

**Final Report
March 30, 2006**

Project Title: Crop Nitrate Availability and Nitrate Leaching under Micro-Irrigation for Different Fertigation Strategies

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Project Objectives

1. To determine fertigation strategies for microirrigation systems using state-of-the-art modeling tools to improve water and nutrient use efficiencies and to reduce leaching of nitrates and other nutrients and chemicals;
2. To develop jointly a publication and slide show for our target audience, highlighting the recommendations using color graphics of two-dimensional simulation results to illustrate the effect of proposed fertigation strategies on the movement of nitrate for various microirrigation systems.

Abstract

Microirrigation has the potential to apply water and nutrients both precisely and uniformly throughout a field. However, under microirrigation, water, nutrients, and roots vary spatially around the drip line with the highest water contents and generally the highest root density near the drip lines. Because of this localized variability, it is possible to apply nutrients in a manner such that much of the nutrient is transported beyond the zone of higher root densities, thus potentially reducing the nutrient's availability for plant uptake and increasing leaching of the nutrient.

A recommendation by the drip irrigation industry is to fertigate (application of the nutrient through the microirrigation system) during the middle third or middle half of the irrigation cycle to spread the nutrient throughout most of the wetted soil. However, a common practice by growers is to apply fertilizers for a short time period. The fertigation strategy (duration of fertigation event and timing of the fertigation during the irrigation cycle) could affect the localized distribution of the nutrient around the drip lines.

The main objective of this project was to determine the effect of fertigation strategy and soil type on nutrient availability and leaching using a computer simulation model (HYDRUS-2D) to determine nutrient distributions around drip

lines. The first phase used a nitrate-only fertilizer. Nitrate distributions were determined for five fertigation strategies using four different types of microirrigation systems and four soil types. The second phase investigated the nutrient distribution of phosphorus, potassium, nitrate, ammonium, and urea using three fertigation strategies, two types of microirrigation systems and one soil type.

We concluded that fertigation at the beginning of the irrigation cycle tends to increase seasonal nitrate leaching. In contrast, fertigation events at the end of the irrigation cycle showed reduced nitrate leaching potential. We found that seasonal leaching was the highest for coarse-textured soils. Ammonium, phosphorus, and potassium were strongly adsorbed to soil particles, and as a result, the fertigation strategy had little effect on their distribution in the soil.

Introduction

Microirrigation (drip emitters, drip tape, and microsprinklers) has the potential of precisely applying water and chemicals both in amount and in location throughout a field. Microirrigation systems can be designed and operated so that water and nutrients are applied at a rate, duration and frequency that maximizes both crop water and nutrient uptake, while minimizing leaching of nutrients and chemicals from the root zone of agricultural fields. While high field-wide uniformities are possible under microirrigation, the localized distribution of both water and nitrate about the drip line is very nonuniform. Because of the nonuniform wetting patterns, it is possible that percolation below the root zone and nitrate leaching occurs even if applied irrigation water is equal or less than crop ET.

There are few guidelines on fertigation with microirrigation that consider typical nonuniform distributions of nutrients around drip lines for developing a fertigation strategy. A fertigation strategy consists of the duration of the fertigation event and the timing of the application relative to the irrigation cycle. The drip irrigation industry recommends applying fertilizers during the middle third or middle half of the irrigation cycle to spread the nutrient throughout most of the wetted soil. Many growers, however, apply fertilizers for a short time period of perhaps one to two hours. The fertigation strategy could affect the localized distribution of the nutrient around the drip lines. Some strategies could distribute nutrients beyond most of the root zone, thus reducing nutrient availability and increasing nitrate leaching.

We investigated the effect of different fertigation strategies on the localized nutrient distribution around drip lines using an adapted version of HYDRUS-2D. This computer simulation model can simulate the transient two-dimensional or axis-symmetrical three dimensional movement of water and nutrients in soils. Data obtained from each simulation were 1) the distribution of the nutrient

concentration around drip line; 2) the distribution of pressure head around the drip line; 3) the distribution of soil water content around the drip line; and 4) the mass balance of the nutrient for different parts of the soil profile.

Work Description

Phase 1

Eighty simulations were conducted, each for a 28 day time period. Prior to the fertigation simulations, a 56-day period of water flow only simulations were done to establish a quasi-equilibrium soil water content pattern at the start of the fertigation study. A nitrate-only fertilizer was used. The simulations were run for the following four microirrigation scenarios:

- **SUBTAPE** - subsurface drip tape (processing tomato).
- **SURTAPE** - surface drip tape (strawberry).
- **DRIP** - drip emitter on surface (grape).
- **SPR** - microsprinkler along tree row (citrus).

Soil types used in the simulations were sandy loam, loam, silt clay, and anisotropic silt clay.

For each irrigation scenario/soil type combination, five fertigation strategies were used. These strategies were based on recommendations of the drip irrigation industry and also on observed practices of growers. The strategies were:

- **B** - fertigation at the beginning of the irrigation cycle for 2 hours (after 1 hour of irrigation),
- **M** - fertigation in the middle 2 hours of the irrigation cycle,
- **E** - fertigation at the end 2 hours of the irrigation cycle (1 hour fresh water at the end),
- **C** - continuous fertigation with the water (starting 1 hour after irrigation starts and shutting one hour before irrigation stops),
- **M50** - fresh water for the first 25% of the irrigation set time, fertigation for the middle 50% of the irrigation time and fresh water for the last 25% of the irrigation. Each quarter is the same duration. The interval for initial and final solute free water was reduced to 15 minutes for surface tape irrigation (SURTAPE).

Phase 2

Thirty simulations were conducted using the loam soil type, the DRIP and SUBTAPE microirrigation systems, and the B, E, and M50 fertigation strategies. Simulations were conducted for nitrate, ammonium, urea, phosphorus, and potassium. Percentages of urea nitrogen (14.6%), ammonium nitrogen (7.4%), and nitrate nitrogen (7.4%) used in the simulations reflected the percentages of the respective nitrogen forms in the commonly-used nitrogen fertilizer UAN32. The model described the hydrolysis of urea to ammonium, the nitrification of

ammonium to nitrate, and the adsorption of ammonium, phosphorus, and potassium to soil particles.

Fertigation Manual

A manual, *Fertigation with Microirrigation*, is being published by the University of California Division of Agricultural and Natural Resources. Information developed in this project is used extensively in this publication. The table of contents of the manual is as follows:

- Introduction
- Characteristics of Some Fertilizers Commonly Used for Fertigation
- Where Does the Nitrogen Go?
- Fertigation Strategies
- Applying the Right Amount of Fertilizer
- Nitrogen in the Irrigation Water
- Fertigation Frequency
- Applying Fertilizers Uniformly
- Distribution of Fertilizer Nitrogen Around Drip Lines
- Distribution of Fertilizer Phosphorus and Potassium Around Drip Lines
- Injecting Gypsum
- Mixing Considerations
- Injection Devices
- Preventing Backflow
- Safety Concerns

Powerpoint Presentation

A Powerpoint presentation has been developed for use in meetings and conferences. The presentation has been used numerous times during this project. Modifications to the presentation have been made to customize it for a particular meeting.

Results and Discussion

Soil water content

Soil water content at the start of DRIP irrigation was relatively low near the soil surface (Fig. 1). The water content was maximum between the 60 and 140 cm soil depth, and was controlled by root water uptake. After each irrigation, the wetted region exhibited a vertically elongated pattern and extended to nearly 60 cm horizontally and 100 cm vertically directly beneath the emitter. A zone of relatively wet soil occurred near the surface between 40 and 60 cm from the drip line. This behavior was caused by a combination of the wetting front only reaching about 60 cm from the drip line which prevented wetting beyond 60 cm

and reduced soil water extraction at that location due to fewer roots compared to near the drip line.

