit quality index

The fruit quality index, similar to the one presented by Frusciante et al. (2007), was calculated using the following equation: $F_{QI} = \sum(C_S * K_X)/C_O$, where C_S is the concentration of the quality parameter in the sample, K_X is the coefficient attributed to this quality parameter and C_O is the average optimal concentration of this same parameter in tomato fruit according to literature (Tab. II). Lycopene, β-carotene, ascorbic acid, glucose, fructose, sucrose, nitrate and oxalate content were taken in consideration for the quality index.

2.8. Statistical analyses

The effects of crop systems, cultivars and the interaction of these fixed effects on xylem sap content, relative growth rates, fruit yield and fruit quality index were analyzed using the SAS Mixed Models procedure (SAS Institute, Cary, NC) with replicates (years) and location (blocks) of plots as random effects. When needed, means were compared by the Tukey's multiple range test. The Pearson correlation coefficients between the relative growth rates or the fruit quality and the nutrient content in the soil were determined using the SAS Correlation procedure.

3. RESULTS AND DISCUSSION

3.1. Nutrient availability and nitrogen uptake

This experiment represented the first 3 years following the conversion from a conventional system to a certifiable organic production system. Therefore, this experiment had to

Table II. Optimal concentration and K coefficient of the quality parameters used to calculate the quality index (F_{QI}) of tomato fruits.

Quality parameters	Optimal concentration ($\mu g\ mg^{-1}$ of dry weight)	K coefficient	
Lycopene	1.16	20	(Frusciante et al., 2007)
β−carotene	0.06	10	(Frusciante et al., 2007)
Vitamin C	1.49	15	(Frusciante et al., 2007)
Glucose	220.00	5	(Rosales et al., 2007)
Fructose	250.00	5	(Rosales et al., 2007)
Sucrose	10.00	5	(Rosales et al., 2007)
Nitrate	2700.00	5	(Christou et al., 2002)
Oxalate	6.77	5	(Raffo et al., 2002)

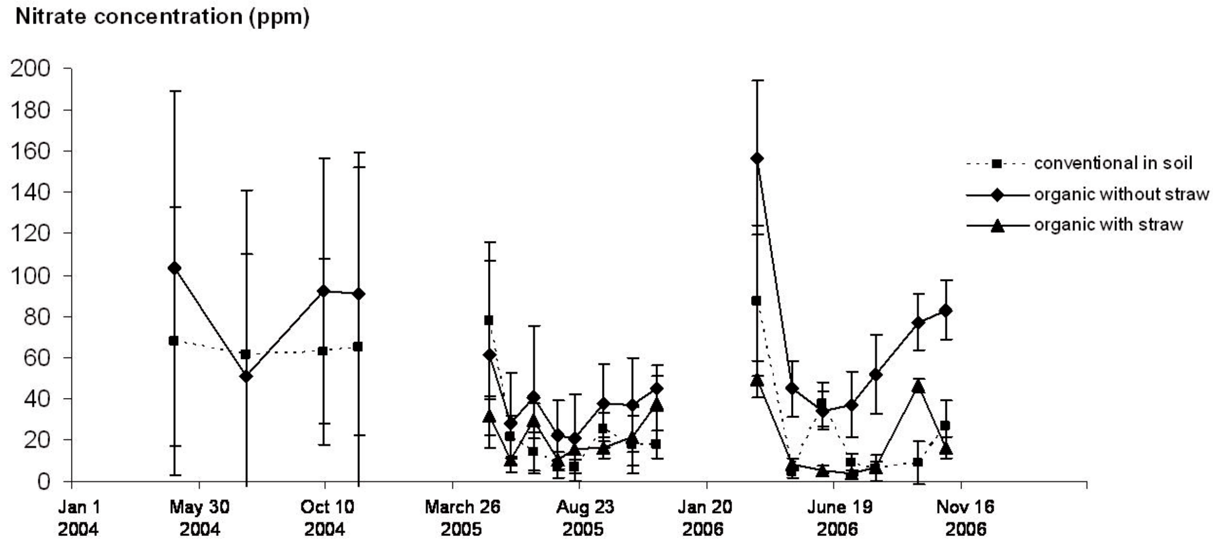

Figure 1. NO_3^- content in the soil (depth from 0 to 25 cm) of the three crops systems over the 3 years of the experiment. Considerable variations in NO_3^- content in soil were observed in 2004. In 2005, following straw incorporation, a trend showing a higher NO_3^- content in the organic system without straw started to emerge. This trend continued in 2006 with a significantly higher NO_3^- content in the organic system without straw compared to the other soil-bound systems.

