Spatial Variability of Nitrogen Uptake and Net Removal and Actual Evapotranspiration in the California Desert Carrot Production System

Aliasghar Montazar 1,*, Daniel Geisseler 2 and Michael Cahn 3

Abstract: Nitrogen (N) and irrigation water must be effectively used in mineral soils to produce carrots with high yield and minimal environmental impact. This study attempts to identify optimal N and irrigation management practices for low desert carrot production in California by investigating consumptive water use and N uptake and removal rates in fresh market and processing carrots. Field experiments were conducted at the University of California Desert Research and Extension Center and nine farmer fields during two growing seasons. The actual evapotranspiration ($\text{ET}_a$) was measured using the residual energy balance method with a combination of surface renewal and eddy covariance equipment. Crop canopy coverage, actual soil nitrate-N from multiple depths as well as total N percentage, dry matter, and fresh biomass in roots and tops were measured over the growing seasons. The length of the crop season had a wide range amongst the experimental sites: from a 128-day period in a processing carrot field to as long as 193 days in a fresh market carrot field. The seasonal $\text{ET}_a$ varied between 305.8 mm at a silty loam furrow irrigated processing carrot field and 486.2 mm at a sandy clay loam sprinkler irrigated fresh market field. The total N accumulated at harvest ranged between 205.4 kg ha$^{-1}$ (nearly 52% in roots) and 350.5 kg ha$^{-1}$ (nearly 64% in roots). While the mean value of nitrogen removed by carrot roots varied from 1.24 to 1.73 kg N/Mg carrot roots, it appears that more N was applied than was removed by carrot roots at all sites. Within the range of N application rates examined at the experimental sites, there was no significant relationship between carrot fresh root yield and N application rate, although the results suggested a positive effect of N application on carrot yield. Sufficient soil N availability over the growing season and the lack of significant yield response to N application illuminated that optimal N rates are likely less than the total amounts of N applied at most sites.

Keywords: carrots; irrigation management; low desert of California; nitrate N; nitrogen uptake curve

1. Introduction

Carrots (Daucus carota L.) are one of the major commodities in the low desert of California, with an average planted area of nearly 8500 hectares over the past decade [1]. Carrot is a cool-season crop that demands specific growing conditions and an adequate supply of mineral N and water for successful commercial production. Optimizing nitrogen and water management in carrot production is crucial for maximizing crop productivity and minimizing costs and nitrogen leaching losses. Appropriate soil fertility and uniform soil water availability are critical for good root formation [1,2]. Carrot roots are vulnerable to forking, which can be caused by over-applying N fertilizer [2]. Excessive watering increases the incidence of hairy roots, discourages good color formation, and may encourage disease incidence [3]. Severe drying and wetting cycles result in the significant splitting of roots.
Carrots have a deep and extensive rooting system \([4,5]\) and are able to access residual N from the previous season that has leached into deeper depths of the soil profile. The N needs of carrots for optimum storage root yield depend on the climate, soil types, and residual soil N \([5]\). In temperate regions, carrot yields are often uninfluenced by pre-plant and sidedress N applications \([6–9]\). High soil organic matter mineralization rates \([7,10]\) and deep and extensive rooting systems \([4,5,11]\) can be reasons for the lack of effect on yield. There is evidence that carrot yields may increase in response to pre-plant and sidedress N applications when the crop is grown for a 2 to 3 year period in the same location in mineral soils \([12]\). While carrot yields showed minimal response to N application rates in temperate regions, the yields positively respond to the application rate in tropical and subtropical regions \([13,14]\). Minimal effects of N application rates were found on quality and storability \([9,15,16]\). In an earlier study in California, researchers reported that seasonal N rates greater than 170 kg ha\(^{-1}\) are seldom necessary to maximize root yield and that excessive N application increases root cracking during harvest and handling \([3]\).

Root yield reduction may be seen if a high rate of N fertilizer is applied during the crop season \([17,18]\). Carrot fields with N deficiency might show an irregular pattern in the height of the shoot growth, but the foliage will still be green in color. The use of slow-release fertilizers in carrot production has been investigated as an approach to considerably enhance the efficiency of fertilization in terms of production and environmental protection \([19]\).

Different deformities of carrots root, root splitting, and root rot, resulting in a lower proportion of marketable roots, can be due to excess soil moisture as well as severe drying and wetting periods; this would suggest the need for careful irrigation management over the growing season. Although nitrogen fertilization marginally increased crop water use due to increases in leaf area, it markedly increased the water use efficiency up to an application rate of 120 kg N ha\(^{-1}\) \([20]\). A study showed that the highest total root yield was reached in sandy and loamy soils at 75% of field capacity and an N application of 150 kg ha\(^{-1}\) \([21]\).

Researchers reported a seasonal water consumption of 234 mm with an application of 100 kg N ha\(^{-1}\) and 320 mm with N application of 300 kg ha\(^{-1}\) in a study conducted in Germany \([22]\). This study concluded that moderate water stress reduced root yield by 32%. Minimizing water deficits is critical to obtaining high yield and quality in carrots. In a study conducted in New Zealand, total biomass and root yields declined linearly with increasing soil water deficits \([23]\). The study showed a sharp reduction of storage root diameter due to severe water stress. The phases of plant establishment and vegetative crop development are the most sensitive stages of carrots to water deficits \([24]\).

Surface renewal (SR) and eddy covariance (ECov) techniques are classified as the residual energy balance (REB) method, which measures sensible heat flux density (H) and calculates latent heat flux density (or actual evapotranspiration) using the measurements of net radiation and ground heat flux density \([25–32]\). The ECov method uses a sonic anemometer to measure sensible heat flux, and the SR method uses a fine-wire thermocouple to measure an uncalibrated sensible heat flux (H0) to estimate H. Since ECov is based on eddy covariance and SR is based on energy conservation, the two methods are independent, and good agreement implies a good estimate for H \([31]\). While these techniques have been used in several crops, they had never been used to measure actual evapotranspiration in carrots.

The California low desert region has a true desert climate, and the soils are naturally low in organic matter. In the region, fresh market and processing carrots are planted from September to December for harvest from January to May. The average rainfall amount during the growing period is 65 mm (Table 1). Most carrots are typically sprinkler irrigated for stand establishment and, subsequently, furrow irrigated for the remainder of the growing season. However, some fields are irrigated by solid set sprinkler systems the entire crop season. Most fields are grown conventionally (non-organic), with a small
percentage of fields grown organically. Seasonal nitrogen application varies widely among growers and fields, ranging from as low as 180 kg ha\(^{-1}\) to over 280 kg ha\(^{-1}\).

