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Effect of surface and subsurface drip fertigation on sweet corn rooting, uptake, dry matter production and yield

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Summary. Subsurface (SS) drip fertigation may increase sweet corn ear yield relative to surface (S) fertigation, because immobile nutrients are delivered at the center of the soil-root volume rather than on top of the soil. A container ($1 \times 1 \times 1$ m) experiment was conducted on a loessial soil (Haploxeralf) to test this hypothesis. Marketable and total ear yields were higher for tricklers placed 30 cm below the soil surface (3.22 and 4.90 kg m^{-2}, respectively) than on the surface (2.86 and 4.30 kg m^{-2}, respectively). Total fresh weight, dry matter production and plant height during the growing season were also greater for subsurface emitters. Deep trickler position significantly increased P and K content at the center of the root zone. The enhanced concentration apparently stimulated plant rooting which, together with the higher nutrient activity in the soil solution, increased P and K uptake rates, which in turn facilitated the higher dry matter production and commercial yield relative to surface trickler placement. The higher root activity in SS than in S fertigation was reconfirmed by soil air CO_2 concentration measurements which showed significant differences between the two treatments during the growth season.

Trickle irrigation has expanded dramatically during the last decade due to increased productivity and greater water and nutrient savings. The high labor requirement in spreading and collecting laterals every season, and deterioration of exposed drip lines limit further expansion. Subsurface location of tricklers may solve these problems. Furthermore, it may have some plant-related advantages over surface drip irrigation: (i) introduction of nutrients to the center of the root system, where water content is relatively high and steady with time (Phene and Howell 1984). (ii) Reduction in water evaporation from the soil surface, thereby leaving more water available to plants, and (iii) movement of nutrients in a spherical volume around the emitter, while in surface application transport is restricted to a hemisphere below the point source (Phene et al. 1986).

The working hypothesis of this study was that the higher moisture content, greater root density, and larger soil volume in which nutrients can move induce greater P and K uptake rates by plants in subsurface than in surface trickle fertigation, and that this differential uptake may result in greater dry matter production and yield. Differences in uptake rate of mobile elements are expected to be smaller, since they are distributed and exploited from much larger soil volumes than the immobile elements.

The objectives of this work were to test the above mentioned hypothesis, and evaluate differences between surface and subsurface drip fertigation with respect to root, water and nutrient distributions in the soil and their effect on sweet corn yield.

Materials and methods

Plants were grown in $1 \times 1 \times 1$ m plastic containers at Bet Dagan, central Israel. Evaporation from a standard Class A pan and maximum and minimum air temperatures during the season are given in Fig. 1. The containers were packed with a loessial well-mixed 0–40 cm top soil (Haploxeralf) with 130 g clay, 230 g lime, 8 g organic matter and 0.8 mmol $NaHCO_3^-$ extractable P kg^{-1} soil, to give a bulk density of 1.25 kg l^{-1}. The bottom 5 cm was filled with coarse gravel which, together with five equidistant holes at the bottom, prevented free water accumulation in the container. No measurable amounts of water leached out of the containers during the experiment. Prior to packing, soil was mixed with fertilizers: the bottom 50 cm was mixed with 0.29 g superphosphate, 0.008 g $(NH_4)_2SO_4$, 0.037 g KNO_3 and 0.164 g KCl kg^{-1} soil. The top 50 cm received the same ingredients, only at double the amount. The containers were placed in a row inside a net house with 20% shading. Sweet corn (*Zea mays* L. 'Jubilee') was seeded on 4 May 1989 in the center line of each container (1 m row) and thinned at the two-leaf stage to nine plants m^{-1}. Emergence, tasseling, silking and harvesting occurred on 11 May (day 131 of the year), 19 June (day 170), 27 June (day 178) and 20 July (day 201), respectively. Fresh ears were sorted into marketable and non-marketable according to commercial criteria.

