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Nitrogen Fertilization of Plants Irrigated with Desalinated Water: A Study of Interactions of Nitrogen with Chloride

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Abstract: The overall aim of this research was to optimize nitrogen (N) fertilization of plants under desalinated water and a wide range of chloride concentrations for high yield while minimizing downward leaching of nitrate and chloride. The response of two crops, lettuce and potato, to N concentration (C_N) in the irrigating solution using desalinated and wide range of Cl concentrations (C_{CL}) was evaluated. The yields of both crops increased with N up to optimal C_N of the irrigating solution and decreased as C_{CL} increased. Optimal C_N in both crops was higher in the desalinated water than high C_{CL} treatments. N uptake by plants increased with C_N in the irrigating solution and the highest uptake was at low C_{CL}. As expected, N fertilization suppressed Cl accumulation in plant tissues. Drainage of N and Cl increased with increase in C_{CL} in the irrigating solution and N fertilization above optimal C_N resulted in steep rise in downward N leaching. The overall conclusion is that as water quality is improved through desalination, higher N supply is required for high yields with less groundwater pollution by downward leaching of N and Cl.

Keywords: fertilization; leachate; lettuce; lysimeter; nitrate; potato; salinity

1. Introduction

The growing demand for fresh water led to an increase in the production of desalinated water, mainly in arid and semiarid regions [1,2]. An annual production of 585×10^6 m^3/year in Israel was reported [3], approximately 40% of the total fresh water consumption [4]. The use of desalinated seawater for irrigation in Israel was estimated at 200×10^6 m^3/year [5], which is ~40% of the national freshwater irrigation consumption.

In intensive agriculture, the majority of crops grown are defined as glycophyte plants, meaning high sensitivity to salinity above a threshold value, which is specific for each crop [6–9]. Salinity may interfere with mineral nutrition acquisition by plants in two ways [10,11]: (i) the total ionic strength of the soil solution, regardless of its composition, can reduce nutrient uptake and translocation, and (ii) uptake competition with specific ions such as sodium and chloride can reduce nutrient uptake. These interactions may lead to Na-induced Ca and/or K deficiencies [12] and Cl^- induced inhibition of $NO_3{}^-$ uptake [13,14]. Antagonism between Cl^- and $NO_3{}^-$ uptake by plants was demonstrated in numerous publications [13]. This antagonism was found in various plants, including substrate-grown crops such as melon and lettuce [15], tomato and melon [16–18], and rose [14]. Direct competition between NO_3^- and Cl^- on uptake by plants was reported in several publications [19–21]. Therefore, there is a possibility that yield reduction due to increased salinity may be partially due to induced deficiency of N by the increased external Cl concentration. Addition of nitrate to the irrigation water reduced chloride accumulation in avocado plant and alleviated its adverse effects [22], whereas another publication suggested that a reduction in water uptake led to the reduced nitrate uptake [23]. Under conditions of salinity, nitrogen concentration in plant leaves decreased due to increasing chloride concentration in pepper [24], tomato [16], lettuce, and Chinese cabbage [25].

Due to the above findings, increasing the NO_3^- supply to sensitive crops irrigated with water containing high chloride concentrations was recommended in several publications [13,16,22]. Consequently, the shift from irrigation with conventional water to using desalinated water calls for adjustment in the amount of additional minerals. Adjustment in the amount of minerals needed for plant growth requires understanding the effects of the quality of water supplied for irrigation on plants response to nutrients.

Irrigation with desalinated water was found to increase maximum yields of bell peppers by 50% and allowed a reduction in irrigation water application rate by half compared to irrigation with local brackish groundwater (electrical conductivity (EC = 3.2 dS·m^{-1}) [26]. It was shown that the higher water dose required with saline water than with desalinated water was due to the required excess water for leaching out soluble salts from the root zone [26]. This leaching application results in high volumes of drainage water that are often enriched with salts and also in other nutrients [27] including nitrate [28]. The reduction in the required leaching fraction with the reduction in water salinity was shown to reduce N leaching and enhance the efficiency of N fertilization [29]. A simulation study of water and salts transport in soil of irrigated orchard in Mediterranean region showed that a shift from natural water to desalinated seawater reduced downward leaching of contaminants to the groundwater [5].

Contamination of groundwater by nitrate is a major problem worldwide [30–32]. In Israel, it has led to disqualification of a greater number of drinking water wells than any other environmental contaminant in the beginning of the 21st century [33]. Nitrate is highly soluble and in most soils it is very mobile within the soil–water solution. Consequently, when nitrogen fertilizer inputs exceed the amount of nitrogen needed by the plant, the excess nitrate is then easily leached by irrigation water and rainwater to deeper soil layers, finally reaching groundwater [34,35].

We hypothesized that optimal nitrogen concentration for the highest yield will be lower and the total uptake of water and nitrogen will increase with decrease in the chloride concentration of the irrigating solution; consequently, chloride and nitrate downward leaching below the root zone will decrease with reducing salinity of the irrigation water. Optimization of N application in combination with irrigation with desalinated water will also lead to reduction of N and Cl fluxes below the root zone and protect underground water sources from N and Cl contamination.

The overall aim of this research was to optimize nitrogen fertilization of plants under desalinated water and a wide range of chloride concentrations for high yield while minimizing downward leaching of nitrate and chloride. The specific objectives were (1) to determine the response curves of lettuce biomass and potato tubers to C_N (N concentration in the irrigating solution) at different C_{Cl} (Cl concentration in the irrigating solution); (2) to explore the effects of C_N at different C_{Cl} values on N and Cl concentrations in the leaves of lettuce and potato; and (3) to determine the effects of N and Cl concentrations in the irrigating water on the water leaching fraction (LF) and the downward leaching of nitrogen and chloride.

2. Materials and Methods

The effect of N concentrations combined with irrigation with desalinated water and a wide range of Cl concentrations on lettuce and potato plants was investigated in five experiments: Three winter season potato (*Solanum tuberosum* L.) experiments (20 January–3 May 2016, 15 January–17 May 2017, and 1 March–27 June 2018) and two summer season lettuce (*Lactuca sativa* L.) experiments (17 August

2016–26 September 2016 and 14 September–22 October 2017). The following varieties were used for the three potato experiments; Sifra, Rozana, and Desire in 2016, 2017, and 2018. The variety Romit-Raviv was used for the two lettuce experiments. The experiments were carried out in automated lysimeters at Bet Dagan, Israel (34°49′15″ E, 31°59′34″ N).

2.1. Description of the Study Site and Lysimeter System

Ninety-six lysimeters of 60 L volume (height: 54 cm; radius in the range of 55 to 60 cm, from bottom to top) were placed on 24 tables. The lysimeters were filled with coarse sand (>1400 µm—13.8%, 1000–1400 µm—56.5%, 500–1000 µm—25%, 250–500 µm—1.8%, 50–250 µm—2.2%, and <50—0.6%), and the following physical properties; bulk density: 1.66 g cm^{-3}, total porosity: 37.4%, and saturated hydraulic conductivity: 3.3 cm min^{-1}. The sand in the lysimeters was used throughout the five experiments with no replacement and/or washing of the medium before starting each experiment. A 60 cm long rockwool drain with a diameter of 5 cm was installed in each lysimeter. The dimensions of the rockwool drain were made according to Ben-Gal and Shani (2002) [36] for preventing saturation at the bottom of the lysimeters and to allow continuous water flow. Below each drain was a container for the collection of the drainage (96 drainage containers) and the weight of the drainage was determined manually every few days. The irrigation was done by nutrient solutions from 24 solution tanks (one for each treatment) each with 200 L capacity. The solution tanks were supplied with desalinated water from two storage tanks with a total volume of 5 m^3. The desalinated water was produced by a desalination device (TROS160LPH, Treatment, Israel) to the level of electrical conductivity EC = 0.005 ds m^{-1}. After the 24 tanks were filled with water, salts and fertilizers that were weighed in the laboratory were added to each container according to treatments. Each solution container had a shipping pump and 4 tubes connected to 4 lysimeters for different repetitions of the same treatment. Each container irrigated 4 lysimeters in sequence using a separate valve for each lysimeter. The entire irrigation system was controlled by a computer using a tailored control software (Crystal Vision, Kibbutz Samar, Israel).

2.2. Experiments Treatments

The two lettuce experiments consisted of 24 treatments of full factorial combinations of 6 N and 4 Cl concentrations (Table 1). The first potato experiment in 2016 included 24 treatments consisted of 6 N and 4 Cl concentrations, the second potato experiment in 2017 included 16 treatments consisted of 4 N and 4 Cl concentrations, and the third potato experiment consisted of 20 treatments consisted of 4 N and 5 Cl concentrations.

Table 1. List of the Lettuce and potato experiments conducted in the lysimeters, Bet Dagan, 2016–2018.

Crop	Potato	Lettuce	Potato	Lettuce	Potato
Planting	15.1.2016	17.8.2016	15.1.2017	14.9.2017	1.3.2018
Harvest	31.5.2016	27.9.2016	17.5.2017	22.10.2017	27.6.2018
Cl (mg L^{-1})	15, 150, 350, 700	15, 150, 350, 700	15, 150, 350, 700	15, 150, 350, 700	15, 200, 600, 1100, 1500
N (mg L^{-1})	10, 20, 30, 40, 60, 80	25, 50, 75, 100, 125, 140	10, 50, 100, 150	225, 45, 65, 85, 100, 1255	10, 50, 100, 150

2.3. Measurements Performed

2.3.1. Plant Growth and Yield

In the lettuce experiment, the heads' (leaves) fresh and dry weights (FW and DW, respectively) were determined. Lettuce roots FW and DW were also recorded. At the termination of the potato experiments, the above ground part of all plants from all lysimeters were cut and separated from tubers and the FW and DW of the above ground part and tubers were determined separately. In all experiments, the fresh samples of the plants organs were rinsed for 15 s with deionized water, dried at 70 °C in a ventilated oven, and weighed again in order to determine dry matter content.

Quadratic equation was used for quantitative expression of the potato tubers yield as a function of C_N at each C_{Cl} value,

$$Y = a X^2 + b X + c \tag{1}$$

where y is the yield; x is the nutrient concentration (C_N); and a, b, and c are coefficients derived by best fitting.

Mitcherlich model Equation (2) was used for quantitative expression of the potato tubers yield as function of C_N at each C_{Cl} value,

$$y = A\,(1 - e^{-Cx}) \tag{2}$$

where y is the yield, x is the nutrient concentration (C_N), A is the potential yield that would be obtained by supplying all growth factors in their optimum amounts, and C is a proportionality constant that depends on the individual growth factor.

2.3.2. Mineral Concentration in Plant Tissues

After harvesting and oven drying, the subsamples of the plant organs were ground to a fine powder. A subsample (100 mg) in powder form was digested using sulfuric acid and peroxide according to Snell and Snell (1948). N was determined in an autoanalyzer (Discrete Autoanalyzer Gallery, Thermo Fisher Scientific, Finland). Chloride was extracted from the leaf powder in water (100:1 water/dry matter) and determined with a Cl analyzer (Sherwood-Scientific, chloride analyzer 926, Cambridge, UK).