Before irrigation with the SUBTAPE system, water content values were smallest near the surface, decreasing with horizontal distance from the drip line (Fig. 1). The soil was slightly wetter at depths below about 35 cm. After irrigation, most wetting occurred above the 70 cm soil depth and extending to near the soil surface. Horizontal water movement was limited to about 35 cm from the drip line. Soil water contents beyond 35 cm horizontally at the end of the irrigation were the same as those at the start of irrigation.

Phase 1 - Nitrate Patterns Around Drip Lines

Examples of the effect of fertigation strategy on soil nitrate distribution at the end of the first irrigation cycle is presented in Fig. 2 for DRIP (loam soil), using contour plots of relative nitrate concentration. Nitrate concentrations in the soil at the start of irrigation were assumed to be zero. All fertilizer concentrations are expressed as nominal concentrations, relative to the concentration of the fertilizer in the irrigation water. The same mass of fertilizer was applied for each fertigation strategy. Results are:

- Nitrate leaching occurred in the immediate vicinity of the drip line for the B strategy with nitrate accumulating near the periphery of the wetted pattern.
- For the E strategy, nitrate was concentrated in the vicinity of the drip line with concentrations much higher compared to the B strategy.
- The M50 and C (not shown) strategies resulted in a more uniform nitrate distribution in the wetted pattern compared to the other strategies.
- Nitrate concentrations were increasingly diluted as the duration of the fertigation event increased and also for longer periods of freshwater application after fertigation (B and M). Hence, the highest nitrate concentrations occur for the E fertigation strategy. Also, the assumed root zone is concentrated in a 30 cm circle around the drip line where most of the nitrate remained at the end of the irrigation. Therefore, the E-strategy is most efficient, as it applies the nitrate to the roots and minimizes leaching.

Contour plots for the SUBTAPE irrigation system are presented in Fig. 3. As for DRIP, leaching near the drip line occurred for the B strategy, while the highest nitrate concentrations occur near the emitter for the E strategy. Nitrate was distributed more uniformly throughout the wetted pattern for the M50 and C (not shown) strategies. The relative root distribution for this system has most roots available for nutrient uptake in a circle of about 40 cm around the drip line, with a maximum root density at the 25 cm depth.

Figure 4 shows the concentration contour plots for the SURTAPE microirrigation system. Similar nitrate patterns occurred for all fertigation strategies. The reason for this behavior is the relatively small irrigation time compared to the other microirrigation systems.

Most of the water applied by the microsprinkler system (SPR) occurred within about one meter from the sprinkler line. Thus, the nitrate patterns reflected this pattern. Considerable leaching occurred near the microsprinkler for the B strategy with nitrate moving down to about 110 cm deep (Fig. 5). Little movement of nitrate down in the profile occurred for the E strategy. As before, the E strategy is likely the most efficient as it eliminates leaching by fresh water after fertigation.

In general, the largest leaching losses occur most often for the B fertigation. This is because its fertigation period is the small (as are M and E) and nitrate is potentially available for leaching during the subsequent irrigation period. A potential exception applies for the SUBTAPE irrigation system. The E scenarios are most efficient and generate the least leaching. An exception to this general rule applies to the SURTAPE irrigation system where the leaching of the E strategy was relatively high for all soil types.

Although not shown here, root nutrient uptake accounted for about 40-60 percent of the total N added, independent of fertigation scenario. Root nitrate uptake was the least for the SPR irrigation system (20-30 %), mostly caused by the highly non-uniform water application, whereas roots extended laterally through the simulated soil domain. Consequently, both water and nutrients were less accessible for the roots further away from the sprinkler system. Most of the applied nitrate (50 – 80 %) was stored in the root zone, potentially vulnerable for leaching after 28 days, later in the growing season.

Phase 2

The effects of different fertigation strategies on the soil distribution of urea, ammonium, and nitrate around a drip line between the first and second irrigation and at the end of the simulation period of 28 days are illustrated in Fig. 6 thru 8. The effect of the B strategy is discussed in detail for the DRIP system for the total simulation period of 28 days, while only presenting the main results of the other strategies. Time $t=0$ is the start of the fertigation simulation period after the 56 days of flow-only simulations. All fertilizer concentrations are expressed as nominal concentrations, relative to the concentration of the fertilizer in the irrigation water. The same mass of fertilizer was applied for each fertigation strategy.

DRIP

The B fertigation strategy generally resulted in a band of urea along the periphery of the wetted pattern (Fig. 1) with little or no urea near the drip line, except

immediately after fertigation ($t=3.63$) (Fig. 6). Urea concentrations decreased over time between irrigations as a result of hydrolysis.

Ammonium remained concentrated in the immediate vicinity of the drip line at all times for all fertigation strategies (Fig. 6). There was only slight movement, because of soil adsorption and subsequent fast nitrification and/or root uptake. Ammonium accumulated over time.

Nitrate moved continuously downwards during the 28 day simulation period, as nitrate is not adsorbed, whereas denitrification was assumed negligible. As expected, high nitrate concentrations occurred near the drip line immediately after fertigation ($t = 3.63$) due to nitrate injection and nitrification, but little nitrate remained near the drip line at the end of the irrigation due to leaching and root uptake ($t = 5.00$, Fig. 4). However, by the start of the next irrigation ($t = 7.00$), nitrate levels near the drip line increased, the result of nitrification of ammonium.

In the case of fertigation at the end of the irrigation cycle (E strategy) (Fig. 7), urea concentrations were maximum near the drip line with concentrations decreasing over time between irrigation cycles as a result of hydrolysis and water redistribution. A noticeable second front occurred at a larger depth because of water movement by irrigation prior to the start of fertigation ($t = 4.88$). As before, ammonium concentrations remained high near the drip line. Nitrate was concentrated near the edge of the wetted pattern due to irrigation before fertigation. After fertigation ($t = 4.96$), nitrate was maximum near the drip line, but then decreased slightly by the end of the irrigation ($t = 5.00$). As with the B strategy, nitrate concentrations increased near the drip line due to ammonium nitrification by the start of the next irrigation ($t = 7.00$).

Fertigation during the middle 50 % of the irrigation event (M50) caused a more uniform and more extended urea and nitrate distribution throughout the wetted region compared to the other fertigation strategies (Fig. 7) because of larger fertigation times. Because of its adsorption, ammonium distributions around the drip line were similar to those of the other scenarios.

SUBTAPE

The distributions for urea and nitrate for the 3 fertigation scenarios are presented in Fig. 8. Overall, results are comparable with the DRIP irrigation system, except that spatial distribution patterns are controlled by the buried drip line, thereby carrying ammonium and nitrate to larger depths and upward from the drip line. For the B strategy, urea and nitrate were moved away from the drip line during irrigation, whereas both species remained near the drip line for the E strategy. After irrigation at $t = 4.65$ days, nitrate concentrations near the drip line increased due to nitrification. Whereas urea concentrations decreased between irrigation cycles as a result of hydrolysis, nitrate concentrations accumulated with time

throughout the soil profile during the 28-day irrigation period. Between irrigation events the nitrate concentrations decreased because of root uptake.

Phosphorus and Potassium

Phosphorus and potassium were concentrated near the drip line for both B and E fertigation strategies for DRIP (Fig. 9) and for SUBTAPE (data not shown). Horizontal movement was about 30 cm. By 28 days, both fertilizers had moved slightly deeper (down to nearly 10 cm) compared to 1.5 days, but no change in horizontal movement had occurred.

