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RESEARCH ARTICLE

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Assessing Nitrate Leaching During Drought and Extreme Precipitation: Exploring Deep Vadose-Zone Monitoring, Groundwater Observations, and Field Mass Balance

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Key Points:

- Deep vadose zone monitoring, shallow groundwater observation, and field-level mass balance were evaluated to assess nitrate leaching
- Nitrate leaching increased during heavy rainfall in the winter following dry summer periods
- Groundwater nitrate concentrations followed the observed leaching with increasing values following heavy rainfall events

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The increasing concern over agricultural practices' impact on groundwater quality necessitates comprehensive studies to evaluate and compare monitoring strategies for nitrate leaching. This work addresses this imperative by examining three methodologies: deep vadose-zone monitoring, shallow groundwater intensive monitoring, and field-level mass balance. The primary objective of the study was to assess nitrate leaching from an intensively cropped processing tomato rotation field using three different methods. Additionally, this study focuses on contrasting conditions between the growing season (characterized by drought in some years) and the winter/rainy season (characterized by extreme precipitation in some years). Results indicate varying degrees of nitrate leaching across methods, with all approaches detecting leaching events during the growing season and off-season precipitation. Despite uncertainties inherent in field-level mass balance estimates, they align reasonably with intensive in-situ monitoring results using the deep Vadose Monitoring System (VMS). Throughout two growing seasons and corresponding fall-winter rainy periods, the VMS effectively tracked seasonal nitrogen leaching below the root zone, correlating with observed groundwater nitrate concentrations increases following extreme precipitation events. Nitrate leaching increased during heavy rainfall in the winter following dry summer periods observed across the deep vadose zone using two VMS systems. This underscores the importance of continuous monitoring and assessment in understanding nitrate dynamics and groundwater contamination risks. In conclusion, this study contributes to knowledge and ongoing research by providing insights into effective monitoring strategies for nitrate leaching into groundwater from intensive cropping systems.

Plain Language Summary

The study assessed the effect of crop production on nitrate contamination of groundwater. The study compared different ways of monitoring nitrate leaching, which is when nitrate from fertilizers moves into the groundwater. The study evaluated three methods: deep vadose-zone monitoring, shallow groundwater intensive monitoring, and field-level mass balance. The main goal was to see how nitrate leaching changes between the dry growing season and the winter/rainy season in a tomato field. The study found that all methods showed nitrate leaching despite some uncertainties, the field-level mass balance method matched well with the intensive in-situ monitoring. The study showed that nitrate leaching increased during heavy rainfall in the winter after dry summer periods. Overall, the study highlights the importance of continuous monitoring to understand nitrate leaching and groundwater contamination risks in intensive cropping systems.

1. Introduction

The impact of agricultural practices on groundwater quality is a growing concern globally (Ascott et al., 2017; Gu et al., 2023). In the United States, regions with intensive agriculture such as the Mid-West and the Central Valley of California are experiencing groundwater contamination from nitrates with some regions such as the Tulare Lake Basin having one-third of the tested drinking and irrigation wells exceeding the 10 mg/l of NO_3-N limit (MCL) (Harter et al., 2012; Nolan & Ruddy, 2016). Groundwater nitrate contamination due to intensive agriculture and the overuse of fertilizers is a significant issue reported in several European Union countries, India, the North China Plain, and New Zealand, often exceeding the MCL (Ahada and Suthar, 2018; EC, 2021; Rogers et al., 2023; Zhang et al., 2023).

One critical issue is the assessment of the effectiveness of conservation practices that can mitigate nitrate leaching to groundwater. Crop-specific nitrogen mass balances in California showed that surplus nitrogen averages 40% of applied nitrogen for vegetables, posing a significant potential nitrate load to groundwater. To address this

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challenge, new regulatory programs have been developed, aimed at minimizing nitrogen surplus and potential leaching to groundwater (ILRP, 2022; Hansen et al., 2017). Examples of such regulations include the Central Valley-wide Salt and Nitrate Management Plan (SNMP) whose goal is to address both legacy and ongoing salt and nitrate accumulation issues. The SNMP prioritizes nitrate discharge to groundwater through individual or management zone permitting (California Regional Water Quality Control Board Central Valley Region, 2020).

Growers are adopting improved irrigation and fertigation practices to comply with these regulations following a recent life cycle assessment that identified the potential for improved resource use efficiencies in processing tomato production in California (Winans et al., 2020). Recent research has identified specific management practices, such as fertigation methods that supply fertilizer and irrigation amounts at the appropriate rate, place, and time, that can be highly cost-effective in mitigating nitrogen pollution, including nitrate leaching (Gu et al., 2023; Hansen et al., 2017). Novel modeling approaches are being used to assess the efficacy of a range of management practices (Gu et al., 2023; Nicolas et al., 2024; Raij-Hoffman et al., 2022), but natural field heterogeneity and the time lag between fertilizer application, uptake in the vadose zone and accumulation in groundwater still pose great uncertainty regarding agricultural nitrogen management for groundwater protection (Ascott et al., 2017, 2021; Basu et al., 2022; Weitzman et al., 2022). In this context, it is essential to monitor water flow and nitrogen transport in the shallow and deep vadose zone for groundwater protection, as proposed by Dahan (2020), rather than focusing solely on groundwater monitoring. One of the widespread nitrogen leaching monitoring approaches is a mass balance, which can be performed at the individual plant, plot or field level. In recent studies, the classic mass balance has been supported by and compared to different vadose zone monitoring techniques wich generally include sampling soil pore water at different depths either with suction cups (Baram et al., 2016, 2017, Pandey et al., 2018; Weitzman et al., 2022), drainage lysimeters or pipes (Constantin et al., 2010; Libutti & Monteleone, 2017) and deep-vadose zone monitoring systems (Turkeltaub et al., 2016).

This paper aims to contribute to knowledge and ongoing research on the impact of agricultural practices on groundwater quality in Mediterranean climates. The main method is the comparison of different monitoring strategies for nitrate leaching from the unsaturated zone into groundwater under contrasting weather conditions in dry summer growing seasons and wet winter seasons. Specifically, the objective of this study was to evaluate three different methods for monitoring nitrate leaching to groundwater from an intensively cropped processing tomato field under contrasting environmental conditions typical of Mediterranean climates. The three methods were deep vadose zone monitoring (VMS), shallow groundwater intensive monitoring, and field level mass balance. A secondary objective was to measure the fate of the surplus nitrogen during drought conditions characteristic of the growing season and extreme precipitation during the winter/rainy season.

2. Materials and Methods

2.1. Field Description

A monitoring site was established in Yolo County, CA composed of a 34-ha field cropped in a processing tomato rotation (coordinates at the center of the field are 38°41'16.67"N and 121°59'15.95"W). Mean field elevation above sea level measured at 11 points was 50.1 m with a standard deviation of 0.5 m. The soil is defined as a Capay silty clay by the NRCS-USDA soil series (https://casoilresource.lawr.ucdavis.edu/gmap/). Processing tomatoes were planted on 6 April 2021, and irrigated using sub-surface drip irrigation (SDI) and fertigation was performed according to best management practices at the grower's discretion. The drip line was buried in the middle of the150 cm wide growing bed at 20 cm depth, with a dripper spacing of 30 cm and a dripper discharge rate of 0.6 l/hr. Two rows of processing tomatoes were transplanted one on either side of the dripline. The processing tomatoes were mechanically harvested on 25 August 2021. The green aboveground biomass was crushed and left on the topsoil during harvest. Following the processing tomato season, cucumbers grown for hybrid seeds were planted on 16 April 2022, and 18 May 2022, and terminated or harvested on 28 July 2022, and 9 September 2022 for male and female plants, respectively.

2.2. Intensive Groundwater Monitoring Network

Groundwater monitoring is used worldwide as the gold standard indicator of the effectiveness of agricultural management practices that aim to prevent or reduce nitrate leaching. Examples from the Netherlands (Fraters et al., 1998) and Denmark (Dalgaard et al., 2014; Hansen et al., 2017) demonstrate how policy induced changes in management affected the groundwater nitrate concentrations. In this study, we include a dense groundwater

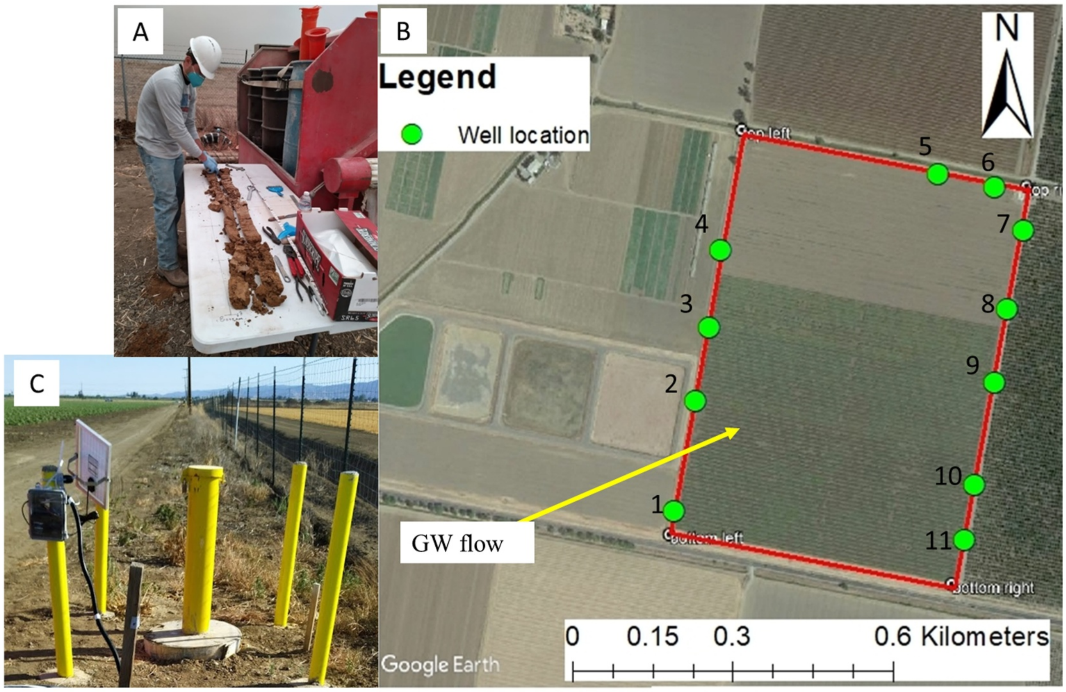

Figure 1. (a) Soil sampling during groundwater well drilling and installation. (b) groundwater monitoring well locations. (c) view of one of the western wells.

monitoring network as the gold standard measurement for nitrate leaching and as the end-of-the-chain result of the plant-soil-atmosphere interaction regarding water and nitrogen.

