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Consideration of total available N supply reduces N fertilizer requirement and potential for nitrate leaching loss in tomato production

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ABSTRACT

Effects of increasing total available N (TAN) on agronomic performance, apparent recovery of TAN (AR_{TAN}), NO_3^- leaching and soil mineral N accumulation were examined in two tomato crops. Total available N was considered to be the sum of soil mineral N at planting, N mineralized from organic material (soil organic matter and manure), and mineral N fertilizer applied by fertigation. In each crop, four different mineral N fertilizer rates were applied as different N concentrations (N1: 0.6–1.1 mM, N2: 4.4–5.2 mM, N3: 13.4–13.6 mM, N4 20.5–21.7 mM) in nutrient solutions applied in all irrigations every 1–4 days throughout the crop. N3 treatments corresponded to local commercial practice. The first crop was grown in autumn–winter 2010 (AW-2010) and the second in spring 2011 (S-2011). For the two crops, TAN values were 165–215 kg N ha^{-1} in N1, 287–361 kg N ha^{-1} in N2, 563–667 kg N ha^{-1} in N3 and 847–976 kg N ha^{-1} in N4. In both crops, maximum fruit production was obtained with the N2 treatments. AR_{TAN} decreased exponentially as TAN increased, from values of close to 1.0 for N1 treatments to approximately 0.3 for N4 treatments. The linear relationship between NO_3^- leaching and TAN had a shallow slope, with a maximum leaching loss of 36–40 kg N ha^{-1} in the N4 treatments; NO_3^- leaching loss was limited by small drainage volumes associated with good irrigation management. There was an exponential increase in residual soil mineral N with increasing TAN. For N3 treatments, corresponding to common local management practices, residual soil mineral N was 234–262 kg N ha^{-1}, and for N4 treatments was 484–490 kg N ha^{-1}. Therefore, increasing TAN very strongly increased the potential for subsequent N loss. Where TAN was excessive to crop N requirements, limiting NO_3^- leaching loss (measured using lysimeters) by good irrigation practices was considered to only delay NO_3^- leaching loss. The N3 treatments of 13–14 mM of N that corresponded to local practice were associated with a large potential N loss. Based on TAN, the optimal treatment was N2 of 4–5 mM which was associated with maximum fruit production and a relatively very small potential loss of N. The results demonstrated that by considering (i) TAN rather than just fertilizer N, and (ii) mineral N fertilizer as a supplement to other N sources, that maximum production can be achieved with high AR_{TAN} and with a much reduced risk of N loss to the environment.

1. Introduction

Vegetable production in relatively simple plastic greenhouses is an important and rapidly growing industry in different parts of the world (Castilla et al., 2004). Crops are mostly grown in soil; some free-draining substrate systems are used. In the Mediterranean Basin, there are an estimated 170,000 ha (Castilla, 2002; Pardossi et al., 2004); in south-eastern (SE) Spain, there are 37,000 ha (Castilla and Hernández, 2005) which are mostly concentrated in the province of Almeria. In China, there are an estimated 3.3 Mha of simple plastic greenhouses (Committees of China Agricultural Statistic Year Book, 2010). Also, in Mexico, the area of plastic greenhouses is increasing rapidly (USDA FAS, 2010).

These greenhouse-based vegetable production systems are commonly associated with excessive N supply and considerable nitrate (NO_3^-) contamination of underlying aquifers

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(Pulido-Bosch, 2005; Thompson et al., 2007a). In Almeria, on-going contamination is such that since the early 1970s, the NO_3^- concentration in these aquifers has increased from <50 mg NO_3^- L^{-1} (Pulido-Bosch, 2005) to currently being >300 mg NO_3^- L^{-1} in a number of wells (Domínguez Prats, 2013). All the areas where greenhouses are concentrated in the province of Almeria, SE Spain have been declared nitrate vulnerable zones (NVZ; BOJA, 2008), in accordance with the EU Nitrate Directive (Anon., 2008). Consequently, there is a requirement to reduce the large NO_3^- leaching loss associated with this system (Thompson et al., 2007b; Granados et al., 2013).

Tomato is one of the most important vegetable crops in these greenhouse production systems. In SE Spain, depending on the season, tomato is the most or second most important greenhouse crop, and is grown from autumn to spring (autumn–winter crop) or from late winter/early spring to summer (spring crop); approximately 80% of tomato is grown in soil, the rest in substrate (Céspedes et al., 2009).

In greenhouse production in SE Spain, soil-grown crops use fertigation in combination with drip irrigation (Pardossi et al., 2004; Castilla and Hernández, 2005); commonly, nutrient are applied on the basis of concentration in all irrigations (Thompson et al., 2007a; Céspedes et al., 2009). Applied N concentrations for soil-grown crops are based on standard recipes (Thompson et al., 2007a). Generally, the N concentrations applied to soil-grown tomato are 12–15 mM (Cadenas et al., 2003; Pardossi, 2005; Muñoz et al., 2008).

Large manure applications have been an integral part of greenhouse vegetable production in SE Spain (Thompson et al., 2007a) and China (Ju et al., 2006). In SE Spain, large manure applications (supplying between 800 and 5000 kg N ha^{-1}) are made at greenhouse construction and smaller applications (commonly supplying 1000 kg N ha^{-1}) are often made every several years, primarily with the objective of enhancing soil physical properties (Bretones, 2003; Thompson et al., 2007a). Substantial amounts of soil mineral N can also be present at planting (Granados et al., 2013). Generally, N mineralized from manure and soil mineral N at planting are not considered when determining application of mineral N fertilizer (Thompson et al., 2007a).

Unlike substrate-grown crops (e.g., Wilcox et al., 1985; Le Bot et al., 2001; Muñoz et al., 2008), very few studies (e.g., Lecompte et al., 2008) have examined the N concentration of nutrient solutions, applied by fertigation, on tomato grown in soil in greenhouses. The total available N (TAN) supply, which is the sum of (i) mineralized from both manure and soil organic matter (OM), (ii) soil mineral N at planting, and (iii) mineral fertilizer N, is a recommended approach for crop N management in these systems because of the importance of soil N sources (Thompson et al., 2013). Understanding the response of tomato to increasing TAN will assist in determining optimal N fertilizer application thereby reducing the large NO_3^- leaching losses associated with these systems.