Table 1. Monthly mean temperature, total rainfall, and ET\(_{\text{o}}\) at CIMIS Meloland station #87 for the 2019–2020 and 2020–2021 seasons, as compared with 10-year means. October through April is considered a typical carrot crop season in the region. ET\(_{\text{o}}\) is reference evapotranspiration.

| Month | Season 2019–2020 | Season 2020–2021 | 10-Year Mean | 10-Year Mean | 10-Year Mean |
|-------|------------------|------------------|--------------|--------------|--------------|
|       | Mean Temp. (°C)  | Total Rainfall (mm) | Total ET\(_{\text{o}}\) (mm) | Mean Temp. (°C) | Total Rainfall (mm) | Total ET\(_{\text{o}}\) (mm) |
| October | 28.9          | 0.0              | 146.5         | 30.6          | 0.0              | 131.5         | 23.9          | 30.9          | 129.9         |
| November | 17.1          | 19.4              | 80.5           | 16.9          | 0.0              | 79.4           | 17.2          | 2.8           | 81.3          |
| December | 12.9          | 8.7               | 56.9           | 11.7          | 0.0              | 62.3           | 12.6          | 5.9           | 58.7          |
| January  | 12.6          | 0.0               | 65.9           | 12.9          | 16.5             | 67.6           | 13.0          | 9.0           | 66.3          |
| February | 14.4          | 8.1               | 90.7           | 14.7          | 1.5              | 98.2           | 15.0          | 7.9           | 91.0          |
| March   | 16.5          | 65.6              | 63.4           | 16.6          | 3.8              | 159.2          | 19.1          | 7.6           | 156.3         |
| April   | 22.0          | 3.8               | 192.2          | 22.9          | 0.0              | 205.6          | 22.2          | 1.5           | 197.0         |

Most studies on carrot N and water use were conducted under conditions (e.g., climate and cropping system) that differ from those found in the low desert carrot production system. Currently, the lack of accurate nitrogen uptake and crop water use information is one of the largest uncertainties faced by carrot farmers, hindering efficient water and N management and possibly compromising the economic sustainability of production in the face of increasingly limited and costly water and fertilizer supplies. Studies in other growing regions like Canada have been used to generate carrot uptake N for California’s Irrigated Lands Regulatory Program [33], and, therefore, updated N uptake values for carrot grown under representative conditions for the region are greatly needed. Making changes to cultural practices is extremely difficult, especially when there is a lack of scientific information. The industry needs reliable information on N and water consumptive use in carrots to optimize irrigation and N management, enhance water and nitrogen use efficiency, and achieve full economic gains in a sustainable soil and water quality approach.

The purpose of this study is to characterize current N and irrigation practices in low desert carrots and identify opportunities to improve N and water management. More specifically, this study attempted to monitor water use, N uptake, and N net removal for fresh market and processing cultivars in experimental and commercial fields, thereby serving as a reference for further studies and applications to carrot production in arid and semi-arid regions.

2. Materials and Methods

2.1. Field Experiments

Since the primary focus of this study was the California low desert region, field experiments were conducted at the University of California Desert Research and Extension Center (DREC) and nine commercial fields in this region. The study area has an arid climate, with a mean annual rainfall of 76 mm and an air temperature of 22 °C (Table 1). The region features extremely hot summers and mild winters. At all sites, the Colorado River was the source of irrigation water, with an average pH of 8.1 and average electrical conductivity of 1.1 dS m\(^{-1}\). Nitrate-N (NO\(_3\)-N) content of the Colorado River Water was non-detectable at a reporting limit of 0.4 mg kg\(^{-1}\) during the project period.

DREC research trials: The trials were carried out at the DREC in Holtville, California (32°48’59” N, 115°26’26” W; elevation: 15 m below mean sea level), during the two crop seasons of 2019–2020 and 2020–2021 at the same field. Soil characteristics referring to three genetic horizons selected from a soil survey are given in Table 2. The soil at the study field has a sandy clay loam (the top 30 cm) to sandy loam (30–90 cm) texture, with an average bulk density of 1.74 g cm\(^{-3}\) in the top 60 cm. In the first year of the study, soil pH
ranged between 8.0 and 8.3, organic matter was between 0.53 and 0.96%, and the electric conductivity range of the soil paste extract ranged from 1.1 to 1.7 dS m$^{-1}$ (leaching is a standard practice in the region to manage soil salinity and maintain soil productivity). The average pre-seeding NO$_3$-N, P, K, and CEC of the soil top 60 cm were 9.2 ppm, 14.6 ppm, 254 ppm, and 17.6 meq/100 g in the 2019–2020 season, respectively. Soil organic matter, NO$_3$-N, K, CEC, and EC were at higher levels in the 2020–2021 season.

| Experimental Site | Generic (Horizon m) | Soil Texture | Organic Matter (%) | NO$_3$-N (ppm) | P (ppm) | K (ppm) | CEC (meq/100 g) | EC (dS/m) | pH |
|-------------------|---------------------|--------------|--------------------|----------------|--------|---------|----------------|---------|----|
| DREC (19–20)      | 0–0.3 Sandy clay loam | 0.96         | 14.8              | 18.0           | 283    | 18.4    | 1.7            | 8.0     |    |
|                   | 0.3–0.6 Sandy loam   | 0.69         | 3.5               | 11.2           | 224    | 16.7    | 1.1            | 8.2     |    |
|                   | 0.6–0.9 Sandy loam   | 0.53         | 0.5               | 4.0            | 111    | 12.4    | 1.1            | 8.3     |    |
| I                 | 0–0.3 Silty clay loam | 1.18         | 15.4              | 109.5          | 141    | 30.9    | 1.6            | 8.1     |    |
|                   | 0.3–0.6 Silty clay    | 0.85         | 9.4               | 8.2            | 326    | 45.1    | 1.5            | 8.4     |    |
|                   | 0.6–0.9 Clay          | 0.97         | 7.0               | 5.9            | 360    | 63.7    | 1.6            | 8.6     |    |
| II                | 0–0.3 Sandy loam      | 1.01         | 21.1              | 9.7            | 76     | 17.5    | 1.6            | 7.7     |    |
|                   | 0.3–0.6 Sandy loam    | 0.79         | 11.0              | 13.1           | 63     | 17.9    | 1.0            | 7.0     |    |
|                   | 0.6–0.9 Sandy loam    | 0.71         | 6.3               | 5.4            | 59     | 16.0    | 0.9            | 8.0     |    |
| III               | 0–0.3 Sandy loam      | 0.94         | 18.7              | 11.6           | 87     | 16.8    | 1.5            | 8.0     |    |
|                   | 0.3–0.6 Silty loam    | 1.03         | 11.4              | 14.2           | 67     | 19.2    | 1.0            | 7.9     |    |
|                   | 0.6–0.9 Loamy sand    | 0.59         | 7.8               | 7.3            | 66     | 14.7    | 1.1            | 8.1     |    |
| IV                | 0–0.3 Silty loam      | 1.12         | 10.7              | 14.4           | 74     | 24.2    | 1.8            | 7.9     |    |
|                   | 0.3–0.6 Silty loam    | 0.79         | 6.0               | 5.6            | 55     | 22.4    | 1.6            | 8.0     |    |
|                   | 0.6–0.9 Sandy loam    | 0.50         | 2.7               | 4.3            | 29     | 14.1    | 0.9            | 8.1     |    |
| V                 | 0–0.3 Sandy loam      | 0.99         | 6.8               | 50.9           | 85     | 15.2    | 1.3            | 7.8     |    |
|                   | 0.3–0.6 Silty loam    | 0.72         | 2.3               | 9.9            | 46     | 20.0    | 0.4            | 8.2     |    |
|                   | 0.6–0.9 Sandy loam    | 0.57         | 2.6               | 5.6            | 39     | 17.2    | 0.8            | 8.1     |    |
| DREC (20–21)      | 0–0.3 Sandy clay loam | 0.98         | 16.1              | 19.4           | 303    | 18.9    | 1.7            | 8.0     |    |
|                   | 0.3–0.6 Sandy loam    | 0.73         | 8.2               | 14.2           | 264    | 17.3    | 1.3            | 8.1     |    |
|                   | 0.6–0.9 Sandy loam    | 0.56         | 3.3               | 10.5           | 178    | 13.0    | 1.2            | 8.2     |    |
| VI                | 0–0.3 Sandy loam      | 0.94         | 10.1              | 25.0           | 99     | 14.5    | 1.5            | 8.0     |    |
|                   | 0.3–0.6 Sandy loam    | 0.70         | 6.8               | 9.3            | 66     | 16.7    | 0.6            | 8.2     |    |
|                   | 0.6–0.9 Sandy loam    | 0.51         | 6.7               | 2.9            | 73     | 12.7    | 1.4            | 8.3     |    |
| VII               | 0–0.3 Silty loam      | 1.49         | 15.5              | 79.4           | 101    | 19.3    | 1.6            | 7.9     |    |
|                   | 0.3–0.6 Silty loam    | 0.76         | 5.0               | 10.7           | 65     | 15.6    | 1.3            | 8.2     |    |
|                   | 0.6–0.9 Loamy sand    | 0.6           | 2.5               | 1.9            | 63     | 15.5    | 3.3            | 8.3     |    |
| VIII               | 0–0.3 Sandy clay loam | 1.41         | 30.1              | 5.7            | 78     | 19.2    | 2.3            | 8.2     |    |
|                   | 0.3–0.6 Sandy clay loam | 1.09        | 19.9              | 2.3            | 71     | 23.7    | 2.1            | 8.3     |    |
|                   | 0.6–0.9 Sandy loam    | 0.65         | 14.2              | 1.3            | 71     | 16.2    | 5.7            | 8.0     |    |
| IX                 | 0–0.3 Silty loam      | 1.21         | 30.3              | 8.8            | 80     | 22.1    | 2.0            | 8.1     |    |
|                   | 0.3–0.6 Silty loam    | 1.04         | 24.8              | 2.4            | 61     | 22.4    | 2.4            | 8.1     |    |
|                   | 0.6–0.9 Sandy loam    | 0.62         | 13.8              | 1.8            | 40     | 11.6    | 3.2            | 8.1     |    |