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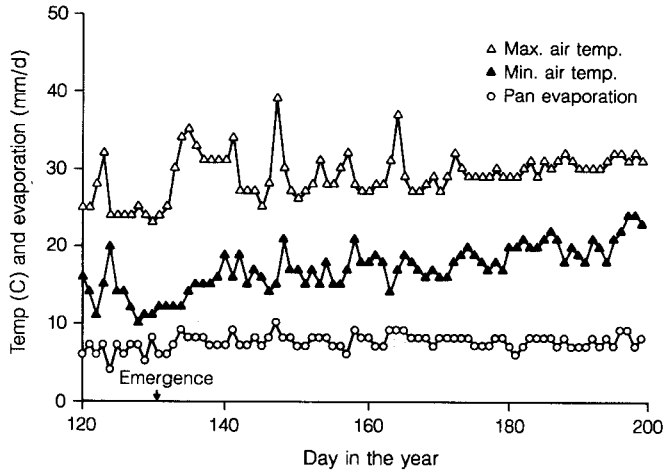

Fig. 1. Evaporation from Class A pan and maximum and minimum daily air temperatures during the growing season

Table 1. Irrigation-to-Class A pan evaporation ratio (Irr/Ev) and N, P, and K application rates during the growth period

Days		Application[a] rates			
In the year	After emergence	Water	N	P	K
		Irr/Ev	$g\ m^{-2}\ d^{-1}$		
140–150	10–20	0.83	0.15	0.08	0.08
151–170	21–40[b]	1.00	0.60	0.13	0.36
171–190	41–60	1.07	0.90	0.33	0.54
191–196	61–70	1.20	0.07	0.13	0.04
		Irr (mm)	$g\ m^{-2}$		
		441	32.2	11.2	19.2

[a] As NH_4NO_3, H_3PO_4 and KNO_3. Fertilization ceased on 14 July (DOY = 196)
[b] Between days 21 and 26, NPK application rate was erroneously sixfold greater than specified in this table

Treatments consisted of surface and 30 cm subsurface emitter ($2\ l\ h^{-1}$) placements, replicated three times. Each container had one trickler, placed in the middle of the plant row. This arrangement simulated one row of plants in a field planted at a density of $9\ pl\ m^{-1}$, 1 m spacing between rows, and 1 m distance between emitters along the laterals. Irrigation and fertilization were applied daily to replenish Class A pan evaporation multiplied by a crop coefficient (Table 1) and N, P, and K consumption estimated from previous results of drip-fertigated sweet corn (Bar-Yosef et al. 1989) (Table 1). Water and nutrients were applied identically in the studied treatments. Plant height was measured every few days, from the soil surface to top of the canopy. Plants for tissue analyses and fresh and dry matter accumulation were sampled at harvest time and sorted according to distance from the emitter. Plants were divided into ears, stems and leaves. For each organ, N, P, and K content was determined in H_2SO_4/H_2O_2 digest using a Technicon autoanalyzer for reduced N and P and a flame photometer for K.

Soil matric potential was measured by four tensiometers inserted either 10 or 30 cm deep and either 10 or 25 cm away from the emitter. The CO_2 concentration in the soil air was measured in plastic cylinders 80 mm long and 25 mm I.D. inserted at distances of 10, 20 and 30 cm from the emitter perpendicular to the plant row at depths of 10, 20, 40, 60 and 80 cm. The cylinders were drilled with 2-mm holes every 5 mm to obtain fast equilibration with the surrounding atmosphere. Air samples (approximately 10 ml) were withdrawn several times during the growing season before and after irrigation by gas-tight syringes and analysed for CO_2 concentration by gas chromatography.

Soil samples were taken 39 days after emergence by coring at increments of 10 cm down to a depth of 100 cm, at distances of 10, 25 and 40 cm from the emitter, perpendicular to the plant row. After harvest, $10 \times 10 \times 10$ cm soil cubes were consecutively excavated in the vertical and horizontal directions from the emitter, both parallel and perpendicular to the plant row. The soil cubes were subsampled for chemical analysis, while the rest was used for root separation by wet sieving. The soil samples were extracted with 1 M KCl for mineral N and with 0.5 M $NaHCO_3$ (1 : 10) for P and K (Bar-Yosef and Akiri 1978).

Results and discussion

Yield, growth and nutrient content in plants

Plant distance from the emitter did not have a significant ($P < 0.05$) effect on the studied plant parameters (data not shown). Consequently, all forthcoming results are averages of the nine plants grown per container. The plants' uniformity within the row indicates that crop roots can compensate plants located at distances up to 50 cm from the point source.

