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Sodium accumulation vs. nitrate leaching under different fertigation regimes in greenhouse soils in South Uruguay

Acumulación de sodio vs. lavado de nitrógeno en suelos bajo invernadero en el sur de Uruguay con diferentes regímenes de fertirriego

Acúmulo de sódio vs. lixiviação de nitrogênio sob solos de estufas no sul do Uruguai com diferentes regimes de fertirrigação

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Abstract

In greenhouse conditions, soil salinity and N leaching depend on the provision of irrigation, the irrigation water quality and the application of fertilizers and organic amendments. The objective of this study was to quantify and analyze the accumulation and/or leaching process of NO_3^- and Na^+ in greenhouse tomato production in the south region of Uruguay in fine-textured soil under different fertigation regimes. The study was conducted in four tomato crops during 2019/20/21 seasons. Three fertigation regimes were applied. Irrigation volume was the same for all treatments. Drainage was determined by using free drainage lysimeters. Concentration in soil solution and leaching of NO_3^- and Na^+ was measured by monitoring soil solution and drainage solution. Yield, N uptake and N utilization efficiency were determined for each treatment. Soil total drainage was the main factor explaining N and Na^+ leaching. The leaching of N ranges from 0 to 23.4 kg N ha^{-1} per tomato crop with total drainage between 0 and 46.2 % of total irrigation. Drainage necessary to avoid Na^+ accumulation was 13 % of total irrigation. This drainage produced 8.4 kg of N leaching per ha^{-1} during tomato cropping period. Optimizing irrigation is the key factor to the salinity-nitrogen leaching paradox. Irrigation amount and timing should attempt: (1) to avoid excessive irrigation when NO_3^- concentration in soil solution is high, and (2) to apply leaching irrigation when Na^+ concentration in soil solution is high. Soil solution monitoring with suction probes and rapid chemical analysis systems could be a useful tool to identify periods of high risk of N leaching and the right time for leaching irrigation.

Keywords: irrigation, deep percolation, nutrient use efficiency, soil salinity, *Solanum lycopersicum*

Resumen

En condiciones de invernadero, la salinidad del suelo y la lixiviación de N dependen del volumen de riego, la calidad del agua y el manejo de los fertilizantes o las enmiendas que se aplican. El objetivo de este estudio fue cuantificar y analizar el proceso de acumulación y/o lixiviación de NO_3^- y Na^+ en la producción de tomate bajo invernadero en la región sur de Uruguay en suelos de textura fina bajo diferentes regímenes de fertirrigación. El estudio se realizó en cuatro cultivos de tomate durante las temporadas 2019/20/21. Se aplicaron tres regímenes de fertirrigación. El volumen de riego fue el

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mismo para todos los tratamientos. El drenaje se determinó utilizando lisímetros de drenaje libre. La concentración en la solución del suelo y la lixiviación de NO_3^- y Na^+ se midieron monitoreando la solución del suelo y la solución de drenaje. Se determinó el rendimiento, la absorción de N y la eficiencia de uso de N para cada tratamiento. El drenaje total del suelo fue el principal factor explicativo de la lixiviación de N y Na^+. La lixiviación de N estuvo entre 0 y 23,4 kg N ha^{-1} por cultivo de tomate con drenaje total entre 0 y 46,2 % del riego. El drenaje necesario para evitar la acumulación de Na^+ fue del 13 % del riego total. Este drenaje produjo una lixiviación de 8,4 kg de N por ha^{-1} durante el período de cultivo del tomate. La optimización del riego es el factor clave de la paradoja de la lixiviación salinidad-nitrógeno. La cantidad y el momento del riego deben intentar: (1) evitar el riego excesivo cuando la concentración de NO_3^- en la solución del suelo es alta y (2) aplicar riego de lavado cuando la concentración de Na^+ en la solución del suelo es alta. El monitoreo de la solución del suelo, con sondas de succión y sistemas de análisis químico rápido, podría ser una herramienta útil para identificar períodos de alto riesgo de lixiviación de N y el momento adecuado para el riego de lavado de sales.

Palabras clave: riego, percolación profunda, eficiencia en el uso de nutrientes, salinidad de suelo, *Solanum lycopersicum*

Resumo

Em condições de casa de vegetação, a salinidade do solo e a lixiviação de N dependem do fornecimento de irrigação, da qualidade da água e do manejo dos fertilizantes ou corretivos aplicados. O objetivo deste estudo foi quantificar e analisar o processo de acumulação e/ou lixiviação de NO_3^- e Na^+ na produção de tomate em casa de vegetação na região sul do Uruguai em solo de textura fina sob diferentes regimes de fertirrigação. O estudo foi realizado em quatro lavouras de tomate cultivadas nas safras 2019/20/21. Foram aplicados três regimes de fertirrigação. A irrigação volumen foi a mesma para todos os tratamentos. A drenagem foi determinada usando lisímetros de drenagem livre. A concentração na solução do solo e a lixiviação de NO_3^- e Na^+ foram medidas monitorando a solução do solo e a solução de drenagem. O rendimento, a absorção de N e a eficiência de uso do N foram determinados para cada tratamento. A drenagem total do solo foi o principal fator explicativo da lixiviação de N e Na^+. Foram encontradas taxas de lixiviação de N entre 0 e 23,4 kg N ha^{-1} por cultura de tomate com drenagem total entre 0 e 46,2 % da irrigação total. A drenagem necessária para evitar o acúmulo de Na^+ foi de 13 % da irrigação total. Essa drenagem produziu 8,4 kg de N lixiviado por ha^{-1} durante o período de cultivo do tomate. A otimização da irrigação é o fator chave para o paradoxo da lixiviação salinidade-nitrogênio. A quantidade e o tempo de irrigação devem tentar: (1) evitar irrigação excessiva quando a concentração de NO_3^- na solução do solo for alta e (2) aplicar irrigação por lixiviação quando a concentração de Na^+ na solução do solo for alta. O monitoramento da solução do solo, com sondas de sucção e sistemas de análise química rápida, poderia ser uma ferramenta útil para identificar períodos de alto risco de lixiviação de N e o momento adequado para o processo de lavagem de vendas.

