Increased irrigation water salinity enhances nitrate transport to deep unsaturated soil

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Abstract
Excessive use of N fertilizers in agriculture often leads to NO$_3^-$ accumulation in the unsaturated zone and to groundwater pollution. There is uncertainty regarding the variability in fertilizer transport and uptake efficiency due to the lack of studies based on continuous nondestructive measurements in unsaturated soils. In this study, we analyzed solute dynamics across the unsaturated zone underlying cultivated agricultural fields. Commercial crop rotations under four treatments, comprising two N fertilization regimes and two irrigation water salinity levels, were conducted in loess soil in the semiarid climate of the northern Negev Desert, Israel. The impact of the various treatments on water and solute dynamics below the root zone was monitored by a vadose zone monitoring system. The patterns of variations in soil water content and solute concentrations were analyzed using nonnegative tensor factorization. We found that irrigating using higher salinity water resulted in the earlier arrival of wetting fronts to the deeper layers and increased NO$_3^-$ concentrations relative to the lower salinity treatments. Surprisingly, this effect was only seen in the deeper soil levels, whereas there was no significant difference in the arrival times and concentrations in the upper soil layers. Possible mechanisms are suggested and discussed.

Abbreviations: CPD, canonical polyadic decomposition; FTDR, flexible time domain reflectometer; PSD, particle size distribution; VMS, vadose zone monitoring system; VSP, vadose zone pore water sampling port.

1 INTRODUCTION

Nitrogen is the most important element for the fertility and productivity of agricultural crops. The unlimited ability to produce N fertilizers through industrial processes,
their relatively low cost, and the uncertainty regarding the spatial variability in fertilizer transport and uptake efficiency have resulted in the widespread practice of surplus N fertilization. Unconsumed NO$_3^-$, which is the mobile and stable form of N fertilizers, often leaches below the root zone where it is out of reach for consumption by root uptake. The NO$_3^-$ may accumulate in the unsaturated zone, migrate down to the water table, and pollute aquifers. Consequently, an elevated NO$_3^-$ concentration in groundwater is often associated with excessive agricultural fertilizer application (Dahan, Babad, Lazarovitch, Russak, & Kurtzman, 2014; Kurtzman, Shapira, Bar-Tal, Fine, & Russo, 2013; Power & Schepers, 1989; Turkeltaub, Kurtzman, & Dahan, 2016; Zhang, Tian, Zhang, & Li, 1996). The maximal concentration of NO$_3^-$-N allowed in drinking water is 10 mg L$^{-1}$ in the United States, 11.3 mg L$^{-1}$ in Europe (Ward et al., 2018), and 15.8 mg L$^{-1}$ in Israel (Israel Ministry of Agriculture, 2007). Therefore, NO$_3^-$ contamination is the reason for disqualifying many drinking water wells (Kurtzman et al., 2013).

Extensive leaching of NO$_3^-$ through the unsaturated zone occurs either when accumulated NO$_3^-$ in the root zone is washed down by large amounts of percolating water, or when some excess NO$_3^-$ is leached with each irrigation cycle (Kurtzman et al., 2013; Power & Schepers, 1989; Turkeltaub et al., 2016). These processes depend on NO$_3^-$ accumulation, root uptake and irrigation regime. It has been shown that the common practice of fertigation through drip irrigation causes the accumulation of NO$_3^-$ and other salts at the edges of the wetted zone surrounding the drippers (Li, Yoder, Odhiambo, & Zhang, 2004). Accumulated salts in the root zone disturb plant development; thus, irrigated soils are often leached intensively between cropping cycles. A by-product of accumulated salt removal is the leaching away of any unexploited N from the root zone (Power & Schepers, 1989). Nitrate is the most common form of N in soil since it is the end product of nitrification, which oxidizes NH$_4^+$ to NO$_2^-$ and then to NO$_3^-$ in aerobic environments (Daniel-Vedele, Filleur, & Caboche, 1998). Nitrification is the dominant N transformation in aerated soil, whereas other microbial N transformation processes, such as denitrification, are considered to only have a minor effect on NO$_3^-$.

These processes may occur at a small scale within the root zone or on the surface if anaerobic conditions develop in locally saturated soil as a result of intensive irrigation or precipitation (Green, Fisher, & Bekins, 2008; Onsoy, Harter, Ginn, & Horwath, 2005). Once NO$_3^-$ is leached below the root zone, it is considered to be transported as a relatively conservative solute through the aerated unsaturated zone, eventually reaching the groundwater (Kurtzman et al., 2013; Turkeltaub et al., 2016).

### Core Ideas

- Water flow and solute transport under an agricultural field were characterized.
- Measurements were taken using a vadose zone monitoring system.
- High Cl$^-$ irrigation resulted in increased NO$_3^-$ concentrations in deep soil.

Irrigation water salinity has great effects on crop production, mainly by influencing water uptake and evapotranspiration. Salinity levels can vary greatly, mostly depending on the water source. In Israel, irrigation water sources include brackish groundwater and some treated wastewater with Cl$^-$ concentrations of >400 mg L$^{-1}$, non-saline groundwater and surface water with intermediate concentrations of Cl$^-$, and desalinated water with Cl$^-$ concentrations of <80 mg L$^{-1}$.

Irrigation water salinity may affect NO$_3^-$ flow and transport through different mechanisms. This salinity was shown to possibly affect NO$_3^-$ uptake due to competition with Cl$^-$ for transport in the roots (Aslam, Huffaker, & Rains, 1984; Cerezo & Garcia, 1997) and by affecting root depth distribution (Russo & Kurtzman, 2019). Salinity also affects the solution surface tension (Jones & Ray, 1941) and clay swelling in the soil (Shainberg & Letey, 1984). These, in turn, affect percolation rates in the soil (Shainberg & Letey, 1984; Weisbrot, Niemet, Rockhold, McGinnis, & Selker, 2004) and thus the observed NO$_3^-$ concentrations in the unsaturated zone.

Estimations of root uptake and residence time of water and solutes in the root zone carry large uncertainties, which contribute to surplus fertilizer application that, in many cases, results in groundwater contamination. These uncertainties are mainly attributed to soil heterogeneity, which is expressed as differences in soil hydraulic characteristics appearing over a broad range of spatial scales (Bastian, Ippisch, Naegele, Reszzez, & Roth, 2007; Vereecken, Kasteel, Vanderborght, & Harter, 2007).

Many vadose zone studies have attempted to quantify and characterize groundwater contamination or to provide tools to aid in its prevention. However, most methods for measuring the properties of soil, water, and solutes in the unsaturated zone are either limited or destructive. Consequently, most studies of percolation processes do not use continuous data in the deep unsaturated zone at the field scale (Dahan, McDonald, & Young, 2003; Dahan et al., 2009).