The trials were irrigated by a solid-set sprinkler system the entire crop season (Table 3). Choctaw fresh market cultivar seeds were planted in the second week of October during both seasons. The experiment consisted of one irrigation regime (replacement of 100% of estimated crop evapotranspiration (ET) and three nitrogen levels including (1) ~20% less than the average N application rate used by local farmers for carrots, (2) the average N application rate, and (3) nearly 20% more than the average N application rate used by local farmers (Table 5). The trial was arranged in a randomized complete block with five replications. Each sub-plot included 12 beds of 1.02 m width (measured as the distance between the centers of furrows) and 18.3 m long (12.2 m × 18.3 m). Ten lines of carrot seeds were planted in each bed.
A pre-plant N fertilizer with monoammonium phosphate was broadcasted at a rate of 448 kg ha\(^{-1}\) (49 kg N ha\(^{-1}\)) over the entire trial area. Urea ammonium nitrate (UAN-32) was injected into the sprinkler system to supply the remaining amount of the N for each nitrogen treatment. The N applications were equally split in every irrigation event, beginning 30 days after seeding to 30 days before the final harvest.

**Commercial field trials:** The trials were conducted in five commercial fields in the 2019–2020 season and four commercial fields in the 2020–2021 season (Tables 2 and 3). The sites represented a range of nitrogen and water management practices (three fields under sprinkler irrigation and six fields under furrow irrigation systems, with different levels of nitrogen application), cultivars (four fresh market carrot fields and five processing carrot fields), and soil types (sandy loam, silty loam, and sandy clay loam). At each site, due to logistical limitations, an experimental plot with an area of 120 by 120 m (with a homogeneous soil that was the dominant soil type at the experimental site) was selected. In each plot, five sub-areas (15 by 15 m) were selected for measurements. The experimental plots represented the common irrigation and N fertilizer management practices followed by farmers (Table 3 and Table 5), while no specific treatment was conducted (Figure 1). Monoammonium phosphate was broadcasted pre-plant at all sites, ranging from 280 to 450 kg ha\(^{-1}\) among sites. During the growing season, N was applied as UAN-32 through irrigation events at all sites until 20–25 days before harvest. On average, 75 to 95 kg N ha\(^{-1}\) was applied by fertigation 50–70 days after seeding at Sites I–VII. The average N applied at Sites VIII and IX was 35 kg ha\(^{-1}\) for the same period. The rest of the N applications were applied equally through irrigation events at each site.

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Figure 1. Layout of a commercial experimental site (not to scale). At this site, the experimental assigned plot is selected in soil type 2. Sampling and monitoring are conducted in five sub-areas (SA1–SA5) over the crop season.
2.2. Instrumentation and Data Collection

The actual crop ET (ET\textsubscript{a}) over the season was estimated by the residual energy balance (REB) method with a combination of SR and ECov equipment at sites I and VIII. SR and ECov are well-recognized methods of estimating sensible heat flux density and calculating latent heat flux density using the REB approach \cite{25,26,28,31,32}. A full flux density tower was set up, consisting of several sensors at these sites (Figure 2a). The towers consisted of an NR LITE 2 net radiometer (Kipp & Zonen, Ltd., Delft, the Netherlands) to measure net radiation, two 76.2 μm diameter, type-E, chromel-constantan thermocouple FW3 models (Campbell Scientific, Inc., Logan, UT, USA) to measure high-frequency temperature data for computing uncalibrated sensible heat flux (H0) using the SR technique, and an RM Young Model 81000RE sonic anemometer (RM Young Inc., Traverse City, MI, USA) to collect high-frequency wind velocities in three orthogonal directions at 10 Hz to estimate H for the latent heat flux density calculations with the ECov technique. In addition, several other sensors were set up in each tower, including three HFT3 heat flux plates (REBS Inc., Bellevue, WA, USA) inserted at 0.05 m depth below the soil surface to measure soil heat storage at three different locations, three 107 thermistor probes (Campbell Scientific, Inc., Logan, UT, USA) to measure soil temperature at three depths in the soil layer above the heat flux plates, three EC5 soil moisture sensors (METER Groups Inc., Pullman, WA, USA) to measure soil volumetric water content at soil depths and locations near the heat flux plate and the thermistor probes, an EE181 temperature and RH sensor (Campbell Scientific, Inc., Logan, UT, USA) to measure air temperature and relative humidity, an SP LITE 2 pyranometer (Kipp & Zonen Ltd., Delft, The Netherlands) to measure solar radiation, and a TE525MM tipping-bucket rain gauge with a magnetic reed switch to measure precipitation.

