Strategies to decrease water drainage and nitrate emission from soilless cultures of greenhouse tomato

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1.1 Abstract

In the spring-summer season of 2005 and 2006, we explored the influence of three fertigation strategies (A-C) on the water and nitrogen use efficiency of semi-closed rockwool culture of greenhouse tomato conducted using saline water (*NaCl* concentration of 9.5 mol m^{-3}). The strategies under comparison were the following: A) crop water uptake was compensated by refilling the mixing tank with nutrient solution at full strength (with the concentrations of macronutrients equal or close to the corresponding mean uptake concentrations as determined in previous studies) and the recirculating nutrient solution was flushed out whenever its electrical conductivity (*EC*)

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surpassed 4.5 dS m^{-1} due to the accumulation of *NaCl*; B) the refill nutrient solution had a variable *EC* in order to maintain a target value of 3.0 dS m^{-1}; due to the progressive accumulation of *NaCl* , the *EC* and macronutrient concentration of the refill nutrient solution tended to decrease with time, thus resulting in a progressive nutrient depletion in the recycling water till $N\text{-}NO_3^-$ content dropped below 1.0 mol m^{-3}, when the nutrient solution was replaced; C) likewise Strategy A, but when *EC* reached 4.5 dS m^{-1}, crop water uptake was compensated with fresh water only in order to reduce $N\text{-}NO_3^-$ concentration below 1.0 mol m^{-3} before discharge. In 2005 an open (free-drain) system (Strategy D), where the plants were irrigated with full-strength nutrient solution without drainage water recycling, was also tested in order to verify the possible influence of *NaCl* accumulation and/or nutrient depletion in the root zone on crop performance. In the semi-closed system conducted following Strategy A, B or C, the nutrient solution was replaced, respectively, in 10, 14 and 7 dates in 2005, and in 19, 24 and 14 dates in 2006, when the cultivation lasted 167 days instead of 84 days in 2005. In both years, there were no important differences in fruit yield and quality among the strategies under investigation. Strategy C produced the best results in terms of water use and drainage, while Strategy B was the most efficient procedure with regard to nitrogen use. In contrast to Strategies A and D, the application of Strategies B and C minimized nitrogen emissions and also resulted in $N\text{-}NO_3^-$concentrations in the effluents that were invariably lower than the limit (approximately 1.42 mol m^{-3}) imposed to the $N\text{-}NO_3^-$ concentration of wastewater discharged into surface water by the current legislation associated to the implementation of European Nitrate Directive in Italy.

1.2 Introduction

Soilless culture is considered one of the main components of sustainable protected horticulture. In fact, the application of closed growing systems, where the drainage water is captured and reused after nutrient replenishment, can reduce the consumption of water and fertilizers and the environmental pollution that are generally associated to over-irrigation (Pardossi et al., 2006).

Unfortunately, the application of closed systems is scarce on a commercial scale and, with the exception of The Netherlands where they are compulsory (Stanghellini et al, 2005), open (free-drain) soilless cultures are commonly used for vegetable and ornamental crops, since the management of fertigation is much simpler in these systems (Savvas, 2002; Pardossi et al., 2006).

Along with the risks consequent to the possible diffusion of root pathogens, the salinity of irrigation water represents the main difficulty for the management of closed growing systems. When the use of saline water is imposed, there is a more or less rapid accumulation of ballast ions, like sodium (Na^+) and chloride (Cl^-), which are dissolved in the water at concentration higher that the uptake concentration (i.e., the ratio between the ions and the water taken up by the plants). Under these conditions, the nutrient solution is normally recirculated till EC and/or the concentration of some potential toxic ion reach a maximum acceptable threshold value, afterwards it is replaced, at least partially; the term 'semi-closed' is used for such systems. In The Netherlands, growers are allowed to leach their systems whenever a crop-specific ceiling of Na^+ concentration is reached (Stanghellini et al., 2005): for example, 8 mol m^{-3} for tomato or 4 mol m^{-3} for cut roses.

According to the conclusions of a simulation study carried out by Stanghellini et al. (2005), when irrigation water has poor quality, in general closed systems are not financially viable under strict environmental rules and the most valuable strategy is likely the improvement of water quality, by means of desalinization or rainwater. Nevertheless, in species with moderate salt tolerance (e.g., tomato and melon) the application of fertigation control procedures may give positive results in terms of both crop sustainability and productivity by prolonging the recirculation of the same nutrient solution and minimizing the content of polluting agents, like nitrate ($N\text{-}NO_3^-$) in the effluents, when the water is ultimately discharged (Pardossi et al., 2006).

Following the implementation of Nitrate Directive (The Council of the European Communities, 1991), in Europe many areas affected by $N\text{-}NO_3^-$ pollution have been designed as Nitrate Vulnerable Zones (NVZs). In NVZs an action program is laid down with a number of measures for the purpose of tackling $N\text{-}NO_3^-$ loss from agriculture and husbandry. The discharge of drainage water from soilless culture, which generally contains high $N\text{-}NO_3^-$ concentration (e.g., Gallardo et al., 2009), is not compatible at all with the rules established in NVZs.

Many papers (e.g., Brun et al., 2001; Klaring, 2001; Savvas, 2002; Pardossi et al., 2002) were published on the procedures to control fertigation in closed soilless culture. To our knowledge, however, few works were conducted on the management of closed systems in the presence of saline water using rose (e.g., Raviv et al., 1998), pepper (Bar−Yosef et al., 2001) or melon (Pardossi et al., 2002) as model crop. Among these, only Raviv et al. (1998) and Pardossi et al (2002) reported a detailed study on the effect of fertigation strategy on crop yield, the use efficiency of water and fertilizers and the environmental impact provoked by the nutrient leakage associated to periodical flushing. In particular, the strategies tested by Raviv et al. (1998) differed for the ratio among drainage, rain and tap water used to prepare the nutrient solution as well as for the ceiling EC_{NS} at which the recycling nutrient solution was partially discharged. Moreover, little attention has been devoted to the application of nutrient starvation as a method to reduce environmental impact of soilless cultures (e.g., Siddiqi et al., 1998; Le Bot et al., 2001; Voogt and Sonneveld, 2004; Muñoz et al., 2008).

With respect to the papers previously cited, the originality of the present study consists in the general approach and in the specific objectives. Indeed, the work aimed to evaluate the influence of four fertigation strategies on the water (*WUE*) and nitrogen (N; *NUE*) use efficiency of semi-closed (Strategies A-C) or open (Strategy D) rockwool culture of greenhouse tomato conducted using saline water ($NaCl$ concentration of 9.5 mol m^{-3}). The Strategies A and B corresponded to two out of five different techniques for nutrient solution recycling illustrated by Savvas (2002), while Strategy C was based on the simple expedient of interrupting the nutrient replenishment for a few days before the renewal of the recycling nutrient solution in order to minimize the $N\text{-}NO_3^-$ concentration in the leachate.

Some preliminary results of this work have been reported in the proceedings of a symposium organized by International Society for Horticultural Society (Pardossi et al., 2009).

1.3 Materials and methods

1.3.1 Fertigation strategies

A growing system that resembled a commercial closed-loop rockwool culture was used in the experiments conducted in 2005 and in 2006. In this system, in order to compensate for crop water uptake (W_U), the mixing tank collecting the water drained from the substrate slabs was systematically refilled with nutrient solution with an ion concentration and an EC that depended on fertigation strategy. $N\text{-}NO_3^-$ was the sole form of N in the nutrient solution, which was prepared using groundwater containing 9.5 mol m^{-3} of $NaCl$ (Table 1). The strategy also defined the conditions for the discharge of nutrient solution (flushing). Open system was identical to the semi-closed ones with the exception that the drainage water was not recycled.

Fig. 1 reports a schematic illustration of the fertigation strategies under investigation, which are described in details below. Hereinafter, $[I]$ will be denoting the concentration (in mol m^{-3}) of the ion I in the argument while the subscripts NS and D will be indicating $[I]$ or EC (in dS m^{-1}), respectively, in the recycling nutrient solution in semi-closed systems and in the effluents from both open and semi-closed systems.