Over the past two decades, a method was developed for the in situ examination of flow and transport across the...
unsaturated zone. The vadose zone monitoring system (VMS) enables continuous long-term measurements of soil moisture and the chemical composition of pore water. The VMS is based on an array of well-known and extensively used moisture sensors and suction cups (with some modification to allow their proper function under the VMS setup), mounted on flexible sleeves, which are installed in slanted boreholes. This setup enables the in situ monitoring of flow and transport processes in unsaturated and relatively undisturbed deep soil (Dahan et al., 2009; Rimon, Nativ, & Dahan, 2011; Turkeltaub et al., 2016).

In a previous study applying VMS, Rimon, Dahan, Nativ, and Geyer (2007) generated some evidence for local variability in water flow under seemingly very similar field conditions. The researchers measured the arrival times of wetting fronts to an array of moisture sensors at depths ranging from ~1 to ~20 m in the unsaturated zone, and documented differences of weeks in the arrival times of the same wetting front to sensors at similar depths. These differences were likely the result of heterogeneity in the soil properties, even though the site was located in sand dunes and the profile was characterized as relatively homogeneous sand.

The main objective of this study was to characterize the impact of irrigation water salinity and N fertilization levels on NO$_3^-$ transport in the unsaturated zone under an agricultural field. The experiment included combinations of two different irrigation water salinities and two N fertilization levels in replicate plots within a single field. Continuous characterization of NO$_3^-$ transport patterns using a VMS is expected to allow better decision making in agricultural and environmental management in order to reduce groundwater contamination.

## 2 MATERIALS AND METHODS

### 2.1 Experimental setup

The experimental site is at the Gilat Agricultural Research Center located in the northern Negev Desert in Israel, which is characterized by a semiarid Mediterranean climate with average precipitation of ~250 mm yr$^{-1}$. Rainfall occurs almost exclusively in winter from November to March, whereas the summer is dry and hot with no precipitation. Typical winter temperatures at the study site vary between 20 °C during the day and 5 °C at night, and in summer, the temperatures vary between 35 °C during the day and 20 °C at night. Penman–Monteith potential evapotranspiration ranges from 1 mm d$^{-1}$ from December to January to 7.5 mm d$^{-1}$ from June to August (Israel Ministry of Agriculture, 2007).

The crops in the experimental field were drip irrigated with water from the national water supply system. In this region, the water is mainly desalinated seawater mixed with a small portion of groundwater. The water was distributed to the different plots using four separate fertigation systems that provided water of different salinity and N fertilizer levels. The treatments included two levels of salinity, normal and increased, and two levels of N fertilization, conventional and increased (Table 1). For the first three crops, the high salinity level was achieved by dissolving NaCl to Cl$^-$ target concentrations of 300 mg L$^{-1}$ as an addition to the existing Cl$^-$ in the irrigation water, reaching an average concentration of 388 mg L$^{-1}$. The N levels, during the growth of the first three crops, were achieved by dissolving NH$_4$NO$_3$ to achieve N target concentrations of either 70 or 100 mg L$^{-1}$. The target concentrations for the fourth crop were changed to ~380 mg L$^{-1}$ of Cl$^-$ addition in the high salinity treatment, and to 35 and 70 mg L$^{-1}$ of N in the low N and high N treatments, respectively. Irrigation water was sampled periodically for measurements of the actual Cl$^-$ and N concentrations, and the average results for each crop are detailed in Table 1.

The field was organized in 20 plots of 240 m$^2$ (20 × 12 m), with five repetitions for each of the four treatments, spatially distributed randomly in blocks. Each of the four fertigation systems fed only its corresponding five plots. All plots were used for plant measurements, whereas eight plots were monitored for unsaturated zone percolation processes, the main focus of this study. The crop rotation started with potato (Solanum tuberosum L.) in March–July 2016, followed by corn (Zea mays L.) in July–November 2016, cotton (Gossypium hirsutum L.) in April–November 2017, and corn in May–September 2018 (Table 1). Intensive sprinkling irrigation, using low-salinity tap water with no additions, took place between the crop rotations. These irrigation periods simulated large rain events of 70 mm in July 2016, 200 mm in January–February 2017, and 160 mm in March 2018. The 2017 irrigation took place during the winter when rainfall also occurred. It should be mentioned that in this particular event, the total amount of rainfall and irrigation was ~320 mm. No natural precipitation occurred during the other two intensive irrigation events.

### 2.2 Vadose zone monitoring system

Eight plots of the experimental field, including two repetitions of each treatment, were each equipped with a VMS. The VMS monitored the soil moisture and solute (NO$_3^-$ and Cl$^-$, for example) concentrations at different depths and locations under the root zone (Figure 1). A technical description of the VMS appeared in previous publications.
TABLE 1  Crop irrigation treatments. Concentrations represent the average of periodic irrigation water measurements during each crop rotation

| Treatment name | Plot no. | Potato 2016 | Corn 2016 | Cotton 2017 | Corn 2018 |
|----------------|---------|-------------|-----------|-------------|-----------|
|                |         | 3 Mar.–10 July | 27 July–5 Nov. | 3 Apr.–9 Nov. | 30 May–16 Sept. |
|                |         | Cl | N | Cl | N | Cl | N | Cl | N |
| Low Cl⁻, low N | 4, 6    | 80 | 60 | 85 | 65 | 80 | 43 | 56 | 35 |
| Low Cl⁻, high N | 1, 5   | 84 | 95 | 57 | 97 | 84 | 83 | 77 | 52 |
| High Cl⁺, low N | 3, 7   | 438 | 60 | 358 | 66 | 350 | 62 | 464 | 22 |
| High Cl⁺, high N | 2, 8  | 454 | 94 | 384 | 96 | 345 | 101 | 477 | 70 |

FIGURE 1  A schematic illustration of the vadose zone monitoring system, not to scale. (a) Side view and zoom in of the monitoring units: vadose zone pore water sampling ports (VSP) and flexible time domain reflectometers (FTDR). (b) All water content data are recorded and water samples are collected through a single control panel. (c) Top view, eight monitored plots. The plots are numbered and colored according to the treatments as detailed on the bottom of the figure and in Table 1

(Dahan et al., 2009; Rimon et al., 2011; Turkeltaub et al., 2016). To avoid overloading this text with known technical details about the VMS, only relevant information is provided here, in brief, with additional site-specific technical information provided in Supplemental Material S1. The system included eight flexible sleeves (one for each monitored plot), each hosting three water content sensors and four vadose zone pore water sampling ports (VSPs), providing a total of 24 water content sensors and 32 VSPs. The flexible sleeves were installed in uncased slanted boreholes. The moisture sensors and VSPs in the sleeves were placed at depths of 1–4.5 m below the surface. Water content readings and water sample collection were done from a single control panel located in the center of the field (Figure 1).