Eleven shallow groundwater monitoring wells were installed in October 2020 (Figure 1a). The wells are located around the field (to minimize interference with tillage operations) along the east, north, and west boundaries (Figure 1b). The groundwater flow direction was estimated from groundwater elevation data as southwest to northeast. Groundwater depth was approximately 10 m below the land surface measured during a previous survey, therefore the wells were constructed with a depth of 15 and a 6 m screen, from 9 to 15 m depth. Groundwater elevation and nitrate concentrations were measured in each well approximately every six weeks during the study period, with a total of 16 sampling events.

2.3. Field Water and Nitrogen Mass Balances

Each component of the water and nitrogen mass balance was either measured or estimated. The corresponding uncertainty was measured or estimated as described below. Percolating drainage and N leaching or loads leaving the bottom of the root zone vertically, were then calculated with the accumulating uncertainty of the different variables in each Equations 1 and 2.

Seasonal field level water mass balance was calculated using Equation 1 where: I is the irrigation amount as reported by the grower and estimated using grower reported dripper distribution and discharge rate together with pressure transducers in the six irrigation areas of the field for irrigation timing; P is the precipitation which was negligible during the spring-summer growing season; ET is the actual crop evapotranspiration measured with an in-situ eddy covariance flux tower from day 12–128 of the growing tomato season and from day 75–137 in the cucumber season and estimated from remote sensing SEBAL energy balance data (https://www.irriwatch.com/en/: IrriWatch, Maurik, The Netherlands) for the days without eddy covariance data; dS is the seasonal change in soil water storage in the top 60 cm measured at six locations on the first and last day of the season using the sampling protocol described in Lazcano et al. (2015).

Seasonal field level nitrogen mass balance was calculated using Equation 2 where: N_{Irr} is the total nitrate applied as a result of a NO_3-N concentration of 11.58 mg/l in the groundwater used for irrigation; N_{Min} is the seasonal

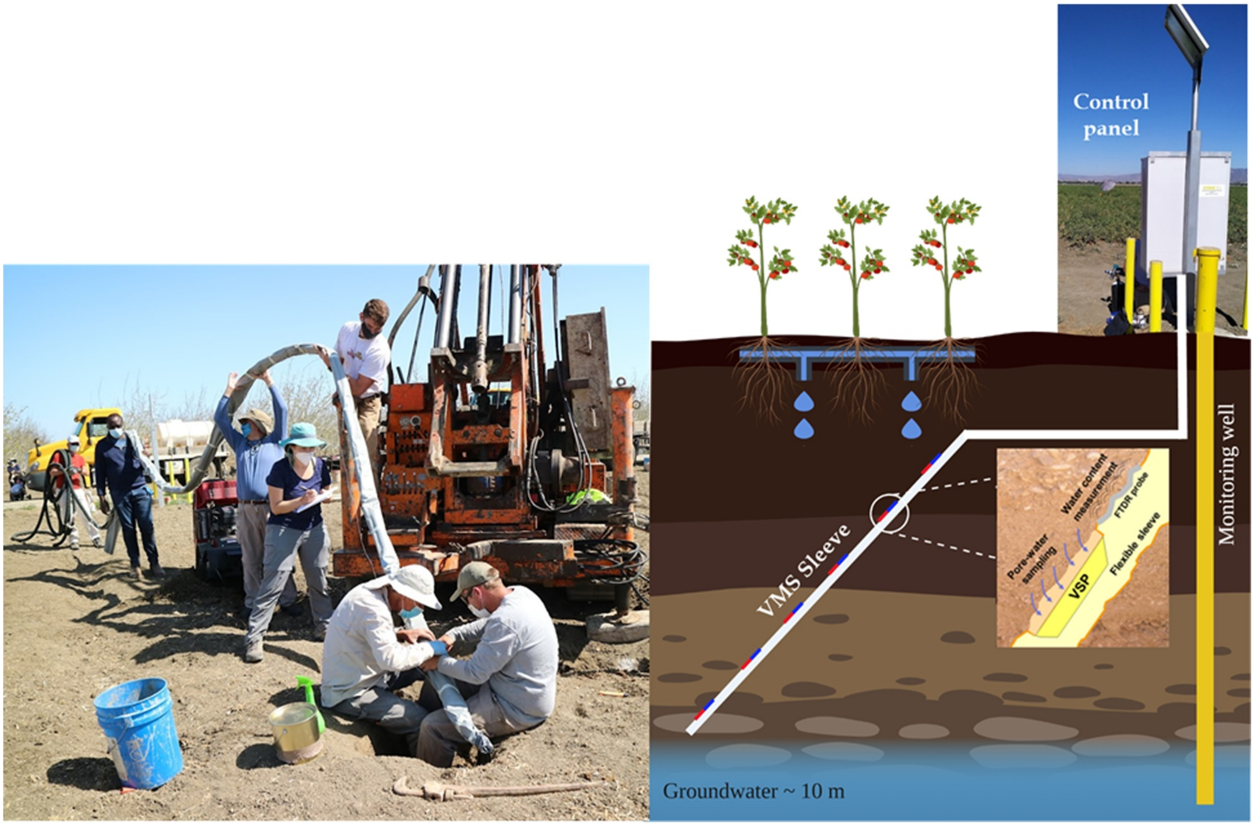

Figure 2. Left: Sleeve insertion during deep VMS (Vadose-zone Monitoring System) installation. Right: VMS control panel next to well #9 and diagram of VMS underground at a processing tomato field site near Esparto California.

estimated mineralized nitrate from organic nitrogen averaged from minimum and maximum values in Geisseler et al. (2019) and Geisseler and Horwath (https://www.cdfa.ca.gov/is/ffldrs/frep/FertilizationGuidelines/Adjustments.html#h6); F is the total mineral N applied as fertilizer diluted in the irrigation water (UN32%–50% Urea, 25% NH_4-N and 25% NO_3-N) as reported by the grower; N_{Upt} is the total mineral nitrogen accumulated in the plants and fruit at the end of the season measured as biomass and N contents at five locations across the field, N_{Denit} is the denitrification estimated as 5% from the N applied as fertilizer (Harter et al., 2017); dSN is the seasonal difference in stored mineral nitrogen in the top 60 cm of soil measured at six locations on the first and last day of the season using the sampling protocol described in Lazcano et al. (2015).

$$I + P - ET \pm dS = Drainage \tag{1}$$

$$N_{Irr} + N_{Min} + F - N_{Upt} - N_{Denit} \pm dSN = N_{Leaching} \tag{2}$$

2.4. Vadose-Zone Monitoring

On 6 April 2021, a SENSOIL.Ltd deep vadose zone monitoring system (VMS) (Dahan et al., 2009; Rimon et al., 2007; Turkeltaub et al., 2016), including two sleeves was installed next to groundwater monitoring well number nine (Figure 1) on the eastern side of the field. The control panel was located next to the groundwater monitoring well next to an access road while the top of the sleeves were located at a distance of ∼14 m west from the control panel into the field and a 0.6 m depth below the drip line and tilling layers. Each flexible sleeve was 8.8 m long, with six flexible time-domain reflectometry probes (FTDR) and six vadose zone pore water sampling ports (VSP), distributed along the sleeve (Figure 2, Table 1). Each sleeve was installed at a 35° from the vertical plane, with a 218° south-west direction and a 320° north-west direction respectively for sleeves A and B (Figure 2). These directions were approximately 45° from the growing bed, with a horizontal footprint of 5.2 m for each sleeve. Soil was sampled from the borehole every 0.76 m and analyzed for silt and clay content using a

Table 1
Vertical Depths of All Flexible Time-Domain Reflectometry Probes and Sampling Ports in the VMS Sleeves

Vertical depth from ground level (m)	
VSP[a]	FTDR[b]
1.60	1.15
2.62	2.18
3.69	3.19
4.75	4.24
5.82	5.31
6.84	6.36

[a]Vadose zone Sampling Port. [b]Flexible Time-domain reflectometry.

modified pipette method as described in Waterhouse et al. (2021) (Figure 3). Both sleeve locations showed a similar textual pattern with depth, with a sandier layer at 4 m below ground level.