Strategy A - In order to maintain a (relatively) constant nutrient concentrations in the recirculating culture solution, the mixing tank was refilled with full-strength (reference) nutrient solution. Different EC and macronutrient concentrations of the reference nutrient solution were used during the early developmental stage (Stage I) and in the following period (Stage II), that is after the plants were top cut above the 5th in 2005 (54 days after planting) or had reached a stable leaf area due to manual defoliation in 2006 (60 days after planting) (Table 1). The concentrations of individual macronutrients were equal or close to the corresponding uptake concentrations (data not shown), which had been determined in previous studies conducted with the same tomato cultivar in similar growing conditions (L. Incrocci and D. Massa, unpublished data). Due to the accumulation of $NaCl$ contained in the raw water (Carmassi et al., 2005) EC_{NS} tended to rise up and, when a ceiling value of 4.5 dS m^{-1} was reached, the nutrient solution in the mixing tank was discharged and a definite volume of pre-acidified (pH = 5.5-6.0) groundwater was applied (without drainage recycling) to wash out the salts accumulated in the substrate. After flushing, EC_{NS} was adjusted to 3.0 dS m^{-1} by adding appropriate volumes of nutrient solution stocks (with a concentration factor of 100:1 with respect to the reference nutrient solution) to the mixing tank.

Strategy B - the refill nutrient solution that had a variable EC in order to maintain the target EC of 3.0 dS m^{-1}. Due the progressive $NaCl$ accumulation in the recirculating water, the EC_{NS} of the refill nutrient solution showed a tendency to decrease with time, till only (pre-acidified) groundwater was used to fill up the mixing tank. This resulted unavoidably in a progressive depletion of the nutrient concentration until $[N\text{-}NO_3^-]_{NS}$ dropped below a critical concentration of 1.0 mol m^{-3}, when the nutrient solution was replaced following the same procedure used for Strategy A. This value was selected since a limit of 20 mg L^{-1} (approx. 1.42 mol m^{-3}) has been imposed to the $N\text{-}NO_3^-$ concentration of wastewater discharged into surface water by the current legislation associated to the implementation of European Nitrate Directive in Italy (Decree 152/2006).

Strategy C - The mixing tank was initially refilled with the reference nutrient solution as in Strategy A. However, when the ceiling EC_{NS} of 4.5 dS m^{-1} was reached, the mixing tank was replenished using only (acidified) groundwater for a few days (generally, two to four) till $[N\text{-}NO_3^-]_{NS}$ decreased below 1.0 mol m^{-3}, afterwards the nutrient solution was replaced in like manner as in Strategy A.

Strategy D - The crop was irrigated with the reference nutrient solution without drainage water recycling. A large (>0.50) leaching fraction (it is the ratio between drainage and irrigation water) was used in order to maintain EC_D below 3.5 dS m^{-1}, thus avoiding any possible stress due to salt accumulation and/or nutrient deficiency in the root zone.

The relevant parameter that defined the fertigation strategies in semi-closed systems was EC_{NS}, which was fairly constant (around 3.0 dS m^{-1}) in Strategy B and oscillated between (approximately) 3.0 and 4.5 dS m^{-1} in Strategies A and C. The procedures also differed for the amount of nutrients fed to the crop. Therefore, another goal of the work was to evaluate the possible effect of salinity oscillation and/or nutrient supply on crop growth and fruit yield. In point of fact, Strategy D was included in the experiments to evaluate the crop performance under non-stressful conditions, and not to assess the well-known environmental impact of open growing systems (Pardossi et al., 2006).

1.3.2 Plant material and growing conditions

Tomato (*Solanum lycopersicum* L., cv. Jama) plants were grown in a glasshouse (240 m^2) at the University of Pisa (Pisa, Italy, latitude 43°43′N, longitude 10°23′E). The cultivations started at the beginning of May and lasted 84 and 167 days in 2005 and 2006, respectively. Five-weeks old tomato seedlings were planted in standard rockwool slabs at density of 3.0 plants m^{-2}. Three plants and five drippers were positioned in each slab to warrant uniform water application. The plants were grown vertically with single stem and top-cut two leaves above the last truss; five or 13 trusses, each bearing not more than five berries, were left on the plants in 2005 and 2006, respectively. In the second experiment, the leaves below the trusses with ripening fruits were removed. Hand-held pollinator was regularly used to improve flower pollination.

Climatic parameters were continuously monitored by means of a weather station (SMC, Pisa, Italy) located in the central part of the greenhouse and connected to a datalogger. The minimum (heating) and ventilation air temperature inside the glasshouse was 16 and 27°C, respectively; maximum temperature reached up to 33–35°C in late spring and summer. Maximum photosynthetic photon flux density ranged from (approximately) 450 to 740 µmol m^{-2} s^{-1}. Daily global radiation and mean air temperature inside the glasshouse averaged, respectively, 12.5 MJ m^{-2} and 25.2 °C in 2005, and 8.6 MJ m^{-2} and 23.1°C in 2006.

Each fertigation strategy was applied to three separate growing systems each consisting of a bench containing 30 plants and a mixing tank with a volume of 60 L (6.0 L m^{-2} expressed on the basis of cultivated area). The total amount of recycling nutrient solution (V_{NS}) was 160 L (16 L m^{-2}), including the one contained in the substrate (10 L m^{-2}). Whenever the water level in the mixing tank dropped off by approx. 10 L (due to W_U), the tank was automatically replenished using water with the appropriate nutrient concentration and EC depending on fertigation strategy.

In open system, irrigation frequency was frequently adjusted during the cultivation and up to 10 irrigations per day during peak-evapotranspiration period were applied. The same irrigation regime was used in semi-closed systems.

In semi-closed systems, the procedures for nutrient replenishment and water discharge were applied contemporaneously to all replicates. In Strategies A and C (as long as EC_{NS} remained below 4.5 dS m^{-1}), the mixing tank was replenished with full strength nutrient solution, which was also used in Strategy D. In Strategy B, the mixing tank was automatically filled up with groundwater, which had been manually acidified (pH = 5.5-6.0) with sulphuric, and the EC_{NS} was daily adjusted to the target EC of 3.0 dS m^{-1} by adding appropriate dose of nutrient stocks to the mixing tank; the nutrient solution was recirculated by means of several consecutive irrigations, in order to homogenize the nutrient solution in the substrate with the one in the tank. In semi-closed systems, the volume of water discharge (V_D) in occasion of each flushing event was the sum of the water contained in the mixing tank (i.e., 6 L m^{-2}) and used for substrate washing (12 and 10 L m^{-2} in 2005 and 2006, respectively); therefore, V_D was 18 L m^{-2} in 2005 and 16 L m^{-2} in 2006.

The nutrient solutions were prepared manually once or twice per week dissolving appropriate amounts of $Ca(NO_3)_2$, KNO_3, K_2SO_4, KH_2PO_4, $MgSO_4$ and chelates for trace elements into pre-acidified groundwater; pH was further adjusted to 5.5-6.0 after salt addition. Both the acidified raw water and nutrient solutions were stored in a light-proof tank in the glasshouse.

1.3.3 Determinations

In semi-closed systems, daily W_U was determined by recording with a volume meter the amount of nutrient solution (or water) used to refill automatically the mixing tank; the accuracy of water meter was checked fortnightly. The water loss (W_L) was calculated as the number of discharges times V_D. In open system, daily W_U was computed as the difference between the water supply (as determined in semi-closed systems) and V_D, which was collected in a tank downstream each hydroponic bench. EC and pH were determined almost daily in the recirculating nutrient solution in semi-closed systems and in the drainage nutrient solution in open system with a pH-meter and EC-meter in the laboratory, while $[N\text{-}NO_3^-]_{NS}$ was measured with a reflectometer (Merck Reflectoquant®, Darmstadt, Germany) every two-four days in Strategy B or daily in Strategy C after EC_{NS} had reached the ceiling value of 4.5 dS m^{-1}. The accuracy of reflectometer was assessed preliminary using a colorimetric assay in the laboratory.

At least once per week and in occasion of each flushing event, samples of irrigation water and stock, refill or recirculating nutrient solutions were collected for the laboratory determination of K^+, Na^+, Ca^{2+}, Mg^{2+}, Na^+, $N\text{-}NO_3^-$ and $P\text{-}H_2PO_4^-$ concentration by means of liquid chromatography (120 DX, Dionex, Bannockburn (IL), Usa). In Strategy D, the drainage nutrient solution was sampled from the tank that had collected the seepage in the previous five to seven days.