The moisture sensors were flexible time domain reflectometry (FTDR) based on a modification of Acclima time domain transmissometer (TDT) SDI-12 moisture sensors (see Supplemental Material S2). The FTDR data were collected by an Arduino-based controller, with a collection setup programmed to perform measurements by the FTDR every 30 min, and the data were later averaged to obtain daily mean values. The absolute volumetric water content accuracy of the original TDT sensor was ±0.02, resulting in very noisy pre-averaged data and undiscernible changes smaller than 0.02. After the modification of the TDT sensor, each FTDR was recalibrated in a set of liquids of known permittivities (see Supplemental Material S2).

Vadose zone pore water sampling ports (VSPs) operate under the principle of suction cups and allow the collection of pore water from the unsaturated zone (see Supplemental Material S3). Water samples can only be collected when there is hydraulic continuity in the soil and when the pressure potential in the sampling system is lower than the matric potential in the surrounding soil. Therefore, pore water sampling was limited during periods of relatively low water content.

Water samples collected from the VSPs were analyzed for their chemical composition. Nitrate concentrations were measured using colorimetry in a Thermo Scientific Gallery Plus auto-analyzer (ThermoFisher Scientific, 2018). Chloride concentrations were measured using a colorimetric titration in a Sherwood MK II chloride analyzer (Sherwood Science, 2019).

2.3  Soil sampling

The soil at the experimental field was classified using soil sampling and a particle size distribution (PSD) analysis. A total of 72 soil samples were collected from different field depths and locations. Eight samples were collected from depths of 1, 2, 3, and 4 m in two vertical boreholes in the field. An additional 64 samples were collected from depths of 10, 50, 100, and 150 cm from 16 additional boreholes, two in each monitored plot, at a distance of a few meters from the monitoring system’s location. In total, 16 samples were collected from a depth of 10 cm, 16 from 50 cm, 18 from 100 cm, 16 from 150 cm, and two from each of the 200-, 300-, and 400-cm depths. All soil samples were analyzed...
for PSD by the laser diffraction method (Eshel, Levy, Mingelgrin, & Singer, 2004) using a Malvern MasterSizer 2000 system at the Soil Erosion Research Station, the Israel Ministry of Agriculture. Pre-analysis preparation included pulverizing, sieving through a 2-mm sieve, soaking in a Calgon solution, and shaking overnight.

2.4 Tracer experiment

Bromide was applied as a tracer at the beginning of the experiment. Bromide is considered conservative in soil and suitable for transport studies (Levy & Chambers, 1987). The tracer was applied to the monitored plots through a single irrigation pulse of \(\sim 10\) mm with a \(\text{Br}^-\) concentration of \(1\) g L\(^{-1}\) in March 2016, before the first crop irrigation. The \(\text{Br}^-\) solution was attained by dissolving \(99\%\) KBr salt in desalinated water.

Changes in \(\text{Br}^-\) concentration in the unsaturated zone were monitored by analyzing the pore water samples collected by the VSPs. The \(\text{Br}^-\) was measured in the samples by reaction with phenol red and chloramine-T (American Public Health Association, 2005), followed by a 590-nm wavelength measurement in a Tecan Infinite M200 spectrophotometer. The minimum detectable \(\text{Br}^-\) concentration using this method is \(0.1\) mg L\(^{-1}\).

2.5 Variation patterns in water contents and nitrate concentrations

The methodology used here for extraction of latent (not directly observable) patterns in water content and \(\text{NO}_3^-\) concentration measurements is based on nonnegative tensor factorization (Cichocki, Zdunek, Phan, & Amari, 2009; Kolda & Bader, 2009). The classical tensor factorization method we used here is the canonical polyadic decomposition (CPD) (Harshman & Lundy, 1994) with nonnegative factors. Nonnegative CPD of a three-dimensional tensor, \(X\), is derived by a nonconvex constraint minimization (Alexandrov, Stanev, Vesselinov, & Rasmussen, 2019). In our case, the values of \(X\) were volumetric water content (\%), as measured by the FTDR sensors, and \(\text{NO}_3^-\) concentration measurements (mg L\(^{-1}\)) in the VSP pore water samples. The three dimensions of the tensor \(X\) represent the time (d), field plot (1–8) and measurement depth level (1–3 for water content and 1–4 for \(\text{NO}_3^-\), where 1 is closest to the soil surface and 3 or 4, respectively, are the deepest).

A more detailed description of the methodology we used here is in Supplemental Material S6. Additional details regarding the nonnegative CPD technique can be found in the work of Alexandrov et al. (2019), where it was used for the analysis of phase transition data, and in the work of Vesselinov, Alexandrov, and O’Malley (2019), where it was used to analyze data of groundwater contamination. In particular, the work of Alexandrov et al. (2019) describes the technique to find the number of latent patterns in the data.

3 RESULTS AND DISCUSSION

3.1 Soil properties

The PSD results (see detailed results in Supplemental Material S4) show a distinction between the shallow samples, 10- and 50-cm depths, and the deeper samples, 100- to 400-cm depths. The shallow samples are classified as sandy loam (Soil Science Division Staff, 2017), whereas the deeper samples, which contain higher fractions of fine particles of clay and silt, are classified as loam and silt loam (Burt, 2011). There was no clear distinction in the depths of 100–400 cm, which corresponds to the depths of the VMS units.

3.2 Water percolation

Measurements under all plots displayed substantial variations in water content throughout the sampling period, indicating downward water infiltration in response to rain and irrigation events (Figure 2). Each change in water content measured by a specific sensor indicates the arrival of a wetting front to the location of the sensor.
or its drainage (Rimon et al., 2007). The water content measurements are shown in Figure 2, together with daily and cumulative values of precipitation and irrigation. Cumulative rain and irrigation curves for three intervals, from 1 Oct. 2015 to 1 Nov. 2016, 1 Nov. 2017, and 2 Oct. 2018, show total values between ~1,000 and ~1,500 mm yr\(^{-1}\). The water content data are displayed for three depth ranges, the shallowest sensors at 150–190 cm, the middle depth sensors at 250–290 cm, and the deepest sensors at 360–400 cm. The moisture data shown here were collected between 1 Jan. 2016 and 2 Oct. 2018, in a temporal resolution of 30 min and processed to obtain daily averages. In general, a clear pattern of sequential wetting that followed rain or irrigation events was observed by all probes at all depths under all plots (Figure 2). The wettings were reflected as increases in water content of 0.02 and up to 0.2 within a few days or longer. Note that the initial water content values, as measured by all probes, expressed relatively low water contents that are partly attributed to the heat generation created during the drilling and installation process, a phenomenon that was previously observed in other studies (Babad, 2011; Rimon et al., 2011).