Palavras-chave: irrigação, percolação profunda, eficiência no uso de nutrientes, salinidade do solo, *Solanumlycopersicum*

1. Introduction

Greenhouse vegetable production has expanded in many parts of the world[1]. In addition to the traditional mild winter coastal areas in the Mediterranean Basin[2-3], greenhouse production is expanding rapidly in South and Central America[4]. During the last decade, greenhouse cultivation increased in area (70 %) and number of farmers (67 %) in substitution of field crops (reduction of 78 % of field tomato production in the country) in Uruguay. The main reasons are higher yields and improved quality obtained by a better control of environmental factors and extension of the cultivation period.

Numerous studies mention that over application of organic and inorganic amendments together with frequent tillage lead to salt accumulation on greenhouse soils, without rainfall effect[5]. Salts, such as sodium (Na^+), accumulated in the soil rooting zone come from: the supply of salt rich irrigation water, organic amendments, fertilizers, or other chemicals, or natural mechanisms such as the mineralization of soil organic matter, the upward movement of ions with evapotranspiration water, or selective absorption by crops[6]. This accumulation of salts can negatively affect crop yield reducing plant uptake of both water and nutrients; increase soil pH and change the distribution of exchangeable cations[7]. In soils with high exchangeable Na^+, soil particles are dispersed, and soil structure is poor. Excess of Na^+ in the soil competes with calcium and potassium (K) and reduce their availability to crops[7]. Soil exchangeable Na^+ is limiting tomato yield in Uruguay[8]. Recent studies demonstrated that soil exchangeable Na^+ at 0-20 cm depth was prioritized as yield gap variability explaining factor for greenhouse tomato in south Uruguay[8]. Na^+ accumulation has implications on irrigation and drainage management. Irrigation should aim at maintenance of sufficiently high soil water potential and cause salt leaching in the soil profile. For this, frequent irrigation events and regimes providing leaching requirements are advocated[9].

Appreciable nitrate (NO_3^-) leaching loss is commonly measured from intensive vegetable production systems, recognized as non-point contamination sources of aquifers[10-14]. NO_3^- leaching is associated with large amounts of nitrogen (N) mineral fertilizer and organic manures applied in many cases to poor irrigation management causing negative environmental impacts[15-17]. If the rate of NO_3^- uptake by the crop is not great enough, it accumulates into the root zone and is easily leached by irrigation water and rainwater in the deeper soil layers, finally reaching groundwater[18]. The greater the N surplus, the greater the risk of NO_3^- loss from the soil[19]. In the north region of Uruguay high levels of NO_3^- were detected at 20-40 cm depth in greenhouse soils[20] and constitute a risk for groundwater. Groundwater reservoirs in southwest region of Uruguay had nitrate concentration above human drinking water standard[21]. The potential of NO_3^- leaching depends on the soil types and the amount of water in the form of precipitation and/or irrigation[19-22]. Soils physics properties affect NO_3^- leaching; those with a sandy texture have a greater potential for NO_3^- leaching than those with a clay texture, due to a greater movement of water in the first one[23].

Nutrient leaching or salt accumulation depend on deep percolation water (water that moves out below the crop root zone). In greenhouse conditions, the effect of rains does not exist, so the effect of soil salinity and leaching process depend on the provision of irrigation, the water quality and the management of fertilizers or amendments that are applied[23-24]. Water management affect both processes at the same time but in opposite directions. A nutrient management plan is necessary to minimize the accumulation of salts, such as Na^+ in the upper layers of the soil, and the leaching of nutrients such as NO_3^- to the deeper layers of the soil[25]. To control soil salinity, salt leaching is required, but, in this way, groundwater contamination by nitrate becomes very likely. A double bound is constraining farmer choices: less or more irrigation water? On this respect, an optimization strategy is needed. The objective of this study was to quantify and analyze the accumulation and/or leaching process of NO_3^- and Na^+ in greenhouse tomato production in the south region of Uruguay with fine-textured soil under different fertigation regimes.

2. Materials and methods

2.1 Sites and experimental treatment

The study was carried out in a greenhouse located in Wilson Ferreira Aldunate Research Station (INIA Las Brujas) in the south region of Uruguay, latitude 34° 40′ 19′′ S; longitudes 56° 20′ 24′′ W. Average mean temperature is 17 °C (minimum: 11 °C, maximum: 23 °C). Mean annual precipitation is 1200 mm, evenly distributed throughout the year, but with major variation between years[26]. Main soils in the region are classified as Mollic Vertisols (Hypereutric), Luvic/Vertic Phaeozems (Pachic), and Luvic Phaeozems (Abruptic/Oxyaquic) following the FAO guideline[27-28].

The study was conducted in an 870 m² greenhouse, with 60 m length and 14.5 m width with gable roof single structure made from wood and covered with plastic film. Height at the ridge was 4.5 m and 2 m at the gutter. The greenhouse had passive lateral and ridge ventilation and north-south orientation. The greenhouse soil was classified as Luvic Phaeozems[27] with a 30 cm silty horizon A and 25 cm of horizon B. Soil physical and chemical characteristics are described in Table 1. Irrigation water characteristics are described in Table 2.

Table 1. Top layer soil physical and chemical characteristics before tomato planting (0-30 cm) (sample collected in January 2019)

Parameter	Value	Parameter	Value
Clay (%)	35	$N\text{-}NO_3^-$ (µg N g^{-1})	4.4
Silt (%)	61	P (µg P g^{-1})	59.7
Sand (%)	4	Ca^{+2} (meq 100g^{-1})	8.3
Organic carbon (%)	2.1	Mg^{+2} (meq 100g^{-1})	2.0
pH	5.4	K^+ (meq 100g^{-1})	1.0
EC (dS m^{-1})	0.4	Na^+ (meq 100g^{-1})	0.7

EC: Electrical conductivity.