Table 2. Effect of trickler placement on total and marketable yield, number of marketable ears, canopy fresh weight and filled ear length

Trickler placement	Ear yield			Canopy fresh wt $kg\ m^{-2}$	Ear length cm
	total $kg\ m^{-2}$	marketable $kg\ m^{-2}$	number ears m^{-2}		
Surface	4.30	2.86	16.2	5.83	18.0
Subsurface	4.90	3.22	16.7	6.42	19.4
Analysis of variance F-test probability					
Placement	0.09	0.02	0.82	0.24	0.004

Subsurface (SS) fertigation resulted in higher total ear yield ($P = 0.09$) and fresh canopy weight ($P = 0.24$) than surface (S) fertigation, and in significantly ($P = 0.02$) higher marketable ear yield (3.22 vs 2.86 $kg\ m^{-2}$) (Table 2). The enhanced marketable ear yield stemmed from larger ears, as indicated by the longer tip-fill ears in the treatment with SS emitters (Table 2) and the equal ear diameter in the two treatments (5.60 ± 0.05 cm). The total number of ears m^{-1} was the same in surface and subsurface fertigation ($16.5\ m^{-1}$, Table 2). In agreement with the fresh weight results, plant height and total and ear dry matter production were greater in SS than in S fertigation (Fig. 2 and Table 3, respectively). The height vs time function (Fig. 2) shows that the beneficial effect of subsurface fertigation was most apparent about one week prior to tasseling, and the difference in height obtained at that growth stage was maintained to the end of the experiment.

Emitter placement did not have a significant effect ($P < 0.05$) on N, P and K concentrations in stems, leaves or cobs, except for the fact that K concentration in cobs was greater ($P = 0.01$) for S than SS emitters.

Table 3. Dry matter production and N, P, and K concentration in stems, leaves and cobs of surface and subsurface drip-fertigated sweet corn plants at harvest

Trickler placement	Dry matter total ears kg m^{-2}		Element concentration g kg^{-1}								
			stems			leaves			cobs[a]		
			N	P	K	N	P	K	N	P	K
Surface	1.84	1.14	15.2	4.7	49.0	21.5	4.7	30.8	17.3	3.3	8.9
Subsurface	2.23	1.44	15.0	4.8	48.2	20.0	4.3	32.5	18.0	3.1	8.4
Analysis of variance F-test probability											
	0.01	0.01	0.73	0.85	0.72	0.07	0.09	0.06	0.58	0.34	0.01

[a] Excluding husks

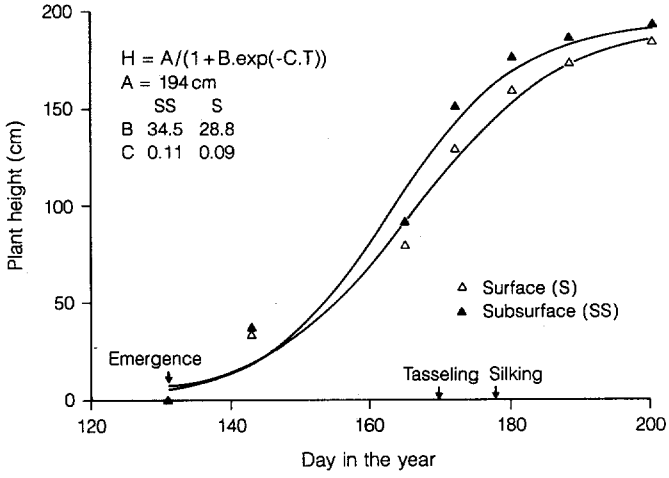

Fig. 2. Sweet corn plant height as a function of time in surface (S) and subsurface (SS) drip fertigation

The data presented so far are characteristic of a single row in the field which is free of interference from surrounding canopies. Water and nutrient supplies per plant were comparable to field situations, but light intensity inside the net house was 80% of that outside the net house. As expected under such conditions, total fresh and dry matter production exceeded by 40±15% weights obtained in a field experiment with similar treatments (Bar-Yosef et al. 1989). The greatest difference was obtained in total dry matter production under SS fertigation and is attributed to the enhanced number of ears per plant and to heavier cobs in the isolated plant row studied here. Nitrogen concentration in stems and leaves was similar, but P and K contents were considerably greater in the container plants than under field conditions.