All measured percolation events, as indicated by the sequential increase in the soil water content, can be attributed to either rain or irrigation events (Figure 2). Extensive infiltration events observed across deeper sections of the unsaturated zone were related to intensive sprinkling irrigation events that took place between the crop rotations. Each wetting event, as measured by each probe at all depths, was followed by a drainage process that was reflected in the measurements as a decrease in water content. These decreases were measured during the time of the regular crop irrigation season, indicating that the water flow caused by the regular irrigation did not affect the deeper parts of the monitored soil. This is most likely due to the fact that the irrigation amounts were adjusted to the crop needs, and therefore the fate of applied water during the seasons was largely evapotranspiration. This irrigation regime is expected to lead to solute accumulation in the soil in and just below the root zone and near or on the surface during the cropping periods.

The shallow moisture sensors (150- to 190-cm depths) measured the first increases about 1–2 mo before the beginning of the first crop rotation. After the first sprinkling event, in July 2016, five plots showed an increase in water content, whereas Plots 2, 3, and 4 did not show any considerable change in the water content (note that these plots represent different treatments). The first event was also measured by a few of the sensors at the middle depth (250–290 cm) about 2 mo after the sprinkling event, indicating slow downwards drainage. The February 2017 sprinkling event was observed as the sequential propagation of a wetting front by all the sensors at all measured depths from March to May 2017, but with some variability in the arrival times and wetting magnitudes. The probes in Plots 2, 3, and 4 at Depth 1 showed very little increase in water content, whereas the other probes at this depth showed a considerable increase. These responses are consistent with the responses to the 2016 sprinkling event.

The arrival of the 2017 wetting front to the deepest probes varied from 1 to 3 mo after the end of the sprinkling. During the cotton crop rotation, all the probes at all depths showed a decrease in water content, except for the deepest probes of Plots 2 and 8, which maintained high water content values (these plots correspond to the “high Cl– high N” treatment). The March 2018 sprinkling event caused a wetting front that was observed by the shallowest probes in five plots, whereas Plots 3, 5, and 6 did not show any considerable increase (Plots 5 and 6 did show responses to previous intensive sprinkling events, whereas Plot 3 did not). During the last crop rotation, additional considerable increases were measured by most of the shallowest probes and by only two of the probes at the middle depth. The different responses to wetting events, described above, can be partly attributed to small differences in irrigation delivery uniformity between the plots but likely stem primarily from heterogeneity in soil properties.

### 3.3 Chemical composition variations in the unsaturated zone

Soil pore water samples, which were collected frequently by the VSPs from the unsaturated zone, were analyzed for Cl\(^{-}\) and NO\(_3\)^{−}. The data enabled the establishment of time series, spanning the entire monitored period, of tested solute concentrations at various depths. The data are presented for four depth levels: 100–135 cm, 195–235 cm, 305–340 cm, and 410–450 cm below ground level.

Pore water sampling by VSPs is limited by the soil water potential (see the Methods section and Supplemental Material S3). Therefore, during the early stages, before the arrival of the first wetting front to the relevant depths, and during periods of low water content, only a small number of water samples were collected or none at all. Accordingly, information on solute concentrations in the soil pore water appears mainly after the arrival of wetting fronts to each relevant depth and after an increase in the water content was observed. For example, the first Cl\(^{-}\) measurements at the deep VSPs (305–340 cm and 410–450 cm) only appeared in March 2017 and later (Figure 3), because no samples were collected from these depths before the February 2017 sprinkling irrigation. The lack of samples before March 2017 can be attributed to the low moisture as measured by sensors at 360- to 400-cm depths during this time, despite the July 2016 sprinkling irrigation (Figure 2).
The first measured concentrations in some of the plots at the second depth level (195–235 cm) showed values of 5,000–7,500 mg L\(^{-1}\) (Figure 3), which are higher than any measurement at the first depth level (100–135 cm). After the February 2017 sprinkling event, the Cl\(^{-}\) concentrations at the two shallowest depth levels in all the plots decreased below 2,000 mg L\(^{-1}\), whereas the concentrations at the lower two depth levels started increasing shortly after. This observation represents the downward leaching of accumulated Cl\(^{-}\). The high initial concentrations at the second depth level can be attributed to two different factors. First, they could have been the result of Cl\(^{-}\) accumulation in the soil during the first crop, and downward leaching with the first sprinkling of July 2016. If this was the only reason, similar concentrations would have been expected at the first depth before the first sprinkling, but we measured lower concentrations at the shallowest level. Secondly, there could have been high levels of Cl\(^{-}\) in the soil between the upper two depth levels and/or at the second depth before the beginning of the experiment, and the intensive sprinkling in July 2016 and subsequent increase in water potential allowed their detection in the pore water samples from the second depth. This hypothesis is supported by Cl\(^{-}\) measurements in the soil samples that were extracted from two boreholes, 4 m deep, which were drilled in the field site at the beginning of the experiment and in which a higher Cl\(^{-}\) concentration was found at a depth of 2 m (Supplemental Material S5). Additionally, the high Cl\(^{-}\) concentrations of ~6,000 mg L\(^{-1}\) were not measured again at the first and second depth levels after February 2017, indicating that these high concentrations were not likely to be solely the result of accumulation during the first crop rotation.

The possible existence of pre-experiment Cl\(^{-}\) in the soil was further examined by calculating the Cl\(^{-}\) mass balance based on the recharge estimation method by Scanlon, Healy, and Cook (2002). This method is basically designed for solute mass balance through steady-state conditions, whereas the conditions in our experiment are obviously nonstationary. Nevertheless, it was used here for a rough assessment of the Cl\(^{-}\) input during the experiment, by allowing the testing of whether the Cl\(^{-}\) inputs were enough to reach the exceptionally high concentrations that were measured, or whether these concentrations were related to earlier Cl\(^{-}\) accumulation in the soil. The estimated Cl\(^{-}\) concentration (mg L\(^{-1}\)) in the unsaturated zone at a certain time point and for each plot was calculated as 

\[
C_{i2} = (PC_p + I_1C_{i1} + I_2C_{i2})/(P + I_1 + I_2 - ET),
\]

where \(P\) is precipitation (mm), \(I_1\) is irrigation using treated water (mm), \(I_2\) is irrigation using nontreated water (mm), and \(C_p, C_{i1},\) and \(C_{i2}\) are Cl\(^{-}\) concentrations in the water types, respectively (mg L\(^{-1}\)). The ET is evapotranspiration (mm) calculated as 

\[
ET = ET_0 \times K_c,
\]

where \(ET_0\) is the calculated daily Penman–Monteith potential evapotranspiration.