DRIP Mass Balance

The mass balance was conducted for 2 zones, the upper 100 cm or root zone (zone 1) and the lower 100 cm (zone 2). It was assumed that the accumulated nitrate in zone 2 eventually would be leached over time because few roots existed in that zone. As expected, the urea mass was maximal at the end of the each fertigation event, but decreased with time thereafter until the next fertigation event (Fig. 10), because of subsequent hydrolysis. The mass values of the first fertigation event reflect mass ratios of the applied fertilizer mixture. No accumulation of urea occurred in the profile over time and no urea moved to zone 2 as all urea either converted to ammonium by hydrolysis. The urea mass was similar for all fertigation strategies. Ammonium accumulation was limited to zone 1, and no ammonia was present in zone 2 because of the relatively quick nitrification and slow transport due to sorption.

Ammonium accumulated between irrigation events, indicating that its supply from fertilizer and urea hydrolysis exceeded removal by plant uptake and nitrification. Typically, the mass of ammonium increased between the end of the fertigation and the end of the irrigation during which that fertigation event occurred due to hydrolysis of urea. In contrast, nitrate accumulated with time for all fertigation strategies indicating that supply of nitrate by the fertilizer and nitrification of ammonium exceeded removal by plant uptake and leaching. Because of the transport of nitrate by the infiltrating irrigation water, nitrate also accumulated in zone 2 during the second half of the simulation period.

The mass balance showed leaching percentages of 6.8 %, 2.6 %, and 5.2 % for the B, E, and M50 fertigation strategies, respectively. These leaching percentages were slightly lower than those found using the nitrate only fertilizer. As expected, no leaching of ammonium or urea took place.

The fertilizer use efficiency (FUE), defined as the ratio of the mass of N uptake to the mass applied, ranged from 50.7% to 64.9%. The E scenario showed the highest efficiency and the B strategy was the lowest.

SUBTAPE Mass Balance

For the SUBTAPE irrigation system, the soil profile was split into three zones: zone 1 - above the drip line, zone 2 - below the drip line to the 75 cm soil depth, and zone 3 - the bottom 25 cm of the soil profile. It was assumed that the accumulated nitrate in zone 3 eventually would be leached over time because few roots existed in that zone.

The urea mass decreased with time following fertigation, however, more urea was found in zone 2 compared to zone 1, because of the location of the subsurface tape (Fig. 10). No urea was present in zone 3. Both ammonium and nitrate mass accumulated during the simulation period, with more mass in zone 2 than in zone 1. This behavior occurred for all fertigation strategies. No ammonium was present in zone 3. Nitrate leached into zone 3 near the end of the simulation period. Urea, ammonium, and nitrate masses were higher in zone 1 and lower in zone 2 for the B strategy as compared to the E and M50 strategies. This result reflects the increased opportunity for upward flow of water and dissolved N species by capillarity near the beginning of irrigation of the B scenarios.

The mass balance indicated similar N uptake for all fertigation strategies. Stored and leached masses were also similar for all strategies. Leaching percentages were 3.9 %, 3.9 %, and 4.4 % for the B, E, and M50 fertigation strategies, respectively. FUE's were nearly equal between strategies (44.8% to 46.6%), with slight differences caused by upward movement above the drip line.

Conclusions

Phase 1

Total seasonal leaching was the lowest for subsurface drip tape (SUBTAPE). Total seasonal leaching was the highest for the surface tape system (SURTAPE), when compared to the other micro-irrigation methods, mostly because of the relatively shallow root depth of strawberries in comparison with furrow depth. We conclude that leaching potential increases as the differences between the extent of the wetted soil volume and rooting zone increases. As expected nitrate distributions for the micro-sprinkler (SPR) system were highly dependent on the non-uniform water application pattern, as most of the irrigation occurred in a small area within one meter distance from the microsprinkler. Seasonal leaching was the highest for the sandy loam soil and the lowest for the silt clay soil.

We conclude that fertigation for a short time at the end of the irrigation cycle (strategy E) generally reduces the potential of nitrate leaching in microirrigation systems, with the exception of surface drip and tape systems in clayey soils. Moreover, we also found that fertigation strategy is not so important for SUBTAPE systems, except that the B strategy may be favorable as it tends to

retain nitrate above the drip tape by capillary action. The leached zone near the drip line was very small for the surface tape (SURTAPE) compared to the other scenarios mainly because of the short irrigation time after fertigation. Long fertigation times resulted in relatively uniform nitrate distributions in the wetted regions for all but one irrigation system. For all surface-applied microirrigation systems on finer-textured soils, lateral spreading of water and nitrates is enhanced by surface water ponding, causing the water to spread across the surface with subsequent infiltration downwards and horizontal spreading of soil nitrate near the soil surface.

Phase 2

The HYDRUS-2D computer simulation model was found to be an effective modeling tool for assessing fertigation strategies using a urea-ammonium-nitrate fertilizer commonly used for fertigation with microirrigation. The model described the movement of urea, ammonium, and nitrate during irrigation and accounted for the reactions of hydrolysis, nitrification, and ammonium adsorption.

In contrast to the Phase 1 results, which used a nitrate-only fertilizer, the model showed that a urea-ammonium-nitrate fertilizer increased the nitrate concentration near the drip line, an area where root density is greatest and most of the plant root uptake of nitrate takes place. This was also the case for the B strategy with a long irrigation after fertigation. Nitrification of ammonium maintained nitrate concentrations near the drip line compared to the nitrate-only fertilizer, in part caused by the sorption of ammonium prior to nitrification, thereby delaying downward transport of soil nitrate.

The results also showed that urea moves readily with the infiltrating irrigation water, potentially moving this nitrate source away from the soil zone with maximum root density. For all strategies, urea did not accumulate in the soil profile, but quickly decreased with time after fertigation by hydrolysis. Because of its adsorption to the soil, most of the ammonium remained near the drip line, with low concentrations near the edge of the wetting zone.

Nitrate mass accumulated, moving down to depths deeper than 150 cm for the DRIP system and deeper than 100 cm for SUBTAPE. Higher nitrate mass occurred above the drip line for the B strategy compared to the other strategies for SUBTAPE.

The leached nitrate mass was smallest for the E fertigation strategy and largest for the B strategy for the DRIP system. No trends were clearly determined for any fertigation strategy for the SUBTAPE irrigation system, mainly due to upward flow and associated movement of N species above the drip line.

Slightly smaller leaching percentages were computed for the urea-ammonium-nitrate fertilizer compared to the nitrate only fertilizer for DRIP. Fertilizer use

efficiency ranged from 50.7% (B strategy) to 64.9% (E strategy) for DRIP and was about 44.4% to 46.6% for SUBTAPE. Based on these results we conclude that fertigation consisting of short injection times near the beginning of long irrigation events should be avoided for surface drip systems. The fertigation strategy is less of a factor for subsurface drip systems.

For these scenarios, drip lines and plant rows coincide. Thus, the root distributions used for these scenarios reflect the wetting patterns typically found under microirrigation with both soil water content and root density highest near the drip lines and decreasing with distance and depth from the drip line. Field data have shown that these root distributions are typical for this condition and that water and nutrients are applied in the areas with maximum root densities.