2.3.3. Mineral Concentration in Drainage

Drainage water was collected continuously under each lysimeter and the accumulated leachate was weighed frequently, every 3 to 7 days and subsamples of water were taken for analyses of ammonium, nitrate, and chloride concentrations in each event of drainage collection (5 to 15 times) using the autoanalyzer described above.

2.3.4. Leaching Fraction and Leached N and Cl

As stated before, drainage water was collected continuously and weighed periodically for calculations of the drainage volume, leaching fraction (LF), and the total amount of N and Cl in the drainage (M_N and M_{Cl}, respectively). LF was calculated as the ratio of the amount of water collected as drainage to the amount of irrigated water. A 25% given as LF was maintained in one of the treatments with high nitrogen and low chloride. The irrigation dose in all other treatments was the same as in the reference treatment. M_N and M_{Cl} were calculated in each measurement event by multiplication of the volume of the drainage by the concentration of N (sum of NH_4^+-N and NO_3^--N) or Cl, respectively, and then the total M_N and M_{Cl} were calculated as sum of all the measured events. The average N and Cl concentrations in the drainage were calculated by dividing the total M_N and M_{Cl} by the accumulated drainage volume.

2.4. Statistics

The main effects of the N and Cl concentrations and their interactions on measured variables were determined statistically using the two-way ANOVA procedure of JMP 14. The significance of comparisons among treatments was tested by the Tukey–Kramer honestly significant difference (HSD) at $p < 0.05$. Response curves of plant biomass production to C_N and N concentration and mass in the drainage water as function of C_N were fit using the NLIN procedure of JMP 14.

3. Results

3.1. Plants Response to N and Cl Concentrations

For achieving the first objective, to determine the response curves of lettuce biomass and potato tubers to C_N at different C_{Cl}, the biomass production of lettuce and the yield of potato were determined in the above described lettuce and potato experiments.

3.1.1. Biomass in Lettuce Experiments

In the two lettuce experiments, the lettuce head fresh and dry weight were significantly affected by C_N and C_{CL}, but no significant interaction between these factors was obtained (Table 2). As expected, lettuce head dry weight increased significantly as C_N was raised from the lowest value of 25 mg L^{-1} to 50 and 45 mg L^{-1} in the first and second experiments, respectively. The highest head weights were obtained with 75 and 65 mg L^{-1} in the first and second experiments. As expected, increasing C_{Cl} had negative effect on lettuce head fresh and dry weights in both experiments. In the first experiment, a significant reduction in the FW and DW was obtained with the increase from 150 to 350 mg L^{-1}, and 15 to 350 mg L^{-1}, whereas in the second experiment significant lower FW and DW were obtained as the C_{Cl} was raised to 700 mg L^{-1}.

Table 2. The effect of C_N and C_{CL} on lettuce head fresh and dry weight and root fresh weight. Probability of *F* values for C_N, C_{Cl}, Block factors, and the interaction of C_N and C_{Cl} were determined using the two-way ANOVA procedure of JMP 14. Different letters on the right side of values indicate significant difference between treatments (HSD) at $p < 0.05$ by the Tukey–Kramer honestly test. No letters are presented when no significant difference was obtained.

		2016 (First Lettuce Experiment)					2017 (Second Lettuce Experiment)		
Variable		Head	Head	Root	Variable		Head	Head	Root
		fwt	dwt	fwt			fwt	dwt	fwt
			g plant^{-1}					g plant^{-1}	
C_N					C_N				
mg L^{-1}					mg L^{-1}				
25		297.0 d	16.0 d	18.9 a	25		116.4 b	7.9 a	18.7 a
50		502.5 ab	25.0 abc	13.8 b	45		182.7 a	10.5 ab	17.3 ab
75		528.8 a	29.8 a	13.5 b	65		182.4 a	13.2 b	15.5 bc
100		509.0 ab	26.7 ab	11.2 b	85		164.5 a	11.1 b	13.5 cd
125		437.5 bc	24.1 bc	10.5 b	100		157.3 a	11.5 b	12.4 d
140		383.3 cd	20.7 cd	9.9 b	125		166.9 a	12.2 b	12.2 d
C_{CL}					C_{CL}				
mg L-					mg L^{-1}				
15		497.2 a	26.8 a	11.5	15		171.2 a	12.2 a	13.7 b
150		484.4 a	24.5 ab	12.9	150		169.8 a	11.5 a	15.1 ab
350		407.6 b	21.5 b	13.6	350		166.9 a	11.1 ab	15.1 ab
700		394.2 b	22.0 b	13.9	700		138.8 b	9.4 b	15.8 a
Factor	df		*p* value		Factor	df		*p* value	
C_N	5	<0.0001	<0.0001	<0.0001	C_N	5	<0.0001	<0.0001	<0.0001
C_{CL}	3	0.0003	0.0009	0.3018	C_{CL}	3	0.0015	0.0032	0.0205
Block	3	0.0029	0.0016	0.0936	Block	3	0.9234	0.2508	0.0047
$C_N X C_{Cl}$	15	0.0774	0.0599	0.8696	$C_N X C_{Cl}$	15	0.216	0.787	0.0378

When the response of the head dry weight as a function of C_N for each C_{CL} level in the first experiment is presented, the same trend is obtained, except the desalinated water (C_{Cl} = 15 mg L^{-1})

treatment in which the maximum weight occurred with the maximal C_N, 125 mg L^{-1} (Figure 1). Equation (1) was employed to fit curves to the response of the lettuce head to C_N at each C_{Cl} value in the two lettuce experiments (Figure 1). In the first experiment, the r^2 at the different C_{Cl} was in the range of 0.58 to 0.94 (Table 3). The obtained optimum C_N of the desalinated water (C_{Cl} = 15 mg L^{-1}) was 94.6 mg L^{-1} and for water with higher C_{Cl}, 150, 350, and 700 mg L^{-1}, the optimum C_N values were 84.3, 80.8, and 90.8 mg L^{-1}, respectively. In the second experiment, the r^2 at the different C_{Cl} were in the range of 0.60 to 0.91 for C_{CL} 15 to 350 mg L^{-1} (Table 3). The relative effect of C_N on the head DW at 700 mg Cl l^{-1} was much smaller than at the lower C_{Cl} values (Figure 1) with low r^2 just 0.39 (Table 3). The obtained optimum C_N of the desalinated water (C_{Cl} = 15 mg L^{-1}) was 129.8 mg L^{-1}, compared with 87.8, 88.9, and 124.0 mg L^{-1}, at C_{Cl} treatments of 150, 350, and 700 mg L^{-1}, respectively. In both experiments, the highest calculated optimal C_N values for lettuce were obtained with desalinated water. In both experiments the lowest optimal C_N values were obtained at the median C_{CL} levels of 150 and 350 mg L^{-1}.

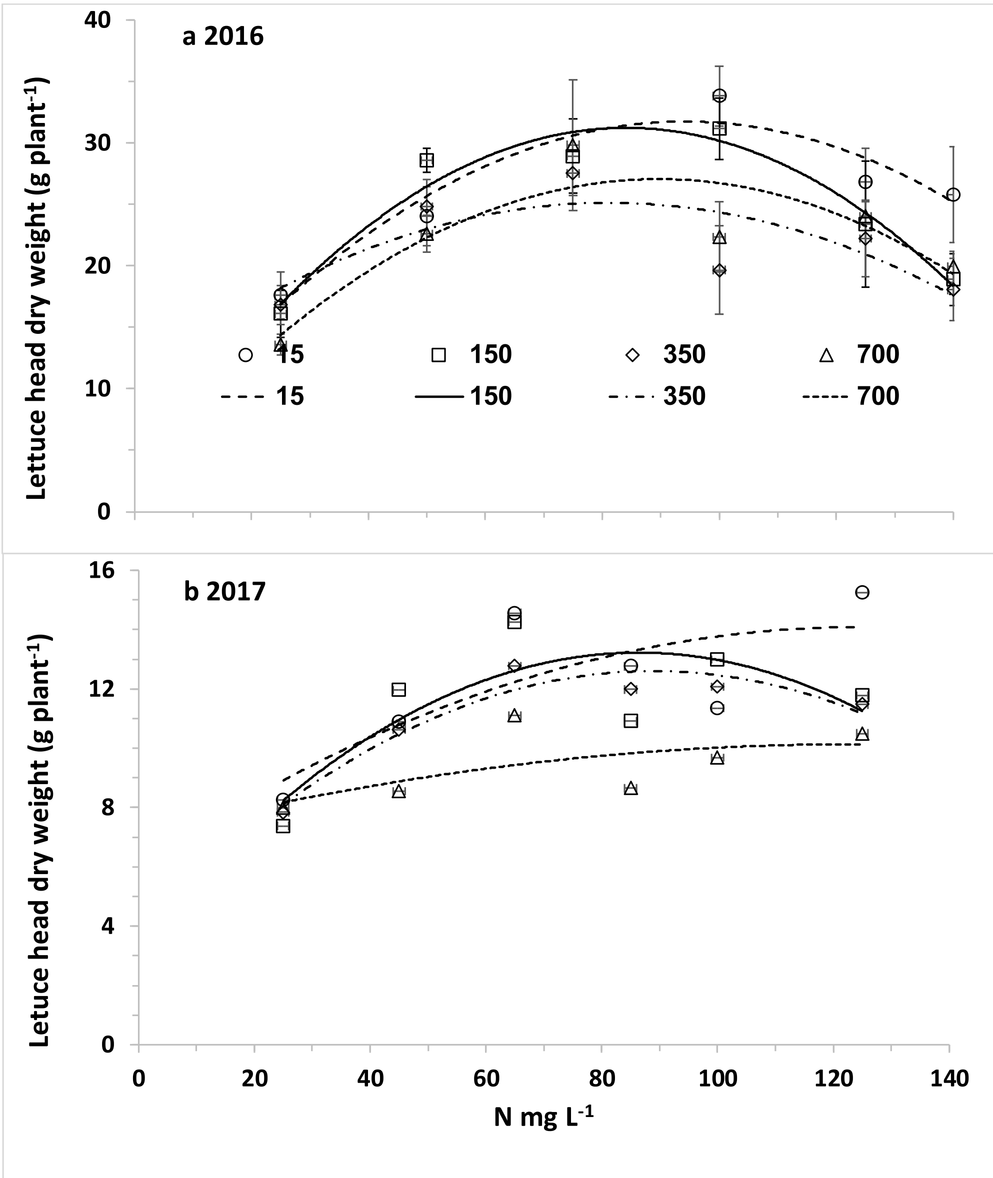

Figure 1. Lettuce head dry weight as a function of N concentration in the irrigating solution at different Cl concentrations in the irrigating solution (**a**) first experiment on 26 September 2016 and (**b**) second experiment on 22 October 2017.

Table 3. Best fit parameters of Equation (1) for best fit curves of Figure 1. r^2—coefficient of determination.

