Drip Irrigation Management Affects Celery Yield and Quality

S.J. Breschini and T.K. Hartz

Department of Vegetable Crops, University of California, Davis, CA 95616

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Abstract. Trials in nine commercial celery (*Apium graveolens* L.) fields were conducted between 1997–99 to evaluate grower drip irrigation management practices and their effects on yield and quality. Surface drip irrigation tapes with flow rates higher and lower than the grower-installed tapes were spliced into the field system; as the cooperating growers irrigated and applied N fertigation according to their routine practices these drip tapes delivered either more or less water and N than the field drip system. Total grower water application during the drip-irrigated portion of the season ranged from 85% to 414% of seasonal reference evapotranspiration (ET_o). Water volume per irrigation varied among fields from 1.8 to 3.8 cm, with irrigation frequency varying from an average of every other day to once a week. Grower management of drip irrigation was not consistently successful in maintaining soil water tension (SWT) in a desirable range. SWT was often below –30 kPa, and in some cases below –70 kPa. These transient stresses were more often a result of inappropriate irrigation frequency than applied water volume. In four of the fields plots receiving less water than that delivered by the field system produced equivalent marketable yield and quality, indicating a significant potential for water savings. An economically important incidence of petiole pithiness (collapse of parenchyma tissue) was observed in four fields. Infrequent irrigation under high ET_o summer conditions, rather than irrigation volume applied, appeared to be the major factor in pith development. N fertigation amount and crop N status appeared to be unrelated to pithiness severity. We conclude that celery drip irrigation management could be substantially improved by maintaining a closer proportionality between irrigation and crop evapotranspiration (ET_c), increasing irrigation frequency, and reducing volume per irrigation.

Drip irrigation has become a commonly used technology. Among the numerous potential benefits of drip irrigation are improved irrigation efficiency and increased yield (Bogle and Hartz, 1986; Bogle et al., 1989; Hanson et al., 1997; Howell et al., 1987). In the major cool-season vegetable production areas of California the use of drip irrigation has grown substantially in recent years, particularly for the production of fresh market celery. One impetus for conversion to drip irrigation is the potential to reduce water and fertilizer inputs used on sprinkler-irrigated celery, which are commonly as high as 75 cm of water and 380 kg·ha⁻¹ N (Koiike et al., 1996). These high inputs, which substantially exceed seasonal reference evapotranspiration and biomass N acquisition (Feigin et al., 1982a; Stark et al., 1982), reflect both the high value of the crop and grower perception that celery is very sensitive to transient water and nitrogen stress.

Most drip irrigation on celery is done through surface systems that are installed after crop establishment and removed just before harvest for reuse in other fields. A number of California celery growers have had difficulty converting from sprinkler irrigation, the standard technique, to drip irrigation. Among the more common problems encountered has been the occurrence of petiole pithiness, a quality disorder involving the breakdown of parenchyma cells in the mar-

ketable petioles. Petiole pithiness has been linked to both irrigation management (Aloni and Pressman, 1979) and N fertility (Burdine and Guzman, 1963; Aloni et al., 1983). The objectives of the present study were to evaluate the drip irrigation management practices currently prevalent in the California celery industry, and to determine the effects of those practices on celery yield and quality.

Materials and Methods

Drip irrigation trials were conducted from 1997–99 in nine commercial celery fields in the coastal valleys of central California. These fields represented seven large commercial celery producers whose annual celery production cumulatively exceeds 1,500 ha. The fields ranged in soil texture from sandy loam to clay loam. Celery was transplanted in these fields from February through August, for harvest June through November (Table 1). Planting configuration was 2 rows of plants per 1.0-m wide raised bed, with plant population ranging from ≈95,000–110,000 plants/ha. All fields were sprinkler irrigated to establish the crop. After crop establishment drip irrigation was installed. A single line of drip irrigation tape was placed on the soil surface of each 1-m wide bed, between the plant rows.