### 3.4 Salinity dynamics in the unsaturated zone

Two salinity treatments of low Cl\(^{-}\) (~80 mg L\(^{-1}\)) and high Cl\(^{-}\) (~388 mg L\(^{-1}\)) in the irrigation water were applied in different field plots (Table 1) via drip irrigation during the cropping periods. The intensive sprinkling, simulating intensive rain events, applied water that had the low Cl\(^{-}\) level (~80 mg L\(^{-1}\)) in all the plots. Measured Cl\(^{-}\) concentrations in VSP pore water samples from all the plots are presented in Figure 3 for the four depth levels. In most cases, the measured Cl\(^{-}\) concentrations are one order of magnitude higher than the concentration in the irrigation water. This indicates downward movement of accumulated solutes. Solute accumulation in the root zone is likely to occur due to evaporation and root water uptake (transpiration) (Li et al., 2004).
(mm) taken from a nearby meteorological station in Gilat (Israel Ministry of Agriculture, 2007), and $K_v$ is the daily crop coefficient that was calculated based on the relevant crops’ known values (Allen, Pereira, Raes, & Smith, 1998). This method assumes a steady state and calculates an estimated Cl$^-$ concentration ($C_{uz}$) in the water flux into the soil for each day independently. The recharge components were considered as cumulative values since the beginning of the experiment up to the time point of interest, whereas the Cl$^-$ concentration components were taken as average values throughout this time period. As compared with the measurements from November 2016 to February 2017, which showed relatively flat curves at the second depth level with exceptionally high values (Figure 3), the maximal $C_{uz}$ values were $\sim$1,700 mg L$^{-1}$ for the high Cl$^-$ treatment plots and $\sim$500 mg L$^{-1}$ for the low Cl$^-$ treatment plots. This implies that the Cl$^-$ input during the experiment was not enough to reach the measured $\sim$6,000 mg L$^{-1}$ and supports the hypothesis of pre-experiment Cl$^-$ in the soil. Considering the possibility of an error in the ET estimation, a 10% higher ET would have resulted in double Cl$^-$ concentrations. A 13% higher ET would have given $C_{uz}$ values of $\sim$6,500 mg L$^{-1}$ for the high Cl$^-$ treatment and $\sim$3,000 mg L$^{-1}$ for the low Cl$^-$ treatment, which are similar to the measurements without considering any pre-experiment Cl$^-$.

The Cl$^-$ measurements showed some considerable differences in plots under the same treatment. For example, the curves at the third depth level in Plots 2 and 8 under the high Cl$^-$ high N treatment showed similar trends, but with a difference of about 3,000 mg L$^{-1}$ throughout. At the same depth, in Plots 1 and 5 under the low Cl$^-$ high N treatment, the measurements showed a different behavior, where the curve of Plot 1 increased, whereas that of Plot 5 decreased. These differences can only be related to heterogeneity in soil properties, since plots under the same treatment were irrigated during the cropping periods using the same irrigation system with the same water treatments and the same timings. Similar observations appear at other depths and other times.

A substantial difference between the two salinity treatments can be seen, as only a single VSP in the low Cl$^-$ plots at all depths showed concentrations higher than 3,000 mg L$^{-1}$, whereas the typical values in the high Cl$^-$ plots were much higher. For the first depth level, and for the second depth level at time points later than February 2017, this difference can be attributed mostly to the direct effect of the Cl$^-$ application differences between the treatments. The third and fourth depth levels, however, were greatly affected by leaching of the high Cl$^-$ levels that were measured earlier at the second depth level, claimed above to be affected by the Cl$^-$ that accumulated in the soil before the experiment. The measured values at the third and fourth depth levels show substantial differences between the two salinity treatments, starting from the very first samples taken from these depth levels. This is in spite of the leaching of the pre-experiment Cl$^-$, which is not expected to show great differences between the treatments. The extensive leaching in February 2017 percolated through the entire soil profile, whereas the upper soil was already affected by the treatments. This indicates that concentrations in the deeper soil were affected by both the pre-experiment Cl$^-$ and the applied Cl$^-$.

### 3.5 Nitrate leaching

Transport of NO$_3^-$ was examined through concentration variations in water samples that were collected by VSPs from the unsaturated zone. The measured NO$_3^-$ in pore water is assumed to approximately represent the total amount of mobile inorganic N in the unsaturated soil, which is considered to have oxidizing conditions that promote transformation of NH$_4^+$ and NO$_2^-$ to NO$_3^-$ (Daniel-Vedele et al., 1998; Hill, 1999). The NO$_3^-$ concentration measurements are presented as NO$_3^-$ N (Figure 4). The initial measurements of some of the VSPs at the second depth (195–235 cm) showed high values of up to 450 mg L$^{-1}$. This pattern, which is similar to the Cl$^-$ concentration pattern that was discussed above, was likely the result of NO$_3^-$ that was present in the soil prior to the initiation of the percolation experiment. Similar to the Cl$^-$, the analysis of extracted soil samples from two boreholes at the beginning of the experiment support this.
by revealing relatively high concentrations of NO$_3$–N at the depth of 2 m (Supplemental Material S5).

The February 2017 sprinkling event promoted deep NO$_3$–N transport that was reflected in the measurements as patterns similar to those seen in the Cl$^-$ measurements of the sharp drop in NO$_3$–N concentrations at the second depth and increasing concentrations at the third and fourth depths.

The N fertilization treatments had some effect on the measured NO$_3$–N concentrations only at the upper two depth levels, and no distinct effect was observed in soil deeper than 3 m. It is possible that the difference in N input in the treatments was not large enough to be substantially expressed in the NO$_3$–N measurements in the soil. Some breakthrough patterns appeared at the first depth in February 2017 in Plots 1, 2, and 5, which were all treated with high N. After the decline of the breakthrough at the first depth, moderate breakthrough patterns appeared at the second depth with slightly higher values for the plots that were treated with high N. This shows that the excess NO$_3^-$ that was not taken up by the plant roots, when treated with high N, accumulated in the root zone during the first two crops in 2016. The excess NO$_3^-$ was leached with the February 2017 sprinkling event and the crop irrigation during summer 2017. No marked difference in NO$_3$–N levels was observed in soil deeper than 3 m.

The Cl$^-$ treatments had a major effect on the measured NO$_3$–N concentrations, which was mostly exhibited at the two deeper VSP levels. The plots that were treated with high Cl$^-$ in the irrigation water had higher concentrations of NO$_3$–N in the collected soil water than most of the low Cl$^-$ plots. This observation will be discussed below.

