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Nitrate leaching from intensive organic farms to groundwater

O. Dahan[1], A. Babad[1], N. Lazarovitch[2], E. E. Russak[3], and D. Kurtzman[4]

[1]Department of Environmental Hydrology & Microbiology, Zuckerberg Institute for Water Research, Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Midreshet Ben-Gurion, Israel
[2]Wyler Department of Dryland Agriculture, French Associates Institute for Agriculture and Biotechnology of Drylands, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Midreshet Ben-Gurion, Israel
[3]Geological and Environmental Sciences, Ben-Gurion University of the Negev, Be'er Sheva, Israel
[4]Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, The Volcani Center, Bet Dagan, Israel

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Correspondence to: O. Dahan (odahan@bgu.ac.il)

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Abstract

It is commonly presumed that organic agriculture causes only minimal environmental pollution. In this study, we measured the quality of percolating water in the vadose zone, underlying both organic and conventional intensive greenhouses. Our study was conducted in newly established farms where the subsurface underlying the greenhouses has been monitored continuously from their establishment. Surprisingly, intensive organic agriculture relying on solid organic matter, such as composted manure that is implemented in the soil prior to planting as the sole fertilizer, resulted in significant down leaching of nitrate through the vadose zone to the groundwater. On the other hand, similar intensive agriculture that implemented liquid fertilizer through drip irrigation, as commonly practiced in conventional agriculture, resulted in much lower rates of pollution of the vadose zone and groundwater. It has been shown that accurate fertilization methods that distribute the fertilizers through the irrigation system, according to plant demand, during the growing season dramatically reduce the potential for groundwater contamination.

1 Introduction

Developing efficient productive agriculture, while preserving groundwater quality, is one of the most important challenges in water resources sustainability. On the one hand, developing agriculture is straightforward wherever agricultural input, as water and nutrients, is unlimited. On the other hand, productive agriculture must inherently include the leaching of excess lower quality water below the root zone to the unsaturated zone and ultimately to the groundwater (Shani et al., 2007; Dudley et al., 2008). As such, maintaining the delicate balance between productive agriculture and groundwater quality requires a broad perspective over different time and dimensional scales. While agricultural productivity is measured on a time scale of seasons (several months to several years), its final impact on groundwater is a long-term cumulative process with a time scale of years to decades.

Public awareness of healthy food products that are free of chemical additives, along with a worldwide demand to reduce industrial pollution, has led, in recent years, to the development of organic farming (http://www.organiccentrewales.org.uk/). Although numerous studies have questioned organic agriculture's efficiency (Seufert et al., 2012), sustainability (Trewavas, 2001) and healthy (Jensen et al., 2012) aspects, organic food markets seem to be thriving in developed countries as their output is perceived by the public to be healthier for both consumers and the environment. This type of agriculture depends mainly on fertilizers from biological sources, such as composted animal manure. Nevertheless, modern agriculture, whether practiced with conventional or organic methods, needs to reach the goals of mass production, i.e., large quantities and high quality, to satisfy market demand while maintaining economic standards of profitability. This goal is usually achieved through intensive agriculture in greenhouses where irrigation water and fertilizers are implemented in excess to satisfy crop demand and maximize productivity. In arid and semi-arid regions, where the climate is warm enough, intensive agriculture in greenhouses operates year round. Moreover in many of these areas the agriculture is heavily dependent on groundwater resources for irrigation and therefore its quality is of great importance.

Mass production through intensive organic farming is very similar to conventional agriculture in its use of agricultural machinery and modern irrigation techniques; the main differences between the two approaches lie in fertilization and pest-control methodologies (http://www.epa.gov/oecaagct/torg.html). Unfortunately, the development of intensive agriculture is often associated with the long-term deterioration of groundwater quality, which is expressed mainly in elevated concentrations of nitrate and salinity (Vitousek et al., 2009; Burow et al., 2010; Kurtzman et al., 2011; Melo et al., 2012; Morari et al., 2012). Groundwater pollution is usually attributed to a very large array of chemicals. Nevertheless, on a global scale the main cause for drinking-water well shut downs is a high nitrate concentration in the aquifer water (Osenbruck et al., 2006; Kourakos et al., 2012; Liao et al., 2012).

The potential for groundwater contamination by nitrate from intensive agriculture is well known (Oren et al., 2004; Vazquez et al., 2006; Thompson et al., 2007). Two main approaches are often used for characterizing nitrate leaching from agricultural fields: (1) characterization of the chemical composition of the soil pore water in shallow depths under the root zone, as may be obtained by application suction lysimeters or sediment samples (Feaga et al., 2010), and (2) determining the cumulative long-term impact on groundwater as may be obtained from the chemical composition of well water (Harter et al., 2002). Apparently, the chemical characteristics of the root zone pore water may vary dramatically in time scales of days to seasons, according to irrigation patterns, fertilizer applications and crop-growing phases. However, the cumulative impact on groundwater develops in time scales of years to decades. The time lag between the initiations of a contamination event near the land surface to its detection in the aquifer water is dependent on the mechanisms controlling flow and transport in the vadose zone. The ability to characterize flow and transport processes in the vadose zone was recently improved following the development of a vadose zone monitoring system (VMS) that provides real time, in situ information on the hydraulic and chemical state of the percolating water across the entire vadose zone. Up to now, the VMS has been implemented in a variety of hydrological setups, including (1) flood water percolation (Dahan et al., 2007, 2008; Amiaz et al., 2011), (2) rain water percolation through thick unsaturated sand and clay formations (Rimon et al., 2007, 2011b; Baram et al., 2012a), and (3) solute transport in the vadose zone (Dahan et al., 2009; Rimon et al., 2011a; Baram et al., 2012b).