Replicated plots were established in the middle of each field. The drip irrigation tape of the field system was replaced by drip tape of different emission rates ranging from 20% to 40% less than to 30% to 60% more than the

field system. As the cooperating growers managed the fields according to their routine practices these plots received either more or less water (and fertigated N) than the plots irrigated by the field system. Among the various drip tapes used emitter spacing ranged from 20–40 cm, with emitter output ranging from ≈0.5–1.0 L·h⁻¹. Three to five irrigation rates were evaluated in each field. Experimental designs were randomized complete blocks with four replications, with individual plots 4 beds wide × 7.5 m long. The plots were arranged sequentially along the same four beds. All data were collected from the middle beds. No precipitation was received during the drip-irrigated portion of the season except in fields 2 and 9, which received 1.8 and 1.1 cm, respectively, in the week before harvest.

Irrigation volume applied in the experimental area was recorded by an in-line water meter on each of the two middle beds of the test plots. The flow from three individual emitters in each plot was periodically captured to document the relative flow rates in the various treatments. A tensiometer (Irrometer Co., Riverside Calif.) was installed 25–30 cm deep in the plant row in each plot to document soil water tension prior to each irrigation. Computerized weather stations from the California Irrigation Management Information System network (CIMIS, Snyder and Pruitt, 1992) provided daily reference evapotranspiration (ET_o, modified Penman) values for each field. Plant canopy development (percentage of ground area covered) was visually estimated in each field several times in the growing season.

Cooperating growers were asked to provide details of their N applications. Plant N status was evaluated at midseason by petiole sampling and at harvest by sampling the marketable portion of whole plants. Tissue samples were oven-dried and ground. Petiole tissue was extracted in 2% acetic acid and analyzed for NO₃-N concentration by the method of Carlson et al. (1990). Total N concentration in the harvest samples was determined by a combustion technique (Carlo-Erba 1500; Fisons Instruments, Beverly, Mass.).

The plots were harvested at commercial maturity. Data collected included mean total and marketable mass, and incidence of petiole pithiness. Plants having two or more marketable petioles showing parenchyma breakdown were considered to have an objectionable level of the disorder; the percentage of plants showing this level of the disorder was recorded. The significance of irrigation treatment effects on celery yield and incidence of pithiness was determined using orthogonal contrasts to compare individual irrigation treatments with the field irrigation rate.

Results

There were vast differences among growers in drip irrigation management strategies (Table 1). Total seasonal water applications ranged from 85% (field 1) to 414% (field 9)

Table 1. Field location, site characteristics, reference evapotranspiration (ET_o), and drip irrigation practices employed in trial fields.

Field	Location	Soil type	Available soil water holding capacity (%) ^a	Drip irrigation period	ET _o during drip period (cm)	Total irrigation applied water (cm) ^b	Mean irrigation frequency (days)	Mean volume per irrigation (cm)
1	Ventura	sandy loam	10–12	3/31–6/3	28.2	23.9 ^x	5	2.0
2	Ventura	loam	16–18	10/10–11/17	10.1	15.9 ^w	6	2.5
3	Santa Barbara	sandy loam	13–15	5/21–7/8	20.8	30.0 ^w	5	3.6
4	Santa Barbara	sandy loam	13–15	9/9–11/6	16.3	23.5 ^w	7	2.5
5	Santa Barbara	loam	16–18	9/9–11/7	16.3	34.6	7	3.8
6	Monterey	sandy loam	13–15	7/2–8/24	26.9	32.8	3	1.8
7	Monterey	loam	14–17	7/5–8/11	20.8	36.6	2	1.8
8	San Benito	clay loam	18–20	8/9–9/7	10.6	26.5 ^y	4	3.0
9	Monterey	loam	14–17	9/9–11/10	18.2	75.4	4	3.6

^aPercentage by volume estimates from USDA Soil Survey of Ventura, Santa Barbara, Monterey and San Benito counties.^bVolume applied by the field drip system during the drip irrigation period.^xGrower also applied sprinkler irrigation in the final 2 weeks before harvest.^yIncludes one furrow or sprinkler irrigation after drip installation.

of ET_o during the drip-irrigated portion of the season. Mean irrigation frequency ranged among fields from every 2 d to every 7 d. The three fields with the most widely spaced irrigations (fields 2, 4, and 5) were grown in the fall, while the summer fields (3, 6, 7, and 8) generally received more frequent irrigation. The exception was field 1, which the grower irrigated on average every 5 d despite

relatively high ET_o, late spring conditions. There was no apparent relationship between available soil water holding capacity and irrigation frequency. Mean volume per irrigation varied among fields from 1.8 to 3.8 cm. Individual irrigations exceeding 2.5 cm were common in a number of fields.