![Figure 2. Monitoring stations: (a) A fully automated surface renewal and eddy covariance evapotranspiration (ET) tower at Site I, (b) multi-depth soil moisture sensor, along with a Tule sensor, at Site IX.](image)

Except for the soil sensors, all sensors were set up at 1.8 m above the ground surface. The data were recorded using a combination of a Campbell Scientific CR1000X data logger and a CDM-A116 analog input module. Direct two-way communication with each monitoring flux tower was possible using a cellular phone modem (model CELL210, Campbell Scientific Inc., Logan, UT, USA).

In addition, a Tule sensor (Tule Technologies Inc., Oakland, CA, USA) was installed in all the experimental sites to estimate ET\textsubscript{a} using a surface renewal technique (Figure 2b). The actual daily crop ET, obtained from the ET towers at Sites I and VI, was used to verify the estimated ET\textsubscript{a} from the Tule sensors.

Watermark granular matrix sensors (Irrometer Company Inc., Riverside, CA, USA) were used to measure soil water tension at depths of 15, 30, 45, 60, 90, and 120 cm on a continuous basis. The data of the Watermark sensors were recorded by a 900 M Monitor data logger (Irrometer Company Inc., Riverside, CA, USA) on a 30 min basis.

Canopy images were taken on a weekly to 15-day basis, utilizing an infrared camera (NDVI digital camera) to quantify crop canopy coverage over the crop seasons. To determine the plant density in each site, the number of plants was counted within a 3 m length...
of beds in five different locations. Plant density tests were performed 25–30 days after seeding fields. The applied water was measured using multi-jet impeller water meters (Netafim type M) for the DREC trials, while the water delivered, as reported by the water supplier (Imperial Irrigation District), was considered the applied water in each of the commercial sites.

Soil nitrate content (NO$_3$-N) and total N percentage in tops and roots were determined monthly through laboratory analysis. Soil samples for nitrate analysis were collected following the instructions of “Sampling for Soil Nitrate Determination” [34]. Preplant and post-harvest soil samples were taken from four depths (0–30, 30–60, 60–90, and 90–120 cm). At other sampling dates, soil was collected from the top three depths (0–30, 30–60, and 60–90 cm). A composite soil sample was analyzed from each layer for NO$_3$-N content. Plant measurements were carried out on 40-plant samples collected randomly per replication of each treatment, and determinations were made on marketable yield and biomass accumulation. Fresh weight and dry weight of roots and foliage were measured on a regular basis.

At the commercial sites, soil and plant samples were collected from the five sub-areas located in the experimental assigned area; 40-plant samples were collected randomly from each sub-area. The information of N applied over the season was tracked, and residual soil NO$_3$-N was measured after harvest, as described above.

2.3. Date Analyses

The canopy images were analyzed using PixelWrench2 software (TETRACAM Inc., Chatsworth, CA, USA). The statistical significances of mean fresh storage root yields were analyzed using t-tests. The Regression Data Analysis tool in Excel was used to derive significant linear and quadratic regression equations between N application rates and NO$_3$-N concentrations at various depths and N accumulated in the roots/tops/plant. Q-Q plots and Levene’s test were used to test the data assumption of normality and homogeneity of the variance, respectively. Details on the data processing of the SR and ECov techniques and the calculation of ET$_a$ can be found in previous publications from the senior author [28,32,35].

Using the daily ET$_a$ determined in each experimental site, and the daily ET$_o$ retrieved from the spatial CIMIS data [36] for the coordinates of the monitoring station, the daily actual crop coefficient was calculated as the ratio of ET$_a$ to ET$_o$. Spatial CIMIS combines remotely sensed satellite data with traditional CIMIS stations data to produce site-specific ET$_o$ on a 2-km grid, which is a more accurate estimate of ET$_o$ for the individual sites.

3. Results

3.1. Plant Density and Canopy Growth Model

The plant density assessment indicated that there were substantial plant population differences between fresh market and procession carrots at the experimental sites (Table 4). The average mean plant population per m$^{-2}$ was 307 for processing carrots versus 133 for fresh market carrots, a difference of 220%. The mean plant density ranged between 126 (Site II) and 141 (Site III) plants per m$^{-2}$ for fresh market carrots and varied from 292 (Site VII) to 320 (Site V) plants per m$^{-2}$ for processing carrots.

| Site       | DREC (19–20) | I    | II   | III  | IV   | V    | DREC (20–21) | VI   | VII  | VIII | IX   |
|------------|--------------|------|------|------|------|------|--------------|------|------|------|------|
| Plant Density | 140 ± 7     | 129 ± 12 | 126 ± 14 | 141 ± 5 | 318 ± 11 | 320 ± 16 | 133 ± 6 | 297 ± 25 | 292 ± 31 | 128 ± 9 | 307 ± 13 |

A wide range in the length of the crop season (seeding through harvest) was observed amongst the sites, ranging from a 128-day period in a processing carrot field to a 193-day period in a fresh market carrot field (Table 3). Since the most common range of carrot
crop season in the low desert is 150–165 days, the crop canopy curves were presented for a 160-day period (Figure 3). The crop canopy coverage curves illustrate that the leaf density of processing carrots was slightly behind that of fresh market carrots during the first 100 days after seeding. Nearly 25% of the carrot canopy coverage occurred 40 days after seeding (40 DAS). Carrots were approximately at 72% and 85% canopy coverage by 80 and 100 DAS, respectively. The results suggest that carrot fields may reach a maximum canopy coverage of 92% by 120–130 DAS, which then decreases by 4–6% until harvest in a low desert cropping system.

![Canopy coverage curves for fresh market (a) and processing carrots (b) over the growing season.](image)

**Figure 3.** Canopy development curves (sigmoidal) for fresh market (a) and processing carrots (b) over the growing season. A total data set of 208 and 88 was used to develop the curves for fresh market and processing carrots, respectively. DAS stands for day after seeding.

### 3.2. Applied Water and Soil Water Tension Status

The common irrigation practice in carrot stand establishment in the low desert is to irrigate the field every other day using a sprinkler system during the first two weeks after seeding. The average applied water for this period (nearly four weeks after seeding) was 224.3 mm at the commercial sites and 157.1 mm at the DREC trials (Figure 4). It appears that carrots were typically over-irrigated during plant establishment. The seasonal applied water ranged from 480.7 (Site DREC (20–21) to 905.4 mm (Site III)) at the experimental sites.

Meaningful differences were observed between the seasonal applied water of the commercial fields irrigated by solid-set sprinklers the entire season and the fields converted to furrow irrigation after germination. An average of 815 mm seasonal irrigation water was applied at the furrow irrigated sites for a 160-day crop season. In contrast, the average irrigation water applied at the sprinkler irrigated sites was 583 mm for the same period. Sprinkler irrigation may be considered a more effective irrigation method when compared with furrow irrigation. More frequent and light irrigation events are possible by sprinklers. Sprinklers may also reduce salinity, a potential hazard in the low desert production system, which is important since carrots are very sensitive to salt accumulation.