face challenges similar to those encountered by tomato growers going through the process of converting their production system. One of the main concerns in organic tomato cropping is adequate fertilisation and especially the availability of nitrogen. There were large variations in the NO_3^- content in the soil (depth of 0–25 cm) in 2004 (Fig. 1). This was expected considering that it was the first year following the initial soil preparation and organic fertilisation. In 2005, trends in treatment differences with respect to NO_3^- content emerged although variations were still quite important but in 2006, the soil in the ORG system had a significantly higher NO_3^- content than the other soil-bound systems (Fig. 1). No significant difference was observed among crop systems in N content at a depth of 25 to 50 cm (data not shown). The nutrient (P, K, Ca, Mg, and SO_4) contents in the CONV-RW systems were significantly higher than in the ORG, ORGWS and CONV-S systems but no significant difference was observed between the three soil-bound systems (data not shown).

Xylem sap of leaves was evaluated for various N forms in the different cropping systems. Similar trends were observed in 2004 and 2005. Only the results from the 2005 analyses are shown (Tab. III) since more complete data were obtained. The concentration of amino acids was significantly higher in the xylem sap of leaves of tomato plants grown in the ORG system (Tab. III). A cultivar effect was also observed for the concentration of amino acids, NO_3^- and the ratio of amino acids to NO_3^- (Tab. III). The higher amino acids content in the xylem in organic systems, especially without the addition of straw, suggests that tomato plants are able to selectively take up nitrogen in forms other than NO_3^- when grown in systems where other forms of N, such as organic N and NH_4^+, are readily available even if NO_3^- is not limiting (Fig. 1).

Even though tomato plants are believed to take up NO_3^- preferably over NH_4^+, which can even be harmful to tomato plant development (Benton Jones, 2004), the results from this study suggest that tomato plants can take up N either in the form of amino acids or in the form of NH_4^+ and convert it rapidly to amino acids prior to translocation in the xylem (Andersen et al., 1999). Considering that the NO_3^- concentration in the xylem sap did not vary among the treatments, this could indicate that nitrate was not a limiting factor in the case of this experiment. The concentration of NO_3^- available in the

Table III. Concentrations of amino acids, NO_3, NH_4^+, and the ratios of amino acids/ NO_3^- and amino acids/NH_4^+ in the xylem sap of tomato plants grown under five different cropping systems with four tomato cultivars in 2005.

Crop systems	Amino acids (μM)	NO_3^- (μM)	NH_4^+ (μM)	Ratio aa/ NO_3^-	Ration aa/NH_4^+
Crop systems					
ORG	38.91 a	915.27 a	39.84 a	0.04 a	1.43 a
ORGWS	32.53 ab	749.72 a	24.80 a	0.05 a	1.60 a
CONV-S	30.59 b	803.18 a	36.93 a	0.05 a	1.32 a
CONV-RWL	29.60 b	701.70 a	29.98 a	0.04 a	1.01 a
CONV-RWH	27.52 b	750.63 a	38.95 a	0.04 a	1.71 a
P values	0.0501	0.3643	0.3164	0.6791	0.5591
	(0.0070)[a]	(0.7250)[a]		(0.0050)[a]	
Cultivars					
15	34.74 bc	914.57 a	41.79 A	0.04 b	1.25 a
40	36.50 c	752.18 ab	27.72 A	0.05 a	1.93 a
45	26.01 a	649.66 b	30.58 A	0.04 b	1.51 a
93	29.99 ab	819.19 ab	36.31 A	0.04 b	0.95 a
P values	0.0031	0.0421	0.1229	0.0008	0.0951
	(0.0026)[a]	(0.0004)[a]		(0.4201)[a]	

[a] *P* values for the 2004 analyses.

Crop systems were: organic system in soil with (ORG) or without straw (ORGWS), conventional system in rockwool with a high nutritive solution concentration (CONV-RWH), conventional system in rockwool with a low nutritive solution concentration (CONV-RWL), and conventional system in soil (CONV-S). The interaction between crop systems and cultivars was not significant and therefore, only the main effects were considered. For each parameter (crop systems and cultivars), within each column, values followed by a similar letter are not significantly different according to Tukey test ($P \leqslant 0.05$).