Cl	a	b	c	r^2	N Optimum
mg L^{-1}			mg L^{-1}		mg L^{-1}
			2016		
15	−0.0031	0.5865	4.1	0.91	94.6
150	−0.0041	0.6914	2.2	0.94	84.3
350	−0.0022	0.3557	10.7	0.58	80.8
700	−0.003	0.5447	2.6	0.77	90.8
			2017		
15	−0.0005	0.1298	6.00	0.60	129.8
150	−0.0013	0.2284	3.36	0.63	87.85
350	−0.0011	0.1957	3.89	0.91	88.95
700	−0.0002	0.0496	7.05	0.39	124.0

In both lettuce experiments, the root fresh weight was much smaller than the head (Table 2); the shoot to root ratio was in the range of 45.9 to 15.7 in the first experiment and 13.7 to 6.2 in the second experiment. In both experiments, the root fresh weight was affected significantly by $C_{N.}$ In both experiments, the highest root FW were obtained at the lowest C_N of 25 mg L^{-1} and decreased insignificantly with further increase in C_N from 50 and 65 mg l^{-1} in the first and second experiments, respectively (Table 2). In the first experiment, the root fresh weight was not affected by C_{Cl} and no significant interaction of C_N with C_{Cl} was obtained, whereas in the second experiment it was significantly increased as the C_{Cl} increased in the studied range of 15 to 700 mg L^{-1}. A significant interaction effect of C_N with C_{Cl} on the root FW was obtained in the second experiment (Table 2), but no change in the trend of the effect of C_N at different C_{Cl} was obtained.

3.1.2. Biomass in Potato Experiments

Potato biomass, tubers fresh and dry weight, and shoot dry weight responded positively to C_N in the three potato experiments (Table 4). In the first experiment, significant increases in the tuber and shoot mass were obtained with each increment of raising C_N by 10 or 20 mg L^{-1} with the highest masses at 80 mg L^{-1}. In the second and third experiments, the range of C_N was extended to 150 mg L^{-1}. In the second experiment, the highest shoot and tuber masses were obtained at 100 mg N L^{-1} and they decreased with a further raise of C_N to 150 mg L^{-1}. In the third experiment, the highest shoot and tuber masses were obtained at 150 mg N L^{-1}, but the difference between the mass at C_N 100 and 150 mg L^{-1} were insignificant. In the first and second experiments, the effect of C_{Cl} on the potato plants was tested in the range of 15 to 700 mg L^{-1}. In the first experiment, the increase of C_{CL} in this range had negative effect on potato shoot and tubers masses, as expected; however, in the second experiment the effects on the shoot and tubers mass were insignificant. Therefore, in the third experiment the range of C_{CL} was extended to 1500 mg L^{-1} resulting in a significant negative effect on the shoot dry mass and the tubers fresh and dry mass. Significant interaction of the effects of C_N with C_{CL} was obtained just for the shoot and tubers dry weights in the first experiment and shoot dry weight and tubers fresh weight in the third experiment. The significant interactions between C_N and C_{Cl} in the first and third experiments are due to differences in the magnitudes of the effect of C_N on the tubers mass at different C_{Cl} values, whereas the general trend is similar, as shown for the tubers fresh weight in Figure 2.

Table 4. The effect of C_N and C_{CL} on potato shoot dry weight and tubers fresh and dry weight and N, Cl, and nitrate-N concentrations in leaf tissue. Probability of *F* values for C_N, C_{Cl}, Block factors, and the interaction of C_N and C_{Cl} were determined using the two-way ANOVA procedure of JMP 14. Different letters on the right side of values indicate significant difference between treatments (HSD) at $p < 0.05$ by the Tukey–Kramer honestly test. No letters are presented when no significant difference was obtained.

		2016					**2017**					**2018**		
Variable		**Shoot**	**Tubers Weight**		**Variable**		**Shoot**	**Tubers Weight**		**Variable**		**Shoot**	**Tubers Weight**	
		dwt	fwt	dwt			dwt	fwt	dwt			dwt	fwt	dwt
		g plant^{-1}	kg plant^{-1}				g plant^{-1}	kg plant^{-1}				g plant^{-1}	kg plant^{-1}	
C_N				C_N	C_N					C_N				
mg L^{-1}				mg L^{-1}	mg L^{-1}					mg L^{-1}				
10		9.3 f	0.777 f	0.092 f	10		34.1 b	0.54 c	0.150 c	10		6.3 c	0.229 c	0.029 c
20		16.5 e	1.132 e	0.133 e	50		47.4 a	1.19 b	0.351 b	50		32.2 b	0.610 b	0.077 b
30		25.3 d	1.540 d	0.191 d	100		55.4 a	1.63 a	0.498 a	100		49.0 a	0.693 ab	0.088 ab
40		33.0 c	1.916 c	0.229 c	150		48.6 a	1.36 b	0.418 ab	150		57.4 a	0.811 a	0.109 a
60		43.6 b	2.397 b	0.299 b										
80		53.6 a	2.640 a	0.354 a										
C_{CL}					C_{CL}					C_{CL}				
mg L^{-1}					mg L^{-1}					mg L^{-1}				
15		20.8 c	1.686 ab	0.220 ab	15		46.4	1.27	0.382	15		49.6 a	0.753 ba	0.105 a
150		30.9 b	1.843 a	0.234 a	150		49.8	1.24	0.374	200		49.6 a	0.771 a	0.103 ab
350		35.4 a	1.737 ab	0.209 b	350		43.8	1.1	0.331	600		33.5 b	0.582 bc	0.072 bc
700		33.9 ab	1.667 b	0.203 b	700		45.6	1.1	0.329	1100		29.5 b	0.472 cd	0.054 c
										1500		19.0 b	0.350 d	0.045 c
Factor	df	Probability of F			Factor	df				Factor	df			
C_{Cl}	3	<0.0001	0.0426	0.0031	C_{Cl}	3	0.4991	0.1914	0.1533	C_{Cl}	3	<0.0001	<0.0001	<0.0001
C_N	3	<0.0001	<0.0001	<0.0001	C_N	3	0.0001	<0.0001	<0.0001	C_N	4	<0.0001	<0.0001	<0.0001
Block	3	0.1232	0.4346	0.289	Block	3	0.0007	0.4065	0.3209	Block	3	0.6334	0.0095	0.0200
$C_N XC_{Cl}$	9	0.0351	0.4951	0.025	$C_N XC_{Cl}$	9	0.4483	0.1892	0.3250	$C_N XC_{Cl}$	12	0.0008	0.0435	0.3120

The response of the tubers fresh weight to C_N at each level of the studied C_{Cl} value is presented in Figure 2. In the first experiment, the highest tuber yield at all C_{Cl} values was observed at the highest C_N treatment, 80 mg L^{-1}. However, the increase in mass as C_N was raised from 60 to 80 mg L^{-1} was bigger as C_{Cl} was lower: 407, 317, 220, and 20 g plant^{-1} for 15, 150, 350, and 700 mg L^{-1}, respectively. In the second experiment the highest tuber yield at all C_{Cl} values was observed at 100 mg L^{-1}. However, the increase in mass as C_N was increased from 50 to 100 mg l^{-1} was bigger as C_{Cl} was lower: 663, 642, 340 and 119 g plant^{-1} for 15, 150, 350 and 700 mg L^{-1}, respectively. In the third experiment, the main difference in the tubers yields at the highest C_N (150 mg L^{-1}) between C_{Cl} treatments stemmed from the difference in the increase in yield as the C_N was raised from 50 to 150 from mg L^{-1}.

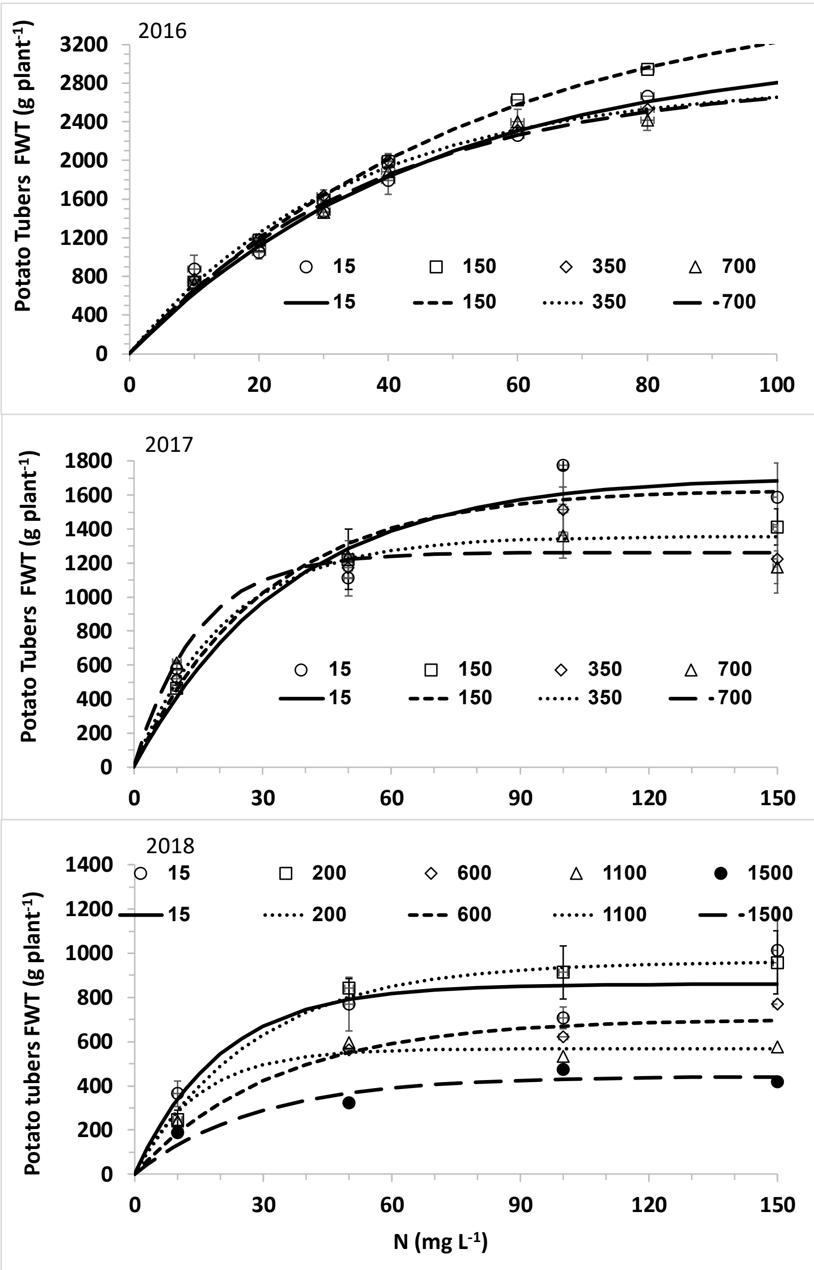

Figure 2. Potato tubers fresh weight (FWT) as a function of N concentration in the irrigating solution at different Cl concentrations in the irrigating solution, (**bottom**) 26 May 2016, (**middle**) May 2017, and (**top**) May 2018.