Recommendations for Fertigation with Microirrigation

Based on these results along with results from other studies and field experiences, the following are recommended for fertigation with microirrigation:

- Do not start injection until irrigation water has reached the end of the irrigation system
- Inject for sufficient time for the chemical to reach the end of the irrigation system
- After injection, flush system with irrigation water until the fresh water reaches the end of the irrigation system
- Avoid long periods of water application after injection of fertilizers that are mobile
- Maintain high uniformity of emitter discharge rates throughout the irrigation system
- Use good irrigation water management techniques
- Apply the right amount of fertilizer

Appendix A. Presentations

Date	Meeting	Title of Presentation	Location	Attendance
07/16/03	Plant Health Assoc.	Fertigation	Salinas	45
09/30/03	Veg. crops workshop	Fertigation	Texas A&M, College Station, TX	50
02/10/04	Irrigation workshop	Fertigation with drip irrigation	Santa Maria	15
02/24/04	Sweet potato meeting	Fertigation with drip irrigation	Merced	60
11/03/04	Fertigation Workshop	N fertilizer requirements Principles of fertigation Keeping fertilizer in the root zone	Tulare (AgTAC)	25
11/09/04	FREP Conference	Nitrate availability and leaching with microirrigation	Tulare	30
11/18/04	Calif. Plant Health	Nitrate availability and leaching with microirrigation	Woodland	50
01/21/05	Veg. Prod. meeting	Fertigation of row crops with drip irrigation	Five Points	80
02/02/05	Calif. Plant and Soil Conference	Effect of fertigation strategies on nitrate availability and leaching	Modesto	60
05/07/05	Warm Season Crop Series	Effect of fertigation strategies on nitrate availability and leaching	Gilroy	30
10/20/05	Citrus Grower Mtg	Fertigation with microirrigation	Tulare	40
12/13/05	Tree Grower Mtg	Principles of Fertigation	Modesto	80
02/23/06	Tree Grower Mtg	Principles of Fertigation	Placerville	35

2004 ASAE/CSAE Annual International Meeting, Ottawa, Canada. Aug 1-4, 2004.

Crop nitrate availability and nitrate leaching under micro-irrigation for different fertigation strategies.

American Society for Horticultural Science Annual Conference, Las Vegas, NV. July 17-21, 2005. Effect of fertigation strategy on nitrogen availability and nitrate leaching using micro-irrigation.

The Irrigation Association 26th Annual International Irrigation Show, Phoenix, AZ. November 6-8, 2005. Fertigation with drip irrigation for maximum availability and minimum leaching of nitrate.

Soil Science Society of America International Annual Meeting, Salt Lake City, UT. November 6-10, 2005. Fertigation with drip irrigation for maximum availability and minimum leaching of nitrate.

Appendix B. Publications

Gärdenäs, A., Hopmans, J.W., Hanson, B.R., Šimůnek, J., 2005. Two-dimensional modeling of nitrate leaching for different fertigation strategies under micro-Irrigation. *Agric. Water Management* 74, 219-242.

Hanson, B, J. Hopmans, J. Šimůnek, and A. Gärdenäs. 2005. Effect of fertigation strategy on nitrate availability and nitrate leaching under micro-irrigation. Proceedings of the 2005 California Plant and Soil Conference. California Chapter of the American Society of Agronomy. Modesto, CA. Feb. 1-2, 2004.

Hanson, B.R. 2005. Irrigation system design and management: Implications for efficient nutrient use. Proceedings of the 2005 Western Nutrient Management Conference, Salt Lake City, Utah. March 2–4, 2005

Hanson, B., J. Hopmans, J. Šimůnek, and A. Gärdenäs. 2005. Fertigation with drip irrigation for maximum availability and minimum leaching of nitrate. Proceedings of the 26th Annual Irrigation Show of the Irrigation Association, November 6 – 8, 2005, Phoenix, AZ.

Hanson, B.R. J.W. Hopmans, J. Šimůnek and A. Gärdenäs. 2004. Crop Nitrate Availability and Nitrate Leaching under Micro-Irrigation for Different Fertigation Strategies. FREP Progress Report, May 2004. University of California, Dept. LAWR, Davis, CA 95616. 141 p.

Hanson, B., J.W. Hopmans, J. Šimůnek, and A. Gärdenäs. 2004. Crop nitrate availability and nitrate leaching under micro-irrigation for different fertigation strategies. Proceedings of the 12th Annual Fertilizer Research and Education Program Conference. Tulare, CA. Nov. 9, 2004.

Hanson, B. and J.W. Hopmans. 2003. Crop nitrate availability and nitrate leaching under micro-irrigation for different fertigation strategies. Proceedings of the 11th Annual Fertilizer Research and Education Program Conference. Tulare, CA. Nov. 20, 2003.

Hanson, B., J.W. Hopmans, J. Šimůnek, and A. Gärdenäs. 2004. Crop nitrate availability and nitrate leaching under micro-irrigation for different fertigation strategies. ASAE Paper No. 042033. 2004 ASAE/CSAE Annual International Meeting, Ottawa, Canada. Aug 1-4, 2004.

Hanson, B.R., Šimůnek, J., Hopmans, J. 2006. Numerical modeling of urea-ammonium-nitrate fertigation under microirrigation. *Agric. Water Management*. In Press

Hanson, B., Hopmans, J., O'Connell, N., Šimůnek, J., Beede, R. 2006. *Fertigation With Microirrigation*. UC ANR Publication. In Press.

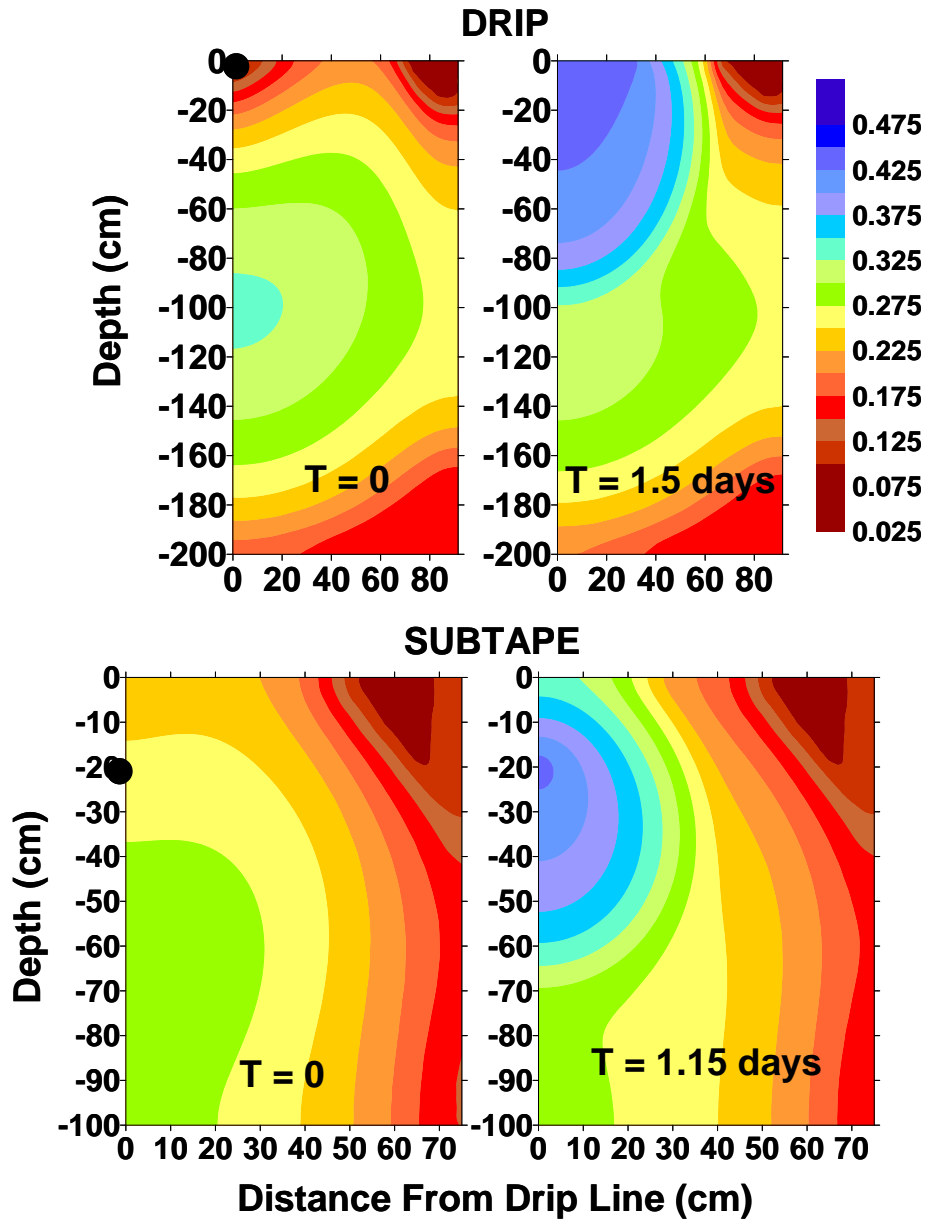


Figure 1. Volumetric soil water content distributions at the start and conclusion of irrigation for DRIP and SUBTAPE microirrigation systems.