Higher marketable yield and greater ear dry weight in SS than in S fertigated plants were obtained under field conditions too (Bar-Yosef et al. 1989). However, more field trials are needed in order to determine whether the same response in yield, rooting and uptake to emitters position in the soil can be obtained under wider climatic conditions and different soils as well.

Root distribution

Root density (R, g dry roots kg^{-1} dry soil) decreased with increasing vertical or lateral distance from the emitter (Table 4). This behavior could have resulted from two effects: (i) the root system of the plant nearest the point source was greater than the root system of plants farther away from it. (ii) All plants had a similar root weight, but root growth towards the water source exceeded root growth in other directions. Since R in the perpendicular direction to the plant row decreased much faster than that in the parallel direction (Table 4), and plant canopies were uniform within the row, the second alternative seems the more realistic.

The center of gravity of the root system in SS and S fertigation was near the emitter, namely, at depths of 30 and 10 cm below the soil surface, respectively. No roots were found below a soil depth of 70 cm (Table 4), even though sufficient water and nutrients were found in the 70–100 cm layer (see later), and no barrier to root growth was observed in the soil. This agrees with a previous report on trickle-irrigated sweet corn root distribution in the same soil under field conditions, according to which root density below a depth of 70 cm was negligible (Bar-Yosef and Sagiv 1985).

Total root dry weight (TR) in SS fertigation exceeded TR in S fertigation (132 vs. 93 g m^{-1}, Table 5). These weights comprise approximately 5% of the above-ground dry matter at harvest (Table 3). The difference in TR between treatments stemmed mainly from a nearly twofold greater root weight in the 5–15 cm soil column and a nearly threefold greater root weight in the 11–30 cm soil layer in SS than in S fertigation (Table 5).

Bar-Yosef and Sagiv (1985) reported that total fresh root weight of a mature field-grown sweet corn plant was 120 g pl^{-1}. Assuming nine plants m^{-1} and approximately 10% dry matter content in roots, this is equivalent to approximately 100 g dry roots m^{-1}, similar to current results.

CO_2 distributions in the soil

The soil air CO_2 concentration varied considerably during the day (Table 6) and during the growing season (Fig. 3). Within a soil layer of 0-to-20 cm, CO_2 concentration decreased between 2, 5 and 21 h after termination of irrigation. The maximum after 2 h stemmed from low CO_2 diffusivity due to water filled soil pores, and reflects

Table 4. Root density distribution in the soil (g dry wt kg^{-1} dry soil) at harvest in surface and subsurface drip fertigated sweet corn. Left-parallel, right-perpendicular direction to plants row

Emitter placement	Depth (cm)	Distance from emitter (cm)							
		Parallel				Perpendicular			
		5–15	16–25	26–35	36–50	5–15	16–25	26–35	36–50
Surface	0–10	3.33[a]	0.84	0.22	0.40	2.04	0.43	0.08	0.07
	11–20	0.57	0.22	0.16	0.16	0.35	0.31	0.11	0.09
	21–30	0.12	0.20	0.11	0.07	0.13	0.10	0.08	0.09
	31–40	0.06	0.11	0.18	0.04	0.09	0.10	0.13	0.12
	41–50	0.05	0.06	0.13	0.05	0.06	0.10	0.06	0.09
	51–60	0.06	0.09	0.05	0.03	0.07	0.09	0.04	0.08
	61–70[b]	0.06	0.08	0.07	0.02	0.03	0.10	0.06	0.02
Subsurface	0–10	1.81	0.47	0.25	0.09	1.60	0.47	0.08	0.02
	11–20	1.99	0.34	0.31	0.14	1.80	0.28	0.15	0.03
	21–30	2.33	0.24	0.18	0.14	2.29	0.36	0.13	0.07
	31–40[a]	0.22	0.18	0.13	0.20	0.50	0.10	0.11	0.07
	41–50	0.13	0.15	0.17	0.14	0.07	0.11	0.07	0.05
	51–60	0.08	0.07	0.11	0.09	0.03	0.13	0.08	0.05
	61–70	0.11	0.17	0.06	0.07	0.08	0.14	0.08	0.04
Analysis of variance F-test probability									
Placement			0.0190				0.0007		
Depth			0.0001				0.0001		
Distance			0.0001				0.0001		
Placement · depth			0.0001				0.0001		
Placement · distance			0.0490				0.0001		
Depth · distance			0.0001				0.0001		