During the study period, water contents were monitored continuously with the FTDRs, and soil pore water was sampled weekly and analyzed for NH_4-N and NO_3-N concentrations (Flow injection analyzer method, Hofer, 2003; Knepel, 2003).

Nitrogen leaching below the root zone ($N_{Leaching}$ in kg ha^{-1}) was estimated as mass of mineral nitrogen and as a function of time using the nitrate concentrations in the two shallowest soil pore samplers of the VMS (c in kg mineral N L^{-} - Equation 5). These weekly concentrations were then multiplied by the weekly drainage flux (F in L ha^{-1} - Equation 3) calculated with the water mass balance in Equation 1, neglecting *dS*.

$$\sum_i^f c * F = N_{Leaching} \quad (3)$$

where *i* and *f* refer to initial and final concentrations *c*.

2.5. Comparison Between Monitoring Methods

During the entire study, three methodologies were implemented to monitor nitrate leaching namely groundwater monitoring as the gold standard method for groundwater contamination; deep vadose zone monitoring as a method with a high temporal resolution; and field level mass balance as a method largely used due to its relative simplicity and flexibility. The cumulative nitrate estimated with Equation 3 was compared to $N_{Leaching}$ estimated with Equation 2 for each season. Both methods were assessed against the monthly groundwater nitrate

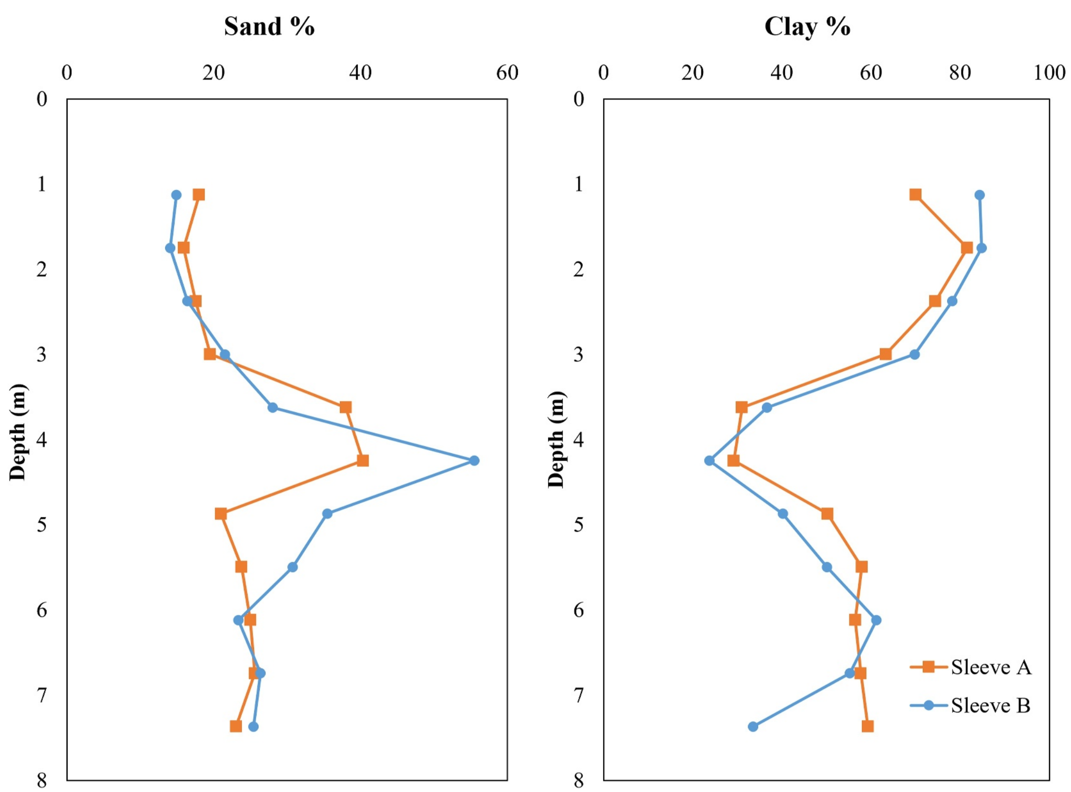

Figure 3. Soil texture as a function of depth for each vadose zone monitoring system (VMS) sleeve as measured from soil sampled during VMS installation in a processing tomato field near Esparto California.

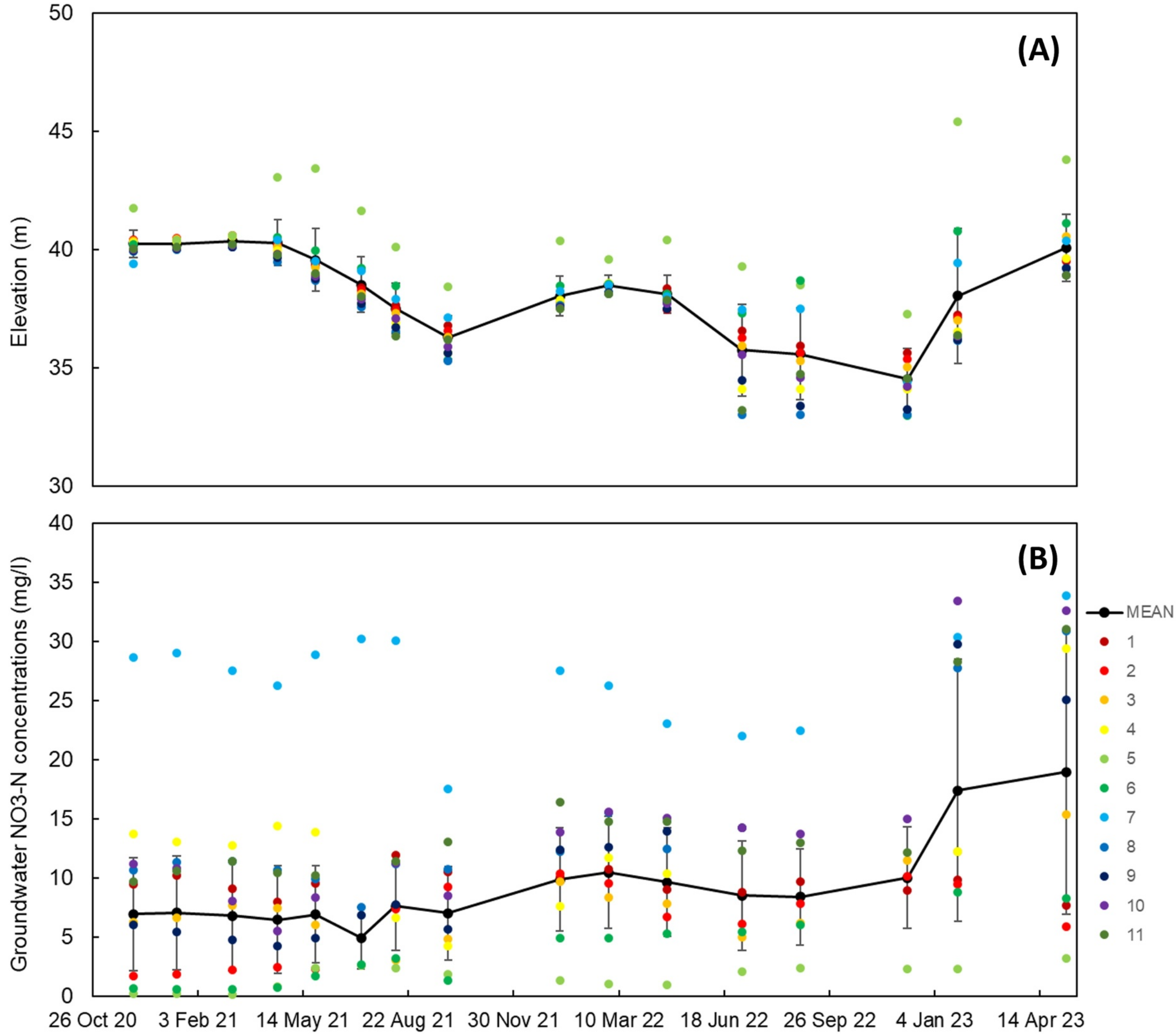

Figure 4. (a) Groundwater level elevation above mean sea level measured in each of the 11 monitoring wells and averaged values for all the wells (black) during the presented study (b) Groundwater NO_3-N concentrations were measured in all the wells and averaged values (black) for all the wells excluding #7. Error bars represent one standard deviation. Well #9, located next to the VMS is represented in full dark blue circles.

concentrations, under the hypothesis that the link between the vadose zone and groundwater is spatially and temporally complex (Weitzman et al., 2022).

3. Results

3.1. Groundwater Levels and Nitrate Concentrations

In both years, groundwater levels decreased during the summer months (Figure 4-a), probably due to regional pumping for irrigation and drought conditions. They increased slightly after the main winter rainfall events. Well #5 had anomalous groundwater elevation values due to its proximity to a slough on the northern border of the field which had intermittent water flow and appeared to be connected to the water table. During the winter of 2023, an extremely wet winter, groundwater elevation increased above summer values, reaching the 2020 winter values.