Balance sheet for both water and macronutrients (apart from sulphur) was computed for each culture. In semi-closed systems, total water use (W_{USE}) was computed as the sum of cumulative W_U and W_L. In open system, W_{USE} corresponded to the volume of nutrient solution supplied to the crop. In all growing systems, total N supply (N_{USE}) was computed from the volume and the $N\text{-}NO_3^-$ content of the nutrient solutions fed to the crop. N loss (N_L) was computed by cumulating the amount of $N\text{-}NO_3^-$ that was leached daily from open system or in occasion of flushings from semi-closed systems. W_L and N_L included, respectively, the volume (equal to V_{NS}) and the $N\text{-}NO_3^-$ content of the residual nutrient solution in each growing system at the end of cultivation. Crop N uptake (N_U) was calculated as a difference between N_{USE} and N_L.

Crop yield was determined by measuring the number and the fresh weight of both marketable and non-marketable fruits. Physiological and technological *WUE* and *NUE* were computed as the ratio of total fruit yield on W_U or N_U, and on W_{USE} or N_{USE}, respectively. Fruit quality was assessed by measuring dry matter, total soluble solids and titratable acidity (as citric acid) in marketable berries picked from the 2nd and 4th truss in 2005, or from 4th and 6th truss in 2006.

1.3.4 Statistics

A randomized block design with three replicates was adopted. Season averages of the *EC* and ion concentrations in the recirculating or drainage nutrient solutions as well as the quantities derived from water or N balance were subjected to ANOVA and means were compared using LSD test. Regression analyses were conducted using the method of least squares. Statistical analysis was performed with Statgraphics Plus 5.1 (Manugistic, Rockwille, USA).

1.4 Results

1.4.1 EC and ion concentrations in the root zone and drainage water

There were no significant differences among the Strategies A-C in the *pH* of the recirculating nutrient solution (data not shown), which fluctuated between roughly 5.0 and 7.5 and averaged 6.32 and 6.81 in 2005 and 2006, respectively. In open system, the *pH* of drainage water was more stable (data not shown), ranging from 5.5 to 7.0, and averaged 6.30.

In 2005, the implementation of Strategies B and D (the latter was tested only in 2005) resulted in a lower EC_{NS} compared to Strategies A and C (Table 2). In open system, EC_D never exceeded 3.5 dS m^{-1} (data not shown) and averaged 2.95 dS m^{-1} (Table 2). In each semi-closed system, the pattern of EC_{NS} variation during the growing season was similar in the two experiments (Fig. 2). In Strategies A and C, EC_{NS} oscillated between 3.0 and 4.5 dS m^{-1}, approximately, and remained around 3.0 in Strategy B (Fig. 2). In all semi-closed systems, EC_{NS} was somewhat higher in 2006 than in 2005 (Table 2 and Figure 2).

In Strategies A and D, the mean of $[N\text{-}NO_3^{-}]_{NS}$ was close to the concentration in the reference nutrient solution (Table 1) while it was considerably lower in Strategies B and C (Table 2). In the latter treatment, this was also due to the cessation of nutrient replenishment for two-four days before flushing. As expected, much larger fluctuations in $[N\text{-}NO_3^{-}]_{NS}$ were observed in Strategies B and C as compared to Strategy A. In this treatment, a noticeable decrease in $[N\text{-}NO_3^{-}]_{NS}$ occurred during the first weeks of cultivation in 2005 while the opposite trend was observed in the following year, when $[N\text{-}NO_3^{-}]_{NS}$ showed larger fluctuations (Fig. 3).

Similar results were found in the time-course (data non shown) and the mean values of $[P\text{-}H_2PO_4^{-}]_{NS}$ and $[K^{+}]_{NS}$, which were significantly higher in Strategies A than in Strategies B and C (Table 2). Conversely, the differences among the strategies in $[Ca^{2+}]_{NS}$ and $[Mg^{2+}]_{NS}$ were small and not significant in most cases (Table 2), most likely as a result of the abundance of these ions in the raw water (Table 1). In open system, the macronutrient concentration in the drainage water differed significantly from the concentration of the recycling nutrient solution in semi-closed systems, apart from Mg^{2+} and Ca^{2+} (for Strategy B; Table 2). Moreover, mean $[H_2PO_4^{-}]_D$ and $[K^{+}]_D$ were noticeably lower than the corresponding concentrations in the reference nutrient solution (Table 2).

In Strategies A and C, the increase in EC_{NS} between two consecutive discharges (Fig. 2) was paralleled by an increment in $[Na^{+}]_{NS}$ (Fig. 4). Grouping the data collected in Strategies A and C in both years, a significant linear relationship was computed between EC_{NS} and $[Na^{+}]_{NS}$ (Fig. 5). The accumulation of Na^{+} in the recirculating nutrient solution was more pronounced in Strategies A and C than in Strategy B due to the lower frequency of flushing in the first two treatments (Fig. 4). Mean $[Na^{+}]_{NS}$ was significantly lower in Strategies B than in Strategies A (not in 2006) and C (Table 2).

1.4.2 Water balance

In both experiments, there were no important effects of fertigation strategy on W_U, although in 2005 a slight but significant difference was found between open culture and the semi-closed systems that were managed following Strategy A or B (Table 3). W_L and thus W_{USE} were massive in Strategy D reaching values as high as 7,198 and 10,841 m^3 ha^{-1}, respectively (Table 3), while these quantities averaged 2,020 and 5,530 m^3 ha^{-1} in semi-closed systems in 2005.

In Strategies A, B and C, the recirculating nutrient solution was discharged, respectively, 10, 14 and 7 times in 2005, and 19, 24 and 14 times in 2006; on average, the nutrient solution was discharged every 8.6, 6.5 and 12.0 days in Strategy A, B and C, respectively. These figures do not consider the discharge of the residual nutrient solution in the growing systems at the end of the experiment. The different frequency of flushing accounted for the large differences among Strategies A-C (n W_L and then W_{USE} (Table 3), since in both experiments the same amount of water (i.e., V_D) was drained out in occasion of all flushing events in each growing system. On average, Strategy C reduced W_{USE} by roughly 8% and 17% with respect to Strategies A and B, respectively.

1.4.3 Nitrogen balance

The application of Strategy D resulted in large N_{USE} (1,215 kg ha^{-1}) and N_L (715.5 kg ha^{-1}), whereas in semi-closed systems N_{USE} and N_L averaged, respectively, 491.7 and 68.0 kg ha^{-1} in 2005, and 840.3 and 139.2 kg ha^{-1} in 2006 (Table 3) . With respect to Strategies A and C, Strategy B decreased N_{USE}, respectively, by 34% and 17%in 2005, and by 53% and 14% in 2006 (Table 3).

Compared to Strategies B and C, the adoption of Strategy A augmented significantly N_L mostly due to the higher $[N\text{-}NO_3^-]_D$ (Fig. 3)). In this treatment, N_L was 168.0 kg ha^{-1} in 2005 and 370.9 kg ha^{-1} in 2006, instead of 20.7 kg ha^{-1} (on average) in Strategies B and C.

In Strategies A and , $[N\text{-}NO_3^-]_D$ was invariably much higher than the limit (1.42 mol m^{-3}) imposed by the Italian legislation on the disposal of wastewater while it was always below this threshold in

Strategies B and C (Fig. 3). In 2005 N_L was higher in Strategy C than in Strategy B (Table 3) owing to the elevated $[N\text{-}NO_3^-]_{NS}$ in the residual nutrient solution at the end of experiment, which took place a few days after the last flushing (Fig. 3).

The lowest N_U was calculated for the plants cultivated following Strategy B while the highest value was found in open system in 2005 and in Strategy A in 2006 (Table 3). Considering only the data determined in semi-closed cultures, a significant correlation was found between N_U and N_{USE} (R^2 = 0.88; n = 18; $p<0.0001$).