Table 2. Irrigation water characteristics (sample collected in January 2020 and 2021)

Parameter	2020	2021
pH	7.2	7.3
EC (dS m^{-1})	0.24	0.22
Ca^{+2} (mg l^{-1})	15.3	17.6
Mg^{+2} (mg l^{-1})	2.2	4.2
K^+ (mg l^{-1})	5.0	6.0
Na^+ (mg l^{-1})	53.0	54.0
$N\text{-}NO_3^-$ (mg N l^{-1})	0.5	1.4
$S\text{-}SO_4^-$ (mg l^{-1})	7.4	7.8

EC: Electrical conductivity.

The study was conducted in four tomato crops (*Solanum lycopersicum* L.), two autumn (Autumn-20 and Autumn-21) and two spring (Spring-19 and Spring-21) crops grown in seasons 2019, 2020 and 2021. Detailed information of these crops is presented in Table 3. The crops were managed following local practices. Five leaves tomato plantlets were transplanted on soil. Tomato plants were topped after the development of the 7th and 8th cluster for autumn and spring crops, respectively. The plants were physically supported using a system of vertically nylon cords and periodic pruning was conducted. Plant density was 2.66 plants m^{-2} (one stem per plant). Above ground drip irrigation was used for combined irrigation and mineral fertilizer application (i. e. fertigation). Drip tape was arranged in paired lines with 0.3 m spacing between lines within each pair, 1.88 m spacing between adjacent pairs of lines, and 0.2 m spacing between drip flat emitters within drip lines, giving an emitter density of 5.3 emitters m^{-2}. The drip emitters had a discharge rate of 1 L h$^{−1}$. The coefficient of uniformity of the drip system was 96 %.

Randomized complete block designs, with four replications, were used for each trial. Replicate plots measured 14 × 1.88 m. Each plot contained one row of tomato plants with 0.2 m between plants. The greenhouse was divided longitudinally into northern and southern plots by a 2 m wide path along its east-west axis, with two plots of each treatment in each of the northern and southern sectors. There were border areas along the edges of the greenhouse.

Table 3. Cultivar, transplanting date, and end of crop date for each trial

Trial	Cultivar	Transplanting date	End of crop date
Spring-19	Lapataia	22/08/2019	23/01/2020
Autumn-20	Elpida	10/02/2020	18/08/2020
Autumn-21	Elpida	01/02/2021	02/08/2021
Spring-21	Lapataia	30/08/2021	22/01/2022

Three treatments, consisting of three different fertigation regimes, were applied: (T1) no fertilizer addition with pH adjusted to pH 6 using phosphoric acid; (T2) complete nutrient solution to ensure that all macronutrient and micronutrient were not limiting using nutrient total absorption suggested by Ciampitti and García[(29)]; (T3) same as treatment 2 with an additional 50% of nitrogen. The composition of the nutrient solution was formulated considering expected yield, nutrient concentration in irrigation water, and soil characteristics. It was also adjusted for phenological stage. Average total N application for each treatment in each trial throughout the entire growing period is shown in Table 4. The differences in total amounts of applied N between individual crops were due to (i) different yield expectations depending on crop growing season (autumn or spring)[(30)], and (ii) variations in soil nutrient supply, which was higher in the 2019 growing seasons because of higher soil fertility, which decreased with succeeding crops. Petiole sap test were conducted every 14 days to ensure that N and K were not limiting crop growth, using reference values[(31)].

Table 4. Total N supplied by fertigation (added fertilizers plus water content) for each treatment in each trial

Treatment	Total N supplied (kg N ha^{-1})			
	Spring-19	Autumn-20	Autumn-21	Spring-21
T1	2.5	1.4	3.2	5.6
T2	143.6	149.7	153.0	434.1
T3	207.6	224.9	230.9	615.7

All treatments received the same irrigation volume. Irrigation was scheduled to maintain the soil matric potential in the root zone, at 20 cm depth, within −10 to −20 kPa in treatment 2 plots. One tensiometer (Irrometer, Co., Riverside, CA, USA) per treatment 2 plot was used to measure soil matric potential every day. Irrigation was applied every 1-4 days, with irrigation being more frequent during warmer periods, and less frequent during cooler periods.

2.2 Measurements

Climatic data

Temperature and relative humidity inside the greenhouses were measured and recorded every 30 min with a weather station (model Vantage Pro2, Davis Instruments, USA) located at the center of the greenhouse, positioned slightly above the height of the crop. Daily global radiation was measured with a pyranometer (model CS320, Campbell Scientific, Logan, UT, USA) located outside the greenhouse, and daily radiation inside the greenhouse was calculated by multiplying outside solar radiation by greenhouse transmissivity. Greenhouse transmissivity for each crop was measured at the beginning and at the end of each growing period. Measurements were made with a ceptometer (model LP-80, Decagon Devices Inc., Pullman, USA) at 1.5 m above ground in 16 positions both inside and outside greenhouse at 12.00

on sunny days. Average climatic information for each tomato crop is described in Table 5.

Table 5. Maximum, minimum and average temperature and relative humidity, and average daily integral of solar radiation for each tomato growing period

Trial	Air temperature (ºC)			Relative humidity (%)			Daily integral of solar radiation (MJ m^{-2} d^{-1})*
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
Spring-19	20.9	13.7	29.5	69.6	46.1	89.5	13.2
Autumn-20	17.6	11.9	25.6	76.4	55.1	91.4	7.8
Autumn-21	17.8	12.2	25.6	77.5	55.1	93.1	8.0
Spring-21	20.9	14.4	28.4	72.2	49.9	100.0	12.6

*Radiation inside the greenhouse.