Average groundwater nitrate concentrations increased during the study period from below the Maximum Contaminant Level (MCL = 10 mg/l NO_3-N) to above MCL (Figure 4-b). The nitrate concentrations in well #9, adjacent to the VMS, also increased from below to above MCL (from 5 to 14 mg/l NO_3-N) between the beginning of the processing tomato season and after the main rainfall events of the 2022 winter. Thereafter, the concentrations stayed above the MCL and continued to increase after the 2023 rainfall season. Well #7 had higher than

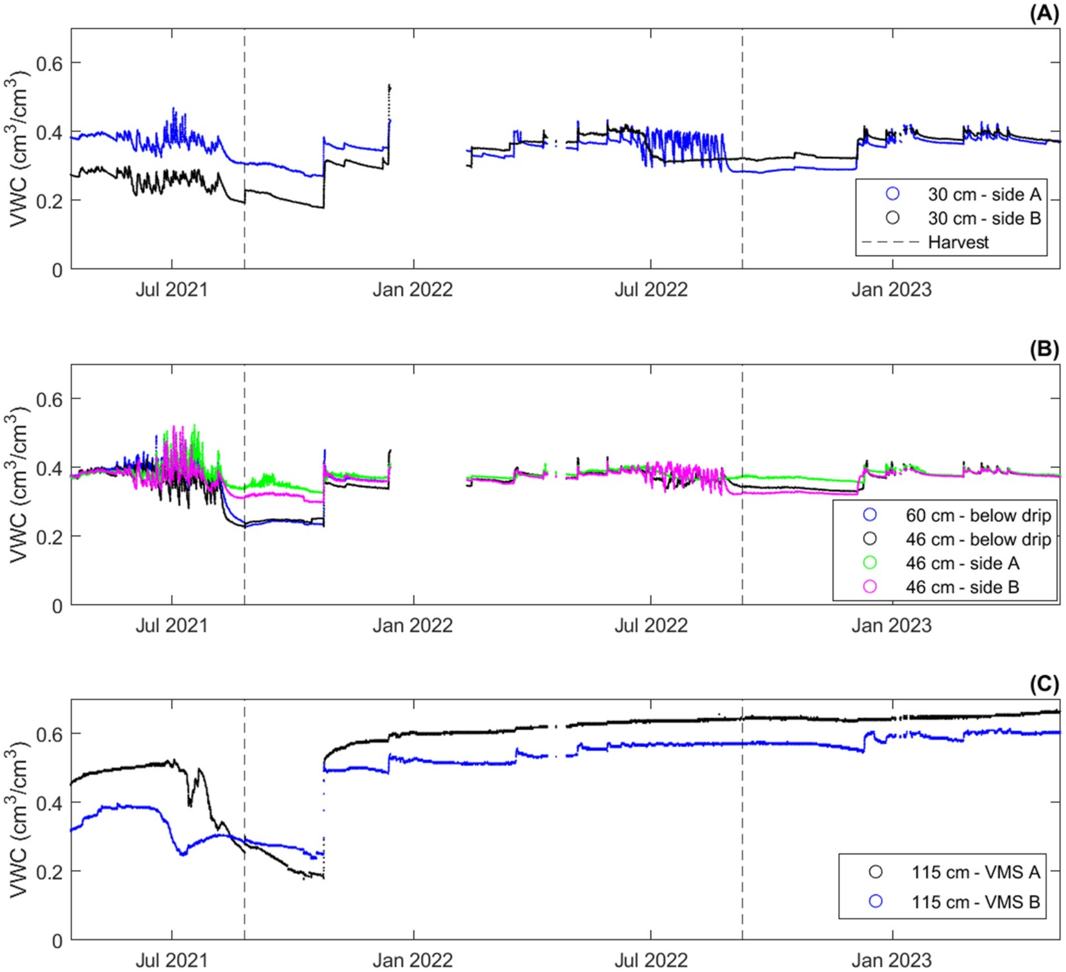

Figure 5. (a) and (b) shallow vadose-zone volumetric soil water content as a function of time measured with Acclima 315 TDR soil moisture sensors. Vertical dashed lines mark the harvest days. (c) Deep vadose-zone volumetric water contents measured with the FTDR in the VMS's sleeves (a) and (b).

average NO_3-N concentrations and was not included in the average because of the outlier nitrate concentrations, with values three to seven times higher than the nitrate concentrations in other wells (Figure 4-b). Hypothetical reasons for these high values are heterogeneity of the aquifer properties, preferential flow in the vadose zone, well installation disturbance, legacy nitrogen, etc. The well is located downstream of the groundwater flow at the north-east corner of the field, at a distance of approximately 150 m from well #8. Well #8 has concentrations within one standard deviation from the average. High variability nitrate concentrations in adjacent monitoring wells have been observed in agricultural fields in California before (Gurevich et al., 2021). For example, Gurevich et al. (2021) found that 10 shallow monitoring wells are needed to properly characterize the variability of groundwater nitrate measurements in a 56 ha almond field. In the aforementioned study, a larger number of monitoring wells did not provide better estimates of field-scale average nitrate, given the variability between wells.

3.2. Vadose Zone Water and Nitrate Monitoring

During the first 2 months of the 2021 and 2022 cropping seasons, the deep vadose zone volumetric water content increased by approximately 5% (Figure 5-c). During the first six weeks of the 2021 tomato season, the water content was stable in the shallow vadose zone (30–60 cm) and once the irrigation frequency increased and plant roots grew, daily soil water content changes can be observed (Figures 5A and 5B). After the last irrigation event on 4 August 2021 all shallow sensors showed a decrease in soil water content. At the beginning of the 2022 cucumber season, there were two sprinkler irrigation events (May 7th and 29th) in order to wet the soil for female

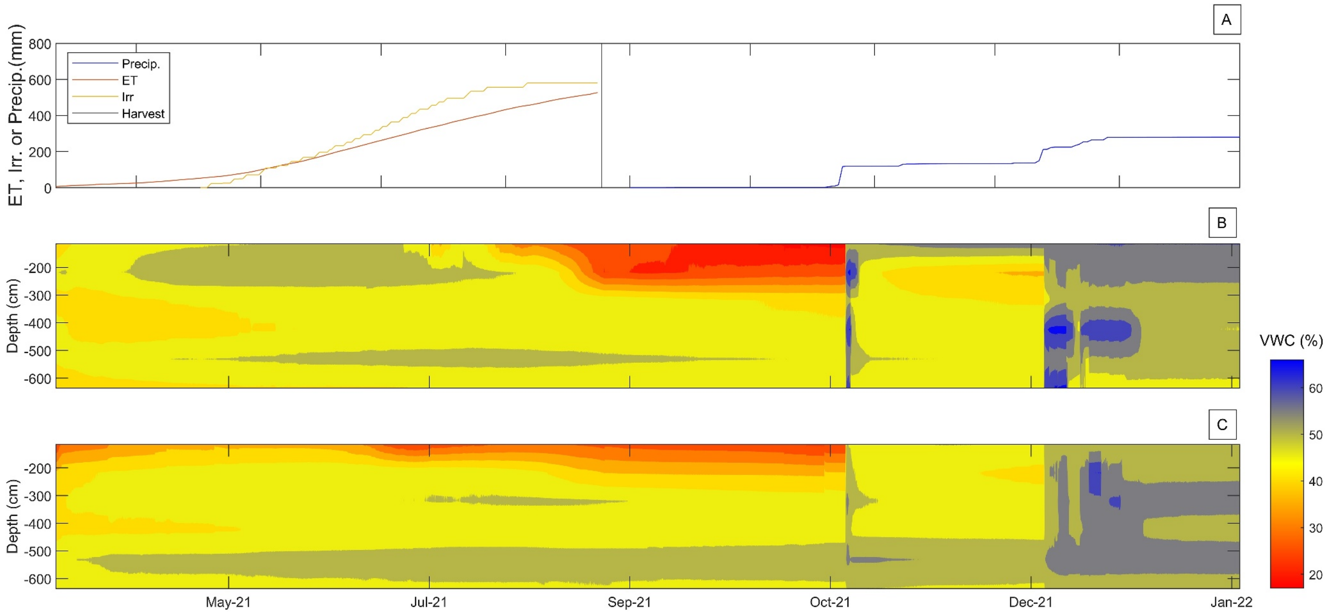

Figure 6. (a) Water balance components, irrigation, and ET during the 2021 processing tomato season, and precipitation during the fall-winter 2021–2022 wet season. The black vertical line represents the harvest day. (b) and (c) are the volumetric water contents in the deep vadose zone as a function of time for the two VMS sleeves respectively. Field site located near Esparto California.

and male plant seeding events. Thereafter, the crop was irrigated similarly using SDI as during the previous season. In both seasons, sharp increases in water content were observed on days with irrigation application. On non-irrigation days, a decrease in water content was observed during the day while water content was stable during the night (Figures 6A and 6B).

In the lower root zone (115 cm) fluctuations in water content, mainly a decrease, were observed from July 2021 on (~3 months after processing tomato transplanting–Figure 5-c). On 4 August 2021, the last seasonal irrigation event was applied, followed by a sharp decrease in the water content in the shallow vadose zone up to 218 cm. This sharp decreasing trend in water content stopped with the harvest on 25 August 2021, indicating the effect of root water uptake in the water content fluctuations, and was followed by a slight water content decrease only in some sensors (Figure 6).