1.4.4 *Plant growth and fruit yield*

In both years, the procedure for fertigation management influenced significantly neither leaf area development nor dry biomass accumulation (data not shown). Moreover, in 2005 no significant differences were found among the treatments in total and marketable fruit yield, apart from a slight reduction in the latter quantity observed in Strategy A in 2005 (Fig. 6) due to a small reduction in both the number and the size of marketable fruits (i.e. those with a fresh weight higher than 80 g fruit^{-1}; data not shown). The absence of any important effect of fertigation strategy on fruit production was confirmed in 2006 (Fig. 6), when total and marketable fruit yield averaged 209 and 189 t ha^{-1} (13 trusses), respectively, against 102 and 97 t ha^{-1} (five trusses) in 2005.

In all treatments, unsalable yield consisted almost exclusively of small-sized berries and very few fruits were affected by blossom-end rot (BER), cracking or other disorders.

In both years, fruit quality was not influenced significantly by fertigation strategy (data not shown). In general, the eating quality of marketable fruits was satisfactory and mean fresh weight, dry residue, total soluble solids, titratable acidity averaged, respectively, 153.0 g, 5.03%, 4.63°Brix and 0.51% in 2005, and 147.2 g, 5.80% and 4.70°Brix, 0.53% in 2006.

1.4.5 *Water and nitrogen use efficiency*

Physiological *WUE* was not affected by fertigation strategy, which in both experiments approximated 0.03 t m^{-3} (Fig. 6). By contrast, significant differences among the treatments were observed in technological *WUE* (Fig. 6); the highest value was found in Strategy C in both years. Fertigation strategy influenced significantly both physiological and technological *NUE* (Fig. 6) and the most efficient culture was the one conducted using Strategy B. In semi-closed cultures, both physiological and technological *NUE* were slightly higher in 2006 than in 2005 in reason of the longer growing season and the higher fruit yield (Fig. 6).

1.5 Discussion

In soilless culture the traditional scheme for the control of crop nutrition is based on the use of relatively high ion concentrations in the nutrient solution and this may lead to luxury mineral consumption by the crop and increase the environmental impact associated to fertilizer leaching (Savvas, 2002; Pardossi et al., 2006). Hence, there is the need for alternative fertilization strategies that can reduce the use of water and fertilisers without negative effects on crop yield. Our findings demonstrated that, under saline conditions, the use efficiency of both water and N as well as the environmental sustainability of soilless cultures can be greatly improved by the implementation of appropriate fertigation strategies, at least in case of crop species with some degree of salinity tolerance, such as tomato.

In both years, we found that Strategy C produced the best results in terms of W_{USE} and W_L , while Strategy B was the most efficient procedure with regard to N supply (Table 3 and Fig. 6). In contrast to Strategies A and D, the application of Strategies B and C minimized N emissions and resulted in $[N\text{-}NO_3^-]_D$ compatible with the limit imposed to the concentration of this ion in wastewater by the legislation associated to the European Nitrate Directive in Italy (Table 3).

The fertigation strategies tested in our experiments resulted in different nutritional and salinity conditions in the root zone (Table 2 and Figs. 2-4). At least in Strategies A and C, the 86% of the total variation in the observed values of EC_{NS} was explained by the observed values of $[Na^+]_{NS}$

(Fig. 5) In a previous work with the same tomato genotype grown in semi-closed systems under similar conditions (Carmassi et al., 2005), the ratio between $[Na^+]_{NS}$ and $[Cl-]_{NS}$ remained around one. Therefore, Na^+ accumulation in the recycling water in semi-closed systems was interpreted as the build-up of $NaCl$ dissolved in the raw water.

The level and oscillation in the culture solution salinity as well the nutrient depletion inflicted to the crop (by Strategies B and C) did not have important effects on crop growth (data not shown) and fruit yield (Fig. 6). These results were in part expected since in all growing systems root zone EC (Table 2 and Fig. 2) never exceeded the maximum value without yield reduction (5.0 dS m^{-1}) found in previous works for the tomato cultivar and the growing conditions considered by the present study (Carmassi et al., 2005; Incrocci et al., 2006).

It should be highlighted that in both experiments very few fruits were affected by BER or cracking, notwithstanding the large oscillation in EC_{NS} in Strategies A and C (Fig. 2). Sudden changes in the root zone salinity are one of the major factors responsible for these disorders in tomato fruits, which generally result from impaired water and/or calcium movement to the growing berries (see Savvas et al., 2008, for review). Different results might have been found in tomato genotypes other than the cultivar used in our work, which has a low propensity to BER and cracking as also observed in previous studies (Carmassi et al., 2005, 2007; Incrocci et al., 2006). For example, tomato cultivars with elongated or plum fruits generally exhibit high susceptibility to *BER* (Latin, 2003; Cantore et al., 2008). Hence, in these tomato cultivars, or in species more sensitive to salinity (e.g., rose and strawberry), Strategy B seems more appropriate in reason of a lower and steady EC_{NS} (Fig. 2).

The fertigation control scheme also affected crop N nutrition. The calculation of N balance did not consider the possible occurrence of gaseous N loss, which was found ranging from 0.006 to 0.085 g m^{-2} per day in rockwool culture of greenhouse cucumber (Daum and Shenck, 1998). Incrocci et al. (2006) and Gallardo et al. (2009) reported a close correspondence between the N_U estimated on the basis of biomass accumulation and N concentration in plant tissues and by the mass balance method. Therefore, we interpreted N_U as genuine crop N absorption. In general, N_U was closely related to the supply (Table 3); in semi-closed systems, the 88% of the variability in N_U was accounted for by the variation in N_{USE}. From N_U (Table 3) and fruit yield (Fig. 6) it emerged that the application of Strategies A, C and, especially, D (in 2005) led to luxury N consumption in tomato plants.

Since plant response to a deficient nutrient supply is determined by its ability to store and re-mobilize the mineral elements (e.g., Walker et al., 2001; Del Amor and Marcelis 2004; Richard-Molard et al., 2008), it was expected that a period of optimal mineral supply followed by a reduced concentration of the nutrient solution for a few days (Fig. 3) did not affect fruit yield in Strategies B and C (Fig. 6). Siddiqi et al. (1998) reported that neither the reduction of macronutrient concentration to 50% or 25% of full-strength nutrient solution nor the interruption of nutrient replenishment for the last 16 days of cultivation influenced significantly fruit yield and quality in greenhouse tomato plants grown in closed substrate (perlite) system. Moreover, in open rockwool culture of tomato Le Bot et al. (2001) observed a reduction in fruit yield only four weeks after the interruption of N supply. By contrast, prolonged exposure to reduced N concentration (5 mol m^{-3} against 11 mol m^{-3} in the control) in the nutrient solution negatively affected tomato fruit yield in open perlite culture (Munoz et al., 2008).

To conclude, by means of *EC* modulation and/or short-term nutrient starvation, it is possible to prolong the recirculation of nutrient solution in semi-closed soilless cultivations of greenhouse tomato conducted under saline conditions with the aim of reducing the use of water and fertilisers and minimizing N emission with no important effects on fruit yield. The implementation of these procedures is quite simple, since *EC* is routinely measured in soilless cultures and $N\text{-}NO_3^-$concentration could be easily measured by means of quick tests (Jiménez et al., 2006). Although fertilizer costs are generally a small fraction of the total production costs of greenhouse crops (e.g., Williams and Uva, 2005), some authors reported that the percent incidence of fertilisation may be significant in soilless cultures, for instance up to 9% (Engindeniz and Gül, 2009) or 19% (Antòn et al., 2009). In these circumstances, any fertigation strategy capable to halve the use of fertilisers without any reduction in crop yield (for instance, like Strategy B with respect to Strategy A; Table 3) has an evident effect on crop profitability.