A commonly used indicator to evaluate the efficiency of crop N use is the apparent recovery of mineral fertilizer N which refers to the proportion of applied fertilizer N that is recovered within the crop (Huggins and Pan, 1993). Where N from other sources contributes appreciably to the N supply, apparent recovery of TAN (AR_{TAN}) is an appropriate indicator because it combines all the major N sources.

Good irrigation management can appreciably reduce NO_3^- leaching during a crop (Quemada et al., 2013). Nevertheless, an excessive N supply combined with good irrigation may only delay appreciable NO_3^- leaching loss if appreciable accumulation of soil mineral N occurs. Good agronomic management must reduce both the NO_3^- leaching during a crop and the likelihood of subsequent NO_3^- leaching loss.

The objectives of this study were to evaluate the effects of increasing amounts of TAN on soil-grown tomato in terms of (1) the agronomic parameters of dry matter and fruit production, and crop N uptake, (2) apparent recovery of TAN, (3) NO_3^- leaching during the crop, and (4) accumulation of soil mineral N and the associated risk of delayed NO_3^- leaching loss in a well-irrigated crop.

2. Material and methods

2.1. Site, experiments and cropping details

The experimental work was conducted in a plastic greenhouse, located at the Experimental Station of the University of Almeria in Retamar, Almeria, south-eastern (SE) Spain (36°51′N, 2°16′W and 92 m elevation). The greenhouse had a multi-span structure with polycarbonate walls and a roof of low density polyethylene cladding; it had no heating, passive ventilation (lateral side panels and flap roof windows), an east–west orientation, with crop rows aligned north–south. The cropping area was 1327 m^2. Two tomato (*Solanum lycopersicum* L.) crops were grown sequentially in soil. Details of the cropping cycles, varieties and nitrogen (N) treatments applied using fertigation are presented in Table 1. There was an autumn–winter crop grown in 2010 (AW-2010) followed by a spring crop in 2011 (S-2011). The crops were grown under similar conditions to those of commercial greenhouse-based vegetable production in SE Spain.

Table 1
Management data for the two tomato crops and eight treatments, including variety, dates of transplanting and end of crop, total irrigation volume and drainage, soil mineral N at transplanting, N fertigation treatments defined on the basis of N concentration (mM) of the applied nutrient solution, total amount of N applied (kg N ha^{-1}) and total available N (TAN) to the crop. Apparent N mineralization, included in the calculation of TAN was 149 and 121 kg N ha^{-1} for the 2010 and 2011 crops respectively. Values in brackets following the end date of the crop correspond to the duration of the crop in days.

Crop (year, season)	Variety	Date transplanting	Date end of crop	N treatment	Irrigation amount (mm)[a]	Drainage (mm)	Mineral N at planting (kg N ha^{-1})	N concentration in nutrient solution (mM)[b]	Total N applied (kg N ha^{-1})[a]	TAN (kg N ha^{-1})
2010-Autumn–winter	Razimo	05/08/10	25/01/11 (172 days)	AW-N1	285	29	33	0.64	33	215
				AW-N2	270	30	53	4.4	159	361
				AW-N3	282	29	27	13.6	491	667
				AW-N4	281	34	96	20.5	731	976
2011-Spring	Ramyle	14/03/11	14/07/11 (122 days)	S-N1	174	34	16	1.1	28	165
				S-N2	218	37	15	5.2	151	287
				S-N3	240	26	17	13.4	425	563
				S-N4	237	25	49	21.7	677	847

[a] Total N and total irrigation applied correspond to the complete cropping cycle.
[b] N concentration values are for the period of N treatments, which commenced 25 days after transplanting in both crops.

The greenhouse had an artificial layered "enarenado" soil typical of the region (Thompson et al., 2007a; Castilla, 2013) consisting of a 30 cm layer of imported soil of silty loam texture placed over the original silty loam soil and a 10 cm layer of gravel placed on the imported soil as a mulch. At greenhouse construction in July 2007, before adding the final gravel layer, 200 $m^3\,ha^{-1}$ of mature sheep manure (63% dry matter, 1.7% N content and 0.7 $t\,m^{-3}$ density) was mixed into the top layer of the imported soil following local practices (Thompson et al., 2007a; Céspedes et al., 2009).

Above-ground drip irrigation was used. The drip tape was arranged in paired lines with 0.8 m spacing between paired lines, 1.2 m spacing between adjacent pairs of lines, and 0.5 m spacing between drip emitters within drip lines, giving an emitter density of 2 emitters m^{-2}. The drip emitters had a discharge rate of 3 $L\,h^{-1}$. Plants were transplanted as 6 week old seedlings; the plant density was as for the emitters, being 2 plants m^{-2}. Plants were vertically supported by nylon cord guides, and pruned and managed following local practices. Complete nutrient solutions were applied, in all irrigations, by the drip irrigation/fertigation system in accordance with local practice (Thompson et al., 2007a; Céspedes et al., 2009). Nutrient addition was managed on the basis of concentration in the applied complete nutrient solutions. Topping (the removal of the apical shoot to arrest stem elongation) was conducted when there were 11 and 8 trusses per plant in winter and spring crops, respectively. High temperature within the greenhouse was controlled by white-washing the plastic cover of the greenhouse (application of $CaCO_3$ suspension) applied from planting to 57 days after transplanting (DAT) in the 2010 crop and in three separate applications at 25, 50 and 73 DAT in the 2011 crop.