During the 2022 growing season, there were almost no changes in the deep vadose zone, with a moderate trend of water content increasing with the season. The Mediterranean climate characteristic of the study area has a distinctive rainy season during the fall-winter-spring seasons. During the study period, both rainy seasons were characterized by "atmospheric rivers." On 24 October 2021, there was 104 mm of rainfall in 23 hr. This high intensity rainfall caused an increase in water content at all depths (Figure 6). Below 3 m, the final water content after the rainfall event was about 1%–2% higher than before the beginning of the rainfall. Between the end of the atmospheric river in October 2021 and the next rainfall event in December 2021, the water content decreased slightly in most sensors above 3 m (Figures 5 and 6). The next rainfall event started on 12 December 2021 and lasted for 2 days with a total of 76 mm. Similarly, as during the previous rainfall event, there was a fast increase of water content at all depths. Notably, after cessation of rainfall, the water content remained stable at the higher value, at least in the upper 3 m. In contrast, below 3 m water content immediately began to drop to similar water content values as before the rainfall event started (Figure 6). During the 2022–2023 fall-winter-spring season a long series of significant atmospheric river events characterized by high rainfall in quick succession occurred during December 2022-January 2023 and March 2023-April 2023. The rainfall events lasted longer than in 2021–2022. However, the precipitation season overall was still characterized by the contrast of periods with zero rainfall and periods with strong precipitation events (Figure 7-a).

Data is shown from 5 May 2021, since that was the day the electrical conductivity (EC) in the soil solution stabilized after VMS installation. In both sleeves there was an increase in nitrate concentrations at all depths from the beginning until the end of each growing season. Soil solution nitrate concentrations had a general decreasing

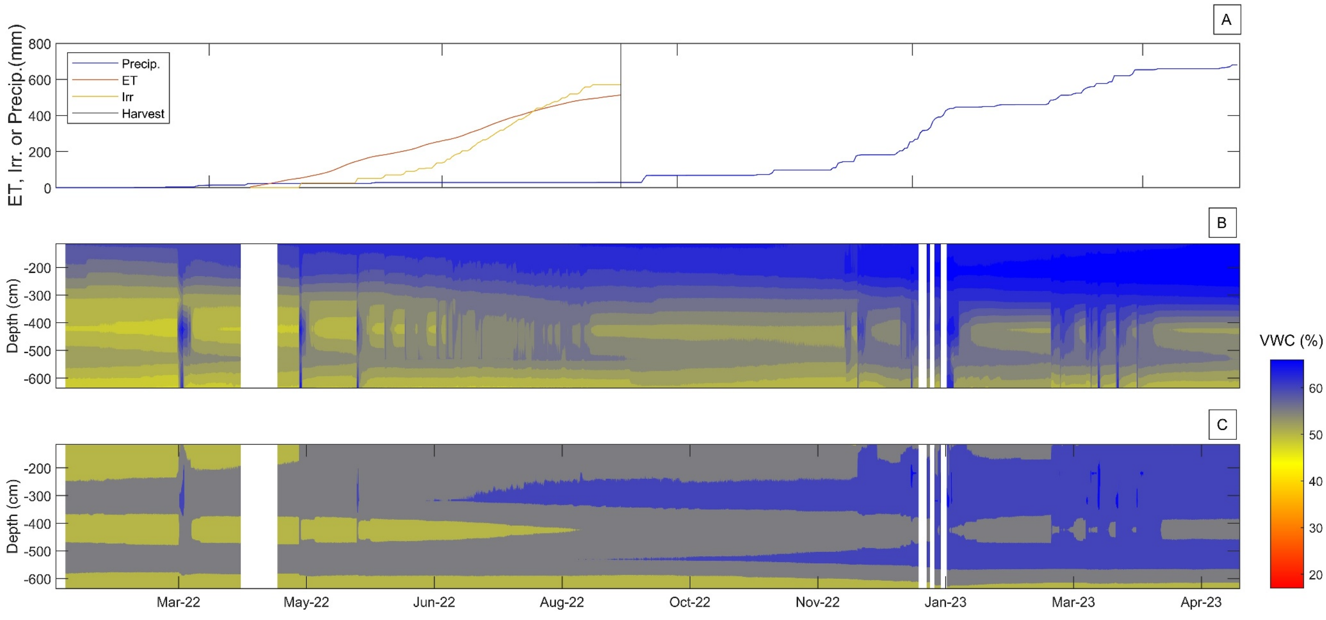

Figure 7. (a)Water balance components, irrigation, and ET during the 2022 cucumber season, and precipitation during the fall-winter-spring 2022–2023 season. The black vertical line represents the harvest day. (b) and (c) are the deep vadose zone volumetric water contents as a function of time for the two VMS sleeves respectively. Field site located near Esparto California.

trend with depth at the beginning of each growing season (Figure 8). On sleeve B, the fifth sampling port installed at a depth of 5.8 m showed higher concentrations than at a depth of 6.8 m. While temporal trends in pore water nitrate remained uniform across all ports and depths, the discontinuity in data along the depth profile is attributed to the variability in nitrate flux between independent vertical soil profiles measured by each sampling port, a consequence of the diagonal installation method.

At the end of the processing tomato season, after the last irrigation and until the first seasonal rainfall event, the soil water content in the top two ports was too low, thus soil pore water could not be collected (white areas in

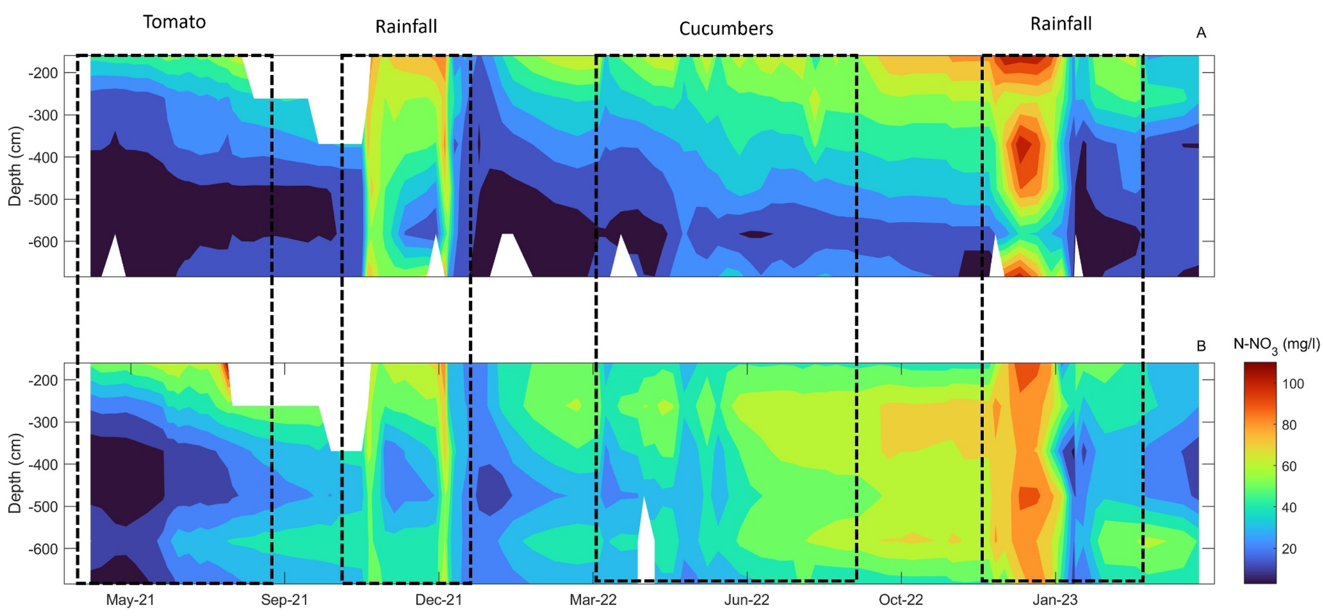

Figure 8. Soil pore water nitrate concentrations as a function of time and depth for Vadose-zone Monitoring System (VMS's) sleeves A and B, respectively, in an agricultural field located near Esparto, California. Dashed boxes represent drying growing seasons and large precipitation events during fall and winter.

Figures 8A and 8B). Both October 2021 and December 2021 rainfall events caused increased nitrate concentrations at all depths. In a comparable pattern to the water content, nitrate concentrations remained high in the upper 3 m, but in the deeper profile below 3 m, began to decrease once rainfall stopped. After the second rain event in December, concentrations went back to pre-rainfall values at all depths below 3 m and to lower than pre-rainfall values above 3 m, indicating flushing on nitrates caused by the extreme rainfall events. At the beginning of the 2022 growing season, irrigation was applied twice with sprinklers in order to promote seed sprouting, causing a decrease in nitrate concentrations in the profile (–May 7 and 9 June 2022). The previous decrease in nitrate concentrations at all depths was due to a 35 mm rainfall event on 21 March 2022. Following the same trend observed in 2021, the atmospheric river events occurring in December 2022-January 2023 promoted nitrate leaching with increased concentrations at all depths in both VMS sleeves. These rainfall events were large enough to reduce soil pore water nitrate concentrations to background pre-growing season concentrations. These results underscore the importance of continuous deep vadose zone monitoring to under fate and transport of nitrates during extreme rainfall events.

3.3. Field Mass Balance

The main components of the water balance during the growing season were irrigation and crop evapotranspiration (Table S2 in Supporting Information S1 - Figure 9c). Soil water content in the top 60 cm decreased between the planting day and harvest with an average change of 39 mm of water in the 2021 season and 11 mm in the 2022 season. The potential drainage estimated using the mass balance (Equation 1) was 85 mm with a CV of 67% for the 2021 season and 61 mm with a CV of 61% for the 2022 season.

The main input of mineral nitrogen during both cropping seasons was in the form of fertilizer, while estimated mineralization and measured nitrate in the irrigation water had similar averages but varying levels of confidence in both years (Table S3 in Supporting Information S1–Figure 9a). The average change in soil mineral nitrogen was negative for the 2021 season, indicating that nitrogen was contributed to the mobile N system from the soil N pool. Contrarily, the average change in soil mineral nitrogen was positive for the 2022 season, indicating that the top 60 cm of soil profile acted like a sink for mobile nitrogen. However, given the high variability in measured soil mineral nitrogen, with a coefficient of variation of 97% and 500% for the 2021 and 2022 seasons respectively, these fluxes out of and into the soil nitrogen pool have low confidence.