A newly established agricultural area that has recently been modified from non-intensive open field agriculture to intensive organic and conventional agriculture in greenhouses provided a unique opportunity to investigate the contamination potential of these two agricultural regimes. As such, the main objective of the study was to compare the groundwater pollution potential of organic vs. conventional greenhouses as it is expressed through the down-leaching of nitrate through the vadose zone underlying these farms. The study was conducted using VMSs that allowed in situ monitoring of the unsaturated zone under selected organic and conventional greenhouses.

2 Method

2.1 Study area

The study area consists of 100 ha of new greenhouses that were constructed during 2008–2009 on land that had previously been cultivated for ∼ 6 decades under a non-intensive growing regime (mostly rain-fed open field crops). The site is located on the Mediterranean coastal plain, south of the city of Ashkelon, Israel (∼ 3–6 km from the sea shoreline). Most of the greenhouses in this area produce high quality vegetables year round through organic methods (80 %), while the rest practice conventional methods.

Underneath these agricultural fields (∼ 15–30 m below the surface) lies a phreatic sandy aquifer that is characterized by high water quality ($Cl^- < 200\ mg\ L^{-1}$; $NO_3^- < 40\ mg\ L^{-1}$). This part of the aquifer is an important water source for the region. Its water is used for domestic and agricultural purposes through a large number of pumping wells. In addition, the aquifer in the region serves as an underground storage area through the artificial infiltration of flood water from the Shikma River and the water surplus from the National Water Carrier.

The climate in the area is Mediterranean with an annual average precipitation of 458 mm (The Israeli Water Authority, 2008). The majority of the rain events take place during the winter, between December and February. The annual average temperature is 20.2 °C. The coldest month is January with average maximum and minimum temperatures of 17.2 and 8.1 °C, respectively. The hottest month is August with average maximum and minimum temperatures of 31.1 and 21.4 °C, respectively (Israel Meteorological Service). The potential evaporation rate changes from an average of 2.3 mm per day in January to 5.4 mm per day in July (Weather 2011). Note that the studied sites are all located inside large greenhouses (∼ 1 ha each) that are not influenced by the rain pattern, and their interior climate is warmer and more humid than external natural conditions. Most of the cultivated areas are located in large interdune valleys, surrounded by sandy dunes with sparse vegetation. The soil in the cultivated zones is mostly sandy loam.

2.2 Monitoring setup

Two representative greenhouses, organic and conventional, that specialize in growing vegetables, such as cherry tomatoes, peppers and zucchini, were selected and instrumented with VMSs (Fig. 1). Technical descriptions of VMS structure, performance and installation procedures have been previously presented in other publications (Rimon et al., 2007, 2011a; Dahan et al., 2008, 2009). To avoid overloading this manuscript with technical information, only a brief description will be presented here. The VMS is composed of a flexible sleeve installed in uncased slanted (35°) boreholes hosting multiple monitoring units at various depths. Each monitoring unit has a flexible time domain reflectometry sensor (FTDR), for continuous measurements of sediment water content, and vadose zone sampling ports (VSP) for frequent collection of pore-water samples from the entire unsaturated zone. Slanted installation ensures that each monitoring unit faces an undisturbed sediment column that extends from land surface to the probe depth. In the borehole, the flexible sleeve is filled with high density solidifying material to ensure sleeve expansion for proper attachment of the monitoring units to the borehole's irregular walls, sealing its entire void and preventing potential cross-contamination by preferential flow along the borehole. Each VMS included nine monitoring units distributed vertically and laterally along the entire vadose zone cross-section (Table 1). Installation orientation was aligned with the growing rows. The representativeness of measurements made by the VMS, with respect to vadose zone sedimentological heterogeneity, has already been discussed in previous publications (Dahan et al., 2007; Rimon et al., 2007).

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The VMS provided continuous information from 18 fixed points from the vadose zone underlying the two selected sites throughout a sampling period of 18 months. Each monitoring unit provided high resolution information from multiple points that are located away from each other vertically and horizontally. Therefore the integrated data from the VMS should be regarded as representing of wider zone rather than a vertical profile (Fig. 1). To overcome potential bias due to local heterogeneity, the VMS results were compared with the chemical composition of sediment samples that were obtained from additional locations in each greenhouse, and from additional greenhouses owned and cultivated by different farmers. In addition to the VMS that monitored the vadose zone, each site was instrumented with an observation well that penetrated the upper phreatic groundwater with screens to 5 m below the water table (Fig. 1). In order to validate the results obtained by the VMS, nitrate profiles in the vadose zone pore water were compared to the nitrate concentrations in sediment samples from an additional three boreholes in each greenhouse. Samples were collected at a 0.5 m depth resolution from the top 3 m of the profile using a standard hand auger.