ORG and CONV systems was under 50 ppm for most of 2005, which is lower than the available NO_3^- in the rockwool systems (more than 1200 mg/L of NO_3^- in the slabs).

3.2. Plant growth

Significant cultivar effects were observed for the relative growth rates of leaves, trusses and specific leaf area, with cultivar 40 always having the lowest values (Tab. IV). Variations in fertilization among the cropping systems had no effect on plant growth as no differences were observed in the three relative growth rates among treatments (Tab. IV). This indicates that fertilization and nutrient availability were not limiting the growth rates of the plants. It has long been recognized that conventional hydroponic tomatoes are often overfertilized. This study shows that the overfertilization of tomato plants in the high EC treatment did not have a beneficial effect on plant growth as the relative growth rates in both rockwool systems were similar. Surplus in nutrients in the high EC solution exceeded plant needs and were therefore not necessary for normal plant growth.

No significant difference was observed in the C and N content in the leaves and stems (data not shown). Differences among cropping systems were, however, observed for fruit yields in this experiment. Yields in both organic systems (with or without straw) were around 85% of the yield obtained in the conventional rockwool system with low EC (Tab. V). The high

Table IV. Relative growth rates (RGR) of leaves, trusses and specific leaf area (SLA) of tomato plants.

	RGR leaves	RGR trusses	RGR SLA
Crop systems			
ORG	0.017 a	0.021 A	0.028 a
ORGWS	0.017 a	0.021 A	0.025 a
CONV-S	0.017 a	0.022 A	0.030 a
CONV-RWL	0.019 a	0.021 A	0.026 a
CONV-RWH	0.018 a	0.021 A	0.029 a
P values	0.0750	0.1881	0.5072
Cultivars			
15	0.019 c	0.022 C	0.027 ab
40	0.016 a	0.019 A	0.024 a
45	0.019 c	0.023 C	0.029 bc
93	0.018 b	0.020 B	0.031 c
P values	<0.0001	<0.0001	0.0188

Crop systems were: organic system in soil with (ORG) or without straw (ORGWS), conventional system in rockwool with a high nutritive solution concentration (CONV-RWH), conventional system in rockwool with a low nutritive solution concentration (CONV-RWL), and conventional system in soil (CONV-S). The relative growth rate (RGR) was obtain by fitting a logistic curve. Specific leaf area was calculated as the surface area/g of dry weight. The interaction between Cultivars and Crop systems was not significant and therefore, only the main effects were considered. For each parameter (cultivar and crop system), within each column, values followed by a similar letter are not significantly different according to Tukey test ($P \leqslant 0.05$).

Table V. Tomato fruit yield of four different cultivars grown in organic or conventional crop systems.

	Weight of fruits (g/plant/week of harvesting)	Number of fruits (nb/plant/week of harvesting)
Cultivars		
15	441.3 c	4.9 c
40	286.0 a	4.1 b
45	372.7 b	4.9 c
93	418.7 c	3.2 a
P values	0.0001	0.0001
Crop systems		
ORG	373.12 ab	4.3 bc
ORGWS	376.08 ab	4.0 ab
CONV-S	312.60 a	3.8 a
CONV-RWL	441.75 c	4.7 c
CONV-RWH	394.85 bc	4.7 c
P values	0.0121	0.0087

Crop systems were: organic system in soil with (ORG) or without straw (ORGWS), conventional system in rockwool with a high nutritive solution concentration (CONV-RWH), conventional system in rockwool with a low nutritive solution concentration (CONV-RWL), and conventional system in soil (CONV-S). The interaction between Cultivars and Crop systems effect was very weak (*P* value = 0.0306) and, therefore, only the main effects were considered. For each parameter (cultivar and crop system), within each column, values followed by a similar letter are not significantly different according to Tukey test ($P \leqslant 0.05$).

Table VI. Tomato quality index of tomato fruits of four cultivars grown in organic or conventional crop systems.