Growers usually applied more water than the cumulative ET_o since the last irrigation,

even relatively early in the crop season when the crop canopy was far less than complete cover (Fig. 1). Crop canopy coverage (percentage of ground area) was estimated at 25% to 40% early in the drip-irrigated season, increasing to >65% a month before harvest and >90% a week before harvest. In most fields there was no consistent proportionality between irrigation applied and crop evapo-

Fig. 1. Seasonal patterns of reference evapotranspiration (ET_o), drip irrigation, and soil water tension.

transpiration (ETc, estimated from ETo and crop canopy coverage). Drip irrigation was manually controlled except in field 5, which was automated.

Grower management did not consistently maintain soil water tension (SWT) in a desirable range. In most fields there were occasions on which SWT fell below -30 kPa, and in some cases below -70 kPa (Fig. 1). In some fields (2, 3, 5, and 8), undesirably low SWT was primarily the result of infrequent irrigation, usually occurring 4 or more days after the previous irrigation. In fields 1 and 6, low SWT was the result of both undesirably long irrigation intervals and water application less than or barely exceeding ETo. In field 7, the grower irrigated every other day, with irrigation volume always substantially exceeding ETo, yet on three occasions SWT fell below -30 kPa. This suggests that a substantial amount of applied water may have leached below the active root zone, resulting in poor irrigation efficiency.

In fields 3, 5, 8, and 9, plots receiving 20% to 25% less water than those irrigated by the grower's practice produced equivalent marketable yield and quality, indicating a significant potential for water savings (Table 2). In the other fields, reducing irrigation volume below the field rate resulted in a

decrease in crop productivity and, in some cases, quality. In fields 1, 6, 7, and 8, an economically significant level of petiole pithiness was observed. In fields 6 and 7, incidence of pithiness declined with increasing irrigation volume (linear trend significant at $P = 0.05$). In fields 1 and 8, all irrigation treatments showed a high incidence of pithiness, with no significant differences among treatments. Infrequent irrigation under summer conditions, rather than irrigation volume applied, was apparently the critical factor in pith development in field 8. In field 1, the grower compounded the error of irrigating infrequently by applying less than ETo, even late in the season when crop canopy coverage approached 100%.

Nitrogen fertilization practices also varied widely among growers. Seasonal N fertigation ranged from 56 to 423 kg-ha⁻¹ (Table 2). Pre-plant and early season sidedress N averaged an additional 140 kg-ha⁻¹. Fertigated N varied proportionally to irrigation rate, resulting in large differences among treatments in seasonal N application. However, there were relatively small differences in crop N status among irrigation treatments within fields, suggesting declining fertilizer N uptake efficiency with increasing water (and N) application. With the exception of midseason petiole NO₃-N concen-

tration in field 4, crop N status in all irrigation treatments in all fields was sufficient based on the standards for California-grown celery reported by Lorenz and Tyler (1983). Additionally, there was no consistent relationship across fields between N status and incidence of petiole pithiness. These factors suggested there was no confounding influence of N fertility on crop response to irrigation treatment, and that water stress, not N status, was the primary factor in the incidence of pithiness.

Discussion

Drip irrigation offers the potential for increased yield and improved irrigation efficiency compared with traditional furrow- and sprinkler-irrigated systems (Bogle and Hartz, 1986; Bogle et al., 1989; Hanson et al., 1997). However, in this study growers did not fully realize the potential benefits of drip irrigation. The percentage of seasonal ETo applied by the growers ranged from 85% to 414%. Since crop evapotranspiration (ETc) would not likely exceed 120% of ETo even when maximum canopy coverage was developed (Snyder et al., 1987), seasonal water application in most of these fields was clearly wasteful.