[a] Emitter placement
[b] No roots were found beyond a depth of 70 cm

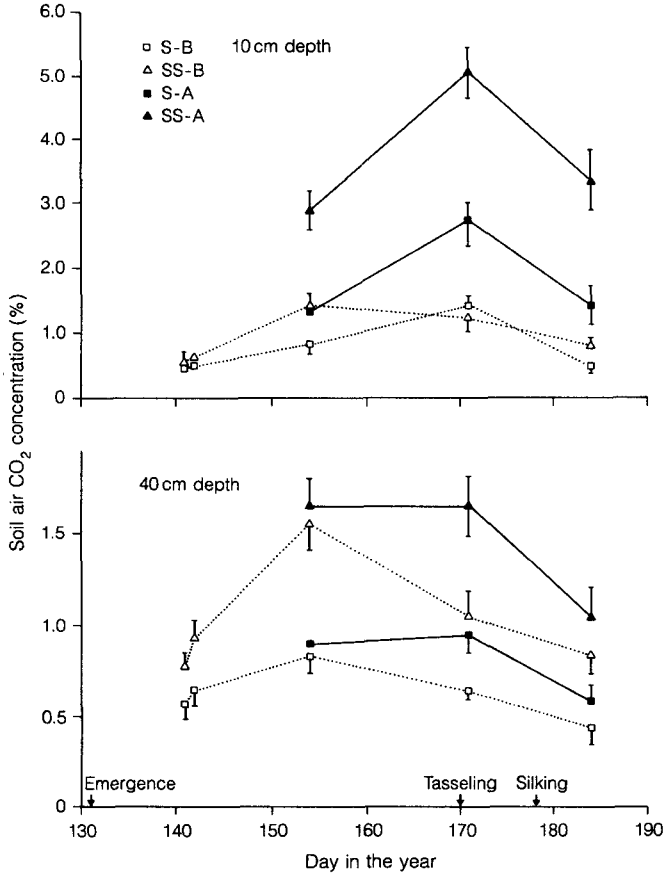

Fig. 3. Soil air CO_2 concentration measured at the 10 and 40 cm depths just before (B) and 2 h after (A) surface (S) or subsurface (SS) drip fertigation, as a function of time during the season. Measurements were made 10 cm from emitters. Bars indicate SD. Time interval between successive irrigations was 24 h

therefore the localized rate of CO_2 release by the roots. The contribution of microbial respiration to CO_2 concentration during the main growing season of plants is usually small relative to CO_2 release by plant roots (Buyanovsky and Wagner 1983). The concentration after 21 h reflects the long-term CO_2 concentration, and is dependent not only on root activity but on the diffusion rate of CO_2 from the root zone to the atmosphere as well.

Deeper in the soil (60 and 80 cm, Table 6) the maximum in CO_2 concentration was obtained 5 h after irrigation termination, which is approximately the time needed for redistributing water to fill soil pores in that region.

In agreement with root density distribution data (Table 4), soil air CO_2 concentration was higher at any given sub-volume within the root zone in subsurface than in surface drip fertigation (Table 6).

The soil-air CO_2 concentration increased with plant age until a certain date, and then declined (Fig. 3). Accepting that soil air CO_2 concentration is an indicator of root activity, one may conclude that sweet corn performance started to decline as early as 30 ± 5 days after emergence, regardless of the trickler position in the soil.

Table 5. Sweet corn root dry weight in various soil subvolumes defined by soil depth and lateral distance from emitters[b] (g in the given subvolume), and total root dry weight in the soil (g m^{-2}) at harvest under surface and subsurface trickle fertigation