In each crop, four treatments of increasing concentration of N in fertigation were applied (increasing N concentration indicated as increasing from N1 to N4) (Table 1). The fraction of mineral N applied as NO_3^- ranged between 97 and 100%, with the rest applied as ammonium (NH_4^+). Fertigation treatments commenced at 25 DAT, once the crops were established. Irrigation was scheduled to maintain the soil matric potential within the range of −15 to −40 kPa. Irrigation was applied every 1–4 days, with irrigation being more frequent during warmer periods and less frequent during cooler periods. Soil matric potential was measured with manual tensiometers located 8 cm to the side of the plants and 5 cm from the drip line, at a depth of 12 cm relative to the surface of imported silty loam soil.

The total amounts of water and N applied to each treatment are also presented in Table 1. In each crop, total available N (TAN) was calculated as the sum of soil mineral N at planting ($N_{initial}$), mineral N applied in fertigation ($N_{fertigation}$) and N mineralized from applied manure and soil organic matter ($N_{mineralized}$).

Nitrogen mineralized ($N_{mineralized}$) was calculated, for each experiment using, a N balance approach (Feller and Fink, 2002; Vázquez et al., 2006) from the experimental data of treatment N1, where very little N was applied, following the equation:

$$N_{mineralized} = (N_{uptake} + N_{leached} + N_{residual}) - (N_{initial} + N_{fertigation})$$

where N_{uptake} is the total crop N uptake, $N_{leached}$ is the total NO_3^--N leached during the crop and $N_{residual}$ is the residual mineral N at the end of the crop. N_{uptake}, $N_{leached}$ and $N_{residual}$ in each crop were measured as described in Section 2.3. In the N balance calculation, it was assumed that gaseous N losses in treatments N1 were negligible. Given the identical history of soil management, and conditions of soil moisture and temperature, it was assumed that $N_{mineralized}$ was equal for all treatments in each experiment. Using this N balance calculation, $N_{mineralized}$ was determined to be 149 and 121 $kg\,N\,ha^{-1}$ for the 2010 and 2011 crops, respectively.

In this work, the treatments were evaluated in the context of the amounts of N available to the crop (TAN) rather than the amounts or concentration of mineral N fertilizer applied by fertigation.

2.2. Experimental design

The greenhouse was organized into 24 plots, each measuring 6 m by 6 m. There were six different irrigation and fertigation sectors with four plots per sector; four sectors were used in this work. The 24 plots were arranged in a randomized block design. Each plot contained three paired-lines of drip tape with 12 paired plants and drip emitters in each line. The greenhouse was divided longitudinally into northern and southern sectors by a 2 m path along its east–west axis. In each treatment, there were two plots in the northern and southern sectors. There were border areas along the southern and northern edges of both the southern and northern halves of the greenhouse, and on the eastern and western edges of the greenhouse. The experimental data were subjected to analysis of variance, verifying assumptions of normality and equal variance. In measurements conducted over time, repeated-measures ANOVA were used with time after transplant as a factor. If main effects or interactions were significant at $P < 0.05$, the least significant difference (LSD) test was conducted for multiple comparison of means. All statistical procedures were performed with Statgraphics Centurion XV (Statpoint Technologies, Warrenton, VA, USA). All differences identified as being statistically significant were significant at a probability of $P < 0.05$.

2.3. Measurements

Air temperature and relative humidity were measured with a ventilated aspirated psychcrometer (model 1.1130, Thies Clima, Göttingen, Germany) and solar radiation with a pyranometer (model SKS 1110, Skye Instruments, Llandrindod Wells, Wales, UK). All data were recorded and stored using a data logger (model CR10X, Campbell Scientific, Inc., Utah, USA).

In all treatments, all measurements of plant and soil parameters were the mean of four values, each from an individual replicate plot. Measurements were made from the central (of three) pair of plant/emitter lines in the plots. Soil was sampled and analyzed for mineral N (NO_3^- and NH_4^+) immediately before and at the end of each crop. Soil was sampled in 20 cm depth increments to 60 cm in each replicate plot of each treatment. To deal with heterogeneity associated with combined drip irrigation and fertigation, each soil sampling in each plot was made in three associated sampling positions in relation to a representative emitter and plant, being (1) 5 cm from the drip emitter, (2) mid-way between lines within paired lines, and (3) mid-way between two paired lines. Each depth increment from each sampling position within each replicate location was treated as a separate sample. Soil mineral N content was determined following extraction by potassium chloride (KCl) (40 g moist soil: 200 mL 2 M KCl). NO_3^- and NH_4^+ concentrations in the extracts were determined with an automatic continuous segmented flow analyzer (model SAN++, Skalar Analytical B.V., Breda, The Netherlands). Soil mineral N (NO_3^--N plus NH_4^+-N) was calculated as: (0.50 × position 1) + (0.20 × position 2) + (0.30 × position 3).

Irrigation volume was measured in each treatment with volume meters. Twice per week, two replicate samples of applied nutrient solutions for each treatment were collected from separate emitters, to determine the concentration of NO_3^- and NH_4^+ in the applied nutrient solution. Drainage was collected from each treatment using two replicate free draining, re-packed lysimeters (4 m long × 2 m wide × 0.7 m deep) located in the southern side of each greenhouse. The bottom and walls of the lysimeters were lined with butyl rubber. The soil profile in the lysimeter reproduced that of the outside area described above to a depth of 0.7 m, with a layer of gravel placed between the butyl rubber sheet and the layered soil. Lysimeter drainage volumes were measured at 9:00 h each working day. Representative sub-samples of daily drainage from each lysimeter were analyzed for concentration of NO_3^-; the concentration of NH_4^+ was negligible. The concentration of NO_3^- and NH_4^+ in the applied nutrient solutions and drainage were analyzed with the automatic segmented flow analyzer described previously.