Soil nutrient content

Soil samples (in two depth: 0-15 and 15-30 cm) were collected and analyzed immediately before planting and at the end of each cropping period, for mineral N (NO_3^- – N), organic carbon, pH, electrical conductivity (EC), exchangeable Na^+, Ca^{+2}, K^+ and Mg^{+2}. Soil solution nutrient concentration was monitored with soil solution suction probes (SPS23531, SDEC, France) installed at 10 cm from the plant and 7.5 cm from the emitter line, 20 cm depth. At weekly intervals, samples of soil solution were collected by applying vacuum (−80 kPa) for 16 h prior to sample collection; no irrigation/application of nutrient solution was made during sample collection and during the 10 h prior to the application of vacuum. The NO_3^-, K^+, Na^+ and Ca^{+2} concentrations were analyzed with LAQUAtwin ion meters (Horiba, Japan). EC and pH were determined with an EC meter (EcoTestr CTS, Oakton, USA) and pH meter (EcoTestr pH2, Oakton, USA), respectively.

Irrigation volume, drainage and nutrient leaching

Irrigation volume was measured in each treatment with volume meters every day. Fertigation solution of one drip emitter was collected in tanks and sampled once a week for each treatment to determine the concentration of NO_3^-, Na^+, K^+, Ca^{+2}, pH and EC in the applied nutrient solution. After sampling the tank was emptied for the next week. Nutrients applied were calculated for treatment by multiplying nutrient concentration by irrigation volume. Drainage was collected from each treatment using three free draining re-packed lysimeters (2 m long × 0.9 m wide × 1.4 m deep) located in the northern side of the greenhouse (one lysimeter per treatment). The soil profile in the lysimeter reproduced that of the outside area described above to a depth of 1.4 m, with a layer of gravel between geotextile meshes placed at lysimeter bottom. Accumulated lysimeter drainage volumes were measured five times per week; representative subsamples from each lysimeter were analyzed to measure the concentration of NO_3^-, Na^+, K^+, Ca^{+2}, pH and EC. Nutrients leaching was calculated for each lysimeter by multiplying nutrient concentration by drainage volume. Na^+ balance was calculated as the difference between Na^+ applied by fertigation and Na^+ leaching.

Yield and dry matter N content

Measurements of aboveground dry matter production (DMP) throughout the growing season, of each crop, were made by harvesting one plant every 20 days (biomass sampling) in each of the four replicate plots. Dry matter determinations were made by weighing all fresh material and by oven-drying at 65 ˚C until constant weight. The amounts of all pruned shoot material and fruit production were determined throughout each crop, in 10 plants per replicate plot. At each pruning and harvest, the amount of dry matter removed was determined, as described previously. For each biomass sampling, total shoot DMP was determined from the sum of dry matter of leaves, stems and immature fruits for that sampling date, plus the combined dry matter of all pruned material and harvested fruit until that sampling date. The N content in dry matter was determined in finely-ground samples of (i) leaves, stems, and fruit from biomass samplings, (ii) pruned material, and (iii) fruit from harvests. The N content was determined by the Kjeldahl method. N uptake was calculated as the sum of the products of DMP and N content for each component. Fresh tomato yield was calculated as the ratio between the sum of all harvest weight and harvested area. N utilization efficiency was calculated as the ratio between fresh tomato yield and N uptake.

2.3 Data analysis

We performed analysis of variance (ANOVA) and LSD Fisher test to compare fertigation treatments with InfoStat Software[32] for the variables N uptake, fresh tomato yield, N utilization efficiency and NO_3^- concentration in soil solution. For the variables measured in one lysimeter per treatment —where no replicates were used in each trial: N leaching, total water drainage, NO_3^- drainage, Na^+ drainage, NO_3^- concentration in nutritive solution— we considered a randomized complete block design where seasons (Spring-19, Autumn-20, Autumn-21 and Spring-21) were the blocks (replicates). No interaction between treatment effects and block effects was confirmed by residual plots. Linear regression analyses between variables were performed and coefficient of determination (R^2) calculated.

3. Results

3.1 N leaching and N utilization efficiency

The N leaching by deep percolation for each fertigation regime is detailed in Table 6. Treatment 1 showed the higher amount of N leaching in all tomato seasons. No significant differences in N leaching were observed between T2 and T3.

Table 6. N leaching according to fertigation regime for each trial. Values within a column followed by different letters are significantly different (P <0.05)

Trial	Treatments	N leaching (kg N ha^{-1})
Spring-19	T1	12.8
	T2	1.9
	T3	2.0
Autumn-20	T1	15.6
	T2	4.9
	T3	0.1
Autumn-21	T1	23.4
	T2	2.6
	T3	2.1
Spring-21	T1	19.0
	T2	0.1
	T3	0
Average	T1	17.7 a
	T2	2.4 b
	T3	1.1 b

Tomato water consumption varied according to growing season (spring or autumn). Autumn crops water consumption was in average 57 % of spring crops water consumption (Table 7). These differences were related to higher radiation and temperatures for spring crops (Table 5). All fertigation treatments received the same irrigation volume, but significant differences were observed in deep percolation amount between treatments (Table 7). In T1 irrigation overcame crop demand causing higher drainage volume (82.1 mm on average). Drainage in T1 was in the range of 12.9 and 46.2 % of total irrigation. In contrast, in treatment 2 and 3 drainage did not exceed 8.2 % of total irrigation. The lower water consumption for T1 was associated with lower canopy development in unfertilized treatment (data not shown).