Emitter placement	Depth (cm)	Distance from emitter (cm)				Σ
		5–15	16–25	26–35	36–50	
Surface	0–10[a]	22.8	9.6	3.4	2.7	38.5
	11–20	3.9	4.0	3.0	5.9	16.8
	21–30	1.0	2.3	2.1	4.1	9.5
	31–40	0.7	1.6	3.5	4.0	9.8
	41–50	0.5	1.3	2.3	3.7	7.8
	51–60	0.6	1.5	1.2	2.9	6.2
	61–70	0.4	1.5	1.5	1.0	4.4
	Σ	29.9	21.8	17.0	24.3	93.0
Subsurface	0–10	14.5	7.2	3.8	2.9	28.4
	11–20	16.1	4.8	5.3	4.4	30.6
	21–30	19.6	4.6	3.5	5.0	32.7
	31–40[a]	3.0	2.0	2.7	6.6	14.3
	41–50	0.9	2.0	2.8	4.6	10.3
	51–60	0.5	1.5	2.2	3.7	7.9
	61–70	0.8	2.4	1.7	2.9	7.8
	Σ	55.4	24.5	22.0	30.1	132.0

Analysis of variance F-test probability

Placement	0.0002
Depth	0.0001
Distance	0.0001
Placement · depth	0.0001
Placement · distance	0.006
Depth · distance	0.0001

[a] Emitter placement

[b] Root wt in a given soil volume was estimated by multiplying root density R (Table 4) by soil weight represented by the sampled soil cube, assuming a cylindrical coordinate system with the axis of symmetry passing through the container mid-point and emitter. Total root weight was estimated by summing over all soil subvolumes. Root density was evaluated as the mean of the parallel and perpendicular R values

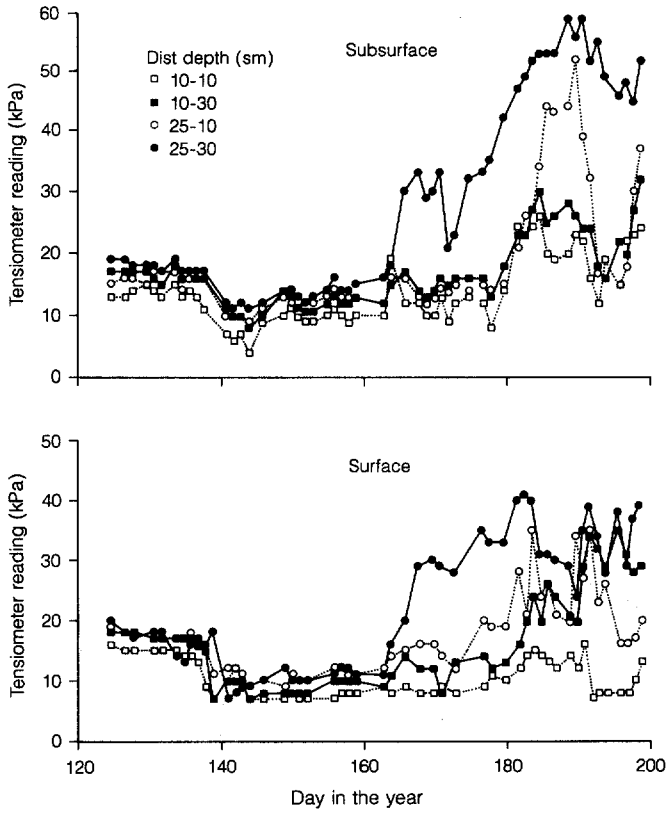

Fig. 4. Temporal variations in tensiometer readings at four points in the root zone (before irrigation) in subsurface and surface drip fertigation

In a calcareous soil found at equilibrium with CO_2 of given partial pressure (PCO_2) and temperature of 25 °C, the soil solution pH can be estimated from the equation $pH = 4.87 - 0.5 \log (Ca) - 0.5 \log (PCO_2)$, where (Ca) is Ca concentration in the soil solution (Lindsay 1977, p 99). At a constant (Ca) of $10^{-2.5}$ M, soil pH is expected to be 7.3, 6.9 and 6.7 at soil air CO_2 concentrations of 0.44, 2.88 and 5% (0.48, 3.1 and 5.4 kPa), respectively. These concentrations are characteristic of the currently studied soil root volumes. At PCO_2 of 0.03 kPa (300 ppm, normal atmospheric concentration), the estimated soil pH is 7.9. Differences in pH between 6.7 and 7.9 might have major effects on P, Fe and Zn solubility in soils.

Water content distribution in the soil

The initial soil moisture content (θ) in the container was 150–170 g kg^{-1}. Thirty nine days after emergence, this θ was maintained only in the 80–100 cm soil layer (Table 7). At distances of 10 and 25 cm from the emitter, two pronounced minima in θ were observed both in the surface and subsurface emitter placements: at the 60–70 and 0–10 cm soil layers. The minimum at 60–70 cm resulted from the absence of roots below 70 cm (Table 4). The minimum at the top soil layer stemmed from surface evaporation.

