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Spatial Distribution of Water and Nutrients in Root Zone under Surface and Subsurface Drip Irrigation and Cantaloupe Yield

M.A. Badr

Department of Plant Nutrition, National Research Center, Cairo, Egypt

Abstract: Drip irrigation has the potential of precisely applying water and nutrients both in amount and in location at a rate which matches the plant requirements. While high field-wide uniformities are possible under drip irrigation, the distribution of both water and nutrients around the drip line is very non-uniform. Both soil moisture content and chemical concentration will be the highest near the drip line after application, but will redistribute thereafter as controlled by soil physical properties. The main objective of this research was to study the wetting pattern and nutrient distribution for the two commonly used drip irrigation systems to develop irrigation and fertigation management practices that maximize crop production. Surface drip irrigation resulted in the further advance of the wetting front in the lateral direction, while subsurface drip allows more water to distribute in vertical direction as a result of capillary forces. An appreciable amount of applied urea moved readily away from the water source and did not accumulate in the soil but continuously decreased with time after fertigation due to hydrolysis. Ammonium distribution was restricted to a volume with a radius of (15-20 cm) around the water source. Behind this range, ammonium concentrations remained at the initial values because of the relatively quick nitrification and slow transport due to adsorption. In contrast to ammonium, nitrate accumulated with time at the boundary of the wetted area (50-70 cm) which proves that nitrate movement in the soil is directly proportional to the water movement. The accumulation trend of the nitrate during the growing season indicating that supply of nitrate by the fertilizer exceeded the removal by plant uptake and leaching. Phosphorus and potassium were presented only adjacent to the water source at most times, independent of irrigation method as both fertilizers are highly adsorbed by the soil, preventing their movement further down the soil profile. Potassium was moved to the lower soil depth due to successive irrigation close to the end of fertigation period. For the subsurface drip irrigation overall, results are comparable with the drip irrigation, except that spatial distribution patterns extended more vertically with capillary forces, thereby carrying water and nutrients to larger soil volume around root zone. Subsurface drip irrigation significantly averaged higher cantaloupe yield (27.65 t/ha) over drip irrigation (23.74 t/ha) and gave higher NUE (110.60 kg yield/kg N) and WUE (61.45 kg yield/mm) over N sources.

Key words: Drip irrigation · soil water · NPK distribution · cantaloupe

INTRODUCTION

Drip irrigation has gained widespread acceptance as an efficient and economically viable method due to its highly localized application of water and nutrients to crops. Fertilizers applied under traditional methods are generally not utilized efficiently by the crop [1]. In fertigation, nutrients are applied through drippers directly into the zone of maximum root activity and consequently fertilizer-use efficiency can be improved over conventional method of fertilizer application [2, 3]. However, less-than-optimum management of drip irrigation systems resulting in excessive water and fertilizer applications may result in inefficient water and nutrient use, thereby diminishing expected yield benefits and contributing to soil and ground water pollution. The quality of soils, ground and surface water is specifically vulnerable in arid regions where agricultural production occurs mostly by irrigation, such as in Egypt. Water soluble (NPK) fertigation, using mixtures of nutrient compounds, are widely used with drip irrigation. Robust guidelines for managing drip irrigation systems are needed so that the principles of sustainable agriculture are satisfied.

Corresponding Author: Dr. M.A. Badr, Department of Plant Nutrition, National Research Center, Cairo, Egypt

Drip irrigation system consists of drippers, which are either buried or placed on the soil surface for discharging water at a controlled rate. All drip irrigation systems have the potential to be very efficient in irrigation water conveyance, control and application [4]. An irrigation system should apply water uniformly so that each part of the irrigated area receives same amount of water. Subsurface drip irrigation (SDI) is the most advanced method of irrigation, which enables the application of the small amounts of water to the soil through the drippers placed below the soil surface with discharge rates generally in the same range as surface drip irrigation [5]. SDI offers many advantages over the surface drip irrigation such as reduction in evaporation and deep percolation losses and elimination of surface runoff [6].

Wetting pattern in the soil and the spatial distribution of soil water, matric potentials and nutrient concentrations depend on soil hydraulic properties, drip discharge rates, spacing and their placement, irrigation amount and frequency, crop water uptake rates and root distribution patterns [7]. A better understanding of the interactions of irrigation method, soil type, crop root distribution and uptake patterns and rates of water and nutrients provides improved means for proper and efficient drip irrigation water management practices [8]. A properly designed drip fertigation systems delivers water and nutrients at a rate, duration and frequency, so as to maximize crop water and nutrient uptake, while minimizing leaching of nutrients and chemicals from the root zone of agricultural fields [7].