Table 7. Total irrigation and drainage amount per treatment for each trial. Values within a column followed by different letters are significantly different (P <0.05)

Trial	Treatment	Irrigation (mm)	Drainage (mm)	Drainage (% of total irrigation)
Spring-19	T1	498.3	64.0	12.9
	T2	494.7	14.1	2.9
	T3	499.2	7.3	1.5
Autumn-20	T1	285.5	74.0	25.9
	T2	290.5	23.9	8.2
	T3	292.1	0.1	0.0
Autumn-21	T1	229.4	106.0	46.2
	T2	264.1	15.5	5.9
	T3	258.5	6.8	2.6
Spring-21	T1	399.1	84.3	21.1
	T2	471.1	0.1	0.0
	T3	463.0	0.0	0.0
Average	T1		82.1 a	26.5 a
	T2		13.4 b	4.3 b
	T3		3.6 b	1.0 b

NO_3^- nutritive solution concentration was lower for T1 (without fertilizers) compared to treatment 2 and 3, as expected (Table 8). This resulted in lower NO_3^- concentration in soil solution and drainage in T1.

N leaching was explained mainly by soil total drainage as shown in Figure 1a (R^2= 0.99) while no significant relationship was found with NO_3^- concentration in soil solution (Figure 1b). N leaching throughout tomato growing period followed total drainage curve for Spring-19 and Autumn-21 (Figure 2a, b, c, d). The same pattern was observed for Autumn-20 and Spring-21 (data not shown). In Spring-19, total drainage increased from 104 days after planting (DAP) onwards in T1. This resulted in a significant increase in N leaching. In Autumn-21, total drainage and N leaching in T1 were higher compared to T2 and T3 during all growing periods. NO_3^- concentration in soil solution was maximum at the beginning of crop growth (0-40 DAP) for all treatments in Spring-19 crop (Figure 2e). The high NO_3^- concentration in soil observed did not pose a hazard to N leaching because drainage was very low in that period (Figure 2c). In Autumn-21, NO_3^- concentration in soil during the first 40 days of crop growth was lower compared to Spring-21. T3 showed higher NO_3^- concentration in soil from 55 DAP onward in Autumn-21 (Figure 2f).

Table 8. Average NO_3^- concentration in nutritive solution, soil solution and drainage per fertigation regime and trial. Values within a column followed by different letters are significantly different (P <0.05)

Trial	Treatment	Nutritive solution NO_3^- (mmol l^{-1})	Soil solution NO_3^- (mmol l^{-1})	Drainage NO_3^- (mmol l^{-1})
Spring-19	T1	0.66	7.50 a	1.58
	T2	3.23	10.88 b	1.82
	T3	4.47	10.90 b	2.43
Autumn-20	T1	1.55	4.09 a	1.48
	T2	6.65	3.16 a	1.66
	T3	11.06	11.45 b	6.16
Autumn-21	T1	1.70	4.65 a	1.58
	T2	5.39	5.78 a	2.52
	T3	7.38	11.85 b	4.33
Spring-21	T1	4.72	-	2.59
	T2	10.0	-	9.19
	T3	13.8	-	21.0
Average	T1	2.16 a		1.81 a
	T2	6.32 b		3.8 ab
	T3	9.18 c		8.48 b

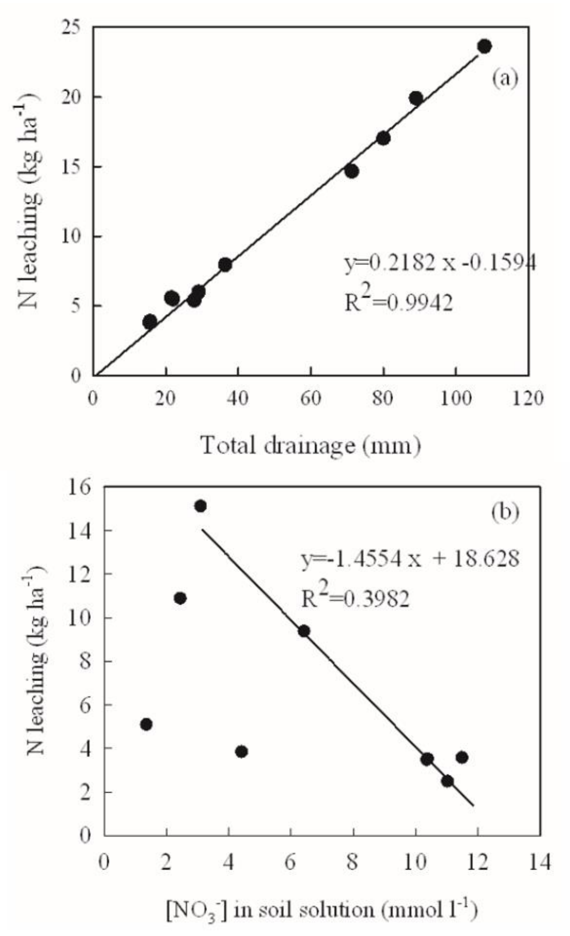

Figure 1. Relationship between N leaching and total drainage (a) and NO_3^- concentration in soil solution (b) for all tomato crops. The linear regression equations and the coefficients of determination (R^2) are given in the figure

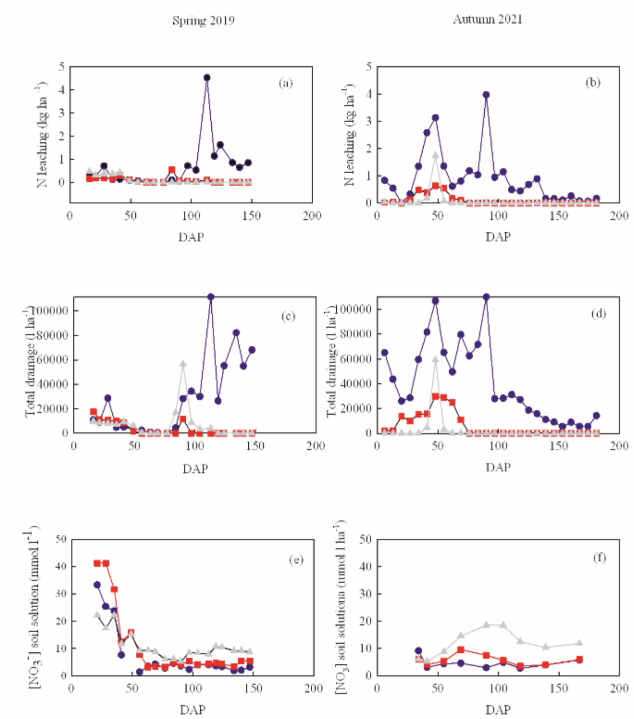

Figure 2. Time course of N leaching, total drainage and NO_3^- concentration in soil solution for Spring-19 (a, c and e) and Autumn-21 (b, d and f) tomato crop. Treatment: 1 (●), 2 (■) and 3 (▲). DAP: Days after planting

Fresh tomato yield and N uptake was higher in T2 and T3 compared to unfertilized (T1) for Autumn-20, Autumn-21 and Spring-21. However, N utilization efficiency was higher in T1 for those trials (Table 9). In Spring-19, no significant differences were observed in fresh yield and N utilization efficiency.