Water content at a lateral distance of 40 cm, which characterizes θ in the midway region between emitters in the field, was significantly lower at any depth than θ at distances of 25 and 10 cm from the trickler. This decrease in water content may have contributed to the decrease in root density with increasing lateral distance from the emitter discussed above. The higher θ at a radius and depth of 10 and 30 cm, respectively, in the SS treatment (near the trickler) than in the S fertigation treatment (156 vs 140 g kg^{-1}), may have contributed to the higher root density observed in that region in the subsurface treatment. The grand mean θ in the soil-root volume was unaffected by emitter placement (Table 7), indicating that, until the tasseling growth stage, total water consumption by the plants in both treatments was similar.

Temporal varations in water status in soil are presented in terms of tensiometer readings (ϕ) at four points in the root zone (Fig. 4). Until a week before tasseling, ϕ was similar in all four tensiometers. Later on, water consumption increased and ϕ at each point decreased, indicating that the crop irrigation coefficient used at that time (1.07, Table 1) was insufficient. When the coefficient

Table 6. Spatial distribution of soil air CO_2 concentration (%) under surface and subsurface drip fertigation at various times in the day (171th day in the year). Irrigation commenced on 0830 and terminated on 1100

Emitter placement	Sampling depth (cm)	Hour in the day								
		0800			1300			1600		
		Distance from emitter (cm)								
		10	20	30	10	20	30	10	20	30
Surface	10	1.42[a]	0.69	–	2.70	1.14	–	2.09	1.06	–
	20	0.96	0.42	–	1.51	1.42	–	1.29	0.97	–
	40	0.69	0.71	0.55	1.00	0.78	0.76	0.97	0.96	0.68
	60	0.63	0.55	–	0.69	0.69	–	0.91	0.76	–
	80	–	–	0.46	–	–	0.60	–	–	0.68
Subsurface	10	1.00	0.78	–	5.04	1.19	–	3.85	2.29	–
	20	1.03	1.99	–	2.34	2.54	–	2.75	2.43	–
	40	1.10[a]	1.46	1.10	1.69	1.37	1.42	1.42	1.81	1.42
	60	1.66	1.20	–	1.65	1.44	–	1.72	1.53	–
	80	–	–	1.56	–	–	1.67	–	–	2.34
Analysis of variance F-test probability										
Placement			0.0001			0.0001			0.0001	
Distance			0.71			0.0001			0.0001	
Depth			0.26			0.0001			0.0001	
Placement · distance			0.02			0.21			0.92	
Placement · depth			0.005			0.13			0.34	

[a] Emitter placement

was increased to 1.20 (day 191 in the year), ϕ indeed increased (Figs. 2, 3).

The difference in ϕ between the S and SS treatments became apparent after day 180 in the year, at points located at a radius of 25 cm from the emitter. At both 10 and 30 cm depth, ϕ in the deep placement treatment was approximately 20 kPa lower than in the surface placement treatment, indicating a greater water consumption in the SS treatment following silking and during kernel-filling.

Results in Fig. 4 were obtained just before irrigation (21 h after irrigation termination of the previous day). The readings 2 h after irrigation termination were 5–10 kPa higher than those presented, the difference being greater for those locations with lower ϕ before irrigation (data not presented).

P and K concentration distributions in the soil

Sodium bicarbonate-soluble P concentrations (Cp) in the soil were maximal near emitters (Table 8). As expected, P moved in a spherical pattern around the emitter in subsurface fertigation and within a hemisphere in surface fertigation (Table 8). This resulted in a higher Cp in the 30–40 cm soil layer in the SS than in the S treatment (40 vs 20 mg kg^{-1}, respectively). P movement outside a radius of 30 cm from the trickler was negligible in both treatments.

The grand mean Cp in the SS treatment was significantly greater than in the S fertigation treatment (Table 8). Since total P application was identical, and P uptake in the former treatment exceeded P uptake in the latter, this result can be explained only by assuming that P recovery percentage by $NaHCO_3$ was lower in surface than in subsurface fertigation. The rationale for this is that in surface fertigation a larger fraction of the total P applied was located in the top soil layer, which was subject to more intensive drying-wetting cycles than deeper soil layers.