2.3 Chemical and isotopic analysis

Nitrate concentrations in the water samples were determined using ion chromatography (DIONEX, 4500I). Soil samples were extracted by KCL and analyzed for ammonium by the Nesslerization method (APHA, 1989), for nitrite using the colorimetric method, and for nitrate using the second-derivative method (APHA, 2005). Total nitrogen in the soil was analyzed following the Kjeldahl method (Benton, 1999). The isotopic composition of δ^{15}N and δ^{18}O of nitrate in the water samples was determined through nitrate reduction to nitrogen dioxide which was then analyzed using a gas mass spectrometer (McIlvin et al., 2005).

Throughout the study, the following data were collected: (1) crop type and growing cycle, (2) irrigation quantity and quality, (3) fertilization regime, (4) temporal variation of the vadose zone water-content profile, (5) chemical composition of the vadose zone and underlying groundwater, and (5) isotopic composition ($\delta^{15}N$–$\delta^{18}O$) of nitrate obtained from the vadose zone pore water.

3 Results and discussion

3.1 Agrotechnical regime

A comparison of agrotechnical regimes implemented in the organic and conventional greenhouses showed very similar general inputs. For example, during a single growing season for cherry tomato, which extended for 183 and 190 days in the organic and conventional greenhouses, respectively, the total irrigation amounts (applied through drip irrigation) were 3440 and 3570 $m^3\,ha^{-1}$, respectively (Fig. 2). In both greenhouses, the growing season began with an establishment irrigation of 200–240 $m^3\,ha^{-1}$. In general, establishment irrigation is implemented to prepare the upper soil for the new planting and down leaching of salts, such as chloride and sodium that have accumulated in the root zone during the previous season (Yin et al., 2007; Ben-Gal et al., 2008). In addition, in the organic regime, the establishment irrigation enhances the mineralization of nutrients from the compost in the soil for plant uptake.

Total N-fertilizer implementation in both greenhouses from their establishment date (∼ 4 yr) was very similar, 3800 and 3700 $kg\,N\,ha^{-1}$ for the organic and conventional greenhouses, respectively. In the organic greenhouse, 98 % of the N was applied as compost (processed from dairy farms and poultry manure) that was mixed with the soil between the growing seasons, and guano (seabird excrement) that was embedded in the top soil by the plant stems during the growing season. In the conventional greenhouse, on the other hand, only 45 % of the N was applied as compost, mainly as a soil amendment in the early stages after the establishment of the greenhouse, while the rest was provided through the drip irrigation system, as mineral liquid fertilizer from industrial sources.

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3.2 Nitrate leaching in the vadose zone

Water samples from the vadose zone and groundwater were collected at both sites every 3 to 6 weeks for 18 months (total of 262 water samples). A comparison of nitrate concentrations in the vadose zone pore water at the two sites throughout all sampling campaigns exhibited a striking difference (Fig. 3). Nitrate concentrations below the root zone (> 1 m) of the organic greenhouses exhibited a very high average concentration of 357 $mg L^{-1}$, with a peak average concentration of 724 $mg L^{-1}$ at a depth of 2.5 m. Nitrate concentrations below the root zone of the conventional greenhouse were much lower, with an average value of only 37.5 $mg L^{-1}$. A closer look at the upper part of the unsaturated zone of both sites exhibited an opposite concentration pattern. Nitrate concentrations under the conventional greenhouse showed a high average concentration of 270 $mg L^{-1}$ in the root zone (< 1 m) which quickly reduced in the deeper part of the vadose zone. This pattern is preferable for both agronomic and environmental reasons as nitrogen is available for root uptake in the shallow zone with minimal down migration of nitrate to the deeper parts of the vadose zone. On the other hand, under the organic greenhouse, the root zone suffered from a relative shortage of nitrate with an average concentration of only 109 $mg L^{-1}$, while a significant increase in the concentration was observed in the deeper parts of the vadose zone, where it is out of reach for plant uptake and poses a threat to groundwater quality. This nitrate concentration pattern is obviously not desirable for either agronomic or environmental reasons. Note that the drinking water standard in most developed countries dictates nitrate concentrations to be lower than 50 $mg L^{-1}$.