Appropriate design of drip fertigation system requires detailed knowledge of water and nutrient distribution pattern in the root zone, nutrient availability in the vicinity of roots and nutrient leaching below the root zone which is the function of discharge of emitter and soil hydraulic and physical properties. Though, some guidelines are available to install, maintain and operate drip irrigation systems [9], there are no clear guidelines for the nutrient movement and distribution under drip irrigation systems [10]. While high field-scale uniformity is possible under drip irrigation, the distribution of both water and nutrients around the drip line is non-uniform. Both soil water content and chemical concentration will be the highest near the drip line after application, but water and chemicals will redistribute thereafter as controlled by soil physical properties. Because of the typical non-uniform wetting patterns, it is essential to use multi-dimensional distribution to develop optimal fertigation practices for optimum nutrient use efficiency.

The main objective of the present study was to determine the spatial distribution of water and NPK nutrients in the wetted region for the two commonly used drip irrigation systems in sandy soil. The performance of the drip line placement was also evaluated on cantaloupe yield.

MATERIALS AND METHODS

The experiment was conducted in a vegetable farm located at Sarabiom area near Ismaillia province east of Cairo during the summer growing season (March-June) 2006 using drip irrigation system. This area is a desert region and the agriculture there is based on growing vegetables on an intensive scale. The soil of the experimental site was deep, well-drained sandy composing of 86.5% sand, 9.2% silt and 4.3% clay, with an alkaline pH 8.2, EC 0.85 dS/m, $CaCO_3$ 1.5%, O.M 0.27%. The available N, P and K were 14, 6 and 35 mg/kg soil, respectively before the initiation of the experiment. The average water content at field capacity from surface soil layer down to 80 cm depth at 20 cm intervals was 12% and the water holding capacity for the corresponding depths was 25% respectively. Before cultivation, drip tubing (GR, 40 cm dripper spacing delivering 4 l/hour) was either placed on soil surface or buried 10 cm deep directly under the soil beds that were 2 m apart. Cantaloupe plants, cultivar (hybrid rocky sweet), were planted into the soil beds on 3 March 2006, 2 seeds in one raw along the center of each bed. Plants were thinned at the 2 to 3 leaf stage to final plant populations of (12 600 plant/ha).

Water requirement of cantaloupe was scheduled based on evaporation replenishment (0.75 class “A” pan evaporation). Reference crop evapotranspiration (ET_0) was calculated on a daily basis by using Penman-Monteith’s formula [11]. Amounts of irrigation water used after planting was 450 mm for the growing season. Irrigation frequency was running on alternate days for a period of two hours over the four-month duration of experiment included 12 irrigation events with fertigation. The experiment was arranged in randomized complete block factorial design consisting of combinations of two N sources (urea and ammonium nitrate) with two irrigation methods (surface and subsurface drip systems). The experimental design included unfertilized control plots and was replicated three times in 6 cm wide × 10 m long plots. Nitrogen was applied on weekly basis at the rate of

(250 kg N/ha) through drip fertigation in a split doses and commenced after two weeks of planting. This was done along with Phosphorus (160 kg P/ha), as phosphoric acid (85%) and potassium (200 kg K/ha) as K_2SO_4 respectively. All NPK fertilizers were injected directly into the irrigation water using venture-type injector. Irrigation water concentrations of urea, ammonium nitrate and potassium sulphate were about 500, 600 and 400 mg/l, respectively while irrigation water concentration for phosphoric acid was 1 ml/l.

To determine water and available NPK distribution for each treatment, soil samples were taken from below the drippers at depths of 10 cm down to 70 cm along with radial line originating at the point-source at distances of 5 cm up to 30 cm periodically at 4 weeks intervals, using tube auger from the experimental area. Soil moisture content was determined gravimetrically. Urea, ammonium and nitrate were extracted with 1 *M* KCl from moist soil samples. Urea was measured by colorimetric the diacetyl-monoxime method [12]. Ammonium and nitrate were measured by the modified-Kjeldahl method [13]. Available phosphorus was extracted with 0.5 M $NaHCO_3$ and P was measured by colorimetric molybdenum blue method [14]. Potassium was extracted with 1 *M* ammonium acetate and K was measured by flam photometer method [15]. At first pick of fruits, all aboveground portions of cantaloupe were collected from each plot and analyzed for total N contents by the modified-Kjeldahl method [13]. Total N uptake, N use efficiency (NUE) and water use efficiency (WUE) were also evaluated.

RESULTS AND DISCUSSION

Distribution of water around drip line: Wetting patterns are determined by the radial distance and the depth of the wetting front from the water source (dripper) (Fig. 1). Surface drip irrigation allows water to move faster both vertically and horizontally and produced a wide surface wetted area at the top of the soil. After irrigation ceased, the wetted region exhibited a vertically elongation pattern and extended to nearly 30 cm horizontally and 70 cm vertically directly beneath the dripper. Maximum water content was recorded between the 10 and 40 cm soil depth and at the depth beyond 50 cm the soil was relatively dry and not suitable for plant uptake.