1.6 Acknowledgments

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Nomenclature

Symbol	Unit	Description
EC	dS m^{-1}	Electrical conductivity
EC_D	dS m^{-1}	Electrical conductivity of the water discharged daily in open system or in occasion of flushing in semi-closed systems
EC_{NS}	dS m^{-1}	Electrical conductivity of the recirculating nutrient solution in semi-closed systems
$[I]_D$	mol m^{-3}	The concentration of ion *I* in the nutrient solution discharged daily in open system or in occasion of flushing in semi-closed systems
$[I]_{NS}$	mol m^{-3}	The concentration of ion *I* in the recirculating nutrient solution in semi-closed systems
N_L	kg ha^{-1}	Nitrogen loss
N_U	kg ha^{-1}	Crop nitrogen uptake
N_{USE}	kg ha^{-1}	Nitrogen use
V_D	L m^{-2}	Volume of the water discharged daily in open system or in occasion of flushing in semi-closed systems
V_{NS}	L m^{-2}	Volume of recirculating nutrient solution in semi-closed systems
W_L	m^3 ha^{-1}	Water loss
W_U	m^3 ha^{-1}	Crop water uptake
W_{USE}	m^3 ha^{-1}	Water use

Table 1. Electrical conductivity (*EC*; dS m^{-1}) and nutrient/ion concentration (mol m^{-3}) of irrigation water and full strength (reference) nutrient solution used in two different developmental stages of greenhouse tomato cultivated in semi-closed or open soilless cultures. Stage II initiated when the plants were top cut above the 5th in 2005 (54 days after planting) or had reached a stable leaf area due to manual defoliation in 2006 (60 days after planting). The nutrient solutions also contained the following concentrations of micronutrients: 40.6 μmol m^{-3} Fe; 35.0 μmol m^{-3} B; 4.6 μmol m^{-3} Zn; 3.6 μmol m^{-3} Cu; 10.9 μmol m^{-3} Mn; 0.2 μmol m^{-3} Mo.

	$N\text{-}NO_3^-$	$P\text{-}H_2PO_4^-$	Cl^-	K^+	Ca^{2+}	Mg^{2+}	Na^+	*EC*
Irrigation water	0.00	0.00	9.50	0.00	1.50	0.80	9.50	1.53
Nutrient solution (stage I)	10.00	1.00	9.50	6.70	4.00	0.80	9.50	2.64
Nutrient solution (stage II)	7.00	0.70	9.50	4.70	3.25	0.80	9.50	2.31

Table 2. Influence of fertigation strategy on the season-average of electrical conductivity (EC) and the concentration of macronutrients and Na^+ in the recirculating nutrient solution in semi-closed soilless cultures (Strategies A-C) or in the drainage water in open cultures (Strategy D) of greenhouse tomato. Mean values (n = 3) separated by different letters are significantly different (p<0.05) according to ANOVA and LSD test. The number of the measurements conducted in triplicate during the growing cycle is shown within brackets.

	Strategy A	Strategy B	Strategy C	Strategy D
Experiment I (2005)				
Electrical conductivity (dS m^{-1})	3.64 a [83]	2.95 b [76]	3.67 a [77]	2.95 b [76]
$N\text{-}NO_3^-$ concentration (mol m^{-3})	8.67 a [30]	4.97 d [57]	5.43 c [53]	7.80 b [24]
$P\text{-}H_2PO_4^-$ concentration (mol m^{-3})	0.65 a [31]	0.47 b [38]	0.30 c [32]	0.67 a [23]
K^+ concentration (mol m^{-3})	5.56 a [31]	4.67 b [38]	4.81 b [32]	4.11 c [23]
Ca^{2+} concentration (mol m^{-3})	4.03 a [31]	3.31 b [38]	4.02 a [32]	3.67 b [23]
Mg^{2+} concentration (mol m^{-3})	1.13 a [31]	1.08 a [38]	1.19 a [32]	1.07 a [23]
Na^+ concentration (mol m^{-3})	18.26 a [31]	15.87 c [38]	21.29 a [32]	12.95 d [23]
Experiment II (2006)				
Electrical conductivity (dS m^{-1})	3.85 b [43]	3.23 c [50]	4.09 a [46]	
$N\text{-}NO_3^-$ concentration (mol m^{-3})	11.85 a [43]	4.97 c [50]	6.62 b [46]	
$P\text{-}H_2PO_4^-$ concentration (mol m^{-3})	0.57 a [43]	0.35 b [50]	0.25 c [46]	
K^+ concentration (mol m^{-3})	8.46 a [43]	4.14 c [50]	5.14 b [46]	
Ca^{2+} concentration (mol m^{-3})	4.54 a [43]	3.39 c [50]	3.99 b [46]	
Mg^{2+} concentration (mol m^{-3})	1.31 a [43]	1.11 a [50]	1.30 a [46]	
Na^+ concentration (mol m^{-3})	18.81 b [43]	18.32 b [50]	23.22 a [46]	

Table 3. Influence of fertigation strategy on water and nitrogen ($N\text{-}NO_3^{-}$) balance in semi-closed (Strategies A-C) or open (Strategy D) soilless cultures of greenhouse tomato. The mean $N\text{-}NO_3^{-}$ concentration in the effluents is also shown. Water use was computed as the sum of water uptake and water loss, while $N\text{-}NO_3^{-}$ uptake was calculated as the difference between the use and the leaching. Mean values (n = 3) separated by different letters are significantly different ($p<0.05$) according to ANOVA and LSD test.

	Strategy A		Strategy B		Strategy C		Strategy D	
Experiment I (2005)								
Water uptake (m^3 ha^{-1})	3517	b	3428	b	3586	ab	3643	a
Water loss (m^3 ha^{-1})	1960	b	2680	c	1420	d	7198	a
Water use (m^3 ha^{-1})	5477	c	6108	b	5006	d	10841	a
$N\text{-}NO_3^{-}$ use (kg ha^{-1})	600.1	b	397.9	d	477.2	c	1215.0	b
$N\text{-}NO_3^{-}$ leaching (kg ha^{-1})	168.0	b	14.1	c	22.0	c	715.5	a
$N\text{-}NO_3^{-}$ uptake (kg ha^{-1})	432.1	b	383.8	c	455.2	b	499.5	a
Experiment I (2005)								
Water uptake (m^3 ha-1)	6470	a	6524	a	6482	a		
Water loss (m^3 ha^{-1})	3200	b	4000	a	2400	c		
Water use (m^3 ha^{-1})	9670	b	10524	a	8882	c		
$N\text{-}NO_3^{-}$ use (kg ha^{-1})	1250.0	a	586.8	c	684.1	b		
$N\text{-}NO_3^{-}$ leaching (kg ha^{-1})	370.9	a	22.8	b	23.9	b		
$N\text{-}NO_3^{-}$ uptake (kg ha^{-1})	879.1		564.0	c	660.2	b		

1.8 Captions to figures

Figure 1. Schematic illustration of the fertigation strategies tested in the greenhouse experiments with tomato plants grown in soilless culture using saline (9.5 mol m^{-3} $NaCl$) groundwater. The graphs show the contribution of nutritive ions and Na^+ to the electrical conductivity of the recirculating nutrient solution (EC_{NS}) in semi-closed systems (Strategies A-C) or of the drainage nutrient solution (EC_D) in open (free-drain) system (Strategy D). In Strategy A the recirculating nutrient solution was discharged whenever EC_{NS} reached a ceiling value of 4.5 dS m^{-1}. In Strategy B, EC_{NS} was kept around 3.0 dS m^{-1} and the recirculating nutrient solution was flushed out whenever $N\text{-}NO_3^-$ concentration dropped below 1.0 mol m^{-3}. In Strategy C the fertigation was basically managed as Strategy A; however, when EC_{NS} reached 4.5 dS m^{-1}, the crop water uptake was compensated using only raw water until $N\text{-}NO_3^-$ concentration dropped below 1.0 mol m^{-3}, afterwards the nutrient solution was discharged. In semi-closed systems, the different strategies resulted in different frequency of flushing, which is indicated (approximately) by the value on the abscissa. In Strategy D the plants were irrigated with full-strength nutrient solution with an *EC* of 2.6 or 2.3 dS m^{-1}, depending on the developmental stage, and with a leaching fraction large enough to maintain the *EC* of drainage water below 3.5 dS m^{-1}**.**

Figure 2. Electrical conductivity of the recirculating nutrient solution (EC_{NS}) in semi-closed soilless cultures of greenhouse tomato conducted in 2005 (left) and in 2006 (right) with different fertigation strategies (A-C). Mean values ($\pm$ S.E.) of three replicates. The spikes of rapid decline in *EC* represent the discharge of nutrient solution.