3.3 Identification of nitrate sources in the vadose zone

Nitrate concentration profiles in the vadose zone under the two greenhouses indicated significant differences. While investigating the reasons for these differences, one should bear in mind that the two greenhouses differ mainly in fertilization method. Both were established in the same period in the same area on land that was previously used for non-intensive agriculture; both grow similar vegetables, apply a similar amount of N-fertilizers and use a similar amount of water. Nevertheless, the nitrate concentration profiles appear to be very different (Fig. 3). Identification of the nitrate sources in the vadose zone might be examined through the isotopic composition of $\delta^{15}N$ and $\delta^{18}O$ in the nitrate molecules. An isotopic analysis of nitrate in the water samples from the vadose zone exhibited significant differences in isotopic composition in the upper ~ 5 m of each site (Fig. 4). $\delta^{15}N$ values in the upper part of the vadose zone underlying the organic greenhouse are rather heavier (average $\delta^{15}N = 15.6$ ‰; STD = 2.12) in comparison to the depleted $\delta^{15}N$ values observed under the conventional greenhouse (average $\delta^{15}N = 6.26$ ‰; STD = 0.98). The differences in isotopic composition in the upper part of the vadose zone correspond well with the expected isotopic values of processed manure versus synthetic fertilizer and natural soil nitrogen (Fig. 5) (Kendall et al., 1999).

One direct implication of the isotopic composition is the accurate identification of the penetration depth of the agricultural leachates. Though the nitrate concentration profiles are very different (Fig. 3), the isotopic fingerprint shows that agricultural leachates in both greenhouses penetrated to a depth of ~ 5–7 m in four years (Fig. 4). Although the impacted depth in both greenhouses is similar, the concentration pattern beneath the root zone in the conventional greenhouse shows significantly lower concentrations as compared to that of the organic greenhouse.

3.4 Results validation

To validate the representativeness of the results that were obtained by the VMS a sediment sampling campaign that included three boreholes to the upper vadose zone was carried in each greenhouse. Note that the while VMS collects the sediment mobile pore-water, sediment sample extract provides the entire solute capacity of the sediment which include both the mobile and immobile phases (Rimon et al., 2011a). Comparing nitrate concentration that were obtained by the VMS with those obtained from the sediment extract shows that nitrate concentrations in sediment samples from the upper part of the vadose zone under the organic greenhouse gradually increase from average value of 8.8 mg kg^{-1} in the root zone to 85.8 mg kg^{-1} at a depth of 3 m (Fig. 6). However, nitrate concentrations in sediment samples obtained from the conventional greenhouse were significantly lower, with an average value of 14.7 mg kg^{-1} over the entire measured profile. The difference between the mean nitrate concentration under the conventional and organic farms at depths of 1 to 3 m was found to be significant ($P = 0.03$ for two-tail t test). Apparently, the nitrate concentration pattern that was obtained through the sediment samples is very similar to the nitrate concentration pattern that was observed by the VMS. For convenience of comparison, nitrate concentration in water samples that were obtained by the VMS (Fig. 3) were converted in Fig. 4 from concentrations in pore water to concentrations in dry soil.

To extend representativeness of the findings, the survey was extended to six greenhouses, three organic and three conventional. All six greenhouses were established at the same time, in the same area (within a distance of up to 5 km from each other). To avoid potential bias due to farmers' specific working methods, the extended survey included farms that were all owned and operated by different farmers. The top 3 m of the sediment in each greenhouse was sampled in two boreholes with a depth sampling resolution of 0.5 m (total of 72 sediment samples). The nitrate concentrations in the sediment samples from the extended survey showed ambiguous results (Fig. 7). Two organic greenhouses exhibited nitrate concentrations that increased with depth, from 27.1 mg kg^{-1} at 0.5 m to 133 mg kg^{-1} at 3 m. On the other hand, the nitrate concentration patterns under all the conventional greenhouses exhibited lower average concentrations, ranging between 34.2 to 44.1 mg kg^{-1}. This difference in nitrate profile is very similar to the pattern that was observed by the VMS over a long period of continuous monitoring (Fig. 2). Nevertheless, nitrate concentration profiles under one of the organic greenhouses exhibited a rather low concentration profile with an average value of 29.9 mg kg^{-1} (ranging between 27.4 to 32.9 mg kg^{-1}). These results, however, did not match the results obtained from the other organic greenhouses. A closer examination of the fertilization methods practiced by the farmers showed that in the two

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greenhouses where nitrate concentrations increased with depth, the N-fertilizer source had been solid organic matter (compost and guano) mixed into the soil, a method that is commonly practiced in organic farming. On the other hand, in the organic greenhouse that exhibited low nitrate concentrations, N-fertilization relied mainly on the water extracts of guano excrement that had been applied directly through the drip irrigation throughout the growing season, and not as solid compost mixed with the soil prior to the growing season. Fertilization with the irrigation water (fertigation) throughout the growing season in response to the plant nutrient demand is a common practice in conventional agriculture.