	Quality index[a]
Crop systems	
ORG	59.36 a
ORGWS	62.45 a
CONV	62.56 a
CONV-RWL	58.51 a
CONV-RWH	60.92 a
P value	0.2520
Cultivars	
15	56.25 b
40	78.52 a
45	55.68 b
93	52.52 c
P value	< 0.0001

[a] Quality index= $\sum (C_S \text{ sample} * K_X)/C_O$

Crop systems were: organic system in soil with (ORG) or without straw (ORGWS), conventional system in rockwool with a high nutritive solution concentration (CONV-RWH), conventional system in rockwool with a low nutritive solution concentration (CONV-RWL), and conventional system in soil (CONV-S). The interaction between Cultivars and Crop systems was not significant and therefore, only the main effects were considered. For each parameter (cultivar and crop system), within each column, values followed by a similar letter are not significantly different according to Tukey test ($P \leqslant 0.05$).

EC of the nutrient solution seemed to have a detrimental, although not significant, effect on fruit yield. The yield of ORG tomatoes was higher, although not significantly, than the yield in the CONV-S system and similar to the yield in the CONV-RWH system. These results are, therefore, in accordance to earlier reports where similar tomato yields were obtained in organic compared to conventional soil-bound systems (Clark et al., 1998; Colla et al., 2000; Heeb et al., 2005). Once again, a strong cultivar effect was observed for fruit yields, cultivar 40 having the least total fruit weight (Tab. V).

Even though relative growth rates were similar in all systems, strong positive correlations, with a correlation coefficient of +0.72 and +0.75, were observed between the NO_3^- content in the soil of the ORGWS system and the RGR of leaves or trusses, respectively. This indicates that the availability of nitrate can be a limiting factor for plant growth when straw is added to soil. A negative correlation, with a correlation coefficient of –0.73, was observed between the RGR of SLA and the NO_3^- content in soil. Thicker leaves and the resulting reduced photosynthetically active leaf area could be associated with the reduced growth rates observed. Opposite correlations were observed between the growth rates and the NH_4^+ content in the soil. Correlation coefficient were –0.64 and –0.66 between NH_4^+ soil content and RGR of leaves and trusses, respectively whereas it was +0.63 between NH_4^+ soil content and RGR of SLA. This indicates that a too high concentration of nitrogen in that form can have a detrimental effect on plant growth.

3.3. Fruit quality

Cropping systems, especially through the differences in fertilization and nutrient sources, are thought to influence fruit quality. Heeb et al. (2005) demonstrated that reduced N forms (ammonium or organic nitrogen) used as fertilization improves fruit taste compared to nitrate fertilization. In this experiment, a quality index (F_{QI}) was used to express the overall health benefit of fruits harvested in the different systems tested. Lycopene, β-carotene and ascorbic acid were given high K coefficients as they are considered to play an important role in improving human health, whereas glucose, fructose, sucrose and oxalate, which are more related to taste were given a lower K coefficient (Tab. II). Contrary to what has long been believed (Lundegårdh and Mårtensson, 2003), no significant difference was observed in this experiment between the organic and the conventional systems in terms of fruit quality (Tab. VI). This holds also for individual quality variables presented in Table II used to calculate the quality index (data not shown). The cultivar had a stronger influence on fruit quality than the cropping system, cultivar 40 having the highest quality index value (Tab. VI). Mitchell et al. (2007) reported an increase in flavonoids in field tomatoes over a period of 10 years in an organic system which had reached equilibrium levels of organic matter. During the 3 years of this experiment, such equilibrium had probably not been reached yet considering the high availability of N in the ORG soils (Fig. 1), which is known to negatively influence antioxidant accumulation in tomato fruits (Toor et al., 2006).