All the curves in the second and third experiments show steep slope as C_N increased from 0 to 20–30 mg L^{-1} followed by moderate slope, and above 80–120 mg L^{-1} the curves approach maximal values according to the Mitcherlich equation with lower values for the high C_{Cl} Equation (2). The visual fitness of the curves to the observed values for each C_{Cl} value in the second and third years is satisfactory. In the first year only the first two stages of the curves (steep and moderate slope) appear as a result of the narrow C_N range, 10–80 mg L^{-1}, in comparison to 10–150 mg L^{-1} in the second and third experiments. In the first year, the effect of C_{Cl} treatments was small and the interaction was insignificant, therefore only the curve at 150 mg Cl L^{-1} is clearly separated from the other curves. The best fit values of the coefficients A and C at each C_{Cl} Equation (2) in the three potato experiments are presented in Table 5. In the three experiments the A values that are defined in the Mitcherlich equation as the maximal value for each C_{Cl} decrease as C_{Cl} increase above 150 mg L^{-1}. In the first and third years, the A value of the desalinated water (15 mg L^{-1}) was lower than that of 150 and 200 mg L^{-1}; these values are in the range of concentrations of natural water sources used for irrigation in Israel and other semiarid and arid regions. In the third experiment, in which the range of C_{Cl} was extended from 700 to 1500 mg L^{-1}, the strongest impact on A was obtained. The C coefficient can be used to calculate the C_N value to obtain any percentage of the maximal yield at each C_{Cl}. Thus, the C_N value for achieving 95% of the maximal yield (C_{N95}) at each C_{Cl} was calculated and presented in Table 5. In the first and second experiments, the general trend is reduction in C_{N95} as C_{Cl} increased above 150 and 15 mg L^{-1}, respectively. In both years the calculated C_{N95} for desalinated water is higher than that for the two highest salinities, 350 and 700 mg L^{-1}, in contrast to the assumption that the required C_N for optimal yield will be lower for desalinated water. In the third year, no clear trend in the effect of C_{Cl} on the calculated C_{N95} was obtained, probably because of the big effect of C_{Cl} on the A value, which is highly correlated with C.

Table 5. Best fit parameters of the Mitcherlich equation for best fit curves of Potato tubers fresh weight as a function of N concentration in the irrigating solution at different Cl concentrations in the irrigating solutions (Figure 2). Numbers in brackets are the standard errors of the estimated parameters. The values of the parameters and their standard errors were determined using the Nlin procedure of JMP 14.

Cl	A	C	N (Y = 95%) Optimum
mg L^{-1}		2016	
15	3163 (471)	0.022 (0.006)	137.9
150	3810 (272)	0.019 (0.002)	159.8
350	2794 (111)	0.030 (0.002)	101.0
700	2849 (160)	0.026 (0.003)	113.9
		2017	
15	1712 (178)	0.028 (0.010)	107.7
150	1632 (128)	0.033 (0.010)	91.0
350	1356 (91)	0.047 (0.013)	64.1
700	1262 (57)	0.068 (0.015)	43.8
		2018	
15	860 (87)	0.050 (0.024)	59.9
200	963 (76)	0.0355 (0.011)	84.3
600	737 (92)	0.027 (0.012)	110.9
1100	568 (53)	0.068 (0.051)	43.8
1500	443 (63)	0.0353 (0.021)	84.8

3.2. *N and Cl Concentrations in Plants Leaves*

For achieving the second objective, we determined the concentrations of N and Cl in organs of lettuce and potato grown at different combinations of C_N and C_{Cl} in the experiments described in the previous section.

3.2.1. N and Cl Concentrations in Lettuce Heads and Roots

In the first and second lettuce experiments, N concentration in lettuce head was significantly affected by C_N, but was not affected by C_{CL}, and no significant interaction between these factors was obtained (Table 6). In both experiments N concentration in lettuce roots was significantly affected by C_N and it was significantly affected by C_{CL} in the first experiment, while no significant effect was obtained in the second experiment. In both experiments, no significant interaction between these factors on N concentration in the roots was obtained. In both experiments, N concentrations in lettuce head and roots increased significantly with raising C_N from the lowest value of 25 up to 75 mg L^{-1} in the first experiment and 140 mg L^{-1} in the second experiment. In the first experiment N concentration in the roots decreased significantly as C_{Cl} was raised from 15 to 700 mg L^{-1}, however the effect was relatively small, just an 11% difference. As expected nitrate concentration in lettuce head increased significantly as C_N increased. C_{Cl} had also significant effect on nitrate concentration in lettuce head, but no significant interaction between these factors was obtained. N concentration in the roots increased from 0.62 to 3.51 mg N g^{-1} with increasing C_N from the lowest to the highest value, 25 and 140 mg L^{-1}, respectively. Although the effect of C_{Cl} on nitrate concentration was significant it was inconsistent and the differences between treatments were relatively small. The highest and the lowest values were obtained with 15 and 150 mg Cl L^{-1}, whereas no significant differences were obtained between these treatments and the two other treatments (350 and 700 mg Cl L^{-1}).

Table 6. The effect of C_N and C_{CL} on N, Cl, and nitrate-N concentrations in lettuce head and roots. The probability of F values for C_N, C_{Cl}, Block factors, and the interaction of C_N and C_{Cl} was determined using the two-way ANOVA procedure of JMP 14. Different letters on the right side of values indicate significant difference between treatments (HSD) at $p < 0.05$ by the Tukey–Kramer honestly test. No letters are presented when no significant difference was obtained.

		2016					2017		
			Head		Roots			Head	Roots
Variable		**N**	**Cl**	**Nitrate-N**	**N**	**Cl**	**Variable**	**N**	**N**
C_N							C_N		
mg L^{-1}				mg g^{-1}			mg L^{-1}	mg g^{-1}	
25		28.4 c	30.8 a	0.62 d	15.3 d	30.3 ab	25	24.9 e	10.8 d
50		34.4 b	28.0 ab	1.26 c	21.9 c	32.4 a	45	32.8 d	13.0 cd
75		40.1 a	25.1 bc	1.86 b	22.4 c	24.9 bc	65	36.7 c	15.6 bc
100		40.8 a	23.1 c	2.27 b	27.9 b	29.0 abc	85	42.4 b	16.3 bc
125		43.1 a	21.1 c	3.14 a	29.5 ab	25.7 abc	100	44.5 b	19.0 ab
140		43.0 a	20.9 c	3.51 a	32.0 a	23.2 c	125	48.2 a	20.7 a
C_{CL} [1]							C_{CL}		
mg L^{-1}							mg L^{-1}		
15		38	10.5 c	2.36 a	26.9 a	4.6c	15	38.9	16.8
150		38	26.2 b	1.92 b	25.1 ab	26.5 b	150	37.3	16.3
350		39.2	29.5 b	2.05 ab	24.5 ab	37.3 a	350	38.2	14.7
700		37.9	33.2 a	2.09 ab	22.9 b	42.0 a	700	38.6	15.8
Factor	df			Probability of F			Factor	Probability of F	
C_N	5	<0.0001	<0.0001	<0.0001	<0.0001	0.0011	C_N	<0.0001	<0.0001
C_{CL}	3	0.775	<0.0001	0.0241	0.0064	<0.0001	C_{CL}	0.2601	0.1658
Block	3	0.0457	0.3559	0.8499	0.7811	0.9054	Block	0.3707	0.5010
$C_N X C_{Cl}$	15	0.9030	0.5901	0.2804	0.8282	0.2963	$C_N X C_{Cl}$	0.5748	0.2453

Cl concentration in lettuce head and roots were significantly affected by C_N and by C_{CL} and no significant interaction between these factors was obtained (Table 6). As expected, Cl concentration in lettuce head and roots increased significantly from 10.8 to 33.2 mg g^{-1} and from 5.1 to 42.0 mg g^{-1} with increasing C_{Cl} from the lowest to the highest value, 15 and 700 mg L^{-1}, respectively. In agreement with the hypothesis, Cl concentration in lettuce head and roots decreased significantly from 30.8 to 20.9 mg g^{-1} and from 30.3 to 23.2 mg g^{-1}, respectively, with increasing C_N from the lowest to the highest value, 25 and 140 mg L^{-1}.

The correlation of the mean Cl concentrations for all C_{Cl} levels in lettuce heads and roots with the respective N concentrations in these organs in 2016 was examined. High correlation ($r^2 = 0.95$) was obtained for Cl vs. N in lettuce head with significant slope ($p = 0.0008$). In the root the correlation was low, $r^2 = 0.47$, and the slope was insignificant.

3.2.2. N and Cl Concentrations in Potato Leaves and Tubers

In the three potato experiments, N concentrations in the leaves and tubers were significantly affected by C_N, but were not affected by C_{CL} and no significant interaction between these factors was obtained (Table 7a,b). In the three potato experiments, N concentrations in the leaves and tubers increased significantly with raising C_N from 10 to 80 mg L^{-1} in the first experiment, from 10 to 150 mg L^{-1} in the second and third experiments, independently of the C_{Cl} level (Table 7a,b). In the second and third experiments there was gradual decrease in the effect of C_N on N concentrations in the leaves and tubers as C_N became higher. Nitrate concentration in potato leaves was determined just in the first potato experiment and like the reduced N it was significantly affected by C_N. In contrast to the reduced N nitrate concentration in potato leaves was also significantly affected by C_{Cl} and a significant interaction between these factors was also obtained. Despite this significant interaction effect the major effect of each factor (C_N and C_{Cl}) is presented and discussed, because the interaction effect is due to differences in the magnitude of the C_{Cl} effect with each C_N level, rather than the direction of the effect. The nitrate concentration in the leaves increased gradually from 0.41 to 1.53 mg g^{-1} with the incremental raise of C_N from 10 to 80 mg L^{-1}. Note that the concentration of the reduced N was 20 to 56 times that of nitrate-N.

Cl concentrations in the shoot were significantly affected by both C_{Cl} and C_N with significant interaction between these factors in all three experiments (Table 7a,b). In the first and second experiments, Cl concentrations in the tubers were also significantly affected by both C_{Cl} and C_N with significant interaction between these factors, whereas in the third experiment it was affected significantly just by C_{Cl}. The interaction effect of C_N and C_{Cl} in all cases is due to differences in the magnitude of the C_{Cl} effect with each C_N level, rather than the direction of the effect. Therefore, we present the major effects of C_N and C_{Cl}. Overall, Cl concentrations in the shoot and tubers increased with increasing C_{Cl}, with reduction in the relative effect as the C_{Cl} became higher. In the majority of cases, Cl concentrations in shoot and tubers decreased with raising the C_N, except non-consistent effect of C_N on Cl concentration in the shoot in the first potato experiment and nonsignificant effect on Cl concentration in the tuber in the third potato experiment.

The correlation of the mean Cl concentrations for all C_{Cl} levels in leaves and tubers with the respective N concentrations in these organs was examined. In the first experiment, high correlation ($r^2 = 0.87$) was obtained for Cl vs. N in the potato leaves with significant slope ($p = 0.0216$) for all C_N treatments, excluding the lowest C_N level in which low Cl leaf concentration was obtained. High correlation ($r^2 = 0.76$) was also obtained in the tubers and the slope was also significant ($p = 0.0238$). In the second experiment, high correlation ($r^2 = 0.85$) was obtained for Cl vs. N in the potato leaves, but the slope was insignificant ($p = 0.0762$). High correlation ($r^2 = 0.88$) was also obtained in the tubers, and, although the slope was not significant, it indicates tendency ($p = 0.06$). In the third experiment, high correlation ($r^2 = 0.89$) was obtained for Cl vs. N in the potato leaves, with p-value of the slope very close to significant value ($p = 0.052$). High correlation ($r^2 = 0.94$) was also obtained in the tubers with significant value ($p = 0.0322$). Lower correlation ($r^2 = 0.42$) for Cl leaf with N leaf over all the experiments together was obtained but the slope was highly significant ($p = 0.0169$). High correlation ($r^2 = 0.92$) for Cl leaf with N leaf over all the experiments together was obtained and the slope was also highly significant ($p \leq 0.0001$).