3.5 Fertilization method and nitrate leaching

Reexamination of the nitrate concentration profiles in the vadose zone under the greenhouses suggests categorizing the potential down-leaching of nitrate according to the fertilization method rather than the general agro-technical regime of organic versus conventional agriculture. As such the differences in nitrate profiles may be attributed to solid versus liquid fertilizers application. Solid fertilization refers to the application of organic matter such as compost directly to the soil, primarily before planting, as commonly practiced in organic agriculture. On the other hand, liquid fertilization refers to application of fertilizers via the irrigation system throughout the growing season (fertigation), as is commonly practiced in conventional agriculture. Under these two categories, the differences in nitrate concentrations in deep sections (> 1 m) of the vadose zone were much more significant ($P = 0.0002$), showing a tremendous increase in nitrate concentration with depth in farms relying on solid fertilizer application (Fig. 8). Examination of the total nitrogen (TN) amount that was observed in the sediment samples from the upper section of the vadose zone under all of the greenhouses, organic and conventional, showed very similar values. Note that among the main nitrogen forms in the soil (nitrate, ammonium and organic-N) nitrate is considered more mobile compared to other forms. Moreover, under aerobic conditions, which typically prevail in the

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vadose zone of semi-arid conditions, nitrate is considered stable, and therefore, its transport across the vadose zone to groundwater persists.

The observations on enhanced down-leaching of nitrate under intensive organic farms that rely on solid fertilizers may be attributed unsynchronized nutrient release from the compost to the soil with respect to the nutrient uptake capacity of the plants. During the early stages of the growing season, an excess of irrigation water, with respect to the plant water and the nutrient uptake, creates a nutrient surplus in the soil (Pang et al., 2000). At this stage, the soil water content remains high as does the nutrient concentration, which is released from the compost to the wet soil. However, in the early stages of the growing season water and nutrient consumption by the undeveloped roots of the young plants are limited. Therefore down-leaching of water enriched with nitrate to the deeper parts of the vadose zone is unavoidable. On the other hand, accurate fertigation methods that synchronize the fertilizer's implementation with the nutrient up-take capacity of the plants, as is commonly practiced in conventional agriculture, dramatically reduce the amount of nitrate leaching through the vadose zone to the groundwater.

4 Summary and conclusions

Comparison of the groundwater pollution potential of greenhouses that grow year round vegetable under intensive regime shows that commercial organic farm that relay on compost as the main fertilizer source results in substantial down leaching of nitrate compare with conventional greenhouses. The study implemented vadose zone monitoring technology that allowed frequent sampling the sediment pore-water in multiple points across the entire vadose cross section from the root zone to the water table over long time period. Nitrate concentration profiles under the organic farms revealed increased concentration pattern with depth to average of 724 $mg\,L^{-1}$. On the other hand concentration profiles in farms that relay on implementation of liquid fertilizers through the irrigation systems during the growing season exhibited a reducing concentration

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with depth to average concentration of only 37.5 $mg L^{-1}$, immediately under the root zone. Isotopic composition $\delta^{15}N$ and $\delta^{18}O$ in nitrate from the vadose zone under the sites confirmed that the high nitrate concentration under the organic farms is likely to be origin from composted manure while the nitrate under the conventional greenhouse, though in low concentrations, likely to be from industrial or natural soil sources.

All studied greenhouses, organic and conventional, were established at the same time, grow similar vegetables, use similar amounts of water and total N-fertilizers, and share most agro-technical practices. Nevertheless, the main difference between the greenhouses is related to the fertilization regime. While organic agriculture in greenhouses relay mostly on solid fertilizers as compost that is mixed with the top soil prior to plantation, the conventional agriculture usually relay on fertigation methods where liquid fertilizer is implemented through the irrigation system during the growing season. As such, establishment irrigation in intensive organic farms, which is implemented in the early stages of the growing season, is resulted in high down leaching of nitrate that is produced in the wet top soil. This down leaching is unavoidable since the soil is wet while plants roots are undeveloped and incapable for significant water and nutrient uptake. On the other hand in typical conventional agriculture fertilizers are implemented along the growing season with the irrigation system according to the plant demand. As such nutrient uptake by the plant is more efficient, and down leaching of nitrate is minimal. This concept has been approved in one of the organic farms that practice fertigation methods rather than application of solid compost in the soil. In this farm liquid fertilizers which were produced from guano extracts were implemented through the irrigation system. As a results the vadose nitrate profiles characteristics in this organic farm were similar to those observed in conventional farms and significantly lower than those observed in organic farms that relay on compost as the main fertilizer.

Long term decision making on groundwater resources management require substantial data on the fate of pollutant transport from their sources near land surface across the vadose zone to the groundwater. The missing data that is required for proper managing of the land use with respect to groundwater quality may bridgeable through the

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use of monitoring tools that are able to collect real-time data on the quality and quantity of the percolating water across the entire vadose zone. In this study we have demonstrated how implementation of vadose zone monitoring systems provided early warning on pollution threat to groundwater before groundwater pollution became evident.

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Table 1. Vertical distribution of monitoring units across the vadose zone of the organic and conventional farms.