Measurements of dry matter production (DMP) were made by periodically harvesting two plants in each of four replicated plots. Dry matter determinations were made by weighing all fresh material of each plant component (leaves, stems and immature fruits) and by oven-drying representative samples at 65 °C until constant weight. At planting, dry matter was determined in a sample of 100 seedlings. The amounts of all pruned shoot material and fruit production were determined throughout each crop, in four replicate groups of eight plants. At each pruning, the amount of dry matter was determined separately for leaves and stems as described previously. At each harvest of red fruit, fresh and dry weights were determined. Fresh production was separated into marketable and non-marketable according to EU marketing regulations (CE 717/2001). The total number of fruits and the mean fresh fruit weight were determined. Fruit quality was determined at each harvest by measuring in six fruits per replicate plot, firmness, pH, degrees Brix and percentage dry matter content. Firmness was measured at three different points of each fruit, using a digital penetrometer (model PENEFEL DFT, Agro Technologie, 14 Forges Eaux, France). The pH and degrees Brix were measured on extracts of macerated fruit using, respectively, a digital pH meter (Crison model PH-25, Barcelona, Spain) and a digital refractometer (Atago model Pocket Refractometer PAL-1, Tokyo, Japan). Fruit dry matter content was determined as described previously.

For each biomass sampling, DMP to that date was determined by summing the total dry matter of each component for that sampling date with that of all previously sampled pruned material and harvested fruit. Total leaf area index (LAI) was determined by summing the leaf area of the plants at final biomass (maximum LAI) with that of all previously sampled pruned material; leaf area was measured on sub-samples of leaves with a digital leaf area meter (LI-COR model LI-3100C, Lincoln, NE, USA).

The final biomass sampling at the end of the crop was conducted using the group of eight plants in each replicate plot that were previously used for determining pruning and fruit production.

For each sampling of biomass and pruned material and for selected fruit harvests, representative samples of leaves, stems, and fruit were individually ground sequentially in a knife mill and ball mill. Total N content of each sample was determined using a Dumas-type elemental analyzer system (model Rapid N, Elementar, Analysensysteme GmbH, Hanau, Germany). Crop N uptake, in each treatment, was calculated for each intermediate biomass sampling and for the final biomass sampling, from the corresponding data of amounts of dry matter and the N contents of all constituent components. Previous prunings and fruit harvests were included in these calculations to enable calculation of crop N uptake to the date of the biomass sampling.

Apparent recovery of N (AR_{TAN}) was calculated as the ratio between N crop uptake and total available N (TAN) (Huggins and Pan, 1993).

3. Results

3.1. Climatic conditions

Average values for 24 h periods of minimum, mean and maximum air temperature and vapor pressure deficit (VPD), the average daily integral of solar radiation, and the average reference evapotranspiration (ET_o) inside the greenhouse for the growing periods of the two crops are presented in Table 2. The comparatively lower air temperature, VPD, solar radiation and ET_o during the 2010 crop reflect the autumn to winter growing period compared to the spring to summer growing period of the 2011 crop. In general, values of temperature and VPD were within the normal range for plastic greenhouses, without active climate-control systems, on the Mediterranean coast.

3.2. Dry matter production, crop N uptake and fruit production

The seasonal evolution of dry matter production (DMP) and crop N uptake for the two crops are presented in Fig. 1. There were differences between N treatments on DMP over time in the two crops, with significant differences ($P < 0.05$) in the AW-2010 crop (Fig. 1a) and highly significant differences ($P < 0.001$) in the S-2011 crop (Fig. 1b). In the AW-2010, the differences between N treatments were significant only at 102 and 173 DAT. In contrast, in the S-2011 crop, the differences in DMP between the N treatments were significant from 63 DAT until the end of crop. In S-2011, there was a consistent order in DMP of N4 ≈ N3 > N2 > N1 (Fig. 1b). On all sampling dates, in S-2011, there were statistically significant differences between N1 and N2, and on all dates except 63 DAT between the N2 and the N3. The differences between the N3 and the N4 treatments were generally not significant ($P > 0.05$).

In both crops, the applied N treatments had a marked effect on crop N uptake with significant differences ($P < 0.05$) between treatments from 102 in DAT AW-2010 and from 42 DAT in S-2011, until the end of the crops (Fig. 1c and d). There was a consistent order of crop N uptake of N4 > N3 > N2 > N1, in both crops. In the AW-2010 crop, there were generally no significant differences ($P > 0.05$) between the N3 and the N4 treatments and between N1 and N2; in the last sampling there were significant differences ($P < 0.05$) between the N1 and the N2 and between the N2 and the N4 treatments. In the S-2011 crop, there were significant differences between the N1, N2 and N3 treatments from 63 DAT on, and there were significant differences between the N3 and N4 treatments on 63, 81 and 105 DAT.

The effects of the applied N treatments on final LAI and on final distribution of dry matter between plant components were

Table 2
For each tomato crop, average values for the cropping period of 24 h minimum, mean and maximum air temperature and vapor pressure deficit (VPD) values, of the 24 h integral of solar radiation and of average daily reference evapotranspiration (ET_o) inside the experimental greenhouse.

Experiment	Temperature (°C)			VPD (kPa)			Integral of solar radiation ($MJ\,m^{-2}\,d^{-1}$)	ET_o ($mm\,d^{-1}$)[a]
	Minimum	Mean	Maximum	Minimum	Mean	Maximum		
AW-2010	14.2	19.0	26.2	0.17	0.91	1.65	6.7	1.6
S-2011	16.7	22.5	30.1	0.20	1.09	1.99	9.3	2.4

[a] Fernández et al. (2010, 2011),).