Table 7. The effect of C_N and C_{CL} on the concentrations of (**a**) N and nitrate-N, and (**b**) Cl in Potato leaves and tubers. Probability of *F* values for C_N, C_{Cl}, Block factors, and the interaction of C_N and C_{Cl} were determined using the two-way ANOVA procedure of JMP 14. Different letters on the right side of values indicate significant difference between treatments (HSD) at $p < 0.05$ by the Tukey–Kramer honestly test. No letters are presented when no significant difference was obtained.

(a) Nitrogen and Nitrate												
		2016					**2017**				**2018**	
Variable		**Shoot**		**Tubers**	**Variable**		**Shoot**	**Tubers**	**Variable**		**Shoot**	**Tubers**
		N	Nitrate-N	N			N	N			N	N
			mg g^{-1}				mg g^{-1}				mg g^{-1}	
C_N					C_N				C_N			
mg L^{-1}					mg L^{-1}				mg L^{-1}			
10		23.0 c	0.41 d	10.2 bc	10		38.6 b	19.9 b	10		16.9 c	12.3 b
20		24.8 bc	0.48 cd	11.5 bc	50		43.5 ab	21.9 b	50		23.3 bc	15.3 ab
30		25.2 bc	0.61 cd	8.7 c	100		43.2 ab	25.9 ab	100		25.7 ab	17.3 a
40		25.9 bc	0.80 bc	11.7 bc	150		47.9 a	29.1 a	150		31.4 a	18.7 a
60		28.2 ab	1.08 b	12.7 ab								
80		30.3 a	1.53 a	15.1 a								
C_{CL}					C_{CL}				C_{CL}			
mg L^{-1}					mg L^{-1}				mg L^{-1}			
15		27.2	1.47 a	10.7	15		45.6	24.4	15		24.5	16.8
150		25.1	0.69 b	11.2	150		44.6	24.2	200		23.2	14.1
350		26.3	0.56 b	12.2	350		42.0	24.0	600		27.5	15.8
700		26.3	0.56 b	12.4	700		40.8	24.2	1100		22.9	17.5
									1500		23.6	16.0
Factor	df				Factor	df			Factor	df		
C_{Cl}	3	0.2807	<0.0001	0.1549	C_{Cl}	3	0.1834	0.9979	C_{Cl}	4	0.4693	0.693
C_N	5	<0.0001	<0.0001	<0.0001	C_N	3	0.0074	0.0014	C_N	3	<0.0001	0.0040
Block	3	0.4600	0.7808	0.1849	Block	3	0.2351	0.1821	Block	3	0.0629	0.8313
$C_N X C_{Cl}$	15	0.1019	<0.0001	0.0597	$C_N X C_{Cl}$	9	0.9281	0.7288	$C_N X C_{Cl}$	12	0.9857	0.9981

Table 7. *Cont.*

(b) Chloride											
				2017				**2018**			
Variable		**Shoot**	**Tubers**	**Variable**			**Shoot**	**Tubers**	**Variable**	**Shoot**	**Tubers**
		Cl				Cl				Cl	
		mg g^{-1}					mg g^{-1}			mg g^{-1}	
C_N				C_N				C_N			
mg l^{-1}				mg L^{-1}				mg L^{-1}			
10		71.0 d	18.4 a	10		70.7 a	14.8 a	10		68.7 a	16.0
20		92.0 a	19.2 a	50		52.4 b	10.0 b	50		60.2 a	14.5
30		86.1 ab	18.9 a	100		39.3 c	7.3 c	100		49.5 b	13.8
40		79.4 bc	17.2 ab	150		31.8 d	5.8 d	150		47.0 b	12.0
60		72.2 cd	15.3 bc								
80		69.2 d	14.1 c								
C_{CL}				C_{CL}				C_{CL}			
mg l^{-1}				mg l^{-1}				mg l^{-1}			
15		27.1 c	9.0 d	15		18.5 c	4.5 d	15		33.7 b	8.8 b
150		73.9 b	16.0 c	150		46.8 b	9.3 c	200			
350		103.9 a	20.6 b	350		62.5 a	11.0 b	600		64.8 a	15.4 a
700		108.6 a	23.2 a	700		66.5 a	13.1 a	1100			
								1500		70.5 a	18.0 a
Factor	df			Factor	df			Factor	df		
C_{Cl}	3	<0.0001	<0.0001	C_{Cl}	3	<0.0001	<0.0001	C_{Cl}	2	<0.0001	<0.0001
C_N	5	<0.0001	<0.0001	C_N	3	<0.0001	<0.0001	C_N	3	<0.0001	0.1082
Block	3	0.1575	0.8786	Block	3	0.9066	0.0870	Block	3	0.2781	0.2980
C_NXC_{Cl}	15	<0.0001	0.0502	C_NXC_{Cl}	9	0.0005	<0.0001	C_NXC_{Cl}	6	0.0005	0.7343

3.3. Leaching Fraction and Leachate Composition

For achieving the third objective, we determined the volume of the drainage and the concentrations of N and Cl in the leachate as affected by the C_N and C_{Cl} in the described experiments in the previous sections.

3.3.1. Leaching Fraction and Leachate Composition in the Lettuce Experiments

The leachate fractions (LF) in the lettuce experiments were high, above 0.5, due to the excess irrigation used in order to obtain drainage for estimating the water composition in the growth medium. High dose and frequent irrigation were also required in the coarse sand to maintain available water for plants. In the first lettuce experiment, the LF was very high above 0.7 in all treatments (Table 8), due to high dose and frequent irrigations after transplanting. This irrigation management was practiced for preventing water shortage and drying in the high potential evaporation conditions in middle to the end of August (17 to 31 August 2016). During the two last weeks of the lettuce growth, a shading screen was set above the plants, reducing the direct irradiation, wind speed, and the potential transpiration, leading to lower LF values that ranged between 0.5 to 0.62. In the second lettuce experiment, the LF was much lower, in the range of 0.3 to 0.5, as a result of transplanting in September and set up of the shading screen before transplanting. In the first experiment, LF increased slightly to a peak value as C_N increased from 25 up to 75 mg N L^{-1}, but it decreased with further increasing of C_N. The LF was also affected significantly by C_{Cl}, and a significant interaction of C_N with C_{Cl} was obtained. This interaction is due to differences in the relative effect of C_N at the different C_{Cl} levels, but no difference in the general trend. In the second lettuce experiment, both C_N and C_{Cl} had a significant effect on LF, and also a significant interaction was obtained. The highest values of LF were obtained at C_N 25 and 125 mg N L^{-1} with significant lower values at the C_N range of 45 to 100 mg N L^{-1}. The Lf increased significantly from 0.37–0.40 to 0.44–0.45 with increasing the C_{Cl} from 15–150 to 350–700 mg Cl L^{-1}. The significant interaction of C_N with C_{Cl} is due to differences in the relative effect of C_N at the different C_{Cl} levels, but no difference in the general trend. The effects of C_N and C_{Cl} on LF showed a general expected trend, as the biomass was higher the LF became lower.

The drainage N concentration (C_{NL}) in both lettuce experiments increased with C_N with significant differences between all C_N levels (Table 8). The C_{NL} in 2016 was lower than the corresponding C_N values, whereas the opposite results were observed in 2017, probably due to the higher LF values in 2016 than 2017. In both years, C_{NL} increased steeply as C_N increased. C_{Cl} had no significant effect on C_{NL} in the first lettuce experiments. In in the second experiment, significant higher values were obtained at C_{Cl} = 700 mg L^{-1} than all other C_{Cl} treatments, but the relative effect of C_{Cl} was much smaller than the effect of C_N. Although a significant interaction of C_N with C_{Cl} was obtained in 2017, the general trend of C_N effect on C_{NL} was similar at all C_{Cl} concentrations with differences in the relative effect. The drainage N mass (M_{NL}) in both lettuce experiments increased with C_N with significant differences between all C_N levels, similar to the C_{NL}. While higher C_{NL} values were obtained in 2017 than in 2016, the opposite effect on M_{NL} was obtained, due to the much higher LF values in 2016. In the first experiment, the M_{NL} increased linearly with C_N, while in the second experiment it increased exponentially, with steeper increase in M_{NL} as C_N increased above 85 mg N L^{-1} (Figure 3). While C_{Cl} had no effect on M_{Nl} in the first experiment, it had a significant effect in the second experiment (Table 8 and Figure 3), in which the relative effect on M_{NL} was much bigger than on $C_{NL.,}$ probably due to the effect of C_{Cl} on LF.

Table 8. Leaching fraction, the concentrations of N and Cl in the leachate (C_{NL} and C_{ClL}) and the mass of N and Cl in the leachate (M_{NL} and M_{ClL}) and the ratio of M_{NL} of the applied N of the lettuce experiments. Probability of *F* values for C_N, C_{Cl}, Block factors, and the interaction of C_N and C_{Cl} were determined using the two-way ANOVA procedure of JMP 14. Different letters on the right side of values indicate significant difference between treatments (HSD) at $p < 0.05$ by the Tukey–Kramer honestly test. No letters are presented when no significant difference was obtained.