Figure 3. The concentration of $N\text{-}NO_3^-$ in the recycling nutrient solution in semi-closed soilless cultures of greenhouse tomato conducted in 2005 (left) and in 2006 (right) with different fertigation strategies (A-C). Mean values (± S.E.) of three replicates. The spikes of rapid variation in $N\text{-}NO_3^-$ concentration represent the discharge of nutrient solution. In all graphs, the dashed line represents the limit (1.42 mol m^{-3}) imposed to the $N\text{-}NO_3^-$ concentration of wastewater discharged into surface water by the current Italian legislation.

Figure 4. The concentration of Na^+ in the recycling nutrient solution in semi-closed soilless cultures of greenhouse tomato conducted in 2005 (left) and in 2006 (right) with different fertigation strategies (A-C). Mean values (± S.E.) of three replicates. The spikes of rapid decline in Na^+ concentration represent the discharge of nutrient solution.

Fig. 5. The relationship between the electrical conductivity (EC_{NS}) and the concentration of Na^+ of the recirculating nutrient solution in semi-closed soilless cultures of greenhouse tomato conducted in 2005 and in 2006 with two fertigation strategies (A and C). The equation of the linear regression between the two quantities was calculated with all data in plot. Each point represents of the mean of three replicates.

Figure 6. Physiological and technological use efficiency of water (*WUE*) and nitrogen (*NUE*) in soilless cultures of greenhouse tomato conducted in 2005 (left) and in 2006 (right) with different fertigation strategies (A-D). Physiological and technological *WUE* and *NUE* were computed, respectively, as the ratio of total fruit yield on crop water or nitrogen uptake and on total water or nitrogen use. Mean values (n = 3) separated by different letters are significantly different ($p<0.05$), according to ANOVA and LSD test. Statistics were conducted through one-way ANOVA for each experiment.

Figure 1

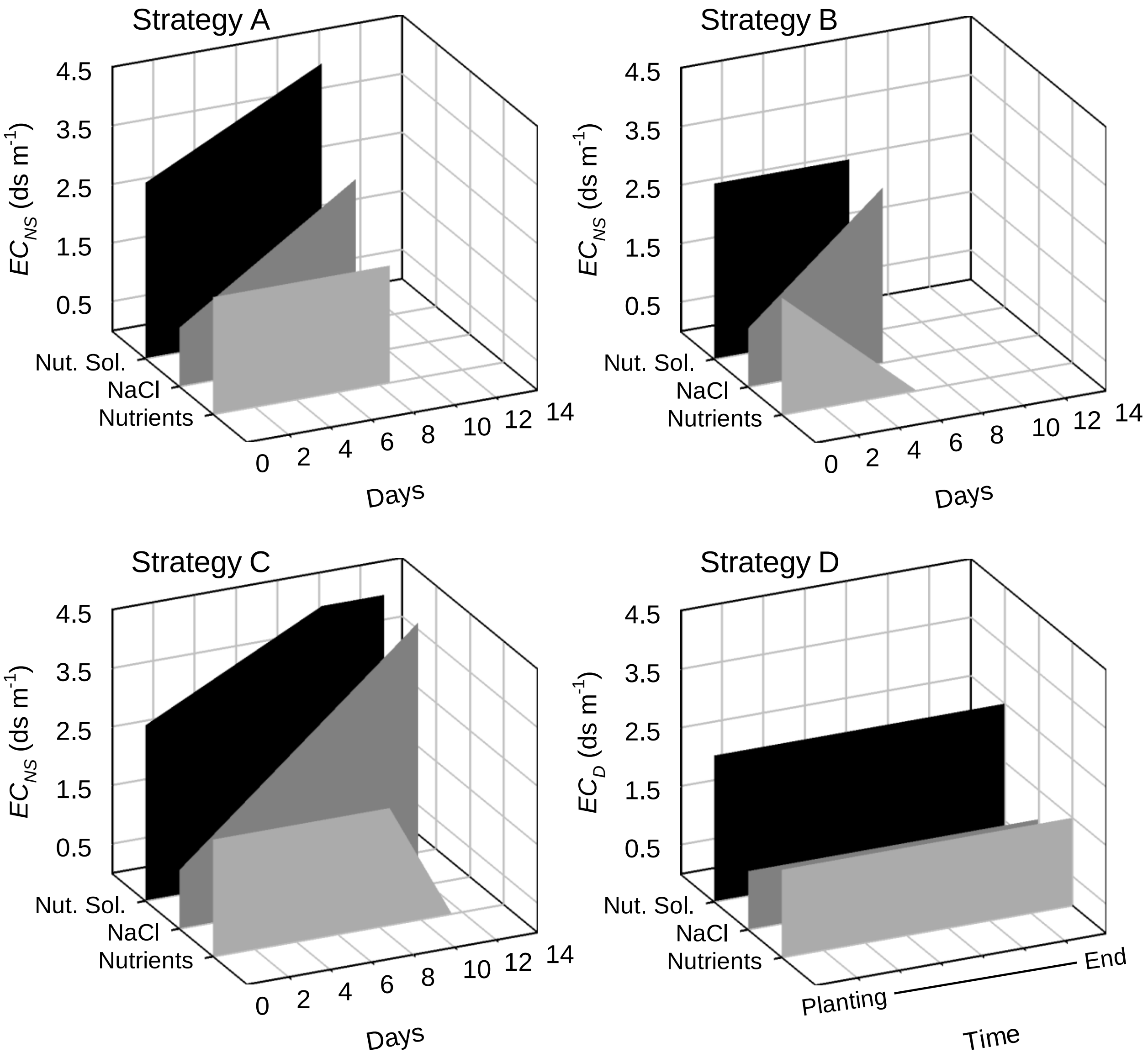

Strategy A
Strategy B
Strategy C
Strategy D
EC_{NS} (ds m^{-1})
EC_{D} (ds m^{-1})
4.5
3.5
2.5
1.5
0.5
Nut. Sol.
NaCl
Nutrients
0
2
4
6
8
10
12
14
Days
Planting
End
Time