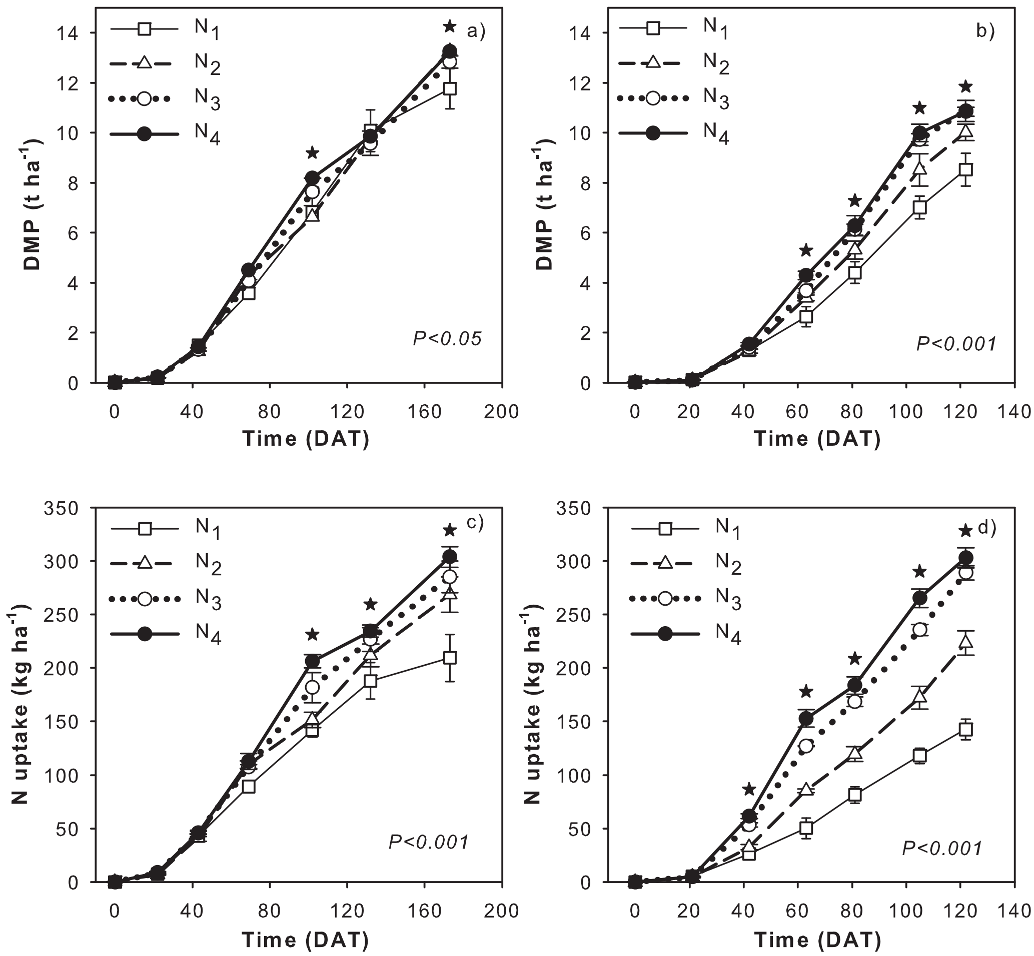

Fig. 1. Time course of measured values for the four N treatments of dry matter production (DMP) (a and b), and crop N uptake (c and d) for the AW-2010 (a and c) and S-2011 crops (b and d). When differences between treatments were significant according to the repeated-measures ANOVA with time, the probability is given in each panel. Bars indicate ±SE of four replicates. The asterisks (*) indicate that on the given date there were statistically significant ($P < 0.05$) differences according to the ANOVA.

different between the two crops; with no significant differences ($P > 0.05$) between N treatments in the AW-2010 crop and significant effects ($P < 0.05$) in the S-2011 crop (Table 3). In the S-2011 crop, LAI was significantly higher in treatments N3 and N4 compared to treatments N1 and N2; between N3 and N4 and between N1 and N2 there were no significant differences (Table 3). The distribution of biomass between crop components was also affected by the applied N treatments in the S-2011 crop. The higher applied N treatments had higher proportions of total DMP as leaf and consistently lower proportions as fruit (Table 3).

The applied N treatments influenced total and marketable fresh fruit production (Table 4), with significant effects ($P < 0.05$) and very significant effects ($P < 0.01$) between treatments in the AW-2010 and S-2011 crops, respectively. In both crops, the highest total

Table 3
Total leaf area index (LAI) and final dry matter in leaves, stems, fruits and total above-ground biomass at the end of the crop for each treatment in the two tomato crops. Values in brackets indicated the fraction of total dry matter in each component. Different letters indicate significant differences ($P < 0.05$) between means according to the procedure of least significant difference (LSD) by Fisher. A summary of the ANOVA is presented with: no significant (ns), significant at $P < 0.05$ (*), very significant at $P < 0.01$ (**) and highly significant at $P < 0.001$ (***).

	LAI ($m^2\,m^{-2}$)	Leaves $t\,ha^{-1}$ (%)	Stems $t\,ha^{-1}$ (%)	Fruits $t\,ha^{-1}$ (%)	Total $t\,ha^{-1}$
AW-2010					
N1	6.1	2.8 (24)	1.8 (16)	7.1 (60)	11.8a
N2	6.4	3.2 (24)	2.0 (15)	8.0 (61)	13.3b
N3	6.6	3.4 (26)	2.0 (16)	7.5 (58)	12.8b
N4	7.2	3.3 (26)	2.0 (15)	8.0 (60)	13.3b
Significance	ns	ns	ns	ns	*
S-2011					
N1	3.7a	2.2a (25)	1.3a (15)	5.1 (60)	8.5a
N2	4.5a	2.5a (25)	1.6b (16)	5.9 (59)	10.0b
N3	6.3b	3.0b (29)	1.8c (17)	5.9 (54)	10.9c
N4	6.1b	3.2b (30)	1.7cb (16)	5.9 (54)	10.9c
Significance	**	**	**	ns	*

Table 4
Total and marketable fresh fruit yield for each treatment in the two tomato crops. Different letters indicate significant differences ($P < 0.05$) between means according to the procedure of least significant difference (LSD) by Fisher. A summary of the ANOVA is presented with: no significant (ns), significant at $P < 0.05$ (*), very significant at $P < 0.01$ (**) and highly significant at $P < 0.001$ (***).