In subsurface irrigation, where drip lines were buried at 10 cm soil depth, upward movement of water took place due to capillary forces and surface soil became moist. Water content values were smallest near the soil surface and obviously decreased with horizontal distance from the drip line. The soil was strongly wetted at depths below 40 cm. After irrigation, most wetting occurred above the 50 cm soil depth and extending to near the soil surface. The subsurface drip irrigation increased downward movement of water on the account of horizontal movement and thus, it will decrease moisture loss by evaporation and save more water in the subsurface soil layers for plant use. Horizontal water movement was limited to about 25 cm from the drip line,since the flow of water from dripper was mostly directed under soil surface and this resulted in increasing

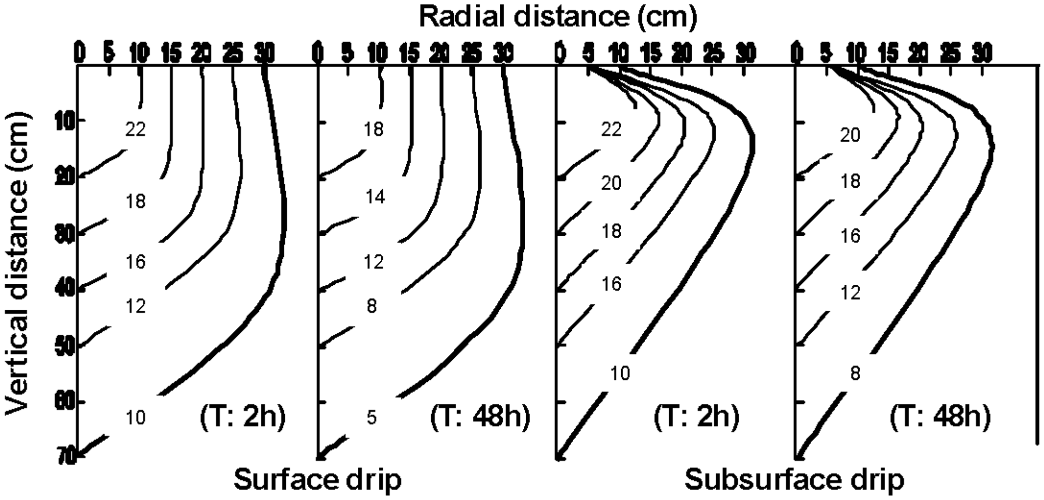

Fig. 1: Distribution of water in soil for surface and subsurface drip irrigation at the end (T: 2h) and before the next (T: 48h) irrigation cycle. The numbers labeling curves of contours lines indicate percentage of moisture content. The heavy peripheral lines are the position of the wetting fronts

the entire soil moisture content. After 48 hours from irrigation start, the wetted volume in the root zone remained around filed capacity and contained higher moisture values which are thought to be more favorable for plant uptake. Any way, the position of the wetting front is commonly used to describe the extent of soil moisture distribution under different conditions. The depth of wetting front increased with buried drips line beneath soil surface and helped to store a reasonable quantity of water below soil surface, which reduces evaporation components.

Distribution of nutrients around drip line

Surface drip line placement: The soil distribution of urea, ammonium and nitrate around a drip line between the first and last fertigation at the end of the growing season are presented in (Fig. 2). Urea was distributed more uniformly throughout the wetted region after the first fertigation event as urea is relatively mobile in the soil and it is not strongly adsorbed by soil colloids [16, 17]. The fertigation of urea resulted in a band of urea along the periphery of the wetted soil volume with little or no urea near the drip line, except immediately after first fertigation. There was relatively little change during subsequent fertigation events, indicating that little urea accumulation occurred in the soil profile as a result of hydrolysis and water redistribution. Ammonium remained concentrated at the proximity of the water source (15-20 cm) at all times for all fertigation period and beyond this distance, ammonium concentration remained at the initial values. There was only a slight movement with time because of soil adsorption and subsequent fast nitrification and/or root uptake. An unfavorable environment for nitrification resulting from the saturated zone around the source may partly account for the peak value [16]. Similar distribution patterns were observed for other experiments [18, 17].

In contrast to ammonium, nitrate moved continuously downward during the 90-day fertigation period, as nitrate is not adsorbed on soil particles. As expected, high nitrate concentrations occurred near the drip line immediately after fertigation due to injection, but little nitrate remained near the drip line during the growth period, because of root uptake and dispersion during downward transport. Nitrate was accumulated near the edge of the wetted region due to subsequent irrigation before fertigation. At the end of the last fertigation event, nitrate was distributed throughout the wetted soil profile to a soil depth of about 70 cm which indicating a potential leaching risk. At this time, most of nitrate was distributed near the periphery of the wetted region due to leaching following the fertigation. The same accumulation trend of nitrate at the boundary of the wetted volume was also observed by many authors [19-21]. Santos *et al.* [22] pointed out that nitrate fate and transport is strongly dependent on the soil water content and its movement. Nitrate is very mobile and if there is sufficient water in the soil, it can move quickly through the soil profile. Careful application of nitrogen and water should be able to minimize the amount of nitrogen moving below the root zone.