Figure 2

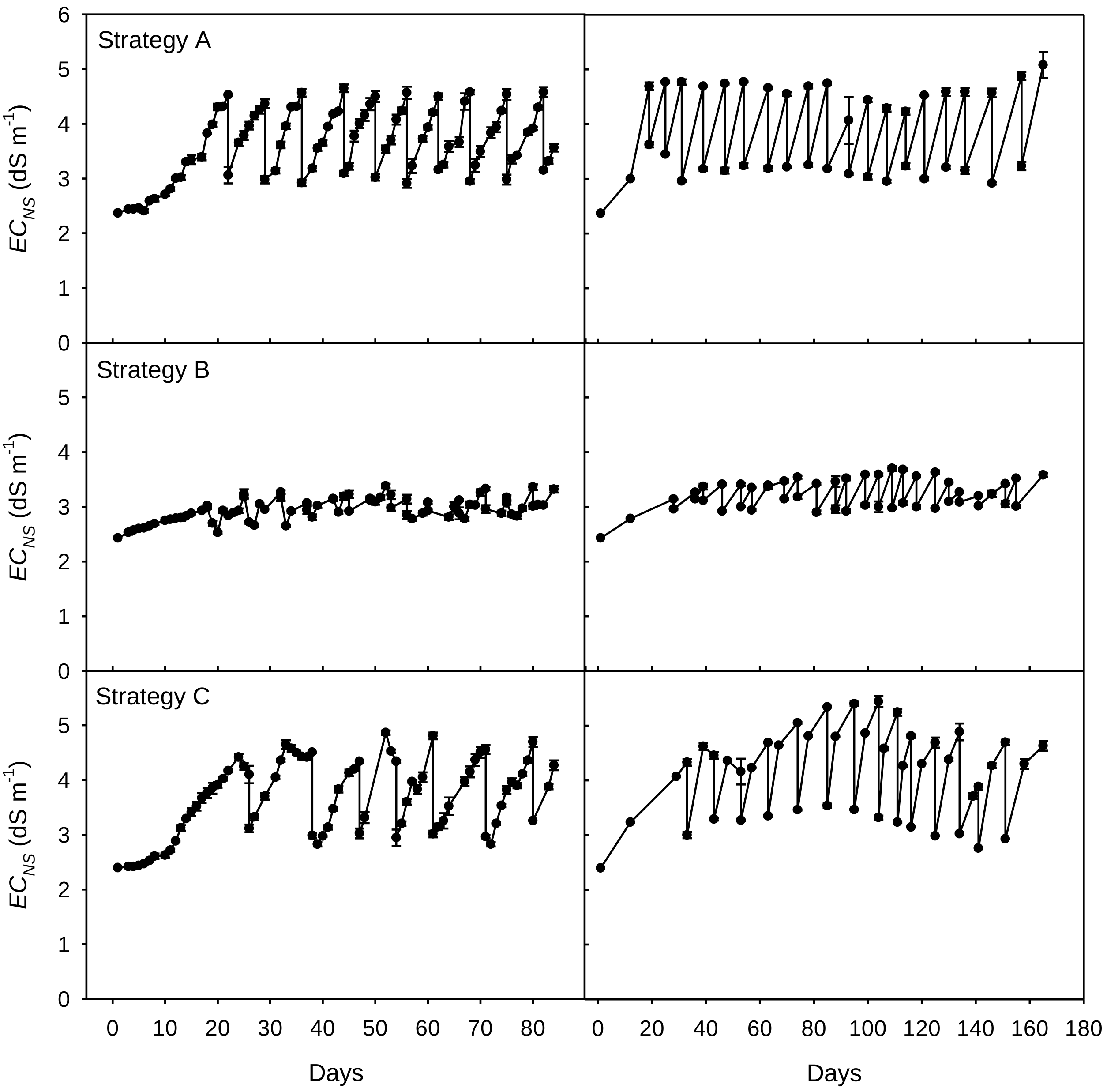
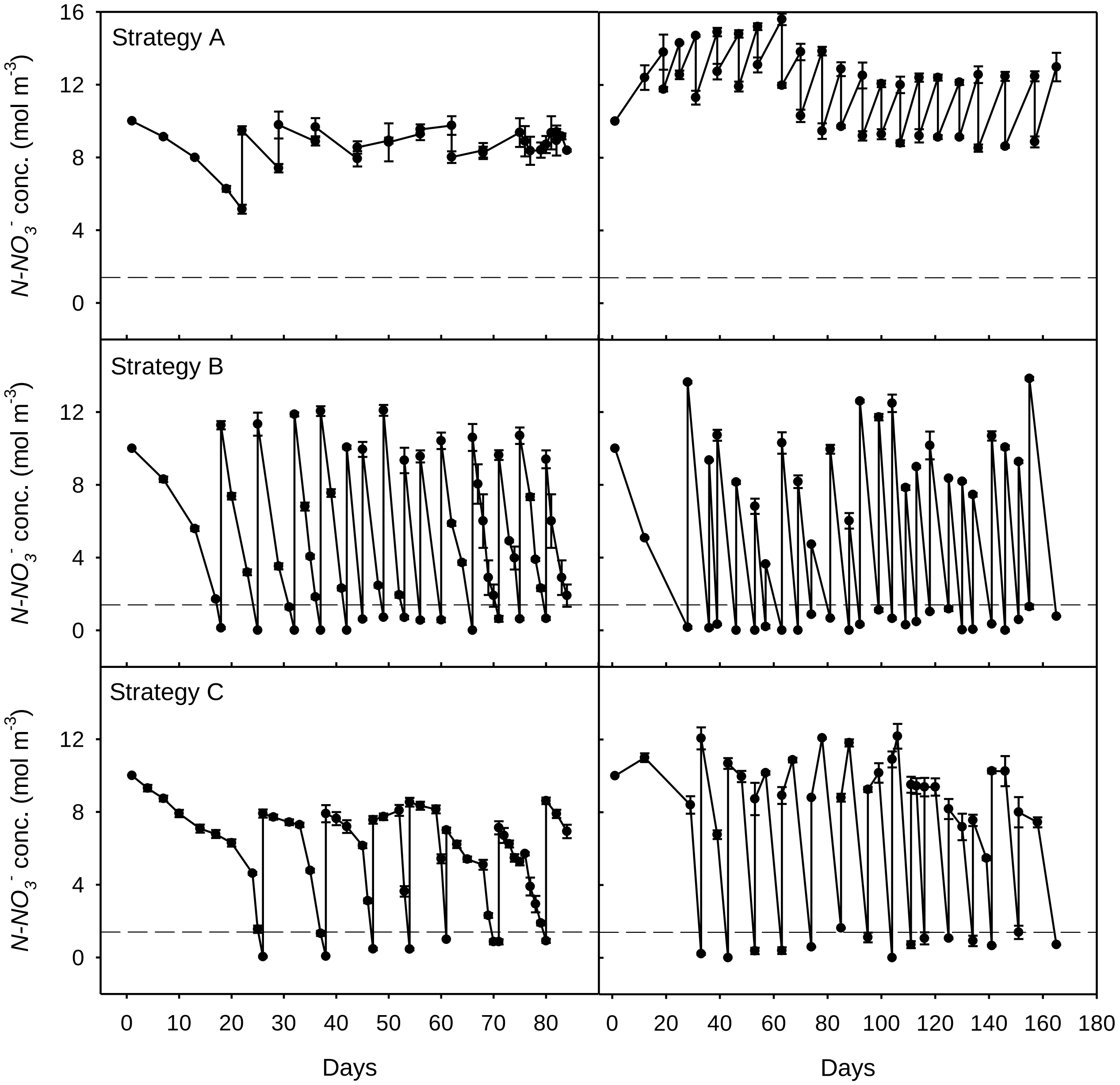

Strategy A
Strategy B
Strategy C
EC_{NS} (dS m^{-1})
EC_{NS} (dS m^{-1})
EC_{NS} (dS m^{-1})
0
1
2
3
4
5
6
0 10 20 30 40 50 60 70 80
0 20 40 60 80 100 120 140 160 180
Days
Days

Figure 3



Strategy A
Strategy B
Strategy C
N-NO$_3^-$ conc. (mol m^{-3})
16
12
8
4
0
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
140
160
180
Days
Days