The main output of mineral nitrogen was plant uptake. During the processing tomato season, 244 kg/ha of N was removed from the field as it accumulated in the fruit and 103 kg/ha accumulated in the leaves and shoots and were crushed and left on-site during harvest. These values correspond to the upper end of N accumulated in above-ground biomass in a replicated trial with three fertilization levels at the University of California Davis (Geisseler et al., 2020).

Potential annual nitrogen leaching was calculated using the uptake of the whole plant, 27.1 kg N/ha/year, or, alternatively. Only the removed N from the field, 130.6 kg N/ha/yr. Combining these results with the water mass balance outcome, we obtain the potential mineral N concentration in the drainage: 32 or 154 mg/l with the whole plant or fruit-only approaches, respectively.

For the 2022 cucumber season, only whole plant uptake is reported. Cucumbers were grown for seeds, therefore left on the field until the fruit reached full maturity and the seeds were viable. Fruit and plant biomass as well as corresponding nitrogen contents were measured six times during the cucumber season. The total N accumulation peaked on 20 July 2022, shortly after both female and male plants reached the complete fruit set. Therefore, the total plant N uptake measured on that date, 136 kg/ha, was the main output in the nitrogen balance of 2022 (Tables S4 and S5 in Supporting Information S1). Combining the water and nitrogen balances, the calculated potential mineral N concentration in the drainage for the 2022 season was 105 mg/l.

4. Discussion

Nitrogen leaching, comprised mostly of nitrate due to the measured negligible NH_4-N values (Figures 4s and 5s), was estimated using two methodologies summarized in Figure 10 and confirmed at the large scale by groundwater monitoring well data (Figure 4).

The "Pore Water + Water Mass Balance" (PWWMB) was calculated using Equation 3, as explained in Section 2, using the weekly water mass balance and measured deep soil pore water nitrate concentrations. Until the end of

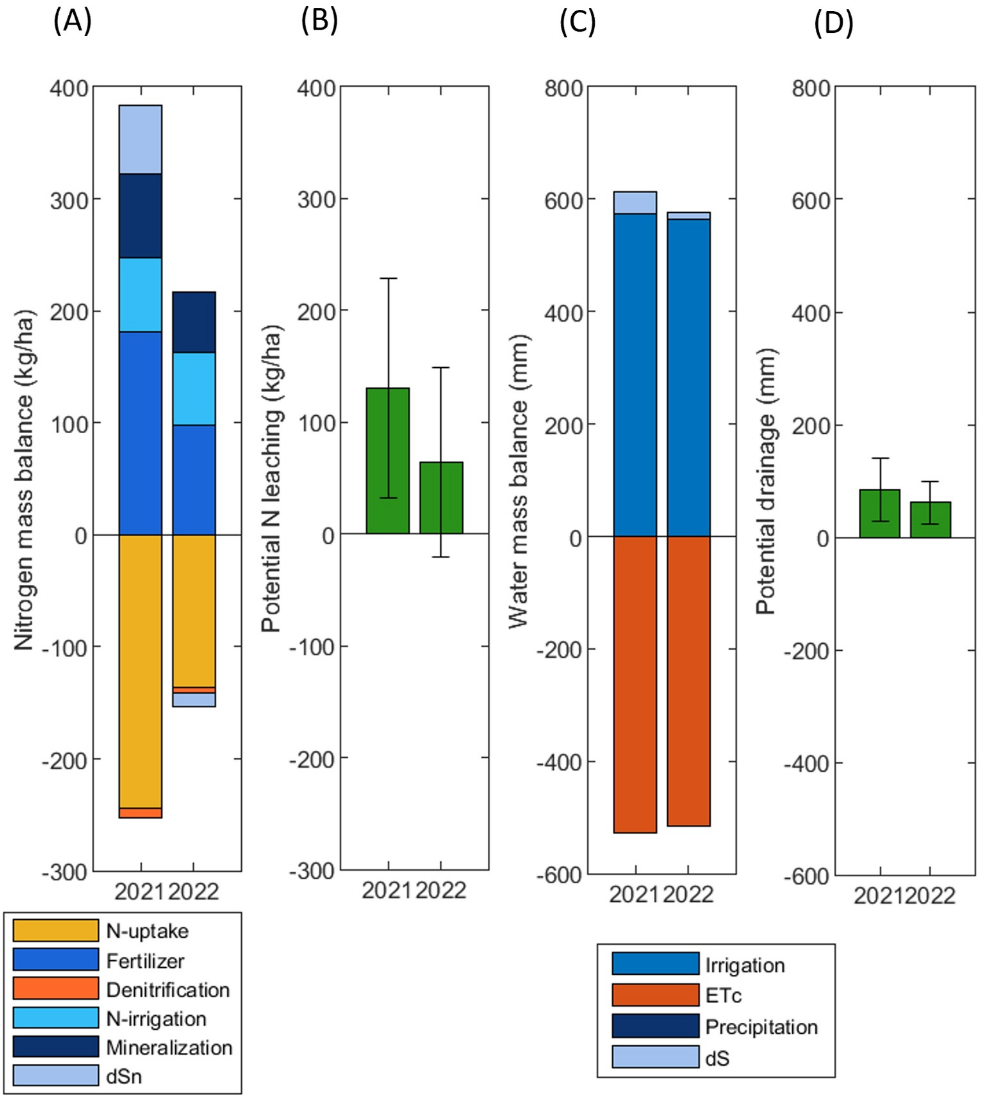

Figure 9. Nitrogen (a)–(b) and water (c)–(d) balances for the 2021 and 2022 growing seasons from a field site near Esparto California. dSn is the seasonal change in soil mineral nitrogen in the top 60 cm and dS is the seasonal change in soil water storage in the top 60 cm of soil. The green bars represent the closure of the mass balance, representing the mass of nitrogen leached assuming no return of N to the mobile soil N pool from the plant mass not harvested and incorporated as organic matter into the soil (b), and the amount of water percolating into the deep vadose zone from the root zone (d).

May, irrigation was lower than evapotranspiration. Therefore, the N leaching estimated with the water mass balance approach (black/gray) remained zero. Estimated potential leaching calculated with a field level nitrogen mass balance for the processing tomato season was performed using either the N uptake of the entire plant (MBAP) or only the N removed in the harvested fruit (MBF), where the MBAP assumes no mineralization of aboveground biomass and the MBF assumes 100% mineralization of aboveground biomass beside fruit. The common agricultural practice is to harvest only the tomatoes and leave any other aboveground biomass in the field, which is generally crushed by the harvester. The MBAP and MBF methods define the upper and lower edges of the field level mass balance N leaching estimation, with the actual N leaching being somewhere in that range. The two field level mass balance methods had high variability as a result of the large number of components included in the calculation (Table S3 in Supporting Information S1). There were no significant differences between the N mass balance and pore water methods (Figure 10, Figure S3 in Supporting Information S1), with all values in the same order of magnitude. Similar trends were described by Baram et al. (2016, 2017) where nitrogen leaching measured with soil pore solution samplers at 2.9 m, field level mass balance and Hydrus model

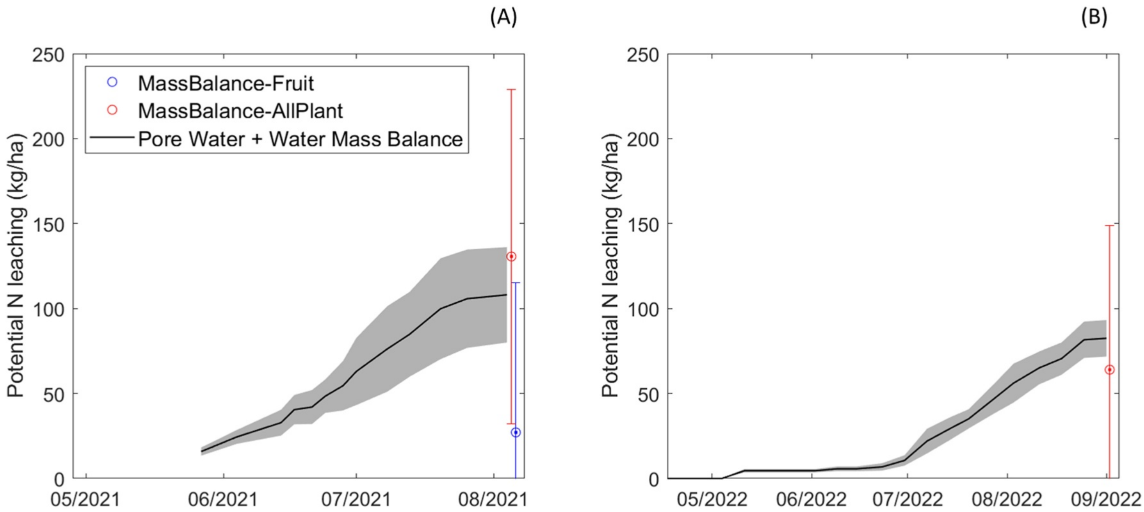

Figure 10. Potential nitrate leaching below the root zone using vadose-zone monitoring and mass balance approaches for the 2021 growing season (a) and the 2022 growing season (b). Field site located near Esparto California.

showed high variability with annual N fluxes of 80–240 kgN/ha/yr in a California almond orchard. Both methods estimated a positive N leaching potential during the season. Furthermore, the higher values estimated as potential leaching using the MBF are not necessarily to be leached during the growing season: the post-season monitoring with the VMS confirmed off-season N leaching. Off season, fall-winter nitrogen leaching was also observed using either intensive mass balance with soil profile N sampling, in-situ draining pipes, and soil pore mineral N concentrations sampled with suction cups in other studies performed in similar Mediterranean climates (Libutti & Monteleone, 2017; Weitzman et al., 2022). The PWWMB and the MBAP for the cucumber season were on the same order of magnitude as during the processing tomato season. The two methods had comparable averaged values, while the PWWMB had a much lower uncertainty than the MBAP (Figure 10). The MBF was not calculated for the cucumber crop due to the complex cucumber seed harvest, which includes separation of the seeds from the fruit at the field, followed by seed fermentation, washing, and drying. Therefore, it was not possible to estimate the total removed biomass and relevant N content.