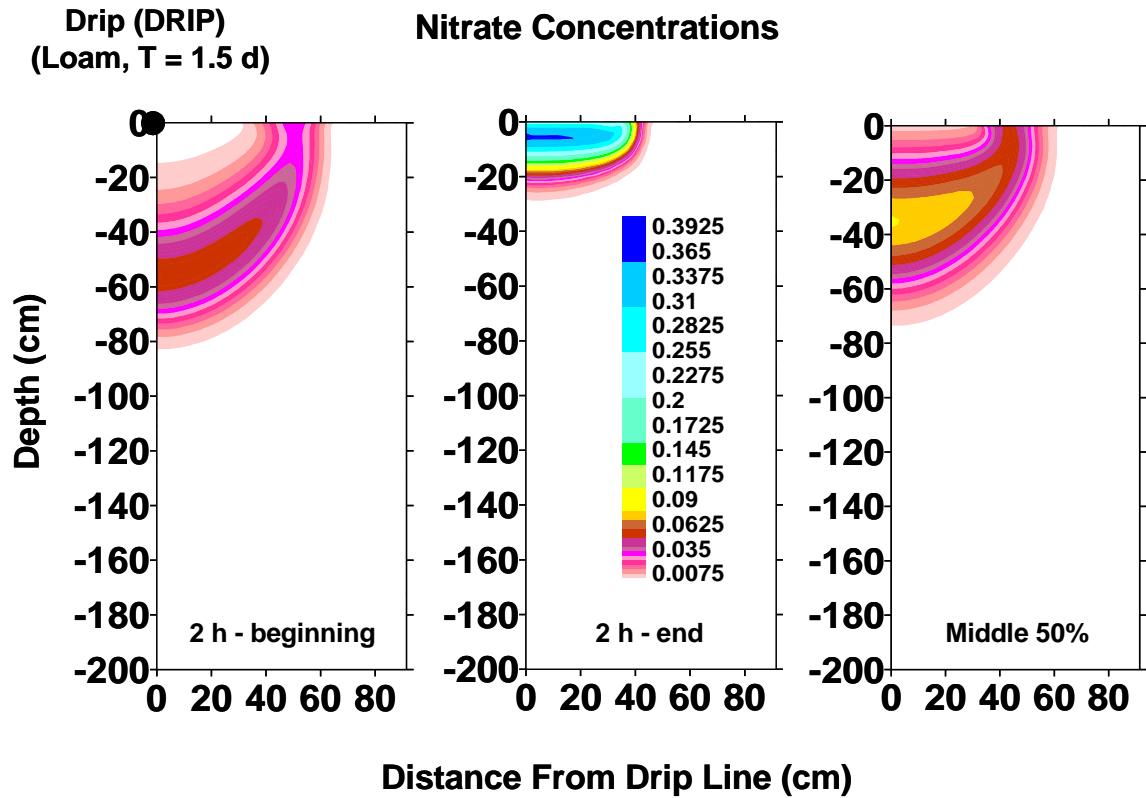


Figure 2. Nitrate distributions around the drip line of a surface drip system (DRIP) in loam soil for nitrate injection for 2 hr at the beginning of the irrigation starting 1 h after start of irrigation; injection for 2 h ending 1h before the end of the irrigation; and injection during the middle 50 percent of the irrigation set. Duration of irrigation was 36 hours. The black dot is the location of the drip line. The color bar shows relative concentrations.

**Subsurface Drip (SUBTAPE)
(Sandy Loam, T = 1.15 d)**

Nitrate Concentrations

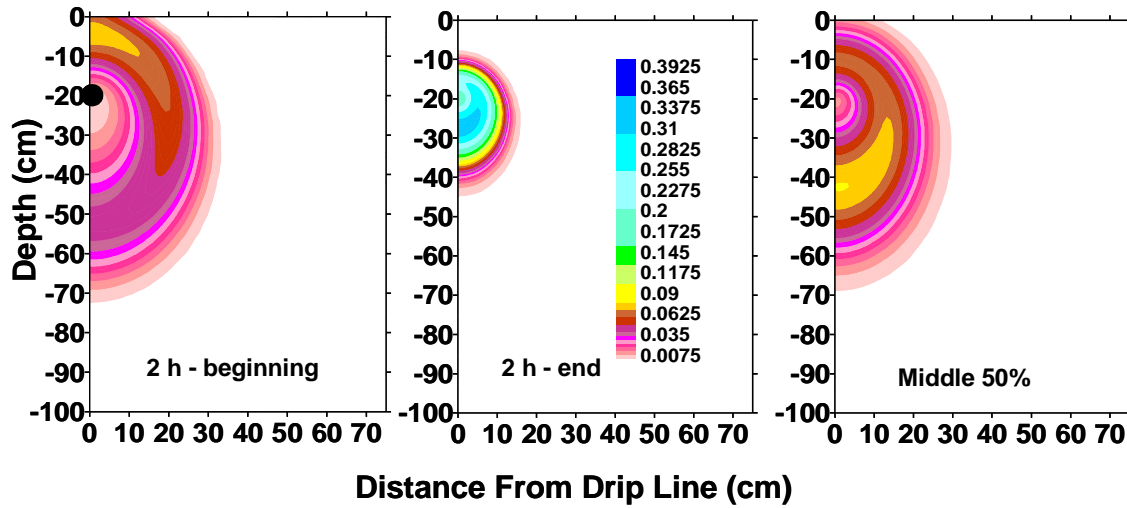


Figure 3. Nitrate distributions around the drip line of a subsurface drip system (SUBTAPE) in sandy loam for nitrate injection for 2 hr at the beginning of the irrigation starting 1 h after start of irrigation; injection for 2 h ending 1h before the end of the irrigation; and injection during the middle 50 percent of the irrigation set. Duration of irrigation was 27 hours. The black dot is the location of the drip line. The color bar shows relative concentrations.