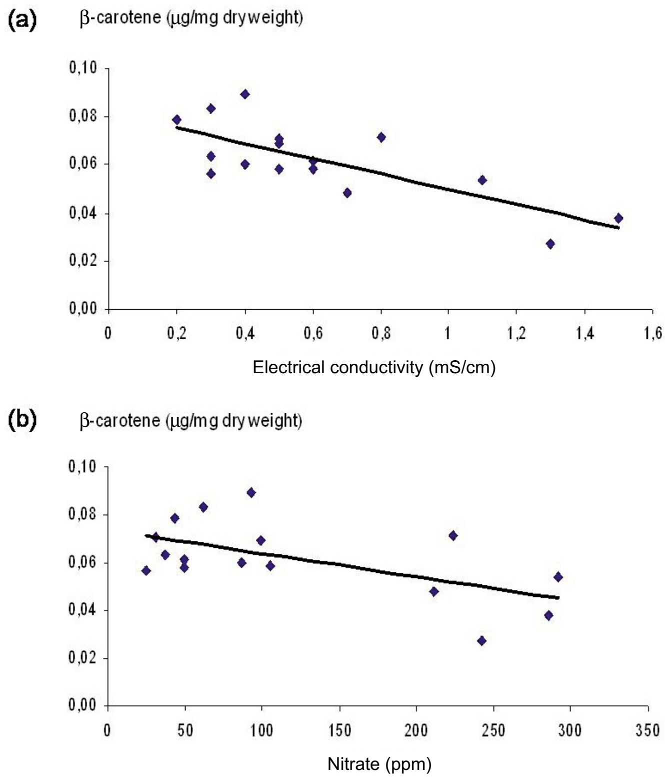

Figure 2. Correlation between β-carotene content in tomato fruits and electrical conductivity (EC) (a) or NO_3^- in the soil (b). β-carotene is negatively correlated with soil EC and NO_3^- content when all soil-bound systems are considered with correlation coefficients of –0.77 and –0.61, respectively.

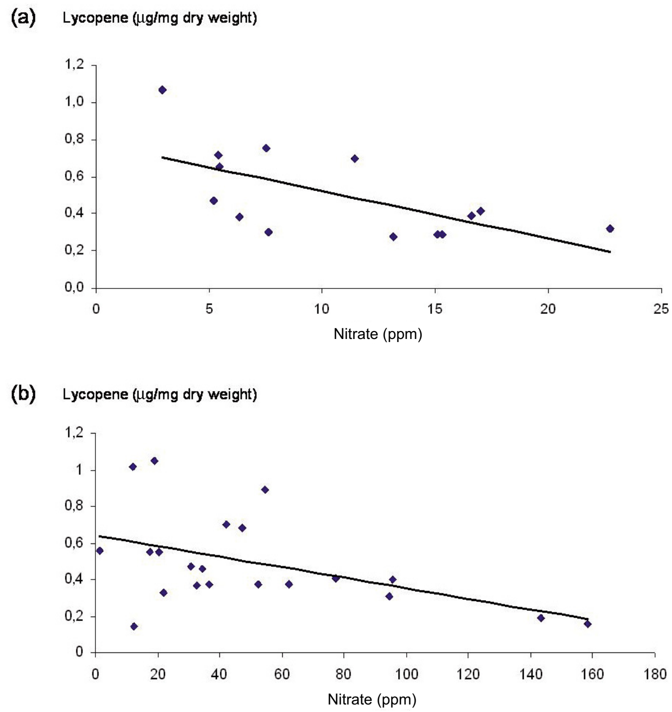

Figure 3. Correlation between lycopene content in tomato fruits and NO_3^- in the organic soil with straw (ORGWS) for cultivar 93 (a) and between lycopene content in tomato fruits and NO_3^- in the organic soil without straw (ORG) for cultivar 45 (b). Lycopene content for cultivar 93 grown in the organic system with straw is negatively correlated with soil NO_3^- content. Lycopene content for cultivar 45 grown in the organic system without straw is negatively correlated with soil NO_3^- content.

Lycopene and β-carotene were also negatively correlated, although only significantly in the case of β-carotene, with the soil EC and NO_3^- content when all crop systems in soil were considered (Tab. VII, Fig. 2). Results for lycopene only showed a significant correlation with NO_3^-in the case of cultivar 93 in ORGWS and cultivar 45 in ORG (Fig. 3). These results also suggest that organic greenhouse tomatoes, when grown in systems with less readily available NO_3^-could have a higher lycopene and β-carotene content compared to conventional hydroponic systems. In this experiment, however, there was no difference in fruit quality between the crop systems, probably because the organic systems were not entirely stable yet in terms of nutrient availability. Nevertheless, the lycopene and β-carotene contents in organic fruits were positively correlated (r = +0.43 and r = +0.43, respectively) with the ratio of amino acids/ NO_3^- in the xylem sap. This suggests that the ratio amino acids/ NO_3^- is a good indicator of the health benefit potential of a crop system as a higher ratio was shown to be associated with a higher content in the antioxidants lycopene and β-carotene.