Table 9. N uptake, fresh tomato yield and N utilization efficiency per fertigation regime and trial. Values within a column followed by different letters are significantly different ($P < 0.05$)

Trial	Treatment	N uptake (kg ha^{-1})	Fresh tomato yield (t ha^{-1})	N utilization efficiency (g of fresh yield per g of N uptake)
Spring-19	T1	286.2 b	180.8 a	640.2 a
	T2	345.6 ab	206.8 a	603.3 a
	T3	378.9 a	219.8 a	581.2 a
Autumn-20	T1	171.6 b	125.3 b	746.2 a
	T2	248.8 a	152.1 ab	611.7 b
	T3	289.3 a	160.1 a	555.4 b
Autumn-21	T1	183.7 b	114.6 b	626.3 a
	T2	264.4 a	148.8 a	562.4 ab
	T3	284.8 a	153.1 a	539.2 b
Spring-21	T1	167 b	114.5 b	693.5 a
	T2	329.1 a	178.9 a	544.8 b
	T3	361.7 a	187.1 a	517.5 b

3.2 Na^+ balance and accumulation in soil

Na^+ leaching was higher in T1, same as for N (Table 10). In T1, Na^+ leaching overcame the amount applied in irrigation water (nutritive solution) in all trials. In contrast, T2 and T3 had values of Na^+ applied (nutrient solution) higher than leaching amount, indicating an accumulation in the soil. This accumulation during crop growth was evidenced in soil solution Na^+ content as shown in Figure 3a and 3b for Autumn-20 and Autumn-21 crop, respectively. The same pattern was observed for Spring-19 and Spring-21 (data not shown). Evolution of Na^+ in soil solution was correlated with EC in soil solution (Figure 3c and d). Na^+ leaching was mainly explained by the drainage volume (Figure 4).

Table 10. Sodium applied by fertigation and leached per fertigation regime and trial. Values within a column followed by different letters are significantly different ($P < 0.05$)

Trial	Treatment	Na^+ (kg ha^{-1}) Nutritive solution	Drainage
Spring-19	T1	110.1	172.5
	T2	115.6	26.2
	T3	115.1	3.2
Autumn-20	T1	114.6	244.2
	T2	119.5	67.1
	T3	115.8	0.1
Autumn-21	T1	41.3	270.9
	T2	46.9	44.0
	T3	47.0	6.2
Spring-21	T1	127.5	204.0
	T2	166.6	0.1
	T3	165.4	0.0
Average	T1		222.9 a
	T2		34.4 b
	T3		2.4 b

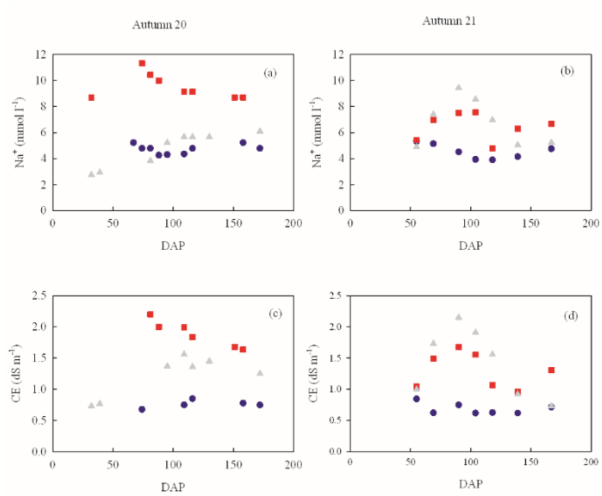

Figure 3. Time course in concentration of Na^+ (a, b) and EC (c, d) in soil solution throughout the growing season for Autumn-20 (a, c) and Autumn-21 (b, d) crop for each treatment. Treatment: 1 (●), 2 (■) and 3 (▲). DAP: Days after planting

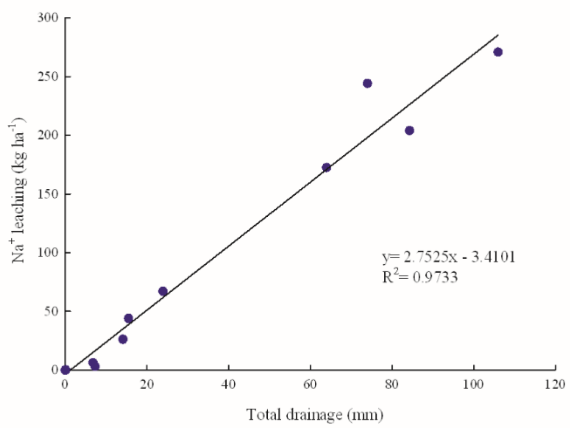

Figure 4. Relationship between Na+ leaching and total drainage for all tomato crops. The linear regression equation and the coefficient of determination (R^2) are given in the figure

3.3 Drainage for optimal salt balance

Na^+ balance was defined as the difference between Na^+ applied by fertigation and Na^+ leaching. Drainage (% of total irrigation volume) necessary to avoid Na^+ accumulation in this soil is 13.1 % (Figure 5a). This % of drainage could cause 8.44 kg of N leaching during cropping period (Figure 5b).