Concentration of phosphorus near the wetting front was very low but closer to the water source this trend was reversed. Total amount of phosphorus was found in soil volume with a radius of 15 and 20 cm in the lateral and vertical directions respectively (Fig. 3). Phosphorus was depleted to some extent from the vicinity of the dripper and its movement towards the vertical direction was relatively greater than in the lateral direction. Phosphorus concentration decreased sharply from the initial 150 mg/l in water solution to about 40 mg/kg soil, which proves that phosphate movement is not directly proportional to water movement. Furthermore, at the end of P fertigation period, the described behavior did not change significantly. Consequently, a combination of pre-irrigation mixing of phosphate with the soil in the root zone and irrigation with a solution including P at an appropriate concentration is imperative to obtain uniform P distribution [20].

The mobility of phosphate ion in soils is of primary importance in plant nutrition. Phosphate transport in both vertical and lateral directions was too slow for the average rate of root growth into the soil, since P fertilizers are prone to fixation at the point of application. Most of the applied P may be turned to non-soluble form in a short time after its application and the observed concentrations build up near the water source could affect root growth and create unfavorable conditions for P uptake. Because of its adsorption, potassium distribution around the drip line was similar to those of the ammonium (Fig. 3). Potassium was found only immediately adjacent to the water source at most times as K^+ is highly adsorbed by the soil, preventing its movement further down the soil profile. Available K throughout the profile tended to move with water toward the edge of the witting front particularly at the end of fertigation period. Many studies have demonstrated that potassium distribution was limited to the most internal bulb layers, where the ion displacement was delayed due soil matrix interactions [2, 23].