Sharp increases in water content as well as pore water nitrate concentrations were observed during seasonal precipitation events in both years and at all depths monitored using the VMS (Figures 7 and 8). This short simultaneous increase in both water content and nitrate concentrations is evidence of nitrate leaching processes to groundwater during strong rainfall events following growing seasons ending during the dry summer. This leaching evidence was further supported by an increase in nitrate concentrations in the shallow groundwater in the well next to the VMS as well as on average around the field. All the processes inferred from the measurements with VMS's sleeves A and B were the same, even though there was variability between the sleeves. Such rapid fluxes are faster than expected, considering the saturated hydraulic conductivities estimated using soil textural data and the Rosetta3 model (Table S1 in Supporting Information S1). We hypothesize that matrix flows govern the water movement during the growing season, while preferential flows happen during the strong precipitation events (Nimo, 2021). While the growing season water inputs are mainly from subsurface drip irrigation characterized by low fluxes, the off-season winter water inputs happen suddenly with dry to very dry soil initial conditions. These results strengthen the need to develop better and inexpensive in-situ, real-time, soil pore water nitrate concentration monitoring technologies (Bonfil et al., 2024; Guerrero et al., 2021; Rogovska et al., 2019; Yeshno et al., 2019; Zhu et al., 2018) that allow for multiple measurements across a field to appropriately capture variability, thus allowing for field-scale monitoring of current management practices; and enabling growers to implement fertilization more precisely, thus improving nitrogen use efficiency.

The post-season nitrate leaching is supported by the N-surplus estimated using field level nitrogen mass balance data. This finding aligns with previous research where post-harvest soil N caused by spatial variability of crop N uptake was found to be one of the most significant predictors of yearly N leaching (Baram et al., 2017; Weitzman et al., 2022). Seasonal mineral N surplus was on average 27 and 64 kg N/ha respectively for 2021 and 2022, when assuming that the total nitrogen that was assimilated by the processing tomato or cucumber plants and fruit was removed from the field. However, the common practice for harvesting processing tomatoes or cucumbers for seeds is that only the fruits, in the case of the processing tomatoes, and only the seeds in the case of the cucumbers are removed from the field. The green biomass, leaves, and shoots are chopped by the harvester and spread on the topsoil as organic matter. This green biomass has a high mineralization potential, as estimated with an organic N budget approach in Geisseler et al. (2019) under similar conditions. The potential for N mineralization from this biomass is the difference between the whole plant N and the N actually removed from the field. Assuming that all plant N mineralizes post-season, the mineral N surplus was on average 130.6 kg N/ha for the processing tomato season, and the potential drainage concentration was 154.4 mg N/l.

5. Conclusions

A variety of methods were used to estimate nitrate leaching in a processing tomato-cucumber rotation field site located near Esparto, CA, USA. These methods included field level water and nitrogen mass balances, shallow and deep vadose zone monitoring using tensiometers, TDRs and soil solution samplers, and shallow groundwater monitoring. All methods estimated some level of nitrate leaching during the season and/or during the off-season due to high precipitation and groundwater levels and concentrations confirm these processes at the field scale. The results presented in this study highlight the uncertainty involved in estimating N leaching with a field level mass balance approach. This uncertainty stemmed from natural and system induced spatial variability in mentioned in studies involving estimating nitrogen leaching in agricultural fields such as Baram et al. (2016, 2017), Constantin et al. (2010), Weitzman et al. (2022), Salo and Turtola (2006), Geisseler et al. (2020). Studies not mentioning the high variability either presented averaged values such as in Pandey et al. (2018) or used only one sampling location such as in Turkeltaub et al. (2016). In the present study, even though the uncertainty is large, the results are of similar magnitude as the intensive in-situ monitoring using the VMS for both seasons. During the duration of this study, two spring-summer growing seasons and two fall-winter rainy seasons, the VMS successfully monitored seasonal N leaching below the root zone and following nitrate leaching to the groundwater following "atmospheric river" precipitation events. Groundwater nitrate concentrations followed the observed leaching with increasing values after the seasonal rainfall events, confirming the effectiveness of the vadose-zone level measurements as early predictors of groundwater pollution. The advantages of the VMS approach include high resolution of water content and nitrogen concentrations in the vertical soil profile as well as high temporal resolution, depending on the availability of a sampling team. These characteristics allowed the observation of the seasonal nitrate leaching during rainfall events, and these observations can help to develop management practices to minimize leaching. The limitations of the VMS approach include the low spatial resolution, as the system, comprised of two sleeves each with six units in diagonal, monitors only 0.01% of the entire field (~34 m^2 of a 34 ha field). However, the potential nitrogen leaching results from the VMS were well within the large range estimated using the field level mass balance approach which due to the large number of measurements and assumptions intrinsic to the method, had a much larger uncertainty range. We conclude that under the conditions of this case-study, both VMS and field level mass balance approaches were successful in estimating nitrate leaching from irrigated agriculture as early predictors of groundwater quality.

Data Availability Statement

The datasets collected during this study and used to create the figures are available to the public through the USDA National Agricultural Library Ag Data Commons (https://doi.org/10.15482/USDA.ADC/26771767).

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References

Ahada, C. P. S., & Suthar, S. (2018). Groundwater nitrate contamination and associated human health risk assessment in southern districts of Punjab, India. *Environmental Science and Pollution Research International*, *25*(25), 25336–25347. https://doi.org/10.1007/s11356-018-2581-2

Ascott, M. J., Gooddy, D. C., Fenton, O., Vero, S., Ward, R. S., Basu, N. B., et al. (2021). The need to integrate legacy nitrogen storage dynamics and time lags into policy and practice. *Science of the Total Environment*, *781*, 146698. Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2021.146698

Ascott, M. J., Gooddy, D. C., Wang, L., Stuart, M. E., Lewis, M. A., Ward, R. S., & Binley, A. M. (2017). Global patterns of nitrate storage in the vadose zone. *Nature Communications*, *8*(1), 1–6. https://doi.org/10.1038/s41467-017-01321-w

Baram, S., Couvreur, V., Harter, T., Read, M., Brown, P. H., Hopmans, J. W., & Smart, D. R. (2016). Assessment of orchard N losses to groundwater with a vadose zone monitoring network. *Agricultural Water Management*, *172*, 83–95. https://doi.org/10.1016/j.agwat.2016.04.012

Baram, S., Couvreur, V., Harter, T., Read, M., Brown, P. H., Kandelous, M., et al. (2017). Estimating nitrate leaching to groundwater from orchards: Comparing crop nitrogen excess, deep vadose zone data-driven estimates, and HYDRUS modeling. *Vadose Zone Journal*, *15*(11), 1–13. https://doi.org/10.2136/vzj2016.07.0061

Basu, N. B., Van Meter, K. J., Byrnes, D. K., Van Cappellen, P., Brouwer, R., Jacobsen, B. H., et al. (2022). Managing nitrogen legacies to accelerate water quality improvement. *Nature Geoscience*, *15*(2), 97–105. Nature Research. https://doi.org/10.1038/s41561-021-00889-9

Bonfil, C., Lahann, L., Ogunmokun, F., Dahlke, H., Arias, A., Brown, H. B., & Kisekka, I. (2024). A critical review of recent advances and applications in in-situ soil nitrate sensing. *Current Opinion in Environmental Sustainability*. Under Review.

California Regional Water Quality Control Board Central Valley Region. (2020). RESOLUTION R5-2020-0057. The sacramento river and san joaquin river basins and the Tulare Lake Basin to incorporate A Central Valley-wide salt and nitrate control program. Retrieved from https://www.waterboards.ca.gov/centralvalley/water_issues/salinity/#toc

Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., & Beaudoin, N. (2010). Effects of catch crops, no-till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture, Ecosystems and Environment*, *135*(4), 268–278. https://doi.org/10.1016/j.agee.2009.10.005

Dahan, O. (2020). Vadose zone monitoring as a key to groundwater protection. *Frontiers in Water*, *2*. https://doi.org/10.3389/frwa.2020.599569

Dahan, O., Talby, R., Yechieli, Y., Adar, E., Lazarovitch, N., & Enzel, Y. (2009). In situ monitoring of water percolation and solute transport using a vadose zone monitoring system. *Vadose Zone Journal*, *8*(4), 916–925. https://doi.org/10.2136/vzj2008.0134

Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N. J., Jacobsen, B. H., et al. (2014). Policies for agricultural nitrogen management—Trends, challenges and prospects for improved efficiency in Denmark. *Environmental Research Letters*, *9*(11), 115002. https://doi.org/10.1088/1748-9326/9/11/115002

EC. (2021). *Report from the Commission to the Council and the European Parliament on the implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources based on Member State reports for the period 2016–2019, COM/2021/1000 final*. European Commission.