The accumulation of certain compounds can also be highly related to the content of other components. Indeed, fruit analysis also showed that flavonol content was positively correlated with the content in lycopene, β-carotene, ascorbic acid and oxalate (r = +0.53 to +0.77). Strong positive correlations were also observed between ascorbic acid and lycopene or oxalate (r = +0.61 and r = +0.60, respectively). Also of particular interest was the strong correlation between naringenin and quercetin (r = +0.69) as well as the correlation between fructose and glucose (r = +0.85). Fruit quality is furthermore often related to other factors which are influenced by the plant nutrition status, such as growth and development. As could be expected (Veit-Köhler et al., 1999), the relative growth rates of leaves and of trusses was negatively correlated with β-carotene and ascorbic acid (r = –0.45 to –0.66) whereas they were positively correlated with nitrate and sulphate (r = +0.46 to +0.70). The relative growth rate of trusses was also negatively correlated, although weakly, with glucose and fructose (r = –0.17 and –0.24, respectively).

This experiment clearly shows that fruit quality and plant growth are highly variable among tomato cultivars. The old cultivar Cv 40 had a lower growth rate and fruit yield (Tabs. IV and V) but a significantly higher fruit quality index (Tab. VI) compared to the other three modern cultivars. This trade-off between yield and quality suggests that old cultivars could perhaps be used in breeding for tomato cultivars that are better suited for organic cropping systems, especially if a higher fruit quality is the main objective (Kumar et al., 2007).

Table VII. Correlation coefficients between fruit quality and nutrients in the soil (including conventional and organic systems with or without straw).

	EC	pH	NO_3	P	K	Ca	Mg	SO_4
Lycopene	–0.37	0.06	–0.06	–0.18	0.10	–0.39	–0.50*	–0.48
β−carotene	–0.77**	0.23	–0.61*	0.07	–0.28	–0.79**	–0.76**	–0.77**
Ascorbic acid	–0.14	–0.14	0.03	–0.38	–0.01	–0.13	–0.13	–0.16
Quercetin	0.90**	–0.93**	–0.09	0.61*	0.60*	–0.28	0.00	0.64*
Naringenin	–0.02	–0.32	0.07	0.15	0.05	–0.03	0.00	–0.09
Fructose	0.33	–0.36	0.19	–0.11	–0.31	0.46	0.51*	0.52*
Sucrose	0.24	–0.41	0.15	0.20	0.023	0.25	0.36	0.35
Glucose	–0.41	0.36	–0.39	–0.07	–0.18	–0.47*	–0.41	–0.41
Myo-inositol	0.40	–0.22	0.18	0.03	–0.01	0.48	0.54	0.60*
Oxalate	0.17	–0.41	–0.03	0.36	–0.21	0.25	0.38	0.40

* Significant (0.05)

** Significant (0.01)

EC: electrical conductivity

3.4. Fruit quality

It is important to mention that in the last year of the experiments (2006), corky root (*Pyrenochaeta lycopersici*) was observed in all the soil-bound crop systems (data not shown). Symptoms were the most severe in the organic system without straw. Considering the conditions of the root systems, the yield in the ORG systems would most likely have been higher if corky root had not been present, perhaps even reaching the yield obtained in rockwool with low EC. Symptoms of corky root were positively correlated with total nitrogen in the soil (data not shown). The high N availability by apparent over-fertilization in the organic systems, especially in the absence of straw, could explain the higher infection rate in the ORG system (Workneh and van Bruggen, 1994). Losses caused by corky root are especially severe in cropping systems with little or no rotations (Clark et al., 1998), as in this experiment. Crop rotations are generally limited in organic greenhouse production, mainly due to the lack of alternative crops that can be cultivated using similar systems and that are not susceptible to diseases such as corky root. Both peppers and cucumbers, which are commonly used as rotation crops in organic greenhouses, are highly susceptible to corky root (Grove and Campbell, 1987).

4. CONCLUSION

In organic greenhouse cropping systems, fertilization is one of the key elements essential for achieving success. In this experiment, recommendations for soil amendments, which were similar to those typically given to organic tomato growers, were high in comparison to organic certification regulations. Nitrate content in soil was therefore not a limiting factor in the organic systems for the three years of this experiment. Even though fruit quality index was not different between conventional and organic systems, it is clear that the content of health-benefitting compounds, such as carotenoids or flavonoids, is dependent on nutrient availability. Also, considering that fruit quality seems highly dependent on tomato cultivar, the focus should be put on cultivar selection and crop management to enhance accumulation of such compounds in organically grown fruits. This could be achieved, for example, through adjustments of the amounts and sources of organic fertilizers and selection of cultivars with high nutrient use efficiency and fruit quality potential.

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