			2016							2017			
Variable		**LF**	**C_{NL}**	**M_{NL}**	**C_{ClL}**	**M_{ClL}**	**Variable**		**LF**	**C_{NL}**	**M_{NL}**	**C_{ClL}**	**M_{ClL}**
			mg L^{-1}	g pot^{-1}	mg L^{-1}	g pot^{-1}				mg L^{-1}	g pot^{-1}	mg L^{-1}	g pot^{-1}
C_N							C_N						
(mg L^{-1})							(mg $L^{-1)}$						
25		0.80 b	15.8 f	0.91 f	300.7 ab	17.1 bc	25		0.47 a	42.4 e	0.55 e	391.6	5.24 ab
50		0.79 bc	33.8 e	1.94 e	304.5 ab	17.5 ab	45		0.38 b	83.5 d	0.85 d	397.1	4.31 b
75		0.86 a	53.0 d	3.31 d	306.4 ab	18.9 a	65		0.37 b	96.3 cd	1.01 cd	416.0	4.40 b
100		0.75 cd	71.0 c	3.83 c	297.4 b	16.0 c	85		0.38 b	116.4 c	1.25 c	424.3	4.60 b
125		0.74 d	93.3 b	5.15 b	311.4 a	17.3 bc	100		0.39 b	162.0 b	1.83 b	412.7	4.47 b
140		0.77 bcd	107.2 a	5.96 a	306.7 ab	16.7 bc	125		0.49 a	232.8 a	3.32 a	432.5	5.94 a
C_{Cl}							C_{Cl}						
(mg L^{-1})							(mg L^{-1})						
15		0.80 a	61.8	3.50	20.2 d	1.0 d	15		0.40 b	117.7 b	1.31 c	196.7 d	2.17 c
150		0.79 ab	62.5	3.66	145.7 c	8.5 c	150		0.37 b	111.8 b	1.22 c	292.8 c	2.90 c
350		0.79 a	61.8	3.38	334.2 b	18.7 b	350		0.44 a	115.7 b	1.59 b	433.5 b	5.30 b
700		0.76 b	63.3	3.53	718.1 a	40.3 a	700		0.45 b	143.8 a	1.79 a	726.3 a	8.94 a
variable	df			Probability of *F* value			variable	df					
C_N	5	<0.0001	<0.0001	<0.0001	0.0133	0.0079	C_N	5	<0.0001	<0.0001	<0.0001	0.786	<0.0001
C_{Cl}	3	0.0041	0.1601	0.0476	<0.0001	<0.0001	C_{Cl}	3	<0.0001	0.0015	<0.0001	<0.0001	<.0001
Block	3	0.0866	0.0977	0.0559	0.9257	0.3459	Block	3	0.283	0.6966	0.6672	0.9923	0.4310
C_N* C_{Cl}	15	<0.0001	0.3129	0.1582	0.4752	0.0839	C_N* C_{Cl}	15	<.0001	0.0011	<0.0001	<0.0001	<0.0001

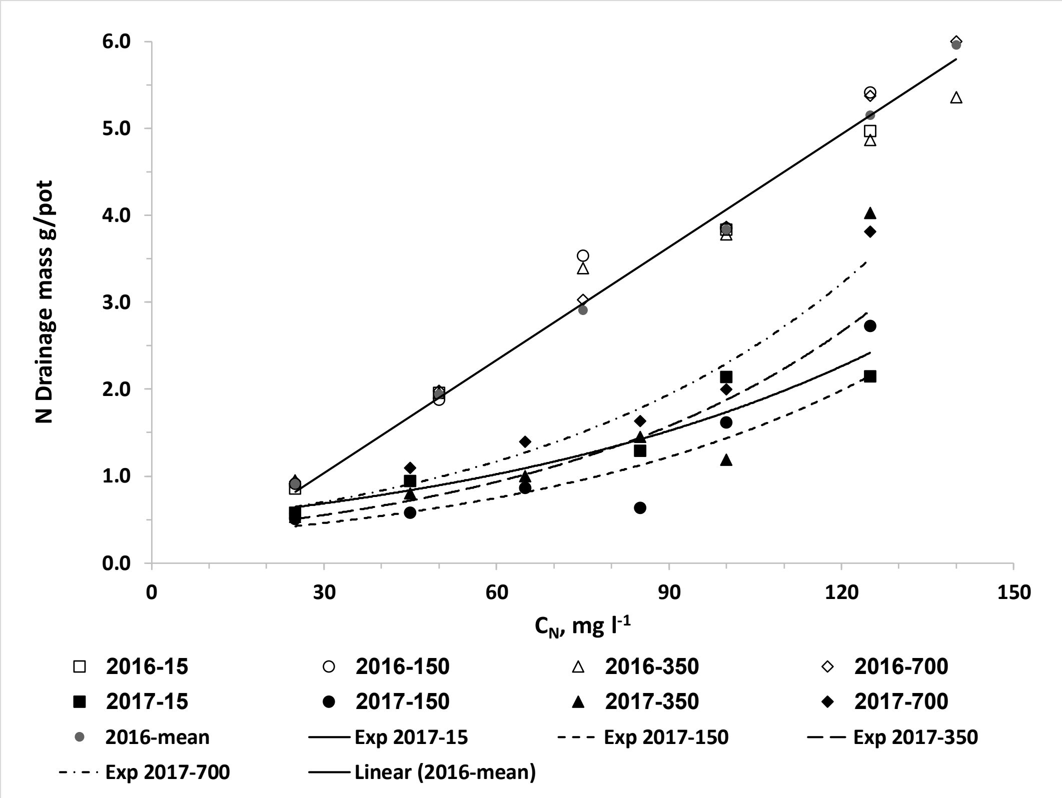

Figure 3. N mass in the leachate of lettuce experiments: 2016 and 2017. The equations of the best fit curves presented in Figure 3 are as follows: 2016, C_{Cl} = 15, Y = $0.4217e^{0.0137X}$, R^2 = 0.873. 2016, C_{Cl} = 150, Y = $0.2834e^{0.0162X}$, R^2 = 0.803. 2016, C_{Cl} = 300, Y = $0.3277e^{0.0174X}$, R^2 = 0.862. 2016, C_{Cl} = 700, Y = $0.425e^{0.0169X}$, R^2 = 0.952. 2017, Mean C_{Cl}, Y = 0.0432X − 0.261, R^2 = 0.995.

The drainage Cl concentration (C_{ClL}) in both lettuce experiments increased with C_{Cl}, with significant differences between all C_{Cl} levels (Table 8). Because of the much bigger LF in the first than the second lettuce experiment, the C_{ClL} values in 2016 were slightly lower than the corresponding C_{Cl}, while the opposite was obtained in 2017. In 2016, C_N had significant effect on C_{ClL}, but the change in C_{ClL} as a function of C_N was not consistent with clear trend, and in 2017 no significant effect of C_N on C_{ClL} was obtained. In 2016, there was no interactive effect of C_N with C_{Cl} on C_{ClL}, while in 2017 there was interactive effect but the same trend of effect of C_{Cl} on C_{ClL} was obtained in all C_N treatments. The drainage Cl mass (M_{ClL}) in both lettuce experiments increased with C_{Cl}, with significant differences between all C_{Cl} levels. Because of the much bigger LF in the first than the second lettuce experiment, the M_{ClL} values in 2016 were greater than in 2017 (Table 8; Figure 4). In the two lettuce experiments, C_N had significant effect on M_{ClL}, but the change in M_{ClL} as a function of C_N, was not consistent with clear trend and it was much smaller than the effect of the C_{Cl}. Significant interactive effect of C_N with C_{Cl} on M_{ClL} was obtained in the second experiment, however the same trend of effect of C_{Cl} on M_{ClL} was obtained in all C_N treatments. Overall, a linear increase of M_{ClL} with raising C_{Cl} was obtained in both years (Figure 4).

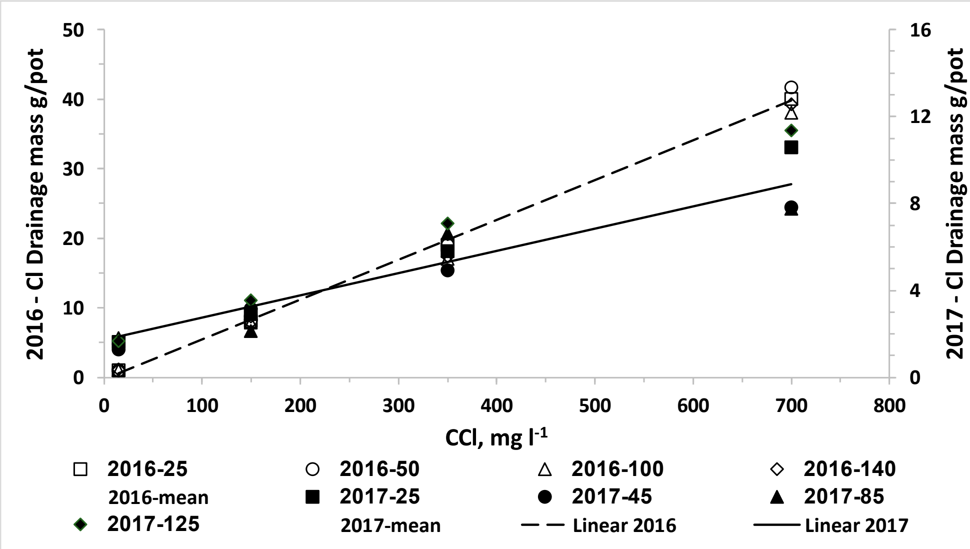

Figure 4. Cl mass in the leachate of lettuce experiments, 2016 and 2017. The equations of best fit curves presented in Figure 4 are as follows: 2016, Y = 0.057X − 0.2646, R^2 = 0.998. 2017, Y = 0.010X + 1.73, R^2 = 0.992.

3.3.2. Leaching Fraction and Leachate Composition in the Potato Experiments

Similar to the lettuce experiments, in the three potato experiments the LF was relatively high, above 0.45, due to the excess irrigation in the coarse sand to maintain available water for plants and to obtain drainage for monitoring water composition in the growth medium. In the three experiments, LF decreased considerably and significantly with increasing the C_N (Table 9a). In the first experiment, C_{CL} had no effect on LF and no interaction of C_N with C_{CL} was obtained. In the second and third experiments, the LF significantly increased as the C_{Cl} increased; a mirror of the effect of C_{Cl} on the biomass production. An interactive effect of C_N with C_{CL} was obtained in the third experiment, due to the different effect of C_{Cl} on LF in the lowest C_N value than in the other C_N treatments. This difference is probably a result of the strong and dominant negative effect of the lowest C_N treatment on biomass production and transpiration.

In the three potato experiments, C_{NL} increased significantly with raising C_N with no effect of C_{Cl} and no interactive effect of C_N with C_{Cl} (Table 9a). The values of C_{NL} were lower than the corresponding C_N in the first experiment, whereas similar and higher values were obtained in the third and second experiments, respectively. The M_{NL} was also significantly increased with raising C_N in all three potato experiments (Table 9a and Figure 5). No effect of C_{Cl} and no interaction of C_N with C_{Cl} were observed in the first experiment, whereas a significant increase of M_{NL} with increasing C_{Cl} and interactive effect of C_N with C_{Cl} was observed in the second and third experiments due to difference in the strength but not the trend of the effect of C_N on M_{NL} at each C_{Cl} level (Table 9a and Figure 5). The effect of C_{Cl} on M_{NL} in the second and third experiments is probably due to the increase in the LF with C_{Cl}, as no effect of C_{Cl} on C_{NL} was observed. In the three experiments, a nonlinear effect of C_N on M_{NL} was observed. In 2016, the predictions of M_{NL} as function of C_N by the exponential model were very close to the measured values, whereas in 2017 and 2018 the predictions of the exponential model underestimated N drainage mass of at C_N 100 mg L^{-1} and overestimated it at C_N 150 mg L^{-1} (Figure 5). Nevertheless, in all three years the slope became steeper as C_N was raised above 40 mg L^{-1}.

Table 9. The effects of C_N and C_{Cl} on (**a**) leaching fraction (LF) and the concentrations and mass of N in the leachate (C_{NL} and M_{NL}), and (**b**) the concentrations and the mass of Cl in the leachate (C_{ClL} and M_{ClL}) in the potato experiments. The probability of *F* values for C_N, C_{Cl}, block factors, and the interaction of C_N and C_{Cl} was determined using the two-way ANOVA procedure of JMP 14. Different letters on the right side of values indicate significant difference between treatments (HSD) at $p < 0.05$ by the Tukey–Kramer honestly test. No letters are presented when no significant difference was obtained.

(a) Leaching fraction (LF), the Concentrations and Mass of N in the Leachate (C_{NL} and M_{NL}).