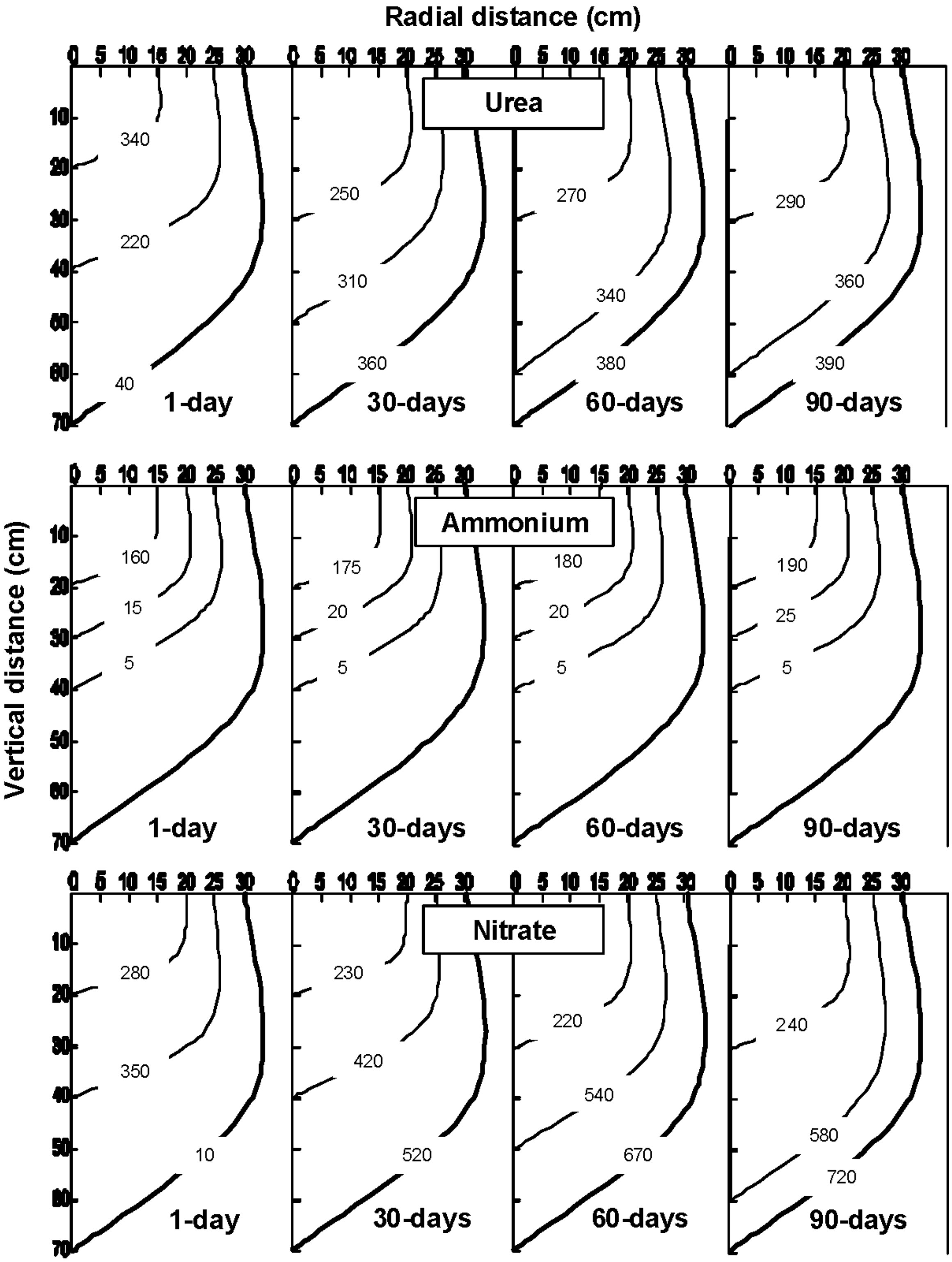

Fig. 2: Distributions of urea, ammonium and nitrate for surface drip line during the growth season. The numbers labeling curves of contour lines indicate concentrations (mg kg^{-1} soil). The heavy peripheral lines are the position of the wetting fronts