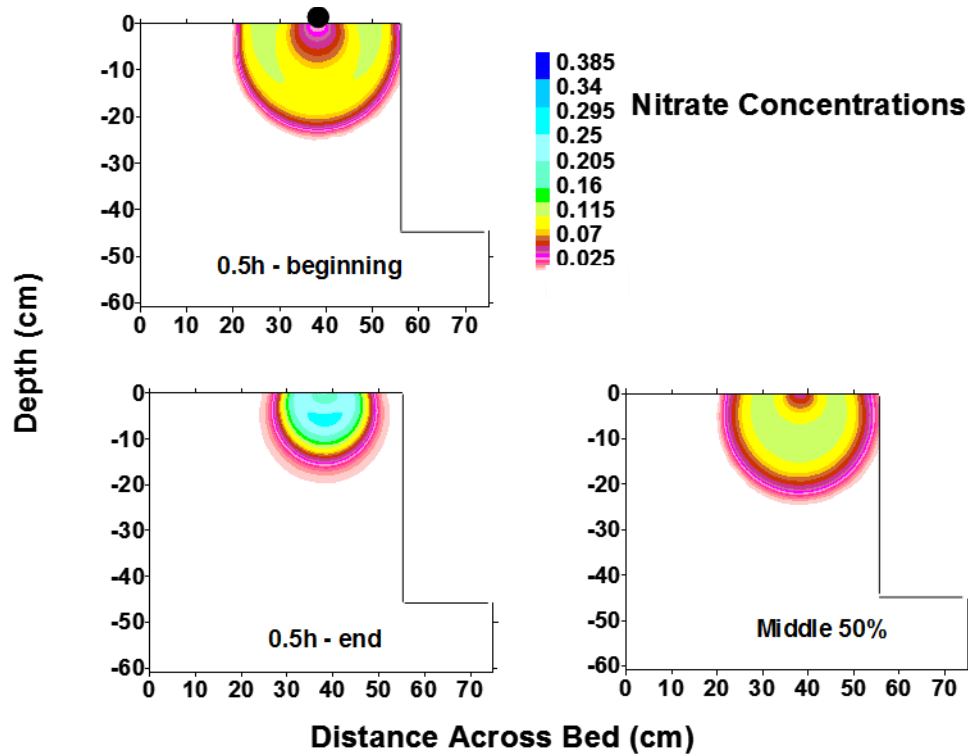


Figure 4. Nitrate distributions around the drip line for a surface drip tape system (SURTAPE) using a raised bed for nitrate injection for 0.5 hr at the beginning of the irrigation starting 15 min after start of irrigation; injection for 0.5 h ending 15 min before the end of the irrigation set; and injection during the middle 50 percent of the irrigation set. The irrigation time was 3.2 hours. The black dot is the location of the drip line. The color bar shows relative concentrations.

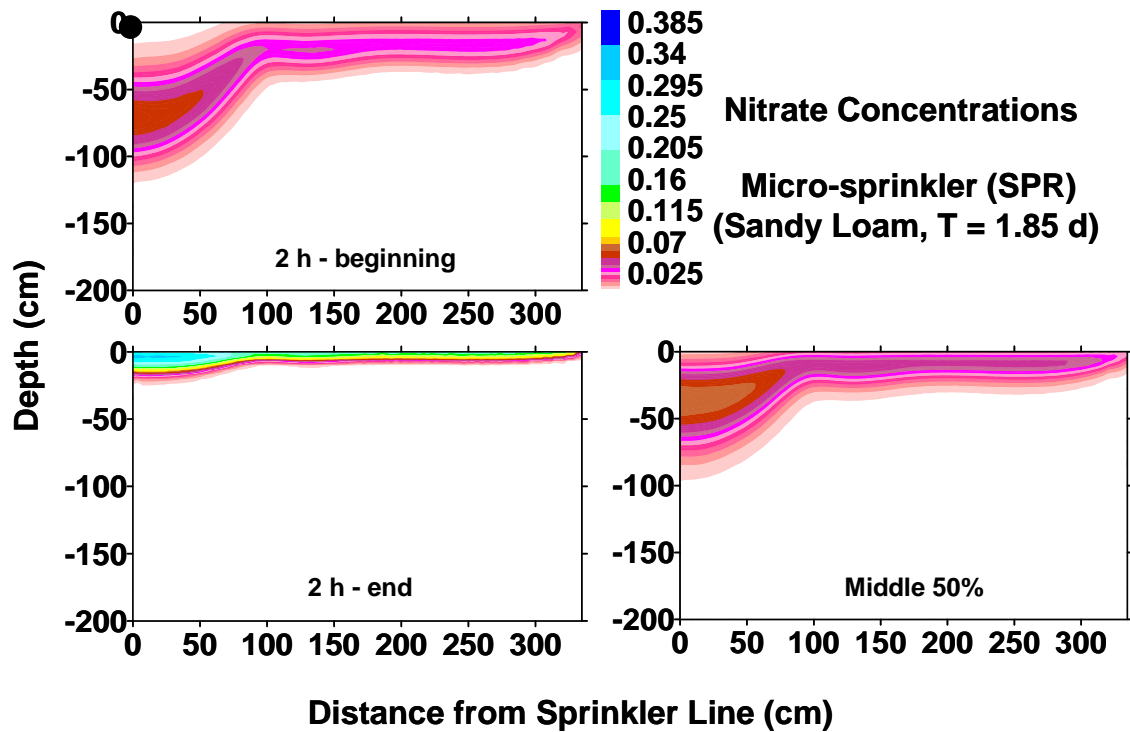


Figure 5. Nitrate distributions around the drip line for a microsprinkler system (SPR) for nitrate injection for 2 h at the beginning of the irrigation starting 1 h after start of irrigation; injection for 2 h ending 1 h before the end of the irrigation; and injection during the middle 50 percent of the irrigation set. The irrigation time was 1.85 days. The black dot is the location of the drip line. The color bar shows relative concentrations.

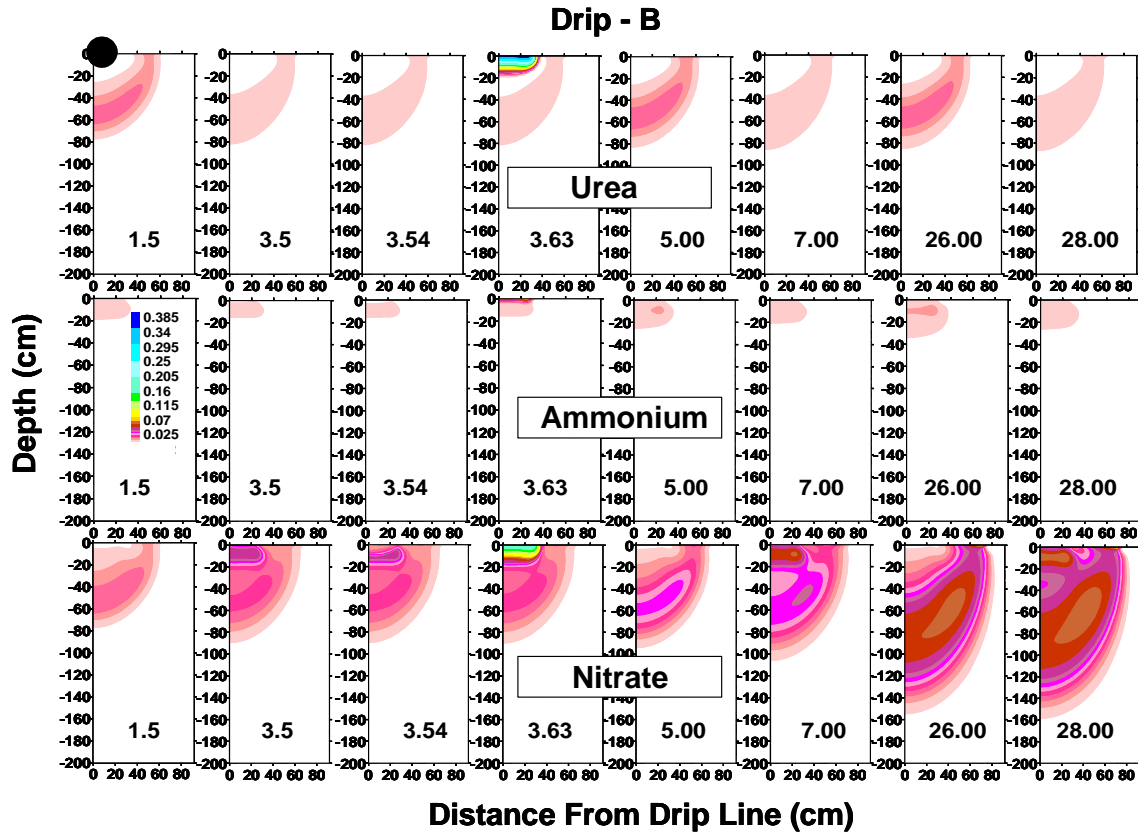


Figure 6. Spatial distributions of soil solution urea, ammonium, and nitrate for the B strategy of DRIP for various days during the simulation period. The times (days) correspond to end of first irrigation (1.50), beginning of the second irrigation (3.5), beginning of second fertigation (3.54), end of second fertigation (3.63), end of second irrigation (5.00), beginning of third irrigation (7.00), end of last irrigation (26.00), and end of simulation period (28.00).