Farm	Probe	Depth to monitoring unit center (m)									Depth to water table (m)
Organic	FTDR	0.2	0.4	0.9	1.9	2.9	4.9	7.8	10	12.8	15
	VSP	0.2	0.4	1.3	2.3	3.3	5.3	8.3	10.5	13.3	
Conventional	FTDR	0.2	0.4	0.7	1.7	2.7	5.7	9.6	14.6	19.6	26
	VSP	0.2	0.4	1	2	3	6	10	15	20	

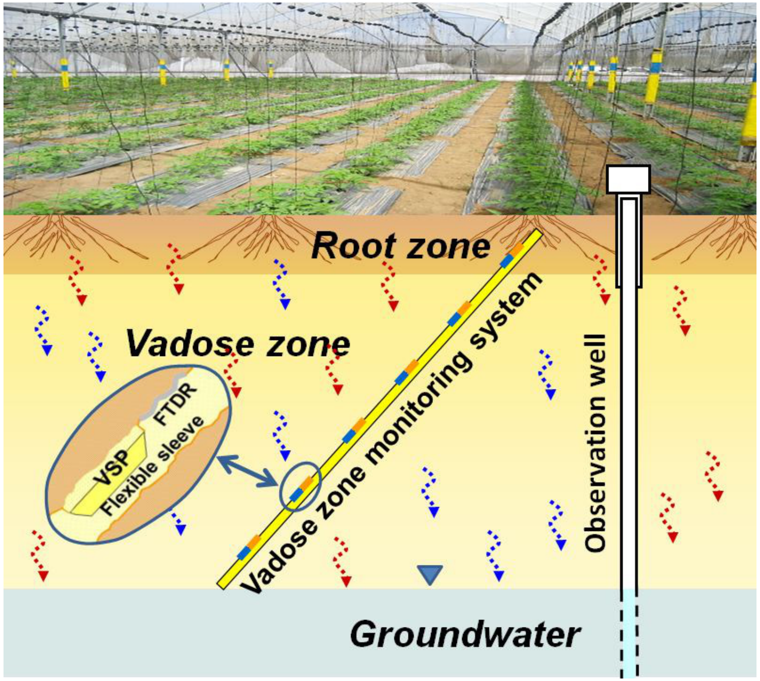

Fig. 1. Schematic illustration of a Vadose zone Monitoring System (VMS) installed under the studied greenhouse. The VMS includes a flexible sleeve hosting multiple monitoring units. The monitoring units are composed of water content sensors (FTDR) and pore water sampling ports (VSP) which are distributed across the entire vadose zone from land surface to groundwater.

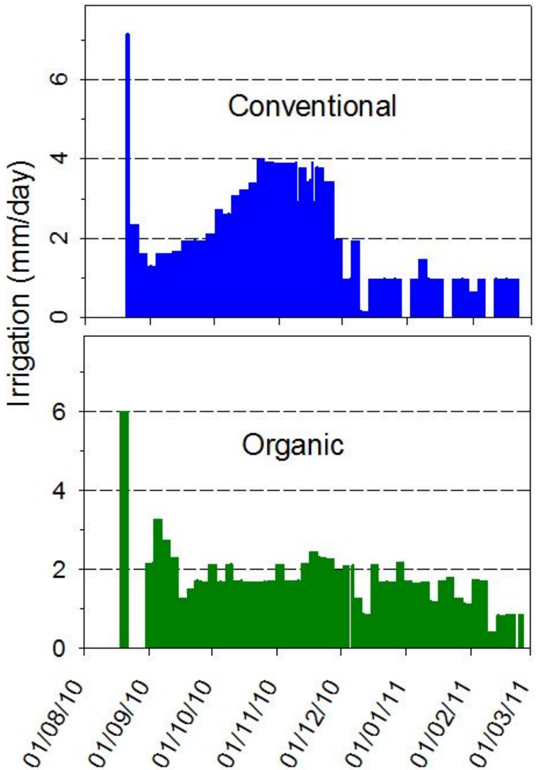

Fig. 2. Daily irrigation during a single growing season of tomato in the organic and conventional greenhouses.

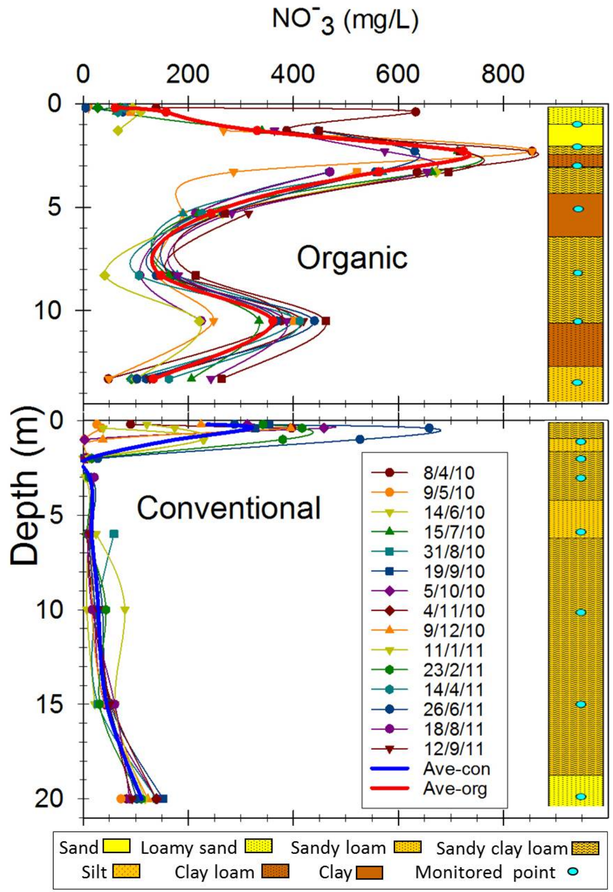

Fig. 3. Nitrate concentrations in the water samples collected by the VMS from the vadose zone underlying the organic and conventional greenhouses along with the lithoogical cross-section of each site. Nitrate profiles were established through 15 sampling campigns over 18 month period.