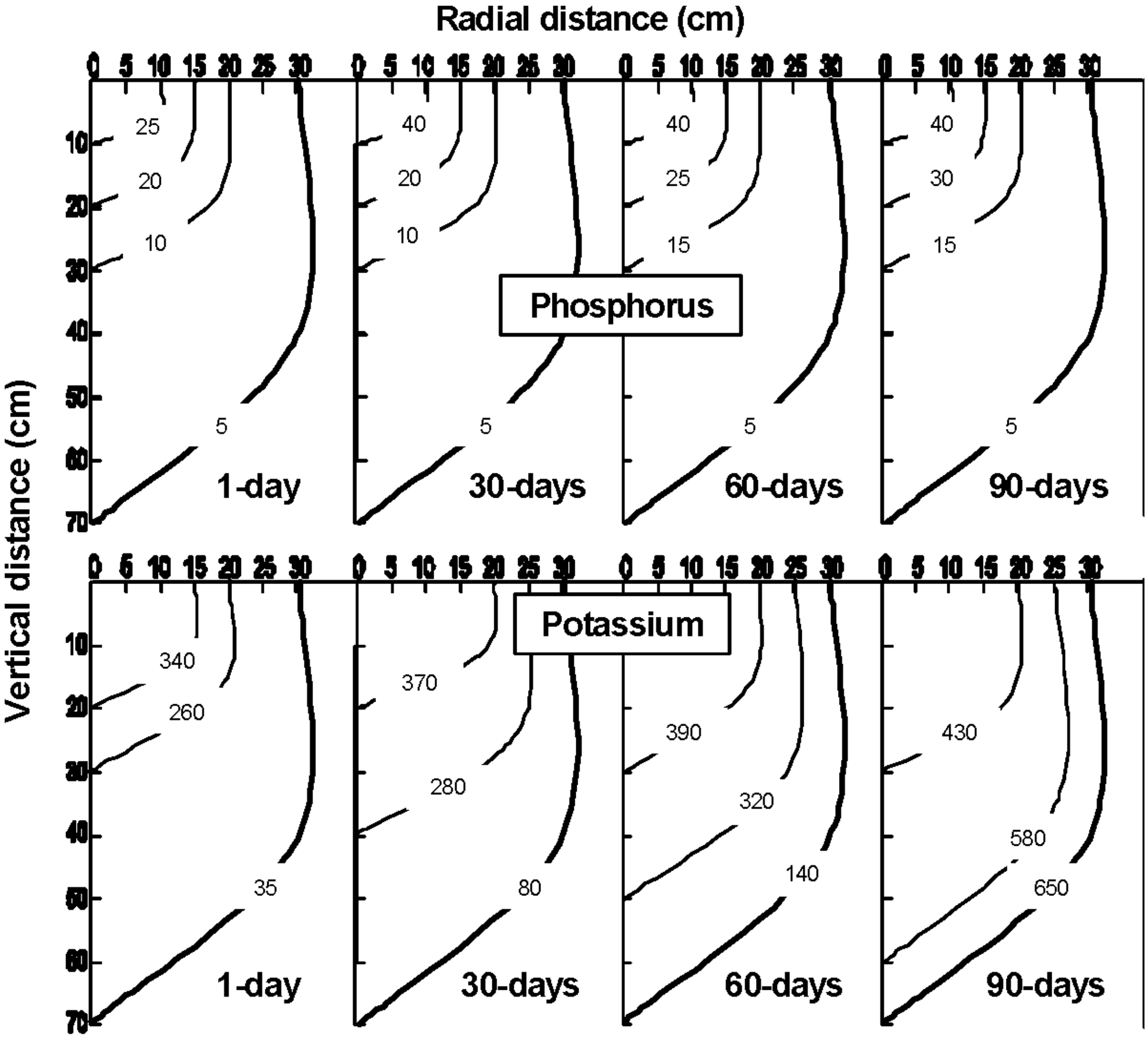

Fig. 3: Distributions of phosphorus and potassium for surface drip line during the growth season. The numbers labeling curves of contour lines indicate concentrations (mg kg^{-1} soil). The heavy peripheral lines are the position of the wetting fronts

Subsurface drip line placement: The distributions of various nitrogen species, urea, ammonium and nitrate for the subsurface placement are presented in (Fig. 4). Overall, results are comparable with the drip irrigation system, except that the capillary forces, through carrying nutrients to larger soil volume around the root system, controlled spatial distribution patterns. Concentrations of ammonium were relatively higher in the root zone with subsurface drip placement compared to surface drip, since the fertigation of ammonium in the later case is more prone to volatilization into the atmosphere through surface soil layer. Urea and nitrate were moved away from the drip line during irrigation, whereas both species remained near the drip line after fertigation. Urea concentrations decreased between irrigation cycles because of hydrolysis while nitrate concentrations accumulated with time throughout the soil profile particularly at the end of fertigation period. This is due to nitrate movement from the surface layers, a fact, which has important implication regarding the frequency of nitrate at a rate that is close to plant uptake. As also demonstrated by the laboratory study of Li *et al.* [21], nitrate distributions are highly affected by the wetting patterns of the drip irrigation system and water mass flow is the major factor responsible for nitrate movement in the soil. However, at this time, the average nitrate was found to be 280 mg/kg soil at 40 cm soil depth that was more than surface drip (240 mg/kg soil). In contrast, at 60 cm soil depth the nitrate was found less in subsurface drip irrigation compared to surface drip.