### 3.6 Salinity impact on nitrate transport

Plotting the Cl$^-$ vs. NO$_3$–N concentrations from all water samples with their linear regressions reveals a distinction between the Cl$^-$ treatments (Figure 5, Table 2). Most of the data from the two low Cl$^-$ treatments did not exceed Cl$^-$ concentrations of 2,500 mg L$^{-1}$, whereas the Cl$^-$ concentrations from the high Cl$^-$ treatments reached almost 8,000 mg L$^{-1}$.

The correlated median and average values (Figure 5) show an important difference between the two Cl$^-$ treatments that is not directly evident from the measurements. The median and average NO$_3$–N values for the two low Cl$^-$ treatments and the high Cl$^-$ low N treatment are similar, whereas only for the high Cl$^-$ high N treatment are the median and average NO$_3$–N values exceptionally high. The measured NO$_3$–N concentrations in the high Cl$^-$ treatments were apparently susceptible to surplus NO$_3^-$, whereas the measured NO$_3$–N concentrations in the two low Cl$^-$ treatments did not show a substantial difference. The significance of this observation was tested using the Mann–Whitney U test, which was done for all the measured NO$_3$–N data. The test compared each of the four treatments to the other three and considered a required $p$ value of $<$ .01 to reject the null hypothesis that the distributions of the NO$_3$–N values from two certain treatments have equal medians. The results showed that for the high Cl$^-$ high N treatment, the null hypothesis can be rejected with very high confidence when compared with any of the other three treatments (Table 3).

![Figure 5](image-url) Correlation of measured Cl$^-$ and NO$_3$–N concentrations in all water samples collected using vadose zone pore water sampling ports. Different Cl$^-$ and N treatments appear in different colors and markers with corresponding linear regression lines; median values are shown as large full markers, and average values are shown as large empty markers.

| Table 2 | Linear regression for the correlation data as presented in Figure 5 |
|---------|---------------------------------------------------------------|
| Treatment | Slope | Intercept | Slope 95% confidence bounds | Intercept 95% confidence bounds |
| Low Cl$^-$, low N | 2.73 | 210.28 | 1.96, 3.49 | 76.9, 343.7 |
| Low Cl$^-$, high N | 1.69 | 635.59 | 0.80, 2.57 | 448.5, 822.7 |
| High Cl$^-$, low N | 12.29 | 376.36 | 10.89, 13.7 | 95.47, 657.2 |
| High Cl$^-$, high N | 5.0554 | 2328.8 | 3.30, 6.81 | 1,767, 2,890 |
TABLE 3  Mann–Whitney U test results for all NO$_3$–N data comparing the four different treatments. The marker shapes and colors correspond to the markers in Figure 5

| Treatment 1 | Treatment 2 | P value |
|-------------|-------------|---------|
| Low Cl$^-$, low N (purple triangles) | Low Cl$^-$, high N (red diamonds) | .1917 |
| Low Cl$^-$, high N (red diamonds) | High Cl$^-$, low N (green circles) | .0105 |
| High Cl$^-$, low N (green circles) | Low Cl$^-$, low N (purple triangles) | .1198 |
| High Cl$^-$, high N (blue squares) | Low Cl$^-$, low N (purple triangles) | $6.1570 \times 10^{-12}$ |
| High Cl$^-$, high N (blue squares) | Low Cl$^-$, high N (red diamonds) | $2.1845 \times 10^{-14}$ |
| High Cl$^-$, high N (blue squares) | High Cl$^-$, low N (green circles) | $2.7078 \times 10^{-10}$ |

Figure 6  Measured Br$^-$ tracer concentrations in water samples collected by vadose zone pore water sampling ports at different depths. The orange line indicates the tracer application time, and colored areas represent the crop rotation and intensive sprinkling. Legend marker labels refer to Cl$^-$ and N treatments and plot numbers. Marker colors represent different Cl$^-$ treatments: purple for low Cl$^-$ and black for high Cl$^-$

3.7 Tracer transport

Results of the Br$^-$ concentrations in water samples collected by VSPs, after one-time application of Br$^-$ as a tracer, are shown in Figure 6. The February 2017 sprinkling event initiated a percolation event reflected as measured breakthrough curves at all depth levels. The first Br$^-$ arrived within 1 mo from the sprinkling at the 305- to 340-cm depth level, and 3–5 mo after the sprinkling at the 410- to 450-cm depth level. The magnitude of the breakthrough peaks decreased with depth as expected, since a single-event tracer application tends to produce a plume that disperses vertically as it infiltrates deeper.

The tracer breakthrough curves showed a difference between the Cl$^-$ treatments similar to the NO$_3$–N curves. The Br$^-$ concentrations at the third and fourth depths (305–450 cm) showed higher values for the high Cl$^-$ plots than for the low Cl$^-$ plots, despite the fact that the Br$^-$ tracer was applied in a single pulse and with no difference between the plots. Note that the NO$_3^-$ and Br$^-$ concentrations in the unsaturated zone are not expected to be directly affected by variations in Cl$^-$ application in the irrigation water. Therefore, the differences in the observed NO$_3^-$ and Br$^-$ concentrations in the deeper soil levels suggest that the different Cl$^-$ treatments had an effect on the percolation process itself. This hypothesis is further discussed below.

3.8 Analyzed patterns in water contents and nitrate concentrations

In addition to the number of latent patterns, nonnegative tensor factorization analysis (Supplemental Material S7, Figure 7) provides the frequency of each pattern’s occurrence as a function of time, field plot, and measurement depth level.

The results for the water content data include five patterns explaining ~85% of the analyzed data (the ratio between the norm of the sum of the pattern tensors and the norm of the measurement data tensor). A description of these results appears in Supplemental Material S7.

The pattern analysis for the NO$_3^-$ concentrations (Figure 7) included data from 29 Mar. 2016 to 7 Nov. 2017 (589 d), which is the period when most water samples were collected. This period is from the beginning of the first crop (potato) to the end of the third crop (cotton); the February 2017 sprinkling event corresponds to Days 282–328 in this time series.

The pattern analysis requires a full tensor that includes data for all the plots and depth levels for each date included; however, NO$_3^-$ was measured in water samples collected in intervals of 1–2 wk. Additionally, not every VSP provided a sample on every sampling day, since sampling was limited by water content. In order to conduct the analysis, we filled in missing data and closed the gaps in two steps by completing the data for locations that were not sampled on a specific sampling day, and filling the data for the days between the sampling days. For these
two steps, we made several assumptions. We assumed that when a VSP did not provide a sample, the water content in its location was very low, and therefore the water flow velocity was low and the concentration changes were small. Interpolating the missing data for locations that were not sampled on specific sampling days was done by assuming that these values were equal to the previous measured value. Extrapolating the late values, when these cases occurred after the last measurement of the specific location, was done in the same way. When these cases occurred before the first measurement of the specific location, extrapolating the early values was done by assuming that these values were equal to the next measured value. In order to have a full time series that can be interpreted in comparison with the measured data, the data for all the days between the “sampling days” were filled in using a linear interpolation based on the values of the two nearest sampling days (one on each side of the missing time points).