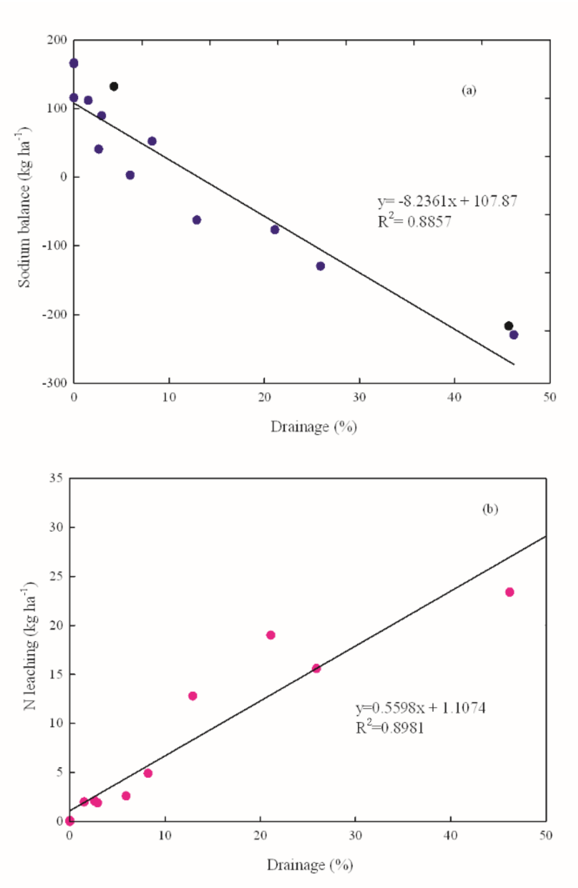

Figure 5. Sodium balance (difference between Na^+ applied by fertigation and Na^+ leaching) (a) and N leaching (b) according to drainage (% of total irrigation) for all tomato crops. The linear regression equation and the coefficient of determination (R^2) are given in the figure

4. Discussion

4.1 N leaching in greenhouse tomato crops

N in the soil that is available to plants is present as NO_3^-, or as NH_4^+, which microbes of the soil soon convert to NO_3^-[(33)]. NO_3^- is completely soluble in water and is prone to be leached, because the negatively-charged NO_3^- anion is repelled by negatively charged surfaces of clay minerals and soil organic matter[(16)]. This keeps nitrate dissolved in the soil solution and moves freely in the soil by percolating rainfall or irrigation[(12-33)]. As the case of study was a greenhouse system, rainfall was not present and percolating irrigation was responsible of salts movements in soil profile. We found that soil total drainage was the main factor explaining N leaching. At open field crops, the amount and intensity of rainfall explained the most variability in NO_3^- leaching instead of excessive irrigation, followed by N fertilizer rate and crop N removal. Other soil and management variables such as soil texture, crop type, tillage and N source, timing and placement had less importance[(35)].

T1 showed higher drainage amounts and N leaching compared to T2 and T3, despite not being fertilized and having the lower NO_3^- concentration in soil solution. Although N leaching is commonly associated with chemical fertilizers used in agricultural crops[(23)(36-39)], it is not the case in this study. In T1, the soil NO_3^- that was leached was produced by mineralization of organic N from soil organic matter, microbes that break down plant residues and other nitrogen-containing residues in the soil[(33)]. Irrigation above demand, due to lower canopy development for unfertilized T1, was the cause of higher total drainage. For greenhouse crops, excessive irrigation during crop growth was also mentioned as N leaching main cause[(17)(40)] in several horticultural crops (tomato, eggplant, pepper, zucchini), especially at the beginning of the crop growth[(14)]. In Spring-19, NO_3^- concentration observed in soil solution was maximum at the beginning of crop growth (0-40 DAP), so irrigation above crop demand could cause high N leaching. Over irrigation at crop beginning aims to ensure crop establishment, since at this stage the exploration of the roots is not too deep. This excessive irrigation often produces NO_3^- leaching[(41)]. In organic systems, the correct management of irrigation at crop establishment is very important, since most of the amendments are applied at the beginning of the crop[(42)].

We found N leaching rates per tomato crop (150 - 190 days of cycle length) between 12.8 - 23.4 kg N ha^{-1} for T1 with total drainage between 12.9 and 46.2 % of total irrigation. For T2 and T3, total drainage was below 8.3% of total irrigation with N leaching lower than 7 kg N ha^{-1}. These values for N leaching coincide with Min and others[(43)] for greenhouse crops. Higher N leaching amount was measured in vegetable open field crops associated with rainfalls[(10)(12)(14)]. Soils with high water retention capacity and low conductivity (e. g. fine-textured), as the soil used for the experiments (Table 1), will have a lower percolation and leaching potential[(22)]. Sandy soils, such as those present in the northern greenhouse horticultural zone of the country, would have higher risk of nutrient leaching[20]. Even though the levels of N leaching were low compared to open field crops, it is extremely important to protect soil when replacing the greenhouse roofs, since the effect of rain can cause N leaching of greater magnitude, as was demonstrated by Min and others[43].