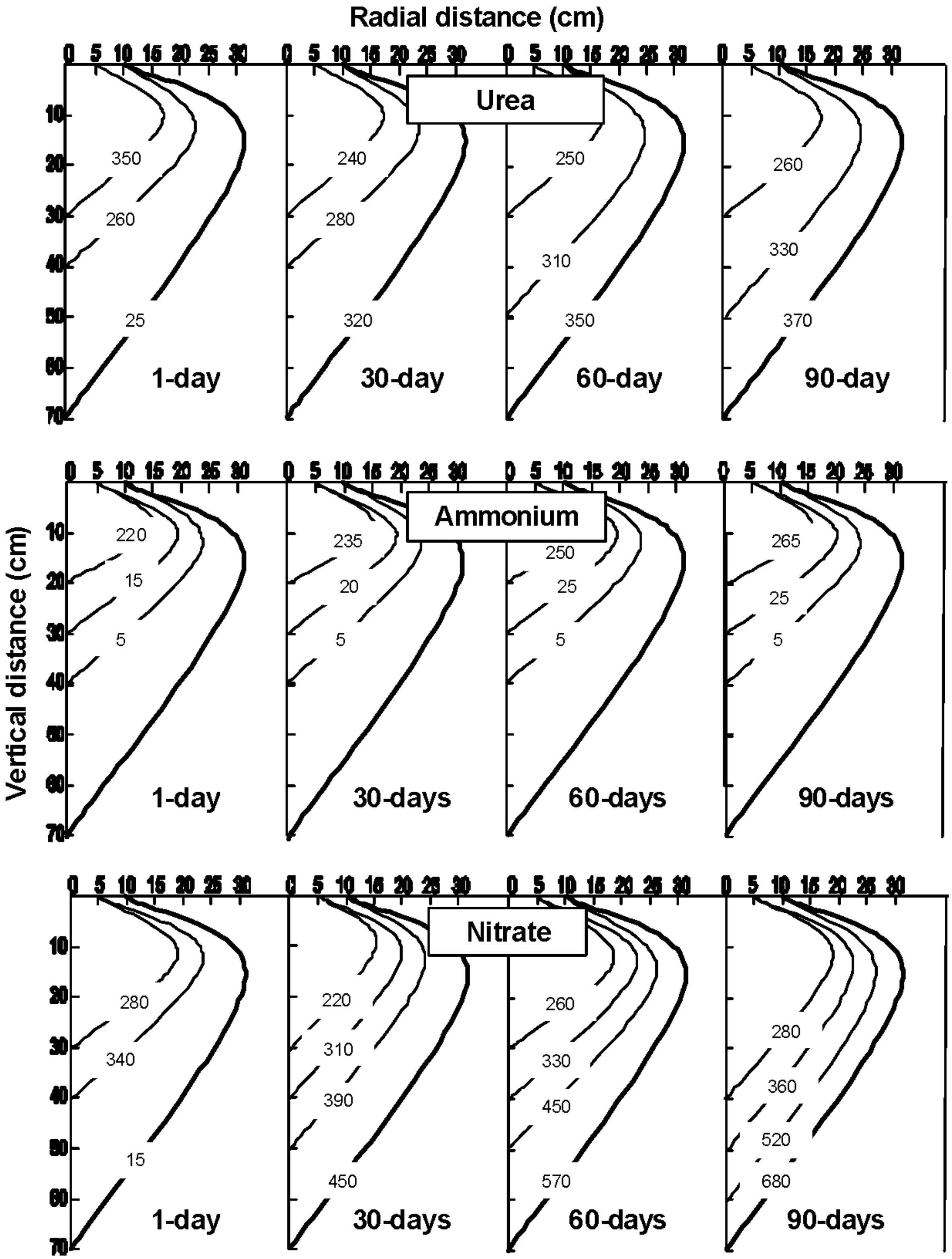

Fig. 4: Distributions of urea, ammonium, and nitrate for subsurface drip line during the growing season. The numbers labeling curves of contour lines indicate concentrations (mg kg^{-1} soil). The heavy peripheral lines are the position of the wetting fronts