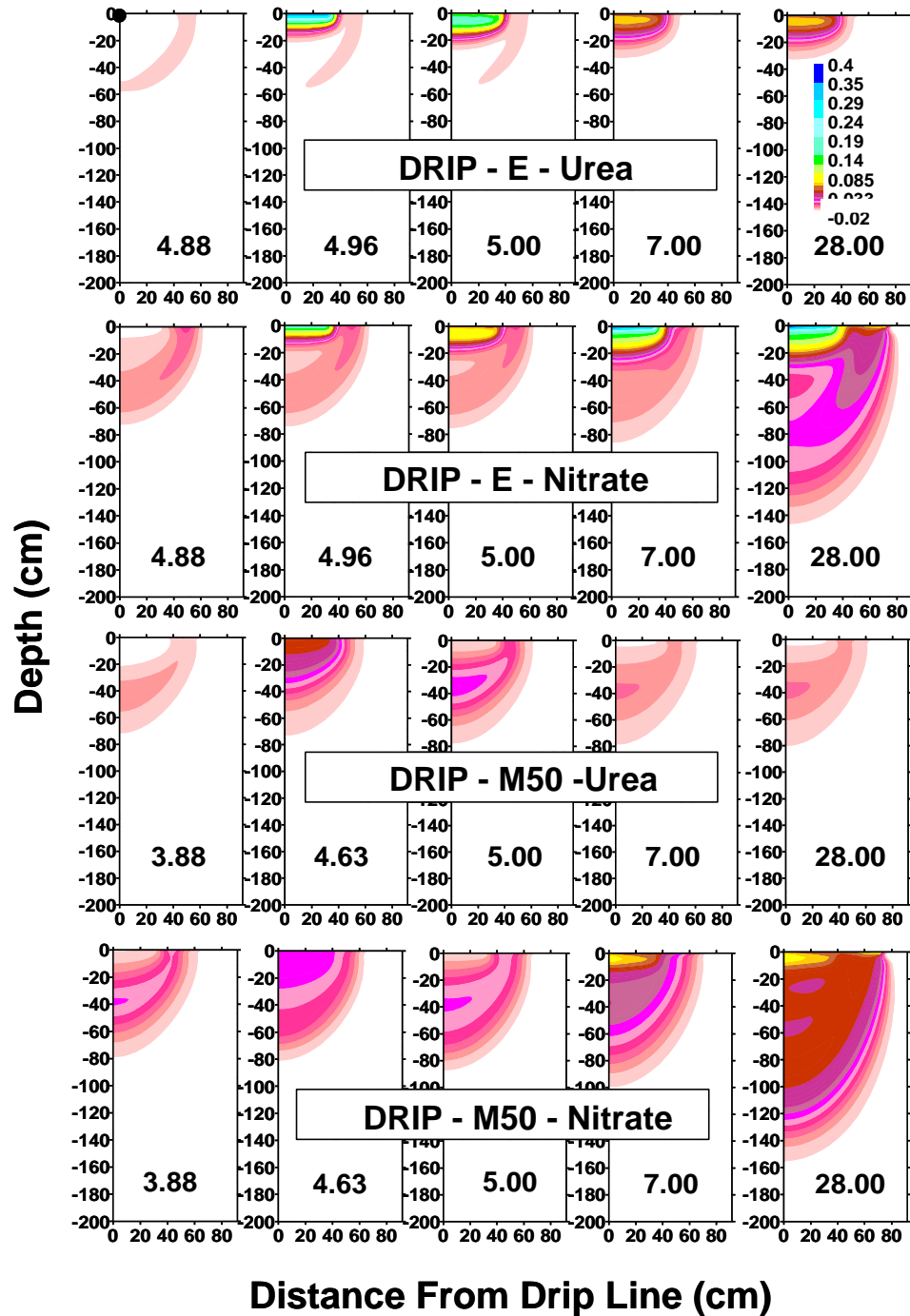


Figure 7. Spatial distributions of soil solution urea and nitrate (M/L^3) for selected times of the E and M50 strategies of DRIP. For the E strategy, the times (days) correspond to the beginning of second fertigation (4.88), end of second fertigation (4.96), end of second irrigation (5.00), beginning of next irrigation (7.00), and end of simulation period (28.00). For the M50 strategy, the times

(days) correspond to the same sequence of events as described for the E strategy.