Figure 5 demonstrates the half-hourly soil water tension at Sites I (sprinkler irrigated field) and II (furrow irrigated field). The fields received natural rainfall on 29 November (10 mm) and 9–11 March (35 mm). There were several days with rainfall less than 4 mm per day in the period as well. Soil water tension data at the depths of 15 and 30 cm show potential water stress between 24 November and early December at Site II. An average soil water tension of 110 kPa at the top 30 cm of the sandy loam soil of this field revealed potential crop water stress in this period when the root development was not yet completed. The long drying period at this field occurred due to common conventional farming practices and a one-week delay in irrigation during the transition from sprinkler irrigation to furrow irrigation. While it is unclear what effect this temporary stress had on carrot growth, this low soil water availability was not observed in any of the other sites. For instance, at Site I, with a silty clay loam soil texture, the soil water potential (an average of 60 kPa in the top 30 cm of the profile) did not decline as low as at Site II. Site II received about 9% more
water than Site I by that time, which means soil property (sandy soil texture) and irrigation management could have influenced the severity of water stress at Site II.

Figure 4. Cumulative applied water (irrigation + rainfall) over the growing season at the experimental sites.

Figure 5. Half-hourly soil water tension measured at multiple depths of 15, 30, 45, 60, 90, and 120 cm at Sites I (sprinkler irrigation) (a) and II (furrow irrigation) (b) over the growing seasons.
The results illustrated that soil water tension fluctuated mostly within the top 45 cm depth at Site I, while some responses were observed at deeper soil depths (45–90 cm) at Site II. In other words, there was a higher potential of deep percolation at Site II. Soil water tension readings below 15 cm indicated that soil moisture was effectively maintained at a relatively uniform and desirable level during the crop season after plant establishment, at an average value of 23 and 18 kPa at Sites I and II, respectively. The soil profile at the 120 cm depth was saturated the entire growing season at these sites (Figure 5).

3.3. Actual Evapotranspiration and Crop Coefficients

The seasonal ET<sub>a</sub> varied between 305.8 mm at Site IV and 486.2 mm at Site VIII (Figure 6). The results clearly demonstrated that the carrot sites had variable water consumptions depending upon early/late planting, processing vs. fresh market, irrigation practices, length of crop season, soil type, and weather conditions. For instance, Site VIII was a fresh market field with a dominant soil texture of sandy clay loam under sprinkler irrigation. This field was harvested very late and had a 193-day crop season. In contrast, Site IV was a furrow irrigated processing carrot field with a silty loam soil texture and a short crop season of 128 days. There was not a considerable difference (less than 3%) between the total ET<sub>a</sub> (CIMIS Meloland station) of October–January in the 2019–2020 and 2020–2021 seasons.

The daily ET<sub>a</sub> varied widely over the crop season in each site. For example, at Site VIII, which had the longest crop season, daily ET<sub>a</sub> varied between 0.66 (68 DAS) and 6.2 mm d<sup>−1</sup>, eight days before harvest. At Site I, with an average length season, the highest and lowest daily ET<sub>a</sub> observed were 0.23 (55 DAS) and 4.9 mm d<sup>−1</sup>, two days before harvest, respectively (Figure 7).

The trends of daily K<sub>a</sub> values over the season were similar across the experimental sites. A maximum and minimum daily K<sub>a</sub> value of 1.12 and 0.32 was obtained at Site VIII, with 1.09 and 0.40 at Site I, respectively (Figure 7). Trivial differences (<4.7%) were found in the average K<sub>a</sub> values of the initial season (seeding to 30 days after seeding), mid-season (100–160 days after seeding), and late season (at harvest) amongst the experimental sites. Average K<sub>a</sub> values of 0.62, 0.90, and 0.82 were determined for the initial season, mid-season, and late season at Site I, respectively. These values could likely represent the ‘potential’ crop coefficient (K<sub>c</sub>) values for fresh market carrots in the region since the applied irrigation

![Figure 6](image-url). Cumulative actual evapotranspiration (ET<sub>a</sub>) at each of the experimental sites in the 2019/2020 season (a) and the 2020/2021 season (b). Surface renewal daily ET<sub>a</sub> is reported for the sites.

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water at this site was nearly 70% higher than the measured actual ET, and soil water tension data suggested that no water deficit occurred over the crop season.

![Graph showing cumulative actual evapotranspiration (ETa) at each site in the 2019/2020 season (a) and the 2020/2021 season (b). Surface renewal daily ETa is reported for the sites.](image)

Figure 7. Daily actual evapotranspiration (ETa) and daily actual crop coefficient (Kca) at Sites I (a) and VIII (b). The daily stress coefficient (Ks) represents water and salt stresses, management, and environmental multipliers. To obtain the actual ET, Ks is needed to adjust the crop coefficient (Kca).

### 3.4. Soil Nitrate-N Availability

Variable soil NO3-N concentrations were observed in the top 30 cm depth of the experimental sites over the growing seasons (Figure 8). Soil NO3-N concentrations ranged from 9.1 (Site IV) to 13.3 mg kg\(^{-1}\) (Site III) pre-seeding and from 3.2 (Site V) to 12.4 mg kg\(^{-1}\) (Site DREC-3) post-harvest in the 2019–2020 season. Greater soil NO3-N contents were observed in most sites prior to seeding in the 2020-2021 season. It ranged from 10.2 (Site VI) to 30.4 mg kg\(^{-1}\) (Site IX), while the NO3-N concentration post-harvest was as low as 1.6 mg kg\(^{-1}\) (Site IX). However, soil NO3-N contents were numerically higher in the early-to-mid season (50–110 days after seeding). A maximum soil NO3-N concentration of 26.8 (Site DREC-3) and 31.0 mg kg\(^{-1}\) (Site IX) was observed in the mid-seasons of 2019–2020 and 2020–2021, respectively.

Soil NO3-N concentrations post-harvest increased with increasing N application rate in some cases, but the pre-seeding NO3-N content (after pre-plant N application) did not increase at most sites (Figure 8 and Table 5). A significant linear trend was found between the N application rate and post-harvest NO3-N available at the depth of 60–90 cm in fresh market carrot fields and at the depth of 90–120 cm in processing carrot fields (Table 5). High rates of N applications (Sites DREC-3 (19–20) and DREC-3 (20–21)) and high rates of water and N applications along with sandy soil texture (Sites II, III, V) can likely be the main reasons for N leaching and the movement of nitrate to deeper depths. The N applied from irrigation water was not considered in the calculations since the value (from nitrate-N) was determined to be less than 1 kg ha\(^{-1}\) for all sites.
Table 5. Effect of N application rates on NO$_3$-N concentrations (mg kg$^{-1}$) in fresh market and processing carrots pre-seeding and post-harvest at various depths.