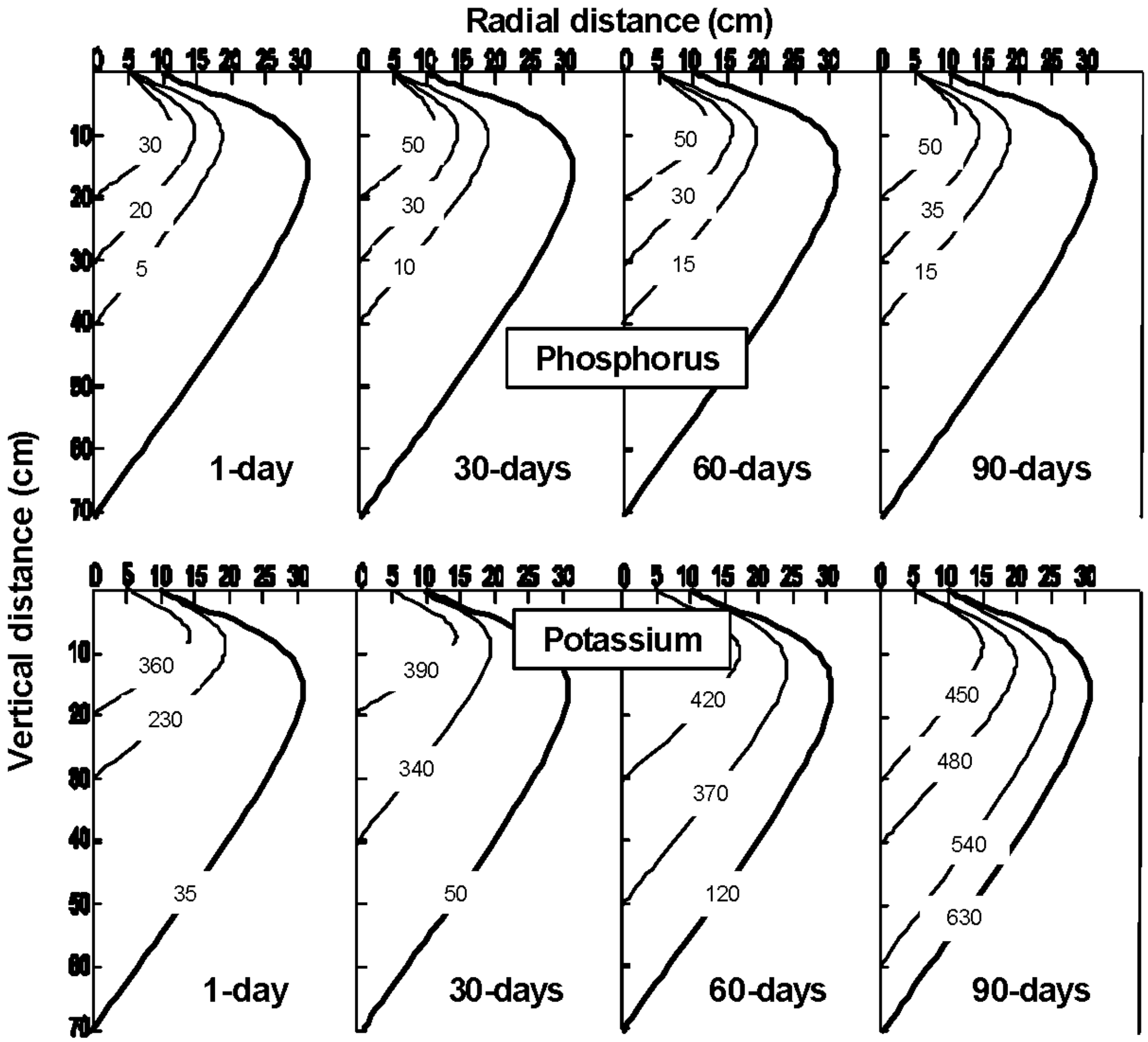

Fig. 5: Distributions of phosphorus and potassium for subsurface drip line during the growing season. The numbers labeling curves of contour lines indicate concentrations (mg kg^{-1} soil). The heavy peripheral lines are the position of the wetting fronts

As expected, phosphorus and potassium moved greater in both the horizontal and vertical directions (Fig. 5). High concentration of P and K developed at the upper part of root zone (above drip line) due to capillary movement and evaporation. The P and K concentrations were significantly higher in the root zone (15–30) cm depth of the subsurface drip irrigation than those of the surface drip line due to capillary upward movement after fertigation. At most times, P and K beyond 15 cm soil depth are hardly available for plant uptake because the supply of nutrients occurred directly at the center of root zone and moved out in all directions. More roots would permeate the greater soil volume to which P and K was delivered.

Nutrients such as N and K are commonly applied through drip system, while P is more difficult to apply and to obtain proper distribution in soil. However, the use of phosphoric acid applied through subsurface drip irrigation resulted in a more favorable P distribution for uptake at identical rate of application. Because of the tendency of P to form insoluble precipitate with Ca and Mg commonly found in irrigation water and in the soil, the use of traditional P fertilizer in drip irrigation is not very successful. Topical application of P fertilizers through surface drip has resulted in poor distribution, where great amounts of P may remain near the soil surface, but this zone is usually not penetrated by roots because of high soil temperatures and lack of moisture, especially in arid and semiarid regions.

Table 1: Cantaloupe total yield, N uptake, NUE and WUE as affected by N source and drip line placement

N source	Total yield t/ha	N uptake kg/ha	NUE kg Y/kg N	WUE kg/mm
Surface drip				
Urea	22.85	104	91.40	50.78
NH_4NO_3	24.62	112	98.48	54.71
Subsurface drip				
Urea	27.13	118	108.52	60.29
NH_4NO_3	28.17	127	112.68	62.60

LSD (P = 0.05) for yield: N = 2.27; drip placement = 2.85; N × drip placement = 4.36.

Cantaloupe yield: The response of cantaloupe to surface or subsurface drip line placement was compared to evaluate total yield, N uptake NUE and WUE (Table 1). Total average yield of cantaloupe was significantly higher in subsurface drip irrigation (27.65 t/ha) over drip irrigation (23.74 t/ha), which accounted for 16.5% yield increase. Although cantaloupe yield tended to be higher with ammonium nitrate than urea but the increase was not significantly different. There were no significant drip line placement × N source interactions for total yield. Uptake of nitrogen under subsurface irrigation was considerable higher over surface drip irrigation due to the considerable amount of nitrogen remained available in the root zone.

The better performance under subsurface drip was attributed to maintenance of favorable soil water status in the root zone, which in turn helped the plants to utilize moisture as well as nutrients more efficiently from the limited wetted area [17]. Higher yield can be achieved, however, by maintaining relatively high water content conducive to good plant growth that is achievable under shallow placement of drip line. The high water content of the soil around the drippers facilitates better water transmission to the surrounding soil and keeps on replenishing the crop root zone [24]. Therefore, keeping the drip line within the crop root zone and sufficiently below the soil surface replenishes the root zone effectively due to gravity flow in light soils and simultaneously cuts of evaporation losses due to restricted upward capillary flow. Higher yields and water use efficiency have reported for many crops under subsurface drip irrigation [3, 4, 25, 26].

Finally, it can be conclude that urea and nitrate moved readily with the irrigation water away from source. Urea did not accumulate in the soil profile, but quickly decreased with time after fertigation by hydrolysis. Ammonium fertilizer increased near the drip line, an area where root density is greatest and most of the plant root uptake takes place. Because of their adsorption to the soil, most of P and K remained near the drip line, with low concentrations near the edge of the wetting zone. Better performance under subsurface drip was attributed to maintenance of favorable soil water status in the root zone, which in turn helped the plants to utilize moisture as well as nutrients more efficiently from the limited wetted area. Across N sources, subsurface drip irrigation resulted in significantly higher cantaloupe yield (27.65 t/ha) over drip irrigation (23.74 t/ha) and gave higher NUE (110.60 kg yield/kg N) and considerable WUE (61.45 kg yield/mm) respectively.

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