Fraters, D., Boumans, L. J. M., van Drecht, G., de Haan, T., & de Hoop, W. D. (1998). Nitrogen monitoring in groundwater in the sandy regions of The Netherlands. *Environmental Pollution*, *102*(1), 479–485. Supplement 1. https://doi.org/10.1016/S0269-7491(98)80072-9

Geisseler, D., Aegerter, B. J., Miyao, E. M., Turini, T., & Cahn, M. D. (2020). Nitrogen in soil and subsurface drip-irrigated processing tomato plants (Solanum lycopersicum L.) as affected by fertilization level. *Scientia Horticulturae*, *261*, 108999. https://doi.org/10.1016/j.scienta.2019.108999

Geisseler, D., Miller, K. S., Aegerter, B. J., Clark, N. E., & Miyao, E. M. (2019). Estimation of annual soil nitrogen mineralization rates using an organic-nitrogen budget approach. *Soil Science Society of America Journal*, *83*(4), 1227–1235. https://doi.org/10.2136/sssaj2018.12.0473

Gu, B., Zhang, X., Lam, S. K., Yu, Y., van Grinsven, H. J. M., Zhang, S., et al. (2023). Cost-effective mitigation of nitrogen pollution from global croplands. *Nature*, *613*(7942), 77–84. https://doi.org/10.1038/s41586-022-05481-8

Guerrero, A., De Neve, S., & Mouazen, A. M. (2021). Current sensor technologies for in situ and on-line measurement of soil nitrogen for variable rate fertilization: A review. *Advances in Agronomy*, *168*, 1–38. Academic Press Inc. https://doi.org/10.1016/bs.agron.2021.02.001

Gurevich, H., Baram, S., & Harter, T. (2021). Measuring nitrate leaching across the critical zone at the field to farm scale. *Vadose Zone Journal*, *20*(2), 1–16. September 2020. https://doi.org/10.1002/vzj2.20094

Hansen, B., Thorling, L., Schullehner, J., Termansen, M., & Dalgaard, T. (2017). Groundwater nitrate response to sustainable nitrogen management. *Scientific Reports*, *7*(1), 1–12. https://doi.org/10.1038/s41598-017-07147-2

Harter, T., Dzurella, K., Kourakos, G., Bell, A., King, A., & Hollander, A. (2017). Nitrogen fertilizer loading to groundwater in the Central Valley. In *Final report to the fertilizer research education program*. Projects 11-0301 and 15-0454. August 2017.333.

Harter, T., Lund, J. R., Darby, J., Fogg, G. E., Howitt, R., Jessoe, K. K., et al. (2012). *Addressing nitrate in California's drinking water with a focus on Tulare Lake Basin and salinas valley groundwater. Report for the state water resources control board report to the legislature* (p. 78). Center for Watershed Sciences, University of California. Retrieved from http://groundwaternitrate.ucdavis.edu

Hofer, S. (2003). Determination of ammonia (salicylate) in 2M KCl soil extracts by flow injection analysis. *QuikChem Method 12-107-06-2-A. Lachat Instruments, Loveland, CO*.

Knepel, K. (2003). Determination of nitrate in 2M KCl soil extracts by flow injection analysis. *QuikChem Method 12-107-04-1-B. Lachat Instruments, Loveland, CO*.

Lazcano, C., Wade, J., Horwath, W. R., & Burger, M. (2015). Soil sampling protocol reliably estimates preplant NO3- in SDI tomatoes. *California Agriculture*, *69*(4), 222–229. https://doi.org/10.3733/ca.v069n04p222

Libutti, A., & Monteleone, M. (2017). Soil vs. groundwater: The quality dilemma. Managing nitrogen leaching and salinity control under irrigated agriculture in Mediterranean conditions. *Agricultural Water Management*, *186*, 40–50. https://doi.org/10.1016/j.agwat.2017.02.019

Nicolas, F., Raij-Hoffman, I., Doro, L., Ghorbanpoura, A. K., Felix A Ogunmokun, A. F., Harter, T., et al. (2024). Evaluating the effectiveness of conservation practices on reducing nitrate leaching in processing tomato using the APEX model. *Journal of Hydrology. Under Review*.

Nimo, J. R. (2021). The processes of preferential flow in the unsaturated zone. *Soil Science of America Journal*, *85*, 1–27. https://doi.org/10.1002/saj2.20143

Nolan, T. B., & Ruddy, B. C. (2016). *Nitrate in the ground waters of the United States--Assessing the risk*. U.S. Geological Survey. Fact. Sheet 092-96.

Pandey, A., Li, F., Askegaard, M., Rasmussen, I. A., & Olesen, J. E. (2018). Nitrogen balances in organic and conventional arable crop rotations and their relations to nitrogen yield and nitrate leaching losses. *Agriculture, Ecosystems and Environment*, *265*, 350–362. https://doi.org/10.1016/j.agee.2018.05.032

Raij-Hoffman, I., Dahan, O., Dahlke, H., Harter, T., & Kisekka, I. (2024). *Data from: Assessing nitrate leaching during drought and extreme precipitation: Exploring deep vadose-zone monitoring, groundwater observations, and field mass balance. Ag data commons*. Dataset. https://doi.org/10.15482/USDA.ADC/26771767

Raij-Hoffman, I., Miller, K., Paul, G., Yimam, Y., Mehan, S., Dickey, J., et al. (2022). Modeling water and nitrogen dynamics from processing tomatoes under different management scenarios in the San Joaquin Valley of California. *Journal of Hydrology: Regional Studies*, *43*, 101195. https://doi.org/10.1016/j.ejrh.2022.101195

Rimon, Y., Dahan, O., Nativ, R., & Geyer, S. (2007). Water percolation through the deep vadose zone and groundwater recharge: Preliminary results based on a new vadose zone monitoring system. *Water Resources Research*, *43*(5). https://doi.org/10.1029/2006WR004855

Rogers, M. K., Raaij, R., Phillips, A., & Stewart, M. (2023). A national isotope survey to define the sources of nitrate contamination in New Zealand freshwaters. *Journal of Hydrology*, *617*(Part C), 129131. https://doi.org/10.1016/j.jhydrol.2023.129131

Rogovska, N., Laird, D. A., Chiou, C. P., & Bond, L. J. (2019). Development of field mobile soil nitrate sensor technology to facilitate precision fertilizer management. *Precision Agriculture*, *20*(1), 40–55. https://doi.org/10.1007/s11119-018-9579-0

10.1029/2024WR037973

Salo, T., & Turtola, E. (2006). Nitrogen balance as an indicator of nitrogen leaching in Finland. *Agriculture, Ecosystems and Environment*, *113*(1–4), 98–107. https://doi.org/10.1016/j.agee.2005.09.002

Turkeltaub, T., Kurtzman, D., & Dahan, O. (2016). Real-time monitoring of nitrate transport in the deep vadose zone under a crop field-implications for groundwater protection. *Hydrology and Earth System Sciences*, *20*(8), 3099–3108. https://doi.org/10.5194/hess-20-3099-2016

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Waterhouse, H., Arora, B., Spycher, N. F., Nico, P. S., Ulrich, C., Dahlke, H. E., & Horwath, W. R. (2021). Influence of agricultural managed aquifer recharge (AgMAR) and stratigraphic heterogeneities on nitrate reduction in the deep subsurface. *Water Resources Research*, *57*(5). https://doi.org/10.1029/2020WR029148

Weitzman, J. N., Brooks, J. R., Compton, J. E., Faulkner, B. R., Mayer, P. M., Peachey, R. E., et al. (2022). Deep soil nitrogen storage slows nitrate leaching through the vadose zone. *Agriculture, Ecosystems & Environment*, *332*, 107949. https://doi.org/10.1016/j.agee.2022.107949

Winans, K., Brodt, S., & Kendall, A. (2020). Life cycle assessment of California processing tomato: An evaluation of the effects of evolving practices and technologies over a 10-year (2005–2015) timeframe. *International Journal of Life Cycle Assessment*, *25*(3), 538–547. https://doi.org/10.1007/s11367-019-01688-6

Yeshno, E., Arnon, S., & Dahan, O. (2019). Real-time monitoring of nitrate in soils as a key for optimization of agricultural productivity and prevention of groundwater pollution. *Hydrology and Earth System Sciences*, *23*(9), 3997–4010. https://doi.org/10.5194/hess-23-3997-2019

Zhang, Y., Chen, Z., Huang, G., & Yang, M. (2023). Origins of groundwater nitrate in a typical alluvial-pluvial plain of North China plain: New insights from groundwater age-dating and isotopic fingerprinting. *Environmental Pollution*, *316*(2), 120592. https://doi.org/10.1016/j.envpol.2022.120592

Zhang, Y., & Schaap, M. G. (2017). Weighted recalibration of the Rosetta pedotransfer model with improved estimates of hydraulic parameter distributions and summary statistics (Rosetta3). *Journal of Hydrology*, *547*, 39–53. https://doi.org/10.1016/j.jhydrol.2017.01.004

Zhu, Q., Castellano, M. J., & Yang, G. (2018). Coupling soil water processes and the nitrogen cycle across spatial scales: Potentials, bottlenecks and solutions. *Earth-Science Reviews*, *187*, 248–258. Elsevier B.V. https://doi.org/10.1016/j.earscirev.2018.10.005