| Experimental Site | N Application Rate (kg ha$^{-1}$) | Pre-Seeding | Post-Harvest |
|-------------------|-----------------------------------|-------------|--------------|
|                   |                                   | 30–60 cm | 60–90 cm | 90–120 cm | 30–60 cm | 60–90 cm | 90–120 cm |
| Fresh Market Carrots |                                  |          |          |        |          |          |          |
| DREC-1 (20–21)     | 197.5                             | 15.2     | 11.2     | 13.7   | 4.3      | 3.8      | 13.0     |
| DREC-1 (19–20)     | 205.2                             | 12.1     | 7.9      | 13.4   | 10.8     | 8.3      | 12.5     |
| I                  | 220.9                             | 10.3     | 9.8      | 8.9    | 10.7     | 7.9      | 8.5      |
| DREC-2 (20–21)     | 232.5                             | 16.7     | 11.5     | 14.1   | 5.6      | 6.5      | 14.7     |
| DREC-2 (19–20)     | 239.4                             | 10.7     | 11.3     | 13.2   | 11.3     | 13.0     | 12.8     |
| VIII               | 256.6                             | 19.9     | 14.2     | 13.4   | 4.4      | 8.2      | 12.6     |
| III                | 277.5                             | 8.7      | 11.1     | 9.5    | 2.7      | 8.9      | 11.5     |
| II                 | 293.7                             | 14.7     | 13.2     | 7.2    | 12.5     | 15.7     | 10.8     |
| DREC-3 (20–21)     | 298.2                             | 15.5     | 12.4     | 12.6   | 16.3     | 14.5     | 14.3     |
| DREC-3 (19–20)     | 305.3                             | 11.0     | 8.8      | 14.7   | 13.3     | 12.3     | 16.1     |
| Significance       | L                                 | NS       | NS       | NS     | NS       | NS       | *        |
| Q                  | NS                                | NS       | NS       | NS     | NS       | NS       | NS       |
| R$^2$              | -                                 | -        | -        | -      | 0.55     | -        | -        |
| Processing carrots |                                  |          |          |        |          |          |          |
| IV                 | 211.8                             | 8.6      | 11.3     | 8.6    | 9.1      | 13.7     | 8.0      |
| V                  | 220.8                             | 6.8      | 6.7      | 3.9    | 2.3      | 4.2      | 5.2      |
| VI                 | 247.7                             | 5.0      | 2.5      | 2.5    | 2.5      | 3.2      | 9.3      |
| VII                | 258.5                             | 24.8     | 13.8     | 12.3   | 16.6     | 15.8     | 11.9     |
| IX                 | 266.0                             | 6.9      | 9.7      | 11.7   | 7.5      | 11.5     | 13.4     |
| Significance       | L                                 | NS       | NS       | NS     | NS       | NS       | *        |
| Q                  | NS                                | NS       | NS       | NS     | NS       | NS       | NS       |
| R$^2$              | -                                 | -        | -        | -      | -        | -        | 0.69     |

NS Non-significant. * Significant at the 5% level of probability. L: linear regression. Q: quadratic regression. R$^2$: coefficient of determination.

3.5. Dry Matter Accumulation

Dry matter (DM) accumulation in roots was generally linear after 60–73 DAS at the experimental sites (Figure 9), for instance, after 60 DAS at Site IV and after 68 DAS at Site DREC-2 (19–20). The first sampling date was 42–48 DAS at all sites when the DM accumulation was less than 0.11 t ha$^{-1}$ at the date, and, accordingly, the values were reported from the second sampling. The results indicated that an average of 11.1% of DM accumulation in roots occurred by 80 DAS.

Dry matter accumulation in tops was greater than in roots from the first sampling date to 88 DAS on average in processing carrots and 84 DAS in fresh market carrots. DM content in tops increased gradually, following a quadratic or linear regression, and, in most sites, leveled off or declined slightly late in the season. Peak DM accumulation occurred between 139 and 147 DAS in most cases. No consistent differences in the patterns of DM content were found between soil types, irrigation practices, or cultivars.

3.6. N Uptake

Total N uptake in roots was similar to DM content at the experimental sites, following a linear regression after 60–73 DAS without declining near harvest (Figure 10). The regression coefficient of the linear models, with a high coefficient of determination between 0.91 and 0.98, varied from 1.434 at Site VII to 1.917 at Site IX. Small gradual increases in both DM and N contents of roots were observed until about 65 DAS. It suggests that DM and N begin to accumulate at a rapid rate between 65 and 80 DAS; however, the period of rapid increase could vary depending on early (September) or late (November) plantings.
Figure 8. Soil nitrate-N (NO$_3$-N) concentrations at the depth of 0–30 cm at the experimental sites over the 2019/2020 (a) and 2020/2021 (b) growing seasons.
3.6. N uptake

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A significant linear trend was found between N uptake in tops and N application rates in both fresh-market and processing carrot fields (Table 6). However, no significant linear or quadratic regression was obtained between N application rates and both N accumulated in roots and total N uptake. Although the N accumulated in tops appeared to drop down or level off in most sites beyond 120 to 145 DAS, the N content decline occurred after DAS 155 at Sites VIII and XI with their longer growing seasons.

Figure 10. Total N accumulation during the growing season for tops and storage roots at the experimental sites.
Table 6. Effect of N application rate on N concentration in roots, tops, and plant (total) in fresh market and processing carrots.

| Experimental Site | N Applied (kg ha\(^{-1}\)) | N in Roots (kg ha\(^{-1}\)) | N in Tops (kg ha\(^{-1}\)) | Total N Uptake (kg ha\(^{-1}\)) |
|-------------------|-----------------------------|-----------------------------|-----------------------------|-------------------------------|
| Fresh Market Carrots |                             |                             |                             |                               |
| DREC-1 (20–21)    | 197.5                       | 164.6                       | 116.1                       | 280.7                         |
| DREC-1 (19–20)    | 205.2                       | 145.6                       | 105.5                       | 251.1                         |
| I                 | 220.9                       | 135.5                       | 90.6                        | 226.1                         |
| DREC-2 (20–21)    | 232.5                       | 159.2                       | 119.8                       | 279.0                         |
| DREC-2 (19–20)    | 239.4                       | 156.8                       | 110.7                       | 267.5                         |
| VIII              | 256.6                       | 227.3                       | 123.2                       | 350.5                         |
| III               | 277.5                       | 152.3                       | 108.8                       | 261.1                         |
| II                | 293.7                       | 145.6                       | 118.7                       | 264.3                         |
| DREC-3 (20–21)    | 298.2                       | 151.2                       | 135.5                       | 286.7                         |
| DREC-3 (19–20)    | 305.3                       | 150.1                       | 131.3                       | 281.4                         |

| Significance      | L: linear regression        | Q: quadratic regression     | R\(^2\): coefficient of determination | NS: Non-significant. * Significant at the 5% level of probability. |
|-------------------|-----------------------------|-----------------------------|---------------------------------------|-----------------------------|
| Fresh Market Carrots |                             |                             |                                       |                               |
| IV                | 211.8                       | 105.3                       | 100.1                                  | 205.4                        |
| VI                | 220.8                       | 153.4                       | 93.7                                   | 247.1                        |
| VII               | 247.7                       | 134.4                       | 106.6                                  | 241.0                        |
| IX                | 258.5                       | 191.5                       | 108.0                                  | 299.5                        |
| V                 | 266.0                       | 117.6                       | 109.4                                  | 227.0                        |

| Processing carrots |                             |                             |                                       |                               |
|-------------------|-----------------------------|-----------------------------|---------------------------------------|-----------------------------|
| IV                | 211.8                       | 105.3                       | 100.1                                  | 205.4                        |
| VI                | 220.8                       | 153.4                       | 93.7                                   | 247.1                        |
| VII               | 247.7                       | 134.4                       | 106.6                                  | 241.0                        |
| IX                | 258.5                       | 191.5                       | 108.0                                  | 299.5                        |
| V                 | 266.0                       | 117.6                       | 109.4                                  | 227.0                        |

The results demonstrated a wide range of N accumulated in both roots and tops at harvest (Table 6). For instance, a total N content of 350.5 kg ha\(^{-1}\) was observed in a fresh market carrot field with a long growing season of 193 days, including 227.3 and 123.2 kg N ha\(^{-1}\) in roots and tops, respectively.