Figure 4

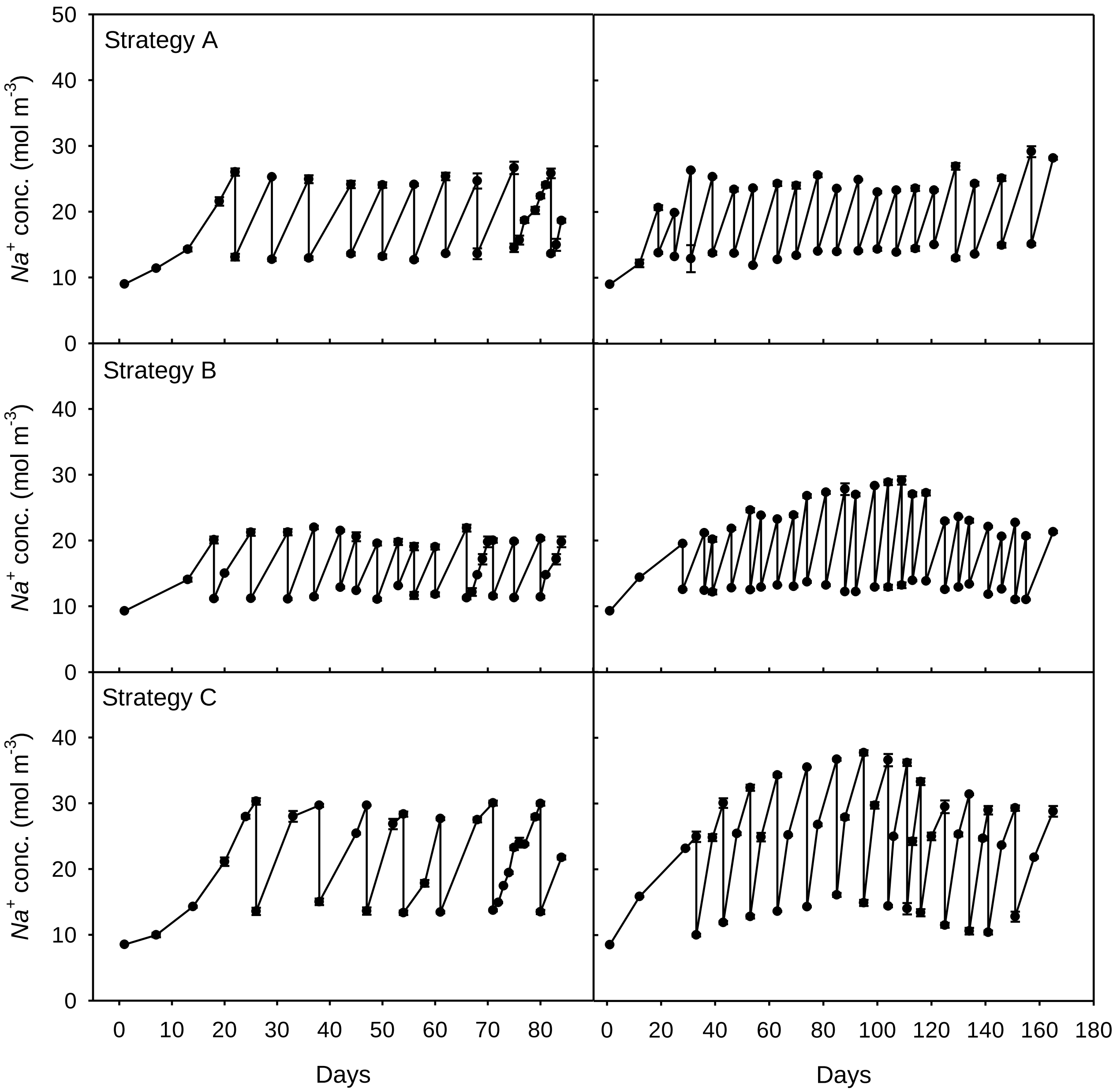
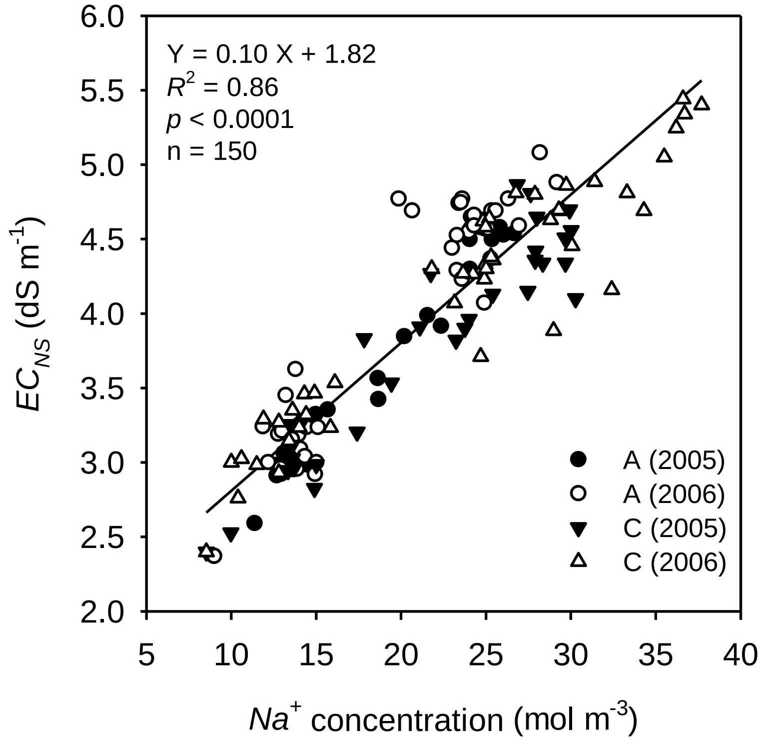
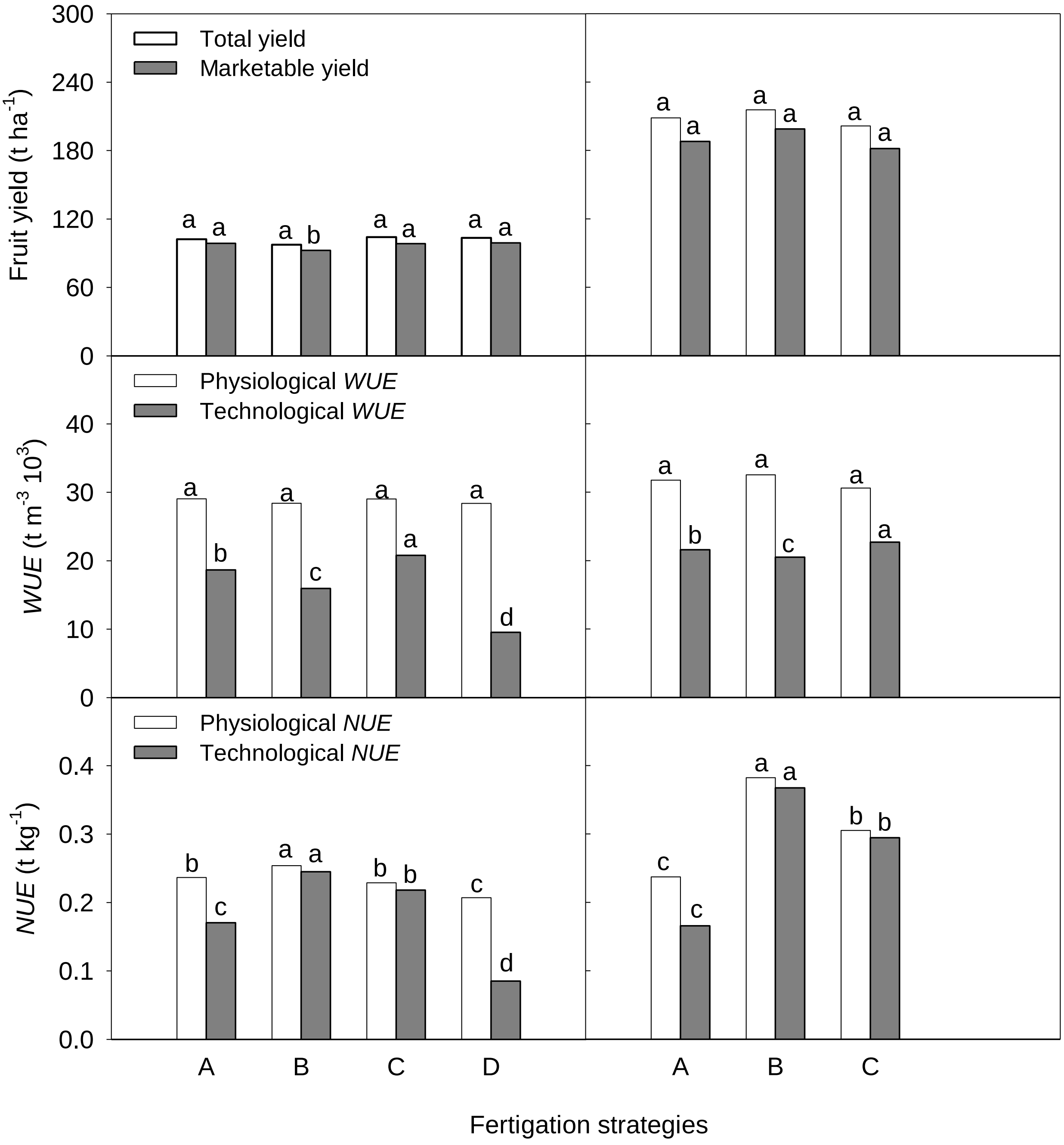

Strategy A
Strategy B
Strategy C
Na^+ conc. (mol m^{-3})
Na^+ conc. (mol m^{-3})
Na^+ conc. (mol m^{-3})
0
10
20
30
40
50
0
10
20
30
40
0
10
20
30
40
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
140
160
180
Days
Days

Figure 5


Y = 0.10 X + 1.82
$R^2 = 0.86$
$p < 0.0001$
n = 150
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
EC_{NS} (dS m^{-1})
5
10
15
20
25
30
35
40
Na^+ concentration (mol m^{-3})
● A (2005)
○ A (2006)
▼ C (2005)
△ C (2006)

599 Figure 6

600



601