		2016					2017					2018		
Variable		**LF**	**C_{NL}**	**M_{NL}**	**Variable**		**LF**	**C_{NL}**	**M_{NL}**	**Variable**		**LF**	**C_{NL}**	**M_{NL}**
			mg L^{-1}	g pot^{-1}				mg L^{-1}	g pot^{-1}				mg L^{-1}	g pot^{-1}
C_N					C_N					C_N				
mg L^{-1}					mg L^{-1}					mg L^{-1}				
10		0.86 a	9.1 e	1.31 d	10		0.66 a	8.8 d	0.71 d	10		0.79 a	9.7 d	0.82 d
20		0.82 b	10.5 de	1.42 cd	50		0.50 b	69.1 c	0.43 c	50		0.70 b	35.7 c	2.80 c
30		0.77 c	12.2cd	1.53 cd	100		0.50 b	210.5 b	1.26 b	100		0.68 b	114.4 b	8.40 b
40		0.73 c	14.0 c	1.65 c	150		0.47 b	315.9 a	1.73 a	150		0.57 c	186.9 a	11.49 a
60		0.66 d	22.5 b	2.39 b										
80		0.60 e	30.6 a	2.96 a										
C_{Cl} mg L^{-1}					C_{Cl} mg L^{-1}					C_{Cl} mg L^{-1}				
15		0.76	16.6	1.94	15		0.51 ab	151.2	7.90 ab	15		0.59 c	84.9	4.44 d
150		0.73	16.0	1.81	150		0.46 b	149.6	7.54 b	200		0.61 c	88.2	5.11 cd
350		0.73	16.6	1.88	350		0.55 ab	155.0	9.59 a	600		0.69 b	80.1	5.64 bc
700		0.74	16.7	1.87	700		0.60 a	148.5	9.88 a	1100		0.75 ab	87.0	6.78 ab
										1500		0.78 a	93.1	7.43 a
variable	df				variable	df				variable	df			
C_N	5	<0.0001	<0.0001	<0.0001	C_N	3	<0.0001	<0.0001	<0.0001	C_N	3	<0.0001	0.1859	<0.0001
C_{Cl}	3	0.0970	0.5740	0.4756	C_{Cl}	3	0.0018	0.8441	0.0057	C_{Cl}	4	<0.0001	<0.0001	<0.0001
Block	3	0.2997	0.1780	0.0797	Block	3	0.4976	0.2018	0.4815	Block	3	0.2711	0.2400	0.3673
C_N * C_{Cl}	15	0.3554	0.9515	0.9907	C_N * C_{Cl}	9	0.0733	0.1841	0.0403	C_N * C_{Cl}	12	<0.0001	0.4624	0.0109

Table 9. *Cont.*

(b) The Concentrations and Mass of Cl in the Leachate (C_{ClL} and M_{ClL}).											
	2016				2017				2018		
Variable		C_{ClL}	M_{ClL}	**Variable**		C_{ClL}	M_{ClL}	**Variable**		C_{ClL}	M_{ClL}
		mg L^{-1}	g pot^{-1}			mg L^{-1}	g pot^{-1}			mg L^{-1}	g pot^{-1}
C_N				C_N				C_N			
mg L^{-1}				mg L^{-1}				mg L^{-1}			
10		282 e	40.4 a	10		390 b	31.5	10		794 b	66.0 b
20		290 de	38.5 ab	50		490 a	31.2	50		894 a	74.0 a
30		306 cd	38.3 ab	100		522 a	30.5	100		953 a	78.5 a
40		318 bc	36.6 b	150		529 a	32.2	150		961 a	64.0 b
60		339 b	36.0 b								
80		3851 a	36.4 b								
C_{Cl}				C_{Cl}				C_{Cl}			
mg L^{-1}				mg L^{-1}				mg L^{-1}			
15		21 d	2.6 d	15		147 d	8.5 d	15		137 e	7.9 e
150		139 c	16.6c	150		324 c	17.5 c	200		396 d	25.4 d
350		351 b	41.8 b	350		512 b	32.7 b	600		847 c	62.8 c
700		768 a	89.8 a	700		949 a	66.7 a	1100		1333 b	107.5 b
								1500		1790 a	149.5 a
variable	df			variable	df			variable	df		
C_N	5	<0.0001	<0.0001	C_N	3	<0.0001	0.7444	C_N	3	<0.0001	<0.0001
C_{Cl}	3	<0.0001	<0.0001	C_{Cl}	3	<0.0001	<0.0001	C_{Cl}	4	<0.0001	<0.0001
Block	3	0.8437	0.8732	Block	3	0.3187	0.5949	Block	3	0.0262	0.3923
C_N * C_{Cl}	15	<0.0001	0.1934	C_N * C_{Cl}	9	0.0503	0.0002	C_N * C_{Cl}	12	0.0020	<0.0001

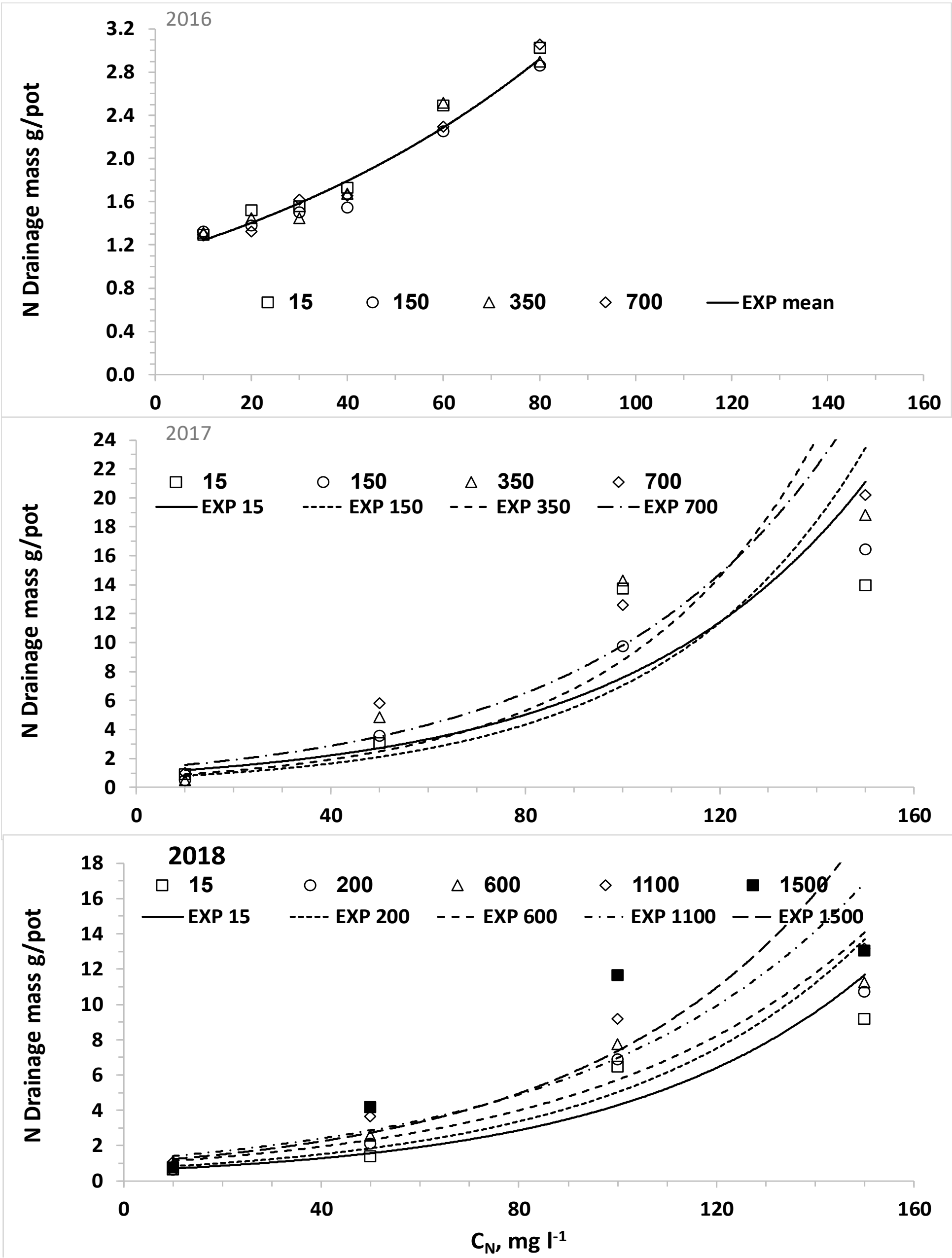

Figure 5. Nitrogen mass in the leachate of three potato experiments: 2016, 2017, and 2018. The equations of best fit curves of N-Drainage mass (M_{NL}) vs. N irrigation concentration (C_N) are presented in Figure 5 as follows: 2016, mean, Y = 1.1008e0.0122x, R2 = 0.975. 2017, 15, Y = 0.9752e0.0205x, R2 = 0.882. 2017, 150, Y = 0.631e0.0241x, R2 = 0.896. 2017, 350, Y = 0.7004e0.0253x, R2 = 0.839. 2017, 700, Y = 1.2692e0.0204x, R2 = 0.887. 2018, 15, Y = 0.5781e0.02x, R2 = 0.948. 2018, 200, Y = 0.6808e0.02x, R2 = 0.952. 2018, 600, Y = 0.9483e0.018x, R2 = 0.951. 2018, 1100, Y = 1.1867e0.0177x, R2 = 0.927. 2018, 1500, Y = 1.1015e0.0198x, R2 = 0.927.

In all three potato experiments the C_{ClL} was significantly affected by C_{Cl} and C_N, and also the interactive effect of these factors was obtained (Table 9b). However, in all three experiments the relative effect of C_{Cl} on C_{ClL} is much bigger than that of C_N and the interactive effect is due to small differences in the relative effect of C_{Cl} at different C_N values, but no difference in the trend of the effect was obtained, therefore the overall main effects are further discussed. C_{ClL} increased linearly with C_{Cl} in the three experiments with the following slopes; 1.01, 1.156, and 1.09 in the first, second, and the third experiment, respectively. In all three experiments, C_{ClL} increased linearly with C_N (Table 9b) as a result of the decreased LF with inncreasing CN as shown above. In all three experiments, M_{ClL} increased considerably and significantly with raising the C_{Cl}, whereas C_N had no considerable effect. In the first experiment, there was no interactive effect of C_{Cl} with C_N, whereas a significant interactive effect was obtained in the second and third experiments. Despite the interactive effect of C_{Cl} with C_N in two of the experiments, the same trend of increasing M_{ClL} with C_{Cl} was obtained at all CN levels in the three experiments. In all three experiments, M_{ClL} increased linearly with C_{Cl} with slopes in the range of 0.086 to 0.128 g Cl/pot/(mg Cl/L) (Figure 6). Unlike the relation of M_{NL} with C_N, there is no a threshold C_{Cl} point above which there is steeper increase of M_{ClL} with further increase in C_{Cl}.