The minimum total N uptake (205.4 kg ha\(^{-1}\)) was observed at Site IV, with 105.3 kg N ha\(^{-1}\) accumulated in roots and 100.1 kg N ha\(^{-1}\) accumulated in tops. It appears that nearly 28% of seasonal N accumulated across all sites, mostly in tops, occurred by 80 DAS (Figure 10) when the canopy cover reached an average of 67% (Figure 3). A large proportion of this N content was stored during a 30-day period (50–80 DAS). The results also suggest that nearly 50% of total N was taken up during a 50-day period (80 DAS through 130 DAS). This 50-day period appears to be the most critical period for N uptake, particularly in the storage roots, when carrots develop their large canopy and extensive rooting system. The majority of N is taken up during the months of December to February, and hence, proper N fertility in the effective crop root zone is essential during this period.

3.7. Fresh Root Yield

The total fresh storage root yield varied from a minimum of 83.9 Mg ha\(^{-1}\) at Site IV (processing carrots harvested 128 DAS) to a maximum of 132.7 Mg ha\(^{-1}\) at Site VIII (fresh market carrots harvested 193 DAS) (Table 7). Site IV was a furrow irrigated field with a silty loam soil texture. A total of 211.8 kg N ha\(^{-1}\) and 684.7 mm water was applied at this site over the growing season. The pre-seeding soil organic matter and NO\(_3\)-N content in the top 30 cm were 1.12% and 10.7 mg kg\(^{-1}\), respectively.
Table 7. Mean fresh storage root yields (± standard deviation) at the experimental sites.

| Experimental Site N Applied (kg ha⁻¹) | Mean ± SD (Mg ha⁻¹) |
|--------------------------------------|---------------------|
| **Fresh market carrots**              |                     |
| DREC-1 (20–21)                       | 197.5 ± 104.7       |
| DREC-1 (19–20)                       | 205.2 ± 111.5       |
| I                                    | 220.9 ± 104.0       |
| DREC-2 (20–21)                       | 232.5 ± 105.8       |
| DREC-2 (19–20)                       | 239.4 ± 112.7       |
| VIII                                 | 256.6 ± 132.7       |
| II                                    | 220.9 ± 104.0       |
| DREC-2 (20–21)                       | 232.5 ± 105.8       |
| DREC-2 (19–20)                       | 239.4 ± 112.7       |
| III                                  | 237.5 ± 120.8       |
| II                                    | 293.7 ± 118.3       |
| DREC-3 (20–21)                       | 298.2 ± 101.1       |
| DREC-3 (19–20)                       | 305.3 ± 109.6       |
| Significance                          |                     |
| L                                     | NS                  |
| Q                                     | NS                  |
| R²                                    | -                   |

| **Processing carrots**                |                     |
| IV                                    | 211.8 ± 83.8        |
| VI                                    | 220.8 ± 97.1        |
| VII                                   | 247.7 ± 101.7       |
| IX                                    | 258.5 ± 110.0       |
| V                                     | 266.0 ± 96.6        |
| Significance                          |                     |
| L                                     | NS                  |
| Q                                     | NS                  |
| R²                                    | -                   |

NS Non-significant. L: linear regression. Q: quadratic regression. SD: standard deviation. R²: coefficient of determination.

At Site VIII, a higher level of soil organic matter (1.49%) and NO₃-N content (30.1 mg kg⁻¹) was observed before planting. Site VIII had a sandy clay loam soil texture and was irrigated by a solid-set sprinkler irrigation system the entire crop season. Total irrigation water and N fertilizer applied were 528.3 mm and 256.6 kg ha⁻¹, respectively. It appears that high soil N availability due to a high residual N content from the preceding crop (it was a carrot field) and a greater N application rate, along with a long growing season and more efficient irrigation system, contributed to the high root yield at Site VIII. The post-harvest soil NO₃-N content in the top 30 cm was 9.9 mg kg⁻¹ at Site IV, which clearly displays the large amount of N left in the soil at harvest. High NO₃-N concentration at the depth of 60–90 cm at harvest could be the result of over-irrigation at Site IV, which likely caused leaching N.

Lower observed yields in the 2020–2021 season at the DREC trials could have resulted for several reasons. There was no considerable difference among N applications, length of crop season, applied water and actual ET (nearly 6% lower in the 2020–2021 season), and plant density (about 5% lower in the 2020–2021 season) between the two seasons. The impact of the year and the lack of crop rotation (even though this is a practice followed by some carrot growers to use the soil N residue of previous seasons effectively) could have contributed to a lower total marketable yield in the 2020–2021 season.

Overall, greater marketable root yield was observed in fresh market carrots when compared with processing carrots. The average root yield was 112.5 Mg ha⁻¹ for the fresh market carrot sites and 97.8 Mg ha⁻¹ for the processing carrot sites. The maximum mean root yield of processing carrots was observed at Site IX (110.1 Mg ha⁻¹).

4. Discussion
4.1. Crop Water and Nitrogen Use

A comparison between applied water and crop water use indicated that the carrot sites could be over-irrigated by 2.1 to 3.3 times the crop water requirements during plant establishment (Figures 4 and 6). While high frequent irrigation events in this period are recommended to keep beds moist, the amount of applied water with each irrigation event
needs to be effectively managed to reduce the leaching of NO₃-N from pre-fertilization or residual soil N from the previous growing season. Residual soil N contribution can be considerable, specifically if the field has been a carrot field in the past season. The results illustrated that a notable amount of N remained in the carrot foliage at harvest, potentially contributing to the following season an average of 42–44% of total N accumulated in the plant (tops and roots) (Figure 10).

An average of 370–390 mm may be considered seasonal ETa for carrots with a 160-day crop season in the region. The average crop coefficients values were determined to be 0.62, 0.90, and 0.82 for the initial season, mid-season, and late season, which are lower than the values proposed in earlier studies. The Kc values were reported to be 0.75, 1.0, and 0.94 for the initial season, mid-season, and late season, respectively, for carrots in Southeast Brazil [24]. The Kc values of 0.7 (initial season), 1.05 (mid-season), and 0.95 (late season) were considered for carrots by FAO 56 [37].

Earlier research conducted in Canada showed that carrots can take up more than 380 kg N ha⁻¹ over the growing season [38]. This amount is close to the total N accumulated of 350.5 kg ha⁻¹ that was observed in a fresh market carrot field in this study.