Treatment	AW-2010		S-2011	
	Total yield (t ha^{-1})	Marketable yield (t ha^{-1})	Total yield (t ha^{-1})	Marketable yield (t ha^{-1})
N1	94.5a	91.4a	75.4a	74.9a
N2	104.3b	102.5b	91.9b	91.9b
N3	91.9a	89.6a	86.3cb	85.8cb
N4	97.3ab	94.8ab	85.0c	84.6c
Significance	*	*	**	**

and marketable fresh fruit production were obtained in treatment N2 (Table 4). The differences in fruit production between N1 and N2 were significant ($P < 0.05$) in both crops. Treatment N2 had significantly higher fruit production than treatment N3 in the AW-2010 crop and than treatment N4 in the S-2011 crop (Table 4). The significantly higher fruit production in treatment N2 compared to N4, in the S-2011 crop (Table 4), occurred despite significantly higher total dry matter production in N4 (Table 3). This difference was attributed to a relatively higher allocation of dry matter to vegetative tissue than to fruit in the N4 treatment (46 versus 41%) which was apparent in the significantly higher amount of leaf tissue and LAI in treatment N4 (Table 3). In both crops, there were general tendencies to (i) allocate proportionately more dry material to leaf tissue and less to fruit and (ii) higher LAI values, in the N3 and N4 compared to N2 treatments (Table 3).

In both crops, there were no statistically significant differences ($P < 0.05$) between N treatments in mean fruit weight (Table 5); however, these values were slightly higher in N2 than in the other treatments (Table 5). In the S-2011 crop, there were significant ($P < 0.05$) differences in fruit number between treatments (Table 5), with lowest values in N1. Regarding fruit quality, the N treatments had no significant effect on fruit dry matter percentage, firmness and degrees Brix; there were differences between treatments in pH which was lower in N1 in both crops (Table 5).

3.3. Effect of total available N on production, N uptake and soil N dynamics

The relationships (i) between total fruit production and total available N (TAN) and (ii) between final DMP and TAN for the two crops are presented in Fig. 2. Considering both crops, maximum fruit production was obtained with quantities of TAN of 287–361 kg N ha^{-1} (Fig. 2a). In the AW-2010 crop, fruit production was comparatively higher presumably because of the longer growing period of 172 days compared to 122 days in the S-2011 crop (Table 1). There was a curvilinear relationship between DMP and TAN (Fig. 2a and b) with R^2 (coefficient of determination) values of 0.54 and 0.97 in the AW-2010 and S-2011- crops, respectively.

For the presentations of crop N uptake versus TAN (Fig. 3a) and of AR_{TAN} versus TAN (Fig. 3b), combined data from the two crops were used to derive an individual equation for each relationship. The relationship between crop N uptake and TAN was strongly curvilinear being described by a polynomial equation with an R^2 of 0.91 (Fig. 3a). Crop N uptake increased appreciably and consistently with increasing TAN until a plateau response occurred at TAN of >600 kg N ha^{-1} (Fig. 3a). The apparent recovery of TAN (AR_{TAN}) decreased rapidly with increasing TAN, the relationship being described by a polynomial equation with an R^2 of 0.96 (Fig. 3b). At the lowest amounts of TAN, corresponding to the N1 treatments, AR_{TAN} was close to 1; at the highest amounts of TAN corresponding to the N4 treatments, minimum AR_{TAN} values of 0.3 were obtained.

Using a combined data set from both crops, NO_3^- leaching increased linearly with increasing TAN, reaching maximum levels of 40 kg N ha^{-1} at TAN values of 847–976 kg N ha^{-1} corresponding to the N4 treatments (Fig. 4). The equation describing this linear relationship (Fig 4) had an R^2 of 0.94. The maximum amounts of NO_3^- leached are small because of the small total drainage volumes of 25–37 mm (Table 1). In both crops, the fraction of drainage in relation to irrigation was generally approximately 0.10–0.12; in treatments N1 and N2 of the S-2011 crop, the drainage fraction was 0.17–0.20 on account of the lower biomass production. Combining data from both crops, residual soil mineral N at the end of the crops increased exponentially with TAN (Fig. 4), the equation describing this relationship (Fig 4) had an R^2 of 0.89. In the N4 treatments with TAN values of 847–976 kg N ha^{-1}, residual N was 484–490 kg N ha^{-1}. In the N3 treatments (13–14 mM), which represent common commercial practice, residual N was 234–262 kg N ha^{-1}.

Table 5
Number of fruits (fruits m^{-2}), mean fruit weigh (g), fruit dry matter (%), firmness, brix and pH for each treatment and experiment. A summary of the ANOVA is presented with: no significant (ns), significant at $P < 0.05$ (*), very significant at $P < 0.01$ (**) and highly significant at $P < 0.001$ (***).

Treatment	Fruit number (Fruits m^{-2})	Mean fruit weight (g)	Fruit dry matter (%)	Firmness (kg cm^{-2})	Brix (°)	pH
AW-2010						
N1	102	92.1	6.1	8.2	4.3	4.5a
N2	111	94.2	6	7.7	4.4	4.6b
N3	99	93.0	6	7.6	4.4	4.6c
N4	106	92.0	6.2	7.9	4.4	4.6c
Significance	ns	ns	ns	ns	ns	***
S-2011						
N1	88a	86.1	6.1	4.6	4.3	4.5a
N2	101b	91.3	5.8	4.5	4.3	4.6b
N3	99b	87.2	5.9	4.5	4.8	4.7b
N4	99b	85.8	6.0	4.7	4.8	4.6b
Significance	*	ns	ns	ns	ns	***