The results for the \( \text{NO}_3^- \) pattern analysis showed six patterns numbered N1–N6 (Figure 7), where patterns N1, N2, and N3 explain 0.284, 0.256, and 0.243 of the data (the identified patterns), respectively, and e patterns N4, N5, and N6 each explained <0.1 of the data.

Pattern N1 of the \( \text{NO}_3^- \) analysis explains data from Depth Levels 2 and 3, mostly in the time period after the February 2017 sprinkling event (mostly after 328 d), and with similar frequencies for all plots. This pattern shows that after a major wetting event, all curves presented similar solute breakthrough behavior, with a gradual increase up to a certain stable value. At each depth level, the measured breakthrough represents the arrival of the \( \text{NO}_3^- \) that was measured earlier at an upper depth, at Depth 1 before it was pushed to Depth 2, and at Depth 2 before it was pushed to Depth 3.

Pattern N2 corresponds to data from Depth 2, mostly in a time period before the end of the February 2017 sprinkling event (mostly in the first 328 d). This data group represents the high values that were measured at this depth before the sprinkling event. This pattern has finite frequencies in all the plots except for Plot 5. Under the assumptions used for the interpolation of the measured solute concentration, Plot 5 showed concentration values lower than those measured in other plots during this period. Plots 2 and 8 had higher frequencies in this pattern. These two plots were both treated with high Cl\(^-\) high N, and within the time frame and depth level of this pattern, they show values that are somewhat higher than the other plots.

Pattern N3 explains data from Depth Levels 3 and 4, with considerable frequency for the entire time series, but with higher frequency for the later time period. The reason for this considerable frequency for the whole time series is the fact that the first measurements at Depth Levels 3 and 4 only appeared at late times, which under our assumptions implies flat curves at earlier times. This pattern mostly includes data from Plots 2, 3, 7, and 8, which were all treated with high Cl\(^-\). This shows, as indicated
above, that the high Cl$^-$ treatment resulted in different breakthrough curves, of higher NO$_3$−N values, at depths of >3 m.

The results for the pattern analyses of both water content and NO$_3$−N illustrate the complexity of the data of different behaviors at different times, field plots, and soil depths. Although some of the patterns are explained by the effects of the treatments, others can only be explained by the heterogeneity in the properties of the soil.

A pattern analysis was also done for the Br$^-$ tracer concentration data. However, in this case, the analysis resulted in seven patterns, which made their interpretation difficult. We did not find any robust meaning in these results, and therefore they are not shown.

### 3.9 Salinity treatment impacts on percolation

The concentration measurements (Figures 4 and 6) with the corresponding statistical analysis and the pattern analyses (pattern N3 in Figure 7 and corresponding text, pattern Θ4 in Supplemental Material S7) showed that irrigating with high Cl$^-$ resulted in relatively high NO$_3$− and Br$^-$ concentrations at depths of 305–340 cm and 410–450 cm. The significance of the differences in the measured concentrations of NO$_3$−N and Br$^-$ between the two Cl$^-$ treatments was tested using the Mann–Whitney $U$ test. The test was done for the measured data of NO$_3$−N and Br$^-$ from 1 Feb. 2017 to 7 Aug. 2018 for Br$^-$ and to 30 Oct. 2018 for NO$_3$−N. Earlier data were not included, since they may still have been mostly affected by pre-experiment NO$_3$−N concentrations at the second depth level. The data in the deeper soil levels may also have been affected by the pre-experiment NO$_3$− that was leached down from the second depth level. However, the measurements at these depths seem to be dominated by the treatment effects. Each depth level of each of the two solutes was tested separately, by comparing two groups of data, from the high Cl$^-$ treatment and low Cl$^-$ treatment. The test considered a required $p$ value of <.05 to reject the null hypothesis that the distributions of the two groups have equal medians. The results showed that for the upper two depth levels, the null hypothesis cannot be rejected regarding both NO$_3$−N and Br$^-$ (Table 4). For the deeper two depth levels, the null hypothesis can be rejected with very high confidence regarding both NO$_3$−N and Br$^-$, where all four $p$ values ≤ 4.7 × 10$^{-11}$.

The NO$_3$− levels in the deep soil can be affected by competition with Cl$^-$ for the transporter in the plant roots (Aslam et al., 1984; Cerezo & Garci, 1997). This competition could have caused less NO$_3$− uptake when irrigating with higher Cl$^-$ concentrations, and as a result, higher NO$_3$− flux from the root zone. However, measurements of mineral concentrations in the plants, which were taken for all the crops (see Supplemental Material S8) showed no substantial differences in the N concentrations and in crop yields between the two different Cl$^-$ treatments. Moreover, the Br$^-$ tracer is not expected to be affected by root uptake, but as indicated above, it did show differences in the breakthrough characteristics between different Cl$^-$ treatments.

A difference in the percolation velocity of the two salinity treatments was observed in the water content measurements. The arrival of the February 2017 sprinkling wetting front to the deep sensors (360–400 cm) was measured earlier at the four FTDR sensors of the high Cl$^-$ treatment than at the sensors of the low Cl$^-$ treatment (Figures 2 and 8). Another piece of evidence for the percolation velocity difference was observed in the collection time of the first pore water samples at Depth Level 3 (305–340 cm), considering water content as a limiting factor for collection of these samples. The first samples of the high Cl$^-$ plots at this depth level were collected 1–2 wk earlier than the first sample of all the low Cl$^-$ plots, which suggests that the water front of February 2017 arrived at this depth level earlier in the high Cl$^-$ plots (Figure 8). The sampling rate of the pore water samples was at 1- to 2-wk intervals, which makes it difficult to connect this last observation to velocity differences. Additional data and statistical significances are needed to solidify this connection. These observations are also partly reflected in pattern Θ4 of the water content pattern analysis where the low Cl$^-$ plots are distinguished at Depth Levels 2 and 3 (Supplemental Material S7). The observation of percolation velocity differences is mostly apparent at the soil levels of 3 m and deeper, whereas the upper levels did not show a clear difference in percolation velocity between the different treatments, except for the arrival time of the first wetting front to the depth of 150–190 cm, at the beginning of 2016. Unlike the arrival time difference at the 360- to 400-cm depth, where an earlier arrival was found for the high Cl$^-$ plots, at the upper depth level, the first wetting front arrived earlier in the low Cl$^-$ treatment plots. However, this difference was substantial in only one of the low Cl$^-$ plots, in which the first wetting front arrived particularly early. The observed differences in percolation velocity at soil depths...
Irrigating with different Cl\textsuperscript{−} levels may have an effect on the vertical distribution of roots in the soil and on the distribution of uptake depth. A study by Russo and Kurtzman (2019) used numerical simulations to test the effect of irrigation water with different salinity levels on NO\textsubscript{3}\textsuperscript{−} fluxes below the root zone of a citrus grove (rooting depth of 1.5 m). They showed that using high-salinity irrigation water (Cl\textsuperscript{−} of 640 mg L\textsuperscript{−1}), in comparison with desalinated water (Cl\textsuperscript{−} of 50 mg L\textsuperscript{−1}), could affect the distribution of root water uptake depth and, in turn, increase the water content and water percolation velocity. Russo and Kurtzman (2019) also showed that the use of high-salinity irrigation water resulted in higher NO\textsubscript{3}\textsuperscript{−} cumulative flux at a depth of 4 m, with the difference in root water uptake as the main mechanism to explain this phenomenon. Considering the typical root depths of the crop rotations that were used in the current study (0.6–0.9 m, 0.6–1.2 m, and ~1 m for potato, corn, and cotton, respectively; Division of Agriculture and Natural Resources, 2019), this mechanism could explain the difference in the solute curve characteristics between Depth Levels 1 and 2 (1–2.35 m) and Depth Levels 3 and 4 (3.05–4.5 m).