Potassium concentration distribution in the soil in surface and subsurface fertigation followed the same pattern as P (data not presented). The grand mean Ck in the two treatments (214 and 216 mg K kg^{-1} soil) did not differ significantly from each other.

Summary and conclusions

The working hypothesis of this study was that ear yield in subsurface drip fertigation has the potential of surpassing the ear yield in surface fertigation. This hypothesis has been validated, thus supporting previous results of this effect obtained under field conditions (Bar-Yosef et al. 1989).

The suggested mechanism is that the enhanced plant growth and higher yield were facilitated by the greater P and K uptake rates of subsurface- rather than surface-fertigated plants. The elevated uptake rates, which emanated from the supply of the immobile elements to the center of the root system, rather than to the top of the soil, and from the resulting different root distribution and total root weight, permitted greater dry matter production by the plants, and subsequently higher ear yield. The enhanced root activity in the SS treatment was proven by root density measurements at the end of the

Table 7. Water content (g kg^{-1}) distribution in the soil in surface and subsurface trickle fertigation 39 days after plant emergence (before irrigation)

Emitter placement	Sampling depth (cm)	Distance from emitter (cm)			Means
		10	25	40	
Surface	10[a]	112	112	98	108
	20	136	126	99	120
	30	136	139	112	129
	40	140	138	108	129
	50	135	127	111	124
	60	119	112	112	114
	70	121	118	123	121
	80	147	130	132	136
	90	152	163	137	151
	100	153	153	162	156
Subsurface	10	128	103	63	98
	20	151	118	70	113
	30[a]	156	130	79	122
	40	151	128	89	123
	50	145	128	103	125
	60	127	115	114	119
	70	130	118	127	125
	80	135	140	147	140
	90	150	152	159	154
	100	165	170	168	168
		Means			
Surface		135	132	119	147
Subsurface		144	131	112	137

Analysis of variance F-test probability

Placement	0.98
Depth	0.0001
Placement · depth	0.69
Placement · distance	0.65
Depth · distance	0.0003

[a] Emitter placement

Table 8. Sodium bicarbonate extractable P concentration (mg P kg^{-1} soil) distribution in the soil in surface and subsurface trickle fertigation at harvest

Emitter placement	Sampling depth (cm)	Distance from emitter (cm)				Means
		10	20	30	40	
Surface	10[a]	119	42	18	15	48
	20	51	23	19	16	27
	30	23	20	18	18	20
	40	20	20	18	19	19
	50	18	18	18	18	18
	60	18	17	14	17	17
	70	14	13	14	13	13
	80	15	13	13	14	14
	90	13	14	13	13	13
	100	12	13	12	13	12
Subsurface	10	88	41	22	20	43
	20	107	33	23	22	46
	30[a]	91	32	24	22	42
	40	41	19	19	19	25
	50	19	16	17	19	18
	60	14	15	16	18	16
	70	15	15	16	15	15
	80	14	13	14	14	13
	90	13	13	13	14	13
	100	12	13	14	14	13
		Means				
Surface		30	19	16	16	20
Subsurface		42	21	18	18	24

Analysis of variance F-test probability

Placement	0.005
Depth	0.0001
Distance	0.0001
Placement · depth	0.0001
Placement · distance	0.009
Depth · distance	0.0001

[a] Emitter placement

experiment, and by soil air CO_2 concentration analyses in the root zone during the experiment. The CO_2 data showed that the difference in root activity between S and SS systems started early in the season and persisted throughout the growth period.

There is an indication that water uptake before silking was similar in S and SS systems, but after silking water consumption was greater in SS than in S fertigation. This late season difference in water uptake seems to be a secondary effect, emerging from earlier differences in plant development and root growth.

The elevated P and K concentrations in a relatively limited soil volume in the heart of the root system, versus on top of the soil were sufficient to trigger the different plant development conductive to the higher ear yield. This required concentration at the specific time and location within the root zone can be obtained by subsurface fertigation only. Base fertilization to this depth is expensive and ineffective due to fixation reactions, which decrease the possible P and K concentrations in the soil solution relative to a continuous supply of P and K solutions at this location.

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