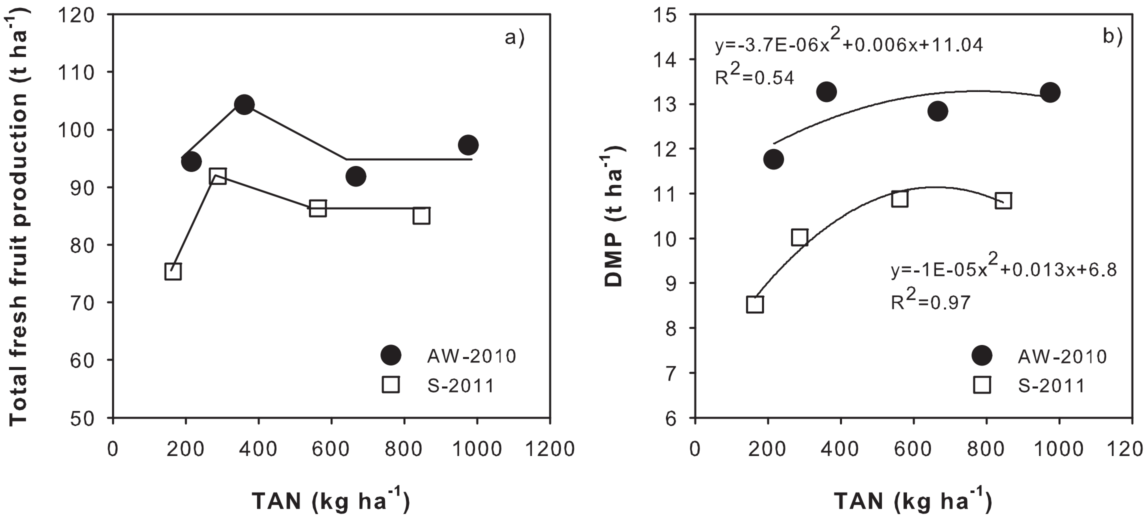

Fig. 2. Relationship between (a) total fresh fruit production and (b) final dry matter production (DMP) and total available N (TAN) for the two crops and the four N treatments in each crop. Data are the means of four replications. In panel (a), for the AW-2010 crop, the horizontal lines associated with treatments N3 and N4 represent average values for these two treatments. In panel (b), the curved lines and equations represent the best fit equations.

4. Discussion

Maximum production with very small NO_3^- leaching loss, little accumulation of soil mineral N and relatively high AR_{TAN} were obtained in both crops with the N2 treatments in which applied mineral N was considerably lower than in common commercial practice (4–5 mM versus 12–15 mM). AR_{TAN} decreased exponentially with increasing TAN values, which was associated with an exponential increase in the potential for N loss as accumulated soil mineral N. The N2 treatments had AR_{TAN} values of 0.7–0.8. These N use efficiency values are similar to the value of 82% determined by Martínez-Gaitán et al. (2007) and Martínez-Gaitán (2013) using ^{15}N to measure the recovery of mineral N fertilizer applied by combined fertigation and drip irrigation in greenhouse-grown pepper, in this system, using improved N and irrigation management practices. This suggests that the N2 treatment achieved maximum levels of production with a very efficient use of the N provided by the different N sources. These data show that when all N sources are considered when determining mineral N fertilizer application rates for greenhouse-grown drip-fertigated tomato that maximum production can be achieved with a low potential for N loss.

In the S-2011 crop, maximum DMP was obtained with higher TAN values than for maximum fruit production. In both crops, there was a tendency at the two highest N application rates to increase the allocation of biomass to vegetative tissue and to increase LAI while there was no increase or decreases in fruit production. This is attributable to the well-known phenomena of excess N favoring vegetative growth (Elia and Conversa, 2012).

Common practice for N management of soil-grown tomato in Mediterranean greenhouses, using fertigation, is the use of standard recipes in which N concentrations of 12–15 mM (Cadenas et al., 2003; Pardossi, 2005) are applied throughout the crop. Additionally, large manure applications, that can supply >1000 kg N ha^{-1} are periodically used (Thompson et al., 2007a) and the N mineralized from manure is normally not considered when planning mineral N fertilizer applications (Thompson et al., 2007a). N balance calculations made on greenhouse vegetable

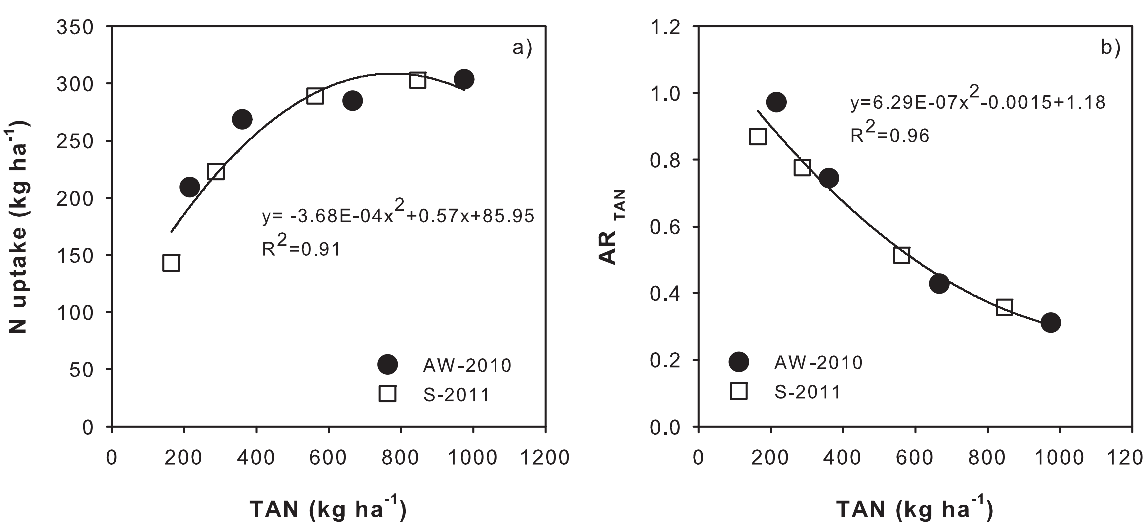

Fig. 3. Relationship between (a) crop N uptake and (b) apparent recovery of TAN (AR_{TAN}) and total available N (TAN) for the two crops and the four N treatments in each experiment. Data are the means of four replications. The lines and equations represent the best fit equations.