The percolation velocity differences when using different salinity levels in irrigation water may also be affected by several physical mechanisms, which can possibly play an important role, regardless of the biological intervention of the plant roots. A few studies showed that increasing the salinity of an infiltrating solution could possibly increase its surface tension and, in turn, enhance the infiltration rate (Jones & Ray, 1941; Weisbrod et al., 2004). However, these studies tested solutions of extremely high salinity (0.75, 2, and 5 M NaNO\textsubscript{3} in Weisbrod et al., 2004), which do not appear in a common agricultural field; therefore, the relevance of the surface tension effect for the results of the current study is not known. Moreover, the abovementioned percolation velocity differences were observed only in the deeper soil sections, whereas the potential effect of increased surface tension would be expected across the entire soil profile.

High levels of Na\textsuperscript{+} in the soil may result in clay swelling, which affects infiltration (Shainberg & Letey, 1984). This effect is different for different anion concentrations in which a moderate Na\textsuperscript{+} level with low Cl\textsuperscript{−}, for example, will reduce the hydraulic conductivity and inhibit the percolation, whereas very low Na\textsuperscript{+}, or high Cl\textsuperscript{−} with high Na\textsuperscript{+}, will result in less inhibition. The soil in the experimental site contains 7–22% clay (see Supplementary Material S4), which can potentially undergo some swelling. The differences in the Na\textsuperscript{+} and Cl\textsuperscript{−} levels in the irrigation water could cause differences in the level of swelling. The effect of this process within the current study could be enhanced swelling in the low Cl\textsuperscript{−} treatment plots, resulting in lower velocities and percolation rates, compared with the high Cl\textsuperscript{−} treatment plots, where clay swelling could be inhibited.

In addition to the effect on the percolation rate, this process may also have a direct effect on solute concentrations in the deep soil. Clay swelling in the upper soil levels could result in the partial immobilization of the percolating solutes. If swelling occurs in interaction with a percolating wetting front that contains a concentrated solute, the first and most concentrated part of the solute breakthrough could be immobilized within the swelling clay. If the remaining portion of the solute, the tail of the breakthrough, percolates deeper through preferential flow, for example, the resulting breakthrough curve could
The mechanisms considered to be possible explanations for the observations of differences in solute concentrations in the soil, and differences in water percolation velocity. Dashed arrows represent connections that are of limited relevance to the current study but may be relevant under different conditions.

High NO$_3^-$ concentrations and enhanced water percolation rates in the deep soil are evidence for enhanced NO$_3^-$ leaching when using high salinity irrigation water. An increased percolation rate, if occurring in the root zone, can also be a cause for enhanced leaching. Fast water percolation results in a short residence time of the NO$_3^-$ in the root zone. Under conditions where differences in NO$_3^-$ levels in the root zone can promote differences in NO$_3^-$ uptake, a shorter residence time may reduce the total NO$_3^-$ uptake and increase the flux to deeper soil levels.

**SUMMARY**

We characterized NO$_3^-$ transport in the unsaturated zone in an experimental agricultural field with different treatments of irrigation water salinity and N fertilization. A VMS provided a large database of water content and solute (Cl$^-$ and NO$_3^-$) concentrations in the deep unsaturated zone over 2.5 yr of in situ measurements.

The patterns in the water content and NO$_3^-$-N concentration data were analyzed using nonnegative tensor factorization. The analyzed patterns showed great variability in response to percolation events (where the measurements in some plots responded to some events, whereas in other plots, there was no response), in both response intensities and response times. This variability appears between the different measurement depths, between the different treatments, and between plots under the same treatment. Therefore, much of this variability is attributed primarily to soil heterogeneity.

The N fertilization treatments (different levels of NH$_4$NO$_3$ additions) had a limited effect on the measured
NO₃-N concentrations, with some of the high N plots showing higher NO₃-N concentrations at the upper measurement depth levels, but with no marked effect at the deeper soil levels. The limited extent of this effect could possibly be the result of the small difference in N input between the two treatments. Considering the overall NO₃-N concentrations, regardless of the depth, the high Cl⁻ high N treatment resulted in significantly higher NO₃-N concentrations compared with the other treatments.

Significant differences were found in solute concentrations between plots under different salinity treatments. Higher concentrations of Cl⁻, NO₃⁻, and the Br⁻ tracer were recorded in the high Cl⁻ plots (added NaCl in irrigation water). These differences were found only at the measurement depths of 3 m and deeper, where it is assumed that root uptake did not take place. Additionally, a difference in the percolation rate between plots of different Cl⁻ treatments was observed as a difference in the arrival time of a wetting front at depths of 360–340 cm. This wetting front arrived earlier in the high Cl⁻ plots. Several mechanisms were suggested as possible causes for these observations. However, none of the suggested mechanisms fully explain the fact that these observations were only apparent in deep soil and not at depths of 1–3 m. We believe that focused experiments under controlled conditions and quantitative modeling are necessary in order to quantify the effects of each of the suggested mechanisms. Regardless of the considered mechanisms, our findings suggest that irrigating with water containing salts, compared with irrigating with desalinated water, can result in elevated NO₃⁻ concentrations and in enhanced water percolation rates in the deep unsaturated soil.

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**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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