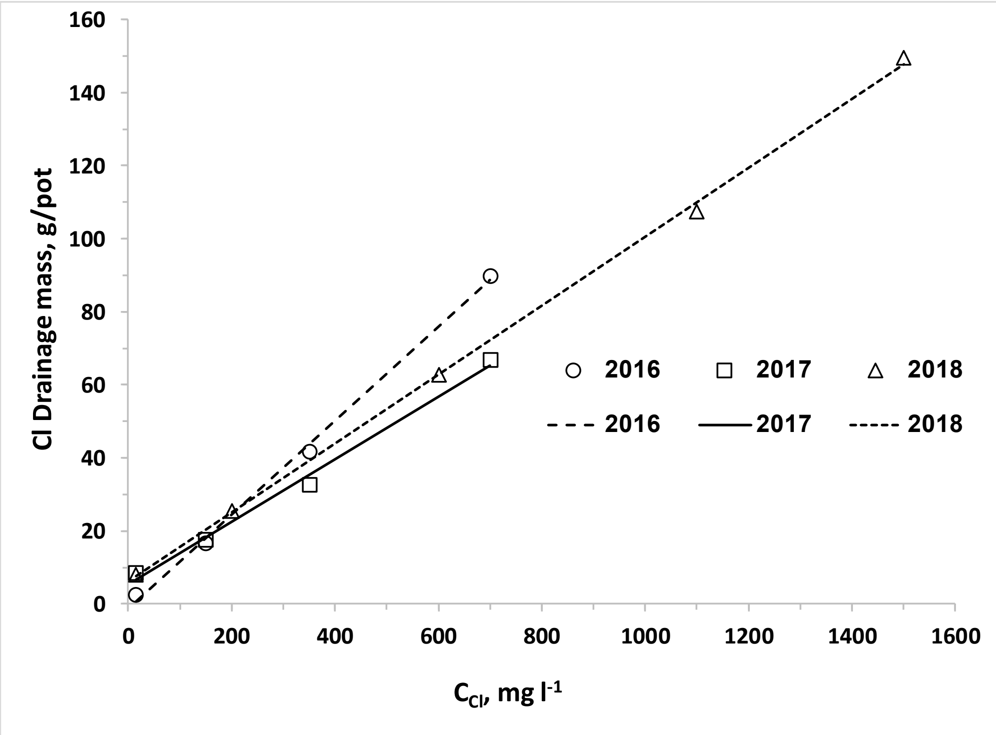

Figure 6. M_{Cl} as function of C_{Cl} in three potato experiments: 2016, 2017, and 2018. The equations of best fit curves of Cl-Drainage mass (M_{ClL}) vs. Cl irrigation concentration (C_{Cl}) are presented in Figure 5 are as follows: 2016, Y = 0.1285X − 1.34, R2 = 0.998. 2017, Y = 0.086X + 5.33, R2 = 0.998. 2018, Y = 0.0944X + 6.15, R2 = 0.999.

4. Discussion

The main hypothesis of this research was that the optimal nitrogen concentration for the highest yield will be lower with decreasing chloride concentration of the irrigating solution. Therefore, we hypothesized that lower nitrogen concentrations will be required with desalinated water for achieving maximum yield. However, the opposite results were obtained in the current experiment with two crops: lettuce and potato. Using the best fit response curves of lettuce heads (quadratic equation) and potato tubers (Mitcherlich model) we found that higher values of C_N were required for obtaining the maximal yield with desalinated or moderate salinity (low chloride concentrations) than for irrigation with high salinity water (high chloride concentrations). However, one should note that the maximum yields under desalinated or moderate salinity were bigger than under high salinity water. Extending the scope of the research from the question of the opportunity to reduce nitrogen fertilization with the use of desalinated water to the wider question of the possible interaction of salinity with fertilization, several published studies showed interactions of nitrogen with chloride in avocado [22], tomato [16–19], and melon [17], whereas other studies found no interaction in maize [37], pepper [38], and various horticultural crops [39].

The hypothesis of the possible interaction of C_N with C_{Cl} leading to the opportunity to reduce the recommended C_N with desalinated water is based on findings on competition between the ions chloride and nitrate in uptake by plants [14,16–18]. Our assumptions were (i) the uptake and the concentration of chloride in organs of plants will be reduced by elevating C_N and (ii) the uptake of and the concentration of nitrogen in organs of plants irrigated with desalinated water will be higher than in plants irrigated with higher chloride concentrations when the same C_N is applied. As expected, we also found that the concentration of chloride in plant organs of lettuce and potato decreased with elevating the C_N (Tables 6 and 7). However, no effect of C_{Cl} on the concentrations of reduced nitrogen in plant organs was found in lettuce and potato (Tables 6 and 7), in agreement with published findings for pepper [38]. On the other hand, nitrate concentration in lettuce and potato leaves decreased with increasing C_{Cl}, but this reduction had negligible impact on the total content of nitrogen in plants organs, because the reduced nitrogen is the main component of nitrogen in plant organs.

The response of plants biomass production to nitrogen is dependent of environmental conditions including salinity. Following Liebig's law of the minimum, when water of low salinity, like desalinated water, is used, the potential for high biomass production is elevated and the demand for nitrogen is higher. Therefore, the optimal C_N for fertigation with desalinated water or another water source with low salinity and chloride concentration is higher or the same than the concentration recommended with other fresh water with relative low salinity. When the irrigating water containing high chloride concentration the salinity leads to reduction in the potential biomass and the demand for nitrogen, consequently in most investigations there was no positive effect of elevating C_N with saline water irrigation. The negative effect of high salinity on plant biomass is caused by two main factors: (i) osmotic effect on water uptake and (ii) specific toxic effects of ions. Elevating C_N as well as other nutrients is useless as a mitigating tool against the negative effect of the osmotic pressure; moreover, the elevated concentrations of nutrients contribute to higher osmotic pressure. Consequently, in many studies no positive effect of elevating nutrients concentrations above the recommended levels with fresh water were observed [18,37,38]. The few cases where positive effects of elevating nutrients concentrations applied with saline water above the optimal concentration for plants irrigated with low salinity water were probably obtained with plants that are highly sensitive to specific toxic effects of some ions, especially Cl and Na [13,22,40]. In the current research with both lettuce and potato, which are defined as moderately salt-sensitive [6,7], the major impact of the high chloride treatments was probably the total salinity affecting the osmotic pressure and the required energy for water uptake. In such crops the optimal required nitrogen is not higher in high salinity and chloride solutions.

Several reviews concluded that the results reported in the literature on the interaction between salinity and nutrients were contradictory or indicated no interactive effects [10,15,37,39,41]. Grattan and Grieve (1999) [39] concluded that "Despite a large number of studies that demonstrate that salinity reduces nutrient uptake and accumulation or affects nutrient partitioning within the plant, little evidence exists that adding nutrients at levels above what is considered optimal in non-saline environments, improves crop yield." Recently, it was reported that nitrogen doses beyond the recommended values exacerbated the negative effects of salinity on growth and photosynthetic rates, in maize and cotton plants growing under moderate to high salinity conditions [42]. They found that the negative effect of high salinity with high dose of nitrogen was stronger in maize which is less tolerant to salinity.

However, part of this conflict can be removed by using the Bernstein definitions [43] of three different types of idealized salinity/nutrition interactions: (a) increased salt tolerance at suboptimal nutritional levels, (b) independent effects of salinity and nutrition at optimal and suboptimal nutritional levels, and (c) decreased salt tolerance at suboptimal nutritional levels. This method requires several salinity levels at each fertilization level. In the current research just in the third potato experiment there were more than four concentrations of C_{Cl} (salinity level) and in that experiment we found that the slope of reduction in yield as a function of C_{Cl} was not affected by the C_N (type b case in Bernstein model).

We also set the hypothesis that the uptake of water and nitrogen of plants irrigated with desalinated water will be higher than that of plants irrigated with water containing higher chloride concentrations;

consequently, the LF and the downward leaching of chloride and nitrate below the root zone will be reduced by irrigation with desalinated water. The results of the current research approved this hypothesis for both crops when the irrigation volume was the same for all combinations of C_N and C_{Cl}. In reality, the optimal management of irrigation with water sources with different salinity levels should be adjusted to minimize the salinity in and below the root zone. Therefore, the required volume and LF of irrigating water decrease as the salinity decreases and thus the lowest water volume is required when plants are irrigated with desalinated water. Consequently, the efficiency of the applied nitrogen is higher and the total amount of applied nitrogen with desalinated water might be lower despite the higher C_N of the fertigation. We expected that the use of desalinated water will enhance plant biomass and water uptake and reduce the LF over water of moderate salinity. However, in most of the lettuce and potato experiments in the current study there was no advantage to desalinated water over the treatment of low C_{Cl} in the range of 100 to 200 mg L^{-1}. It should be noted that the response of the plants is to the effective salinity, in the root zone, rather than the salinity of the irrigated water. The LF in irrigation of commercial fields and in most experiments is much lower than the LF values in the current experiments. Therefore, the effective salinity or Cl concentration in the soil solution in commercial fields is several times higher than that of the irrigation water, while in the current research the Cl concentration of the drainage was similar or just two times higher than C_{Cl}. Therefore, we suggest that in real life the enhancement of biomass production and reduction in LF and downward leaching of nitrate and chloride by a shift from moderate salinity to desalinated water will be bigger than in the current study.

The nonlinear increase of C_{NL} and M_{NL} as a function of C_N with steep increase above a threshold that was obtained in all potato experiments is in agreement with our previous study [44]. This result is typical of the reduced efficiency of N uptake with increased C_N, which is quantitatively described by nutrient uptake models like the Michalis–Menten equation [14]. In part of the experiments, elevating C_{CL} level increased significantly M_{NL} as a result of the smaller biomass production and higher LF. Although the LF values in the current experiments were much higher than those in commercial fields, the general trend of higher leaching fraction with higher salinity is also practiced in commercial fields to prevent salts accumulation in the root-zone [27,28,35,41]. Thus, reduced M_{NL} and higher efficiency of C_N fertigation is expected with desalinated water, although irrigation with desalinated water did not enhance reduced nitrogen concentration in lettuce and potato organs. In contrast to potato, in lettuce no such clear threshold value of C_N was obtained. The main reason for this difference is that in lettuce the uptake of nitrogen in low C_N values is less efficient than in potato and there was no change in the N uptake efficiency as a function of $C_{N.}$

The linear increase of C_{ClL} and M_{ClL} as function of C_{Cl} that was obtained for both crops in all experiments was expected due to the very low uptake of chloride [13], which does not change considerably the concentration of chloride in the drainage from the irrigation water. Although C_N had significant effect on Cl concentration in plant organs, this effect is small relative to the total amount of Cl applied even in the desalinated water, and therefore it had no significant effect on C_{ClL}. Thus, the significant effect of C_N on M_{Cl} is due its' effect on LF discussed above.

5. Conclusions

In contrast to the hypothesis of this research, optimal C_N in both crops was higher in the desalinated water than in high C_{CL} treatments. This result is related to the increase in N uptake by plants at low C_{CL} and with C_N in the irrigating solution. As expected, N fertilization suppressed Cl accumulation in plant tissues without effecting plant biomass production. Drainage of N and Cl increased with increasing C_{CL} in the irrigating solution and N fertilization above optimal C_N resulted in steep rise in downward N leaching. The overall conclusion is that, as water quality is improved through desalination, higher N supply is required for high yields with less groundwater pollution by downward leaching of N and Cl.

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