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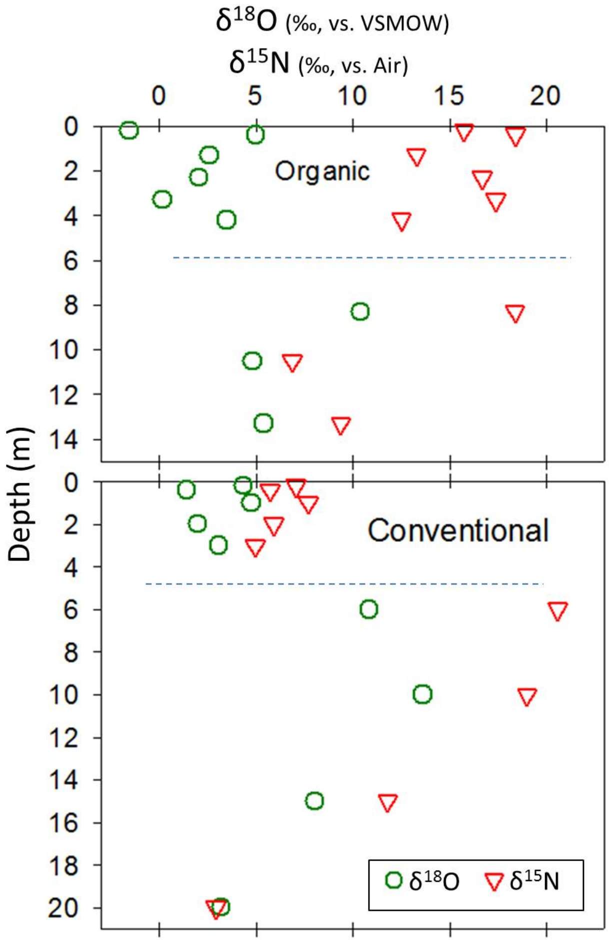

Fig. 4. δ^{18}O and δ^{15}N profiles of nitrate in the water samples obtained from the vadose zone underlying the organic and conventional greenhouses.

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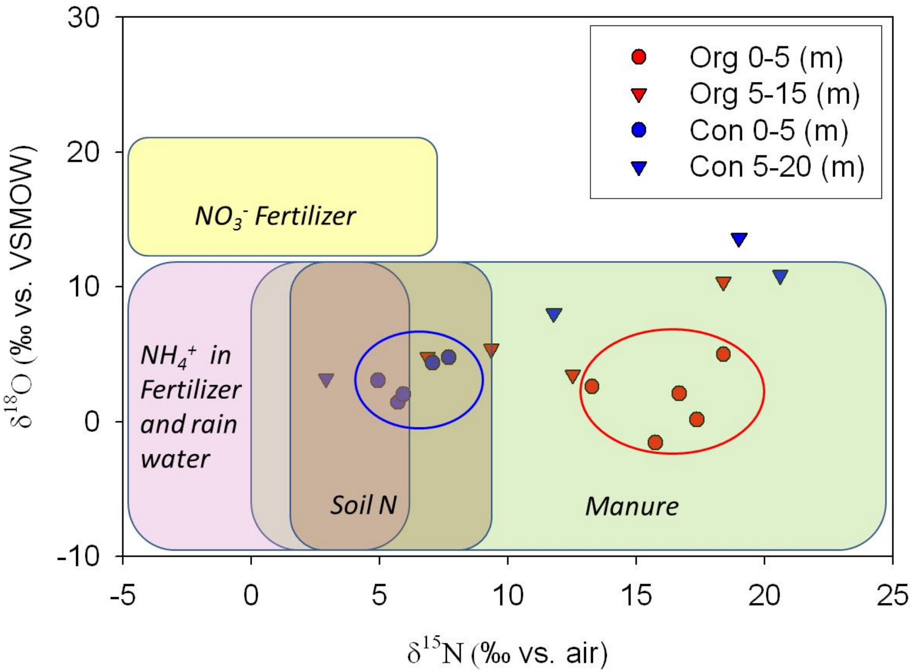

Fig. 5. Isotopic composition of $\delta^{15}N$ vs. $\delta^{18}O$ of nitrate in the water samples from the vadose zone underlying organic (Org) and conventional (Con) greenhouses with respect to typical values in common N sources.