4.2 Sodium balance and accumulation in soil

In soils with high exchangeable Na^+, soil particles are dispersed, and soil structure is poor, affecting water and air movement[9]. Sodic soils become prone to the formation of surface crusts, which impact the emergence of seedlings, favor water stagnation, reduce infiltration and cause anoxic conditions[44]. The excess of Na^+ in the soil competes with calcium and potassium and reduces their availability to crops[7]. Moreover, salt accumulation reduces plant uptake of both water and nutrients. Na^+ was present in irrigation water (Table 2) and therefore it was applied to crops diluted in nutritive solution. Na^+ leaching was determined by % of drainage, hence, T1 showed higher leaching amount associated with high drainage compared to T2 and T3. Na^+ leaching in T1 exceeded the total applied in the nutrient solution (irrigation water content). Therefore, exchangeable Na^+ was removed from soil exchange complex. Natural exchange complexes adsorb calcium and magnesium cations more strongly than sodium from the soil. So, it is more susceptible to leaching[45]. The low % of drainage in T2 and T3 caused an accumulation of Na^+ in soil during crop growth, and EC in soil solution increased. This occurred with an irrigation water considered with slight to moderate restrictive for irrigation because it could affect infiltration rate of water into the soil based on sodium adsorption ratio (SAR) and EC, according to Ayers and Westcot[46] classification. An on-farm study of greenhouse tomato in Uruguay showed that 78% of water sources were classified as slight to moderate restrictive for irrigation based on SAR and EC[8]. Hence, they have the same risk of Na^+ accumulation and could affect structural properties of greenhouse soils. The same study demonstrated that Na^+ in greenhouse soils reduced yield in Autumn tomato crops[8].

Strategies for handling salinity usually aim at preventing the build-up of salts in the root zone to levels that limit the root water uptake, controlling the salt balances in the soil-water system by preventing endless accumulation in the root zone, and minimizing the damaging effects of salinity on crop transpiration and soil evaporation for optimal crop growth[9]. The traditional salinity management approach indicates that the economical way to control soil salinity is to ensure net downward flow of water through the root zone[47]. Leaching requirement depends on EC of saturated extract of soil and EC of irrigation water[46]. In greenhouse systems, it is common to apply leaching irrigation to reduce Na^+ in soil or other salts[41-48]. A survey in greenhouses farms in southeast Spain reveals that additional irrigation to leach salts from soil is the most common strategy to prevent salt accumulation[41]. This irrigation mainly occurred outside the cropping period. None of the greenhouses surveyed applied additional volumes to the normal irrigations in the form of leaching fractions during the crop. The reported volumes applied in individual salt leaching irrigations were between 20 and 40 mm[41]. Another management practice to cope with Na^+ accumulation consisted in the replacement of Na^+ with favorable cations like Ca^{+2}, which improves soil-water relations[9].

4.3 Salt balance

Optimizing irrigation is the key factor to the salinity-nitrogen leaching paradox; to reduce N leaching and its environmental risk, and to avoid Na^+ accumulation in greenhouse soils and its crop damage. Since soil salinity control is bound to increase N leaching, operational criteria should optimize the volumes needed to reduce salinity and those necessary to protect groundwater from nitrate contamination[49].

Drainage necessary to avoid Na^+ accumulation was 13% of total irrigation. This drainage produced 8.4 kg of N leaching per ha^{-1} during tomato cropping period. Necessary drainage could be varied for different soil characteristics, irrigation water characteristics and crop management. However, it is representative of most tomato cropping system in the south region of Uruguay[8][30]. Therefore, it is a useful guide for irrigation management at farm scale. No tool or decision support was being used by farmers to define the daily amount of water applied. Improving irrigation management, adjusting irrigation to match crop demand, is the first step to limit Na^+ accumulation and N leaching at farm scale. VegSyst model, to assist with on-farm decision making, such as when and how much irrigation and nutrient to apply, was calibrated and validated for greenhouse tomato crop in Uruguay for developing a decision support system (DSS)[50-51]. Irrigation requirements are based on simulated ETc, and additionally consider irrigation application efficiency and salinity[52]. Information about drainage needed to avoid salt accumulation as obtained could be useful to consider in DSS development to improve irrigation recommendations.

Soil solution concentration was not a useful indicator for N and Na^+ leaching. Nevertheless, soil solution monitoring with suction probes and rapid chemical analysis systems could assist to decide the right moment to apply leaching irrigation, when NO_3^- level is low and Na^+ is high. Moreover, monitoring soil solution could be useful to identify when the NO_3^- concentration is increasing and the potential for N leaching is high, to reduce drainage by reducing irrigation. For instance, in Spring-19 high NO_3^- concentration in soil solution was measured at the beginning of crop growth (0-40 DAP) (Figure 2e), so in this period low drainage is recommended. In Autumn-21, NO_3^- concentration in soil solution increased from 55 DAP onward (Figure 2f), so irrigation should be adjusted to minimize drainage. Libutti and Monteleone[49] suggested a "decoupling" strategy to manage jointly soil salinity (requiring leaching to remove excess salts) and nitrogen fertilization (not requiring leaching to prevent NO_3^- loss from the soil). In Uruguayan greenhouse systems soil solution monitoring could be a useful tool to find appropriate moments to leaching irrigation and periods of high risk of N leaching to reduce drainage. This should be combined with tools that assist farmers in irrigation management. Soil moisture monitoring techniques like tensiometers are recommended to help farmers to make better decisions about the amount and timing of irrigation[17]. Irrigation management with soil sensors at different depths is a useful tool to reduce nitrate leaching; monitoring the soil water content immediately below the roots is an indicator of deep drainage[52].

5. Conclusions

Soil total drainage was the main factor explaining both processes N leaching and Na^+ accumulation in greenhouse tomato crops. Optimizing irrigation is the key factor to the salinity-nitrogen leaching paradox and has great potential to reduce N losses into groundwater while keeping the greenhouse soil free from excess salt accumulation. Irrigation amount and timing should attempt: [1] to avoid excessive irrigation when NO_3^- concentration in soil solution is high, and [2] to apply leaching irrigation when Na^+ concentration in soil solution is high. Soil solution monitoring could be a useful tool to identify periods of high risk of N leaching and the right time for leaching irrigation.

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Transparency of data

The entire data set that supports the results of this study was published in the article itself.

Author contribution statement

Cecilia Berrueta: Conceptualization, methodology, data curation, investigation, formal analysis, writing –original draft, and review and editing. **Rafael Grasso**: Data curation, investigation, formal analysis, writing –original draft, and review and editing. **Claudio García**: Data curation, investigation, writing –review and editing.

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