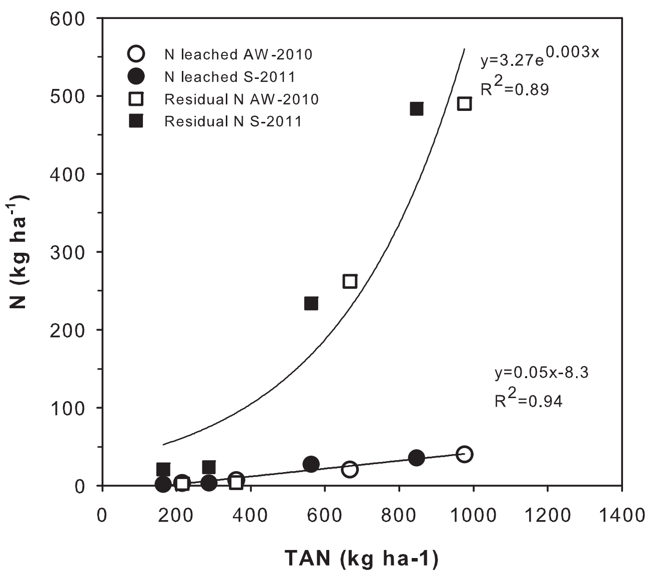

Fig. 4. Relationship between N leaching and residual mineral N in the soil at the end of the crop and total available N (TAN) for the two crops and the four N treatments in each experiment. Data are the means of four replications. The lines and equations represent the best fit equations.

crops in SE Spain suggest substantial amounts of N being supplied by mineralization (Granados et al., 2013; Soto et al., 2014). In the current study, for the N3 treatments of 13–14 mM, which represents common commercial practice, the excess of total N supply over crop N uptake was approximately 300 kg N ha^{-1}. This value is broadly similar to that estimated by a regional N balance for the main greenhouse growing area in SE Spain (Campo de Dalias), where 18,300 ha of greenhouses are concentrated, which suggested that N supplied annually by all sources exceeds crop N uptake by 500 kg N ha^{-1} (Jadoski et al., 2013).

Published studies examining different N rates on tomato production and/or N losses generally focus on mineral fertilizer N (e.g., Elia and Conversa, 2012; Tei et al., 2002; Hartz and Bottoms, 2009; Giuffrida et al., 2012). The current study demonstrates that other N sources can make appreciable contributions to the total N available N supply to the crop, and that these other N sources should be considered when determining mineral N fertilizer application rates. Furthermore, the current study shows that consideration of these N sources can minimize the risk of N loss to the environment.

Several studies in soil-less culture have reported that the threshold N concentration for obtaining maximum fruit production of tomato is 7–8 mM (Muñoz et al., 2008; Steiner, 1966; Wilcox et al., 1985; Larouche et al., 1989). Considering the irrigation volumes in our study (Table 1) a N concentration of 8 mM corresponds to 300 kg N ha^{-1} which is similar to the TAN supply in the N2 treatments in the present study. This suggests that (i) it may be possible to lower the standard N concentration in nutrient solutions to approximately 8 mM and (ii) that this standard concentration could then be further reduced by considering N supplied by other N sources.

There were appreciable effects in the S-2011 crop of increasing TAN on several parameters such as DMP, dry matter distribution, LAI and crop N uptake. In the AW-2010 crop, these effects were smaller or there was no effect. The different degree of response between the two years may be explained by the differences in climate between the two growing periods (Table 2). Average daily ET_o in S-2011 was 33% higher than in AW-2010 on account of higher temperature and solar radiation inside the greenhouse in the spring crop. More rapid growth of the spring crop (S-2011) presumably was associated with more rapid consumption of soil mineral N which would have exacerbated N treatment effects.

Although NO_3^- leaching increased linearly with TAN, the maximum NO_3^- leaching loss of 40 kg N ha^{-1} was much lower than reported in comparable studies in the same region (Granados et al., 2013; Soto et al., 2014; Thompson et al., 2007b). In the current study, the use of tensiometers to schedule irrigation resulted in only 25–37 mm of drainage which substantially restricted NO_3^- leaching loss. This is consistent with the meta-analysis of Quemada et al. (2013) which reported that irrigation management is the most influential management factor controlling NO_3^- leaching, during a crop. However, the results of the present study demonstrate that unless the total N supply is also managed optimally, a substantial accumulation of soil mineral N can occur which is likely to result in a delayed large NO_3^- leaching loss when subsequent drainage occurs from salt leaching irrigations or from rainfall in open field crops.

This study demonstrated that is possible to both optimize production and to minimize the potential for N loss to the environment. The key to simultaneously achieving both of these objectives is consideration of the various sources of crop available N provided by soil: soil mineral N at planting, and N mineralized from organic materials. With appropriate tools, vegetable growers will be able to calculate and apply N concentrations, using drip fertigation, that meet crop N requirements for given conditions while considering soil mineral N at planting and N mineralized from organic material (e.g., manure, soil OM, crop residues).

A recommended approach is the use of decision support systems (DSS) that estimate crop N uptake under given conditions and N mineralized from different organic materials in combination with determination of soil mineral N before planting. For a given crop, this would enable (i) the appropriate quantity of TAN to be determined to meet crop N requirements, and (ii) that the amount of mineral N fertilizer used would supplement other N sources to ensure that TAN was sufficient to ensure maximum production while minimizing the risk of N loss. Gallardo et al. (2014) developed a DSS with these capabilities. To minimize the various uncertainties with this approach such as in the estimation of N mineralization, it is suggested that crop monitoring approaches also be used as a supplementary approach. Thompson et al. (2013) reviewed available crop monitoring approaches, which is currently a very active research area (e.g., Padilla et al., 2014, in press). Additionally, further research is required to optimize the procedures to estimate N mineralization.

5. Conclusions

This study demonstrated for tomato, grown in soil in Mediterranean greenhouses, that by considering all sources of N made available to the crop it was possible to reduce substantially the N concentration of the applied nutrient solutions and therefore the amount of N fertilizer applied without losing production. The minimum levels of total available N (TAN) that produced the highest yield were 287–361 kg ha^{-1} which were associated with AR_{TAN} of 0.7–0.8. In the N3 treatment which corresponded to conventional local practice, TAN was 563–667 kg N ha^{-1} and the large excess of total N supply over crop N uptake resulted in 234–262 kg N ha^{-1} of residual soil mineral N, much of which is likely to be lost to the environment.

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