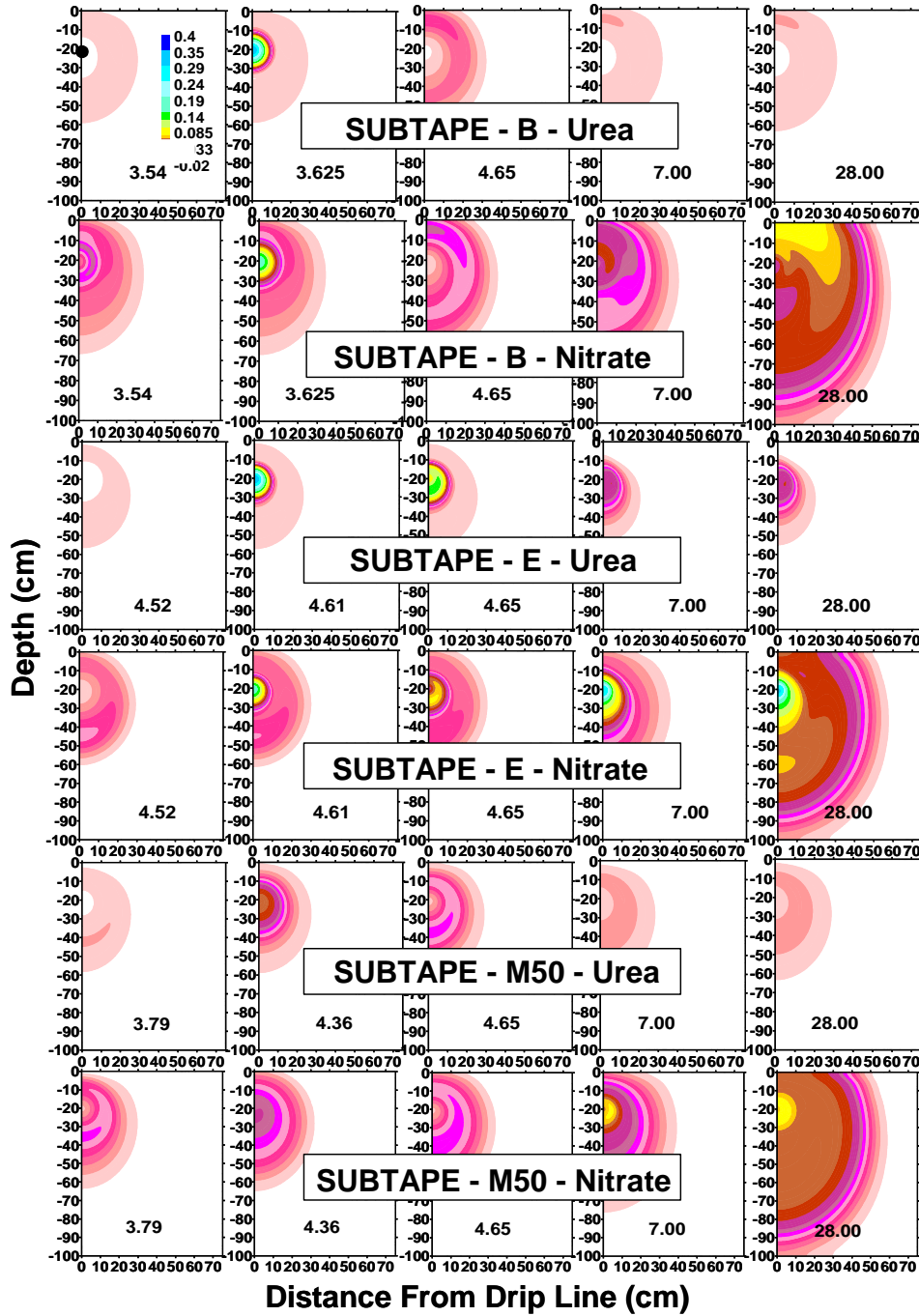


Figure 8. Spatial distribution of urea and nitrate for selected times for the B, E, and M50 strategies for SUBTAPE. The respective times correspond to the beginning of the second fertigation, end of the second fertigation, end of the

second irrigation, beginning of the next irrigation, and end of the simulation period for each fertigation strategy.

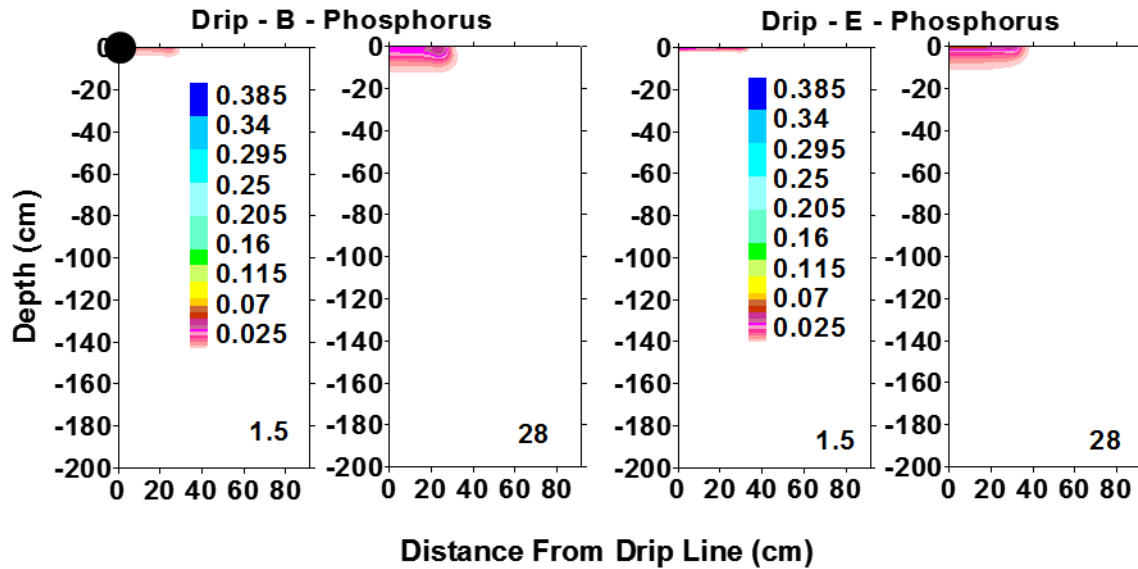


Figure 9. Distribution of phosphorus and potassium under surface drip irrigation (DRIP) in a loam soil at the beginning (1.5) and end (28) of the simulation period. The black dot is the location of the drip line. The color bar shows relative concentrations.

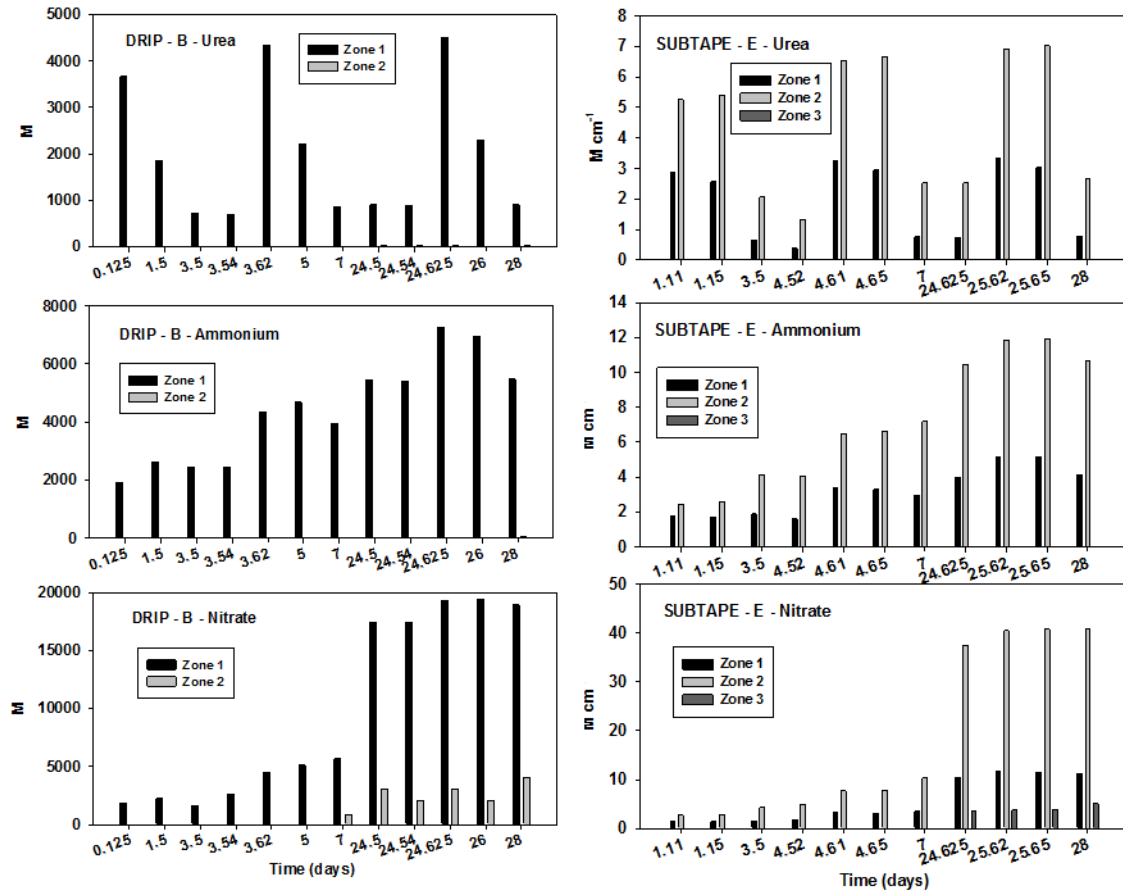


Figure 10. Mass of urea, ammonium, and nitrate over time for the B strategy of DRIP and the E strategy of SUBTAPE.