Tremblay et al. [39] proposed that the appropriate level of residual N following the harvest of carrot fields should not exceed 30 kg ha⁻¹ at the top 30 cm. This level of residual N could be a safety margin index to prevent over-fertilization late in the season, a month before harvesting, where over-fertilization may lead to leaching and cause environmental concerns. The soil post-harvest NO₃-N contents demonstrated that most experimental sites were likely at the appropriate range of residual N except Sites DREC-3 (19–20), DREC-3 (20–21), II, and V. A higher N rate (266–305.3 kg ha⁻¹) was applied at all these four sites.

### 4.2. N Removal

More N was applied than was removed from the field by harvesting the roots (Figure 11). The net N removal (= total N accumulated in roots minus total N applied) at harvest varied from a maximum of −39.3 kg ha⁻¹ at Site VIII to a minimum of −165.2 kg ha⁻¹ at Site DREC-3 (19–20). No positive net N removal occurred in any of the experimental sites, and net N removal declined (larger negative numbers) as the N application rate increased at most sites. A similar conclusion was reported by earlier studies carried out on different carrot cultivars in mineral soils [5,6]. N remains in the field can be potentially leached or contribute as a source of N in the following season.

![Figure 11. Net N removal at the experimental sites at harvest. Net N removal was calculated as total N accumulated in the roots at harvest minus seasonal N applied.](image-url)

Carrots were harvested very late at Site VIII (193 DAS), and as a result of the linear relation of N accumulation by time in roots, the N removal at harvest increased up to 227.3 kg ha⁻¹ at this site. It suggests that the carrots must have removed a high level of nitrogen from the soil at Site VIII. A high N application rate of 305.3 kg ha⁻¹ and lower N taken up by the roots (134.4 kg ha⁻¹) are the main reasons for the larger negative numbers.
of net N removal at Site DREC-3 (19–20). Applications of more or less N than the optimum can cause a dramatic decrease in the dry weight of tops and storage roots [4,12], which could be a reason for lower root storage yield at this site and, consequently, lower N accumulation in roots.

Carrots have a deep rooting system that allows for improved capture of N from deep within the soil profile. Fibrous roots were present at the depth of 1.5 m below the soil surface at Site DREC-2 (20–21). This observation is consistent with the results of previous studies [4,40,41]. There is a risk of leaching soil residual N due to heavy pre-irrigation (a common practice for salinity management in the low desert) in late summer, prior to land preparation. N is likely accumulated at deeper depths by the beginning of the growing season, and, consequently, it is suggested that there is a potential N contribution from the soil for carrots when the roots are fully developed. Carrots require minimal applied N for optimum yield and can be grown to uptake a large amount of N during the growing season [6,9,13].

The nitrogen removed by carrot roots was determined as the ratio of total N accumulated in roots to fresh storage root yield at each of the experimental sites (Figure 12). The mean value of this indicator ranged between 1.24 and 1.73 kg N/Mg fresh carrots at Sites II and IX, respectively. A wide range of 1.48 to 3.73 kg N/Mg fresh carrots was reported by earlier studies for different soil types and locations [2,4,42]. It is suggested that the low value of this indicator could likely be associated with the low desert carrot production system and high potential carrot yield of the region, which is one of the most productive agricultural production regions in California. Careful management of N applications in the low desert carrots appears to be crucial because fertilizers contribute the main source of N, particularly due to the low organic matter content of the soils and the very low nitrate level of Colorado River water. Knowing this fact, the soil NO\textsubscript{3}-N contents pre-seeding and over the growing season at different sites revealed that none of the sites had N deficiencies during the crop season, and, consequently, the N splitting management practices followed by the farmers were likely effective in most cases. The common practice is to apply 9–15% of total seasonal N as pre-plant and the remaining amount through irrigation events over the season. Applying 15–30% of seasonal N through irrigation events, 45–70 days after seeding, was examined at the experimental sites. The optimal N splitting practice could change depending upon soil organic matter and residual N from the preceding crop. Sidedressing (applying solid fertilizers in a shallow furrow or band along the side of beds), 4–6 weeks after planting, is a practice followed by some carrot farmers in other regions [4] to avoid leaching N and minimize root forking and early excessive vegetation that may delay root development [2,4,43,44]. It appears that the practice of 15–30% seasonal N application through irrigation events, 45–70 days after seeding, has similar effectiveness as a sidedress N application.

Within the range of N application rates examined at the experimental sites (197.5–305.3 kg ha\textsuperscript{-1}), there were no significant linear or quadratic relationships between carrot fresh root yield and N application rate, although the results suggest a positive effect of N application on carrot yield (Table 7). Sufficient N availability in the crop root zone over the growing season and the lack of significant yield response to N application explicate that N optimal rates could be likely less than the total applied amounts in most cases. Adequate nitrogen and water applications reduce costs and help prevent leaching, while excess N may lead to excessive N storage in the roots, which may be a concern for processing carrots. It is important to note that due to the over-irrigation of carrots (Figures 4 and 6), positive impacts could also be observed from higher N rates in some cases, particularly in sandy soils with high leaching potential. In other words, integrated optimal N and water management is needed to accomplish greater N and water efficiency and, consequently, keep lower rates that are beneficial to overall profitability. Application rates below 200 kg N ha\textsuperscript{-1} need to be assessed to ensure the potential impact of lower N rates. A recent study conducted in California reported that seasonal nitrogen rates greater
than 170 kg ha\(^{-1}\) are seldom necessary to maximize root yield and that excessive nitrogen application increases root cracking during harvest and handling [44].

![Figure 12](image-url)

**Figure 12.** Removal N per fresh root weights at the experimental sites at harvest. The horizontal lines demonstrate the mean values, and the bars display the maximum and minimum values of removal N per fresh root weights. D1, D2, and D3 represent Sites DREC-1, DREC-2, and DREC-3, respectively.

5. Conclusions

One of the biggest needs of the carrot industry is data on crop N uptake/removal rates, N uptake curves, and irrigation requirements for various soil types, carrot crops, and crop production systems. This study aimed to explore and fill knowledge gaps for N and water management in low desert carrots through conducting experimental trials at a UC research facility and nine farmer fields in the desert and developing strategies to reduce N losses and optimize nitrogen and irrigation water use. The results demonstrated a wide range of N accumulated in roots and tops at harvest, ranging from 105.3 and 100.1 kg N ha\(^{-1}\) accumulated in a fresh market field, respectively, to 227.3 (roots) and 123.2 (tops) kg N ha\(^{-1}\) in a processing carrot field. The results clearly demonstrated that the carrot fields had variable consumptive water use, depending upon early/late planting, cultivars, irrigation practices, length of crop season, soil type, and weather conditions. An average of 370–390 mm may be considered crop water use for a 160-day crop season. Sufficient N availability in the crop root zone over the growing season and the lack of a significant yield response to N application within the range of N application rates suggested that N optimal rates could be likely less than the applied amounts at most sites. Since residual soil N contribution can be considerable in carrots, a pre-plant soil nitrate-N assessment, down to a 60 cm depth, can be a tool that enables farmers to improve N management and maximize yield and quality while minimizing economic and environmental costs. Utilizing the information developed by this study on crop N uptake, net removal rates, and crop water use may have a significant impact on water quality issues and soil water and N availability, potentially increasing the economic sustainability of carrot production as water resources become less available or more expensive and N fertilizer prices rise in the future.

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