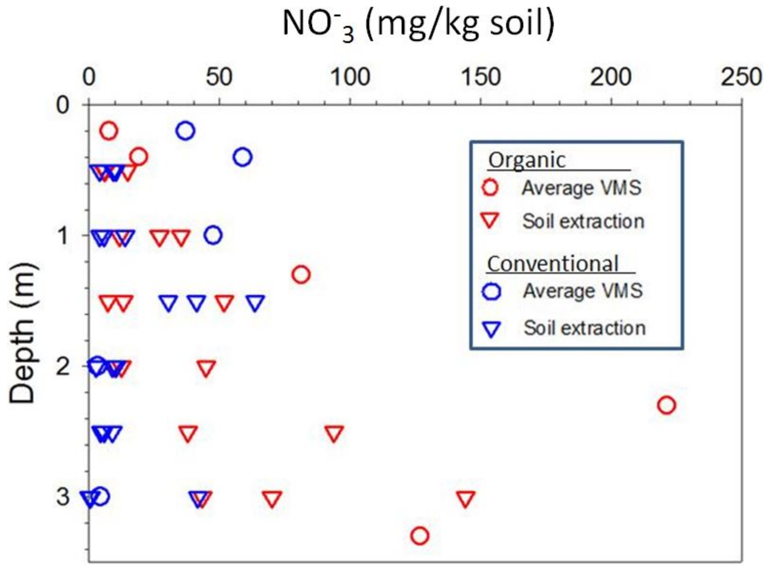

Fig. 6. Nitrate concentrations in sediment samples (soil extraction) and pore water (average VMS) in the vadose zone underlying organic and conventional greenhouses.

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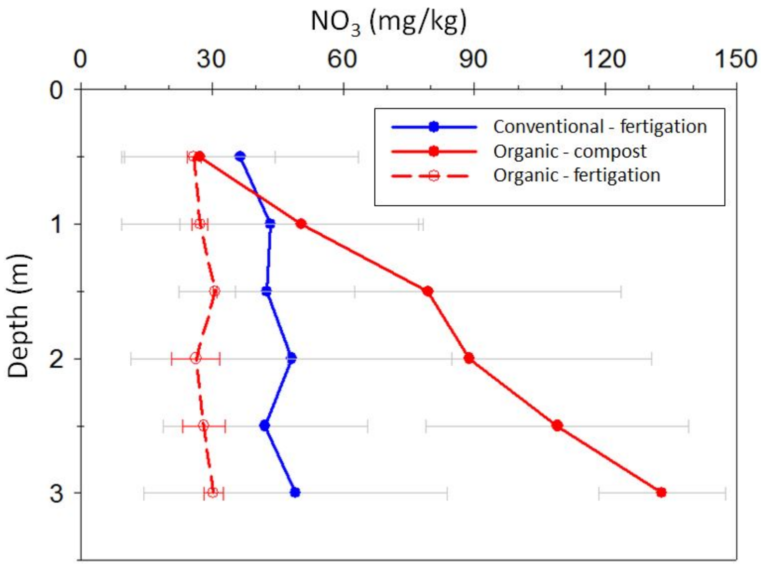

Fig. 7. Average nitrate concentration in sediment samples obtained from the upper part of the vadose zone underlying: (1) organic greenhouses that implement compost as the sole fertilizer, (2) conventional greenhouses that relay on fertigation, and (3) organic greenhouse that practice fertigation rather than solid compost.

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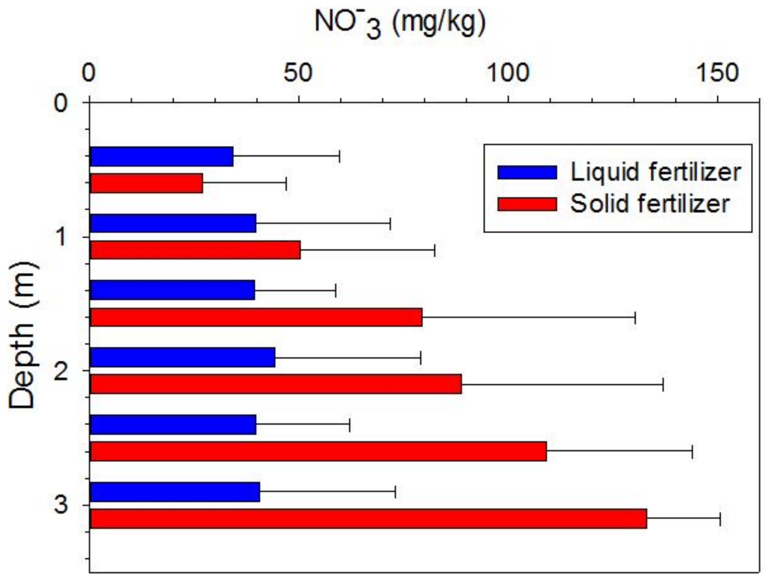

Fig. 8. Nitrate concentrations in the vadose zone underlying greenhouses fertilized by solid fertilizers as compost and guano and liquid fertilizers.

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