Despite excessive irrigation on a seasonal basis, undesirably low SWT was periodically

Table 2. Effect of drip irrigation rate on celery yield and quality, 1997-99 trials.

Field	Drip irrigation treatment	Seasonal ETo applied (%) ^z	Mean whole plant mass (kg)	Mean marketable mass (kg)	Petiole pithiness (% of plants) ^y	Fertigated N (kg-ha ⁻¹)	Midseason petiole NO ₃ -N (mg·kg ⁻¹)	N in harvested stalks (g·kg ⁻¹)
1	80% of field rate	68	1.26	0.79	42	156	5,900	29
	Field rate	85	1.36	0.78	30	195	6,400	30
	130% of field rate	111	1.50 a ^x	0.80	42	254	5,500	30
2	75% of field rate	130	1.17 a	0.65 a	0	89		24
	90% of field rate	147	1.21 a	0.72 a	0	106		22
	Field rate	156	1.55	0.81	0	118		24
	125% of field rate	184	1.35	0.76	0	147		22
	Field rate	156	1.55	0.81	0	118		24
3	60% of field rate	96	1.32	0.77 a	0	89	5,400	21 a
	80% of field rate	120	1.45	0.88	0	119	5,600	23
	Field rate	144	1.42	0.94	0	149	6,100	24
	120% of field rate	168	1.52	0.98	0	179	5,500	22
	160% of field rate	216	1.44	0.96	0	238	6,800	24
4	60% of field rate	99	1.19 a	0.60 a	0	34	2,900	16
	80% of field rate	122	1.39 a	0.68 a	2	45	3,800	18
	Field rate	151	1.69	0.78	7	56	3,100	20
	120% of field rate	166	1.66	0.77	2	67	3,900	20
	150% of field rate	201	1.55	0.72	3	84	3,500	19
5	75% of field rate	157	1.34	0.78	0	119	10,000	25
	90% of field rate	188	1.39	0.80	0	143	10,300	25
	Field rate	209	1.46	0.81	0	159	9,900	27
	135% of field rate	282	1.55	0.84	0	215	11,800	28
	150% of field rate	314	1.44	0.85	0	239	12,200	29 a
6	60% of field rate	73		0.64 a	76 a		7,600	26
	70% of field rate	85		0.73 a	53 a		6,800 a	25
	Field rate	122		1.03	12		7,900	26
	115% of field rate	140		1.04	5		6,800 a	26
	130% of field rate	158		1.12 a	2		8,400	29
7	75% of field rate	132	1.20 a	0.67 a	86 a	317	10,700	24
	Field rate	176	1.42	0.89	20	423	11,800	27
	150% of field rate	264	1.70 a	0.90	3 a	635	12,400	31 a
8	80% of field rate	200	1.77	0.96	83		14,300	20
	Field rate	250	1.83	0.99	93		11,800	21
	125% of field rate	313	1.82	1.02	75		12,600	20
9	80% of field rate	331	1.91	1.06	8	222		34
	Field rate	414	1.97	1.08	8	278		35
	150% of field rate	621	1.92	1.09	0	417		36

^zIncludes sprinkler or furrow irrigation applied in fields 2, 3, and 4 during the drip irrigation period

^yPercentage of plants with 2 or more marketable petioles showing pithiness

^aa = irrigation treatment mean different from field rate at $P < 0.05$, by orthogonal contrast.

observed in most fields. Both Feigin et al. (1982b) and Cannell et al. (1959) reported maximum celery yield and quality with an irrigation regime that maintained SWT at or above -20 kPa. Pogue and Pooley (1985) suggested that SWT should be maintained above -25 kPa for stress-sensitive crops.

In four of the fields, it was shown that irrigation volume could be substantially reduced without reducing crop productivity or quality. However, the true potential for water savings was confounded in other fields by apparent irrigation inefficiency. The relatively infrequent irrigation practiced by a number of the growers often resulted in cumulative ETo >2.5 cm between irrigations; since grower response was generally to apply more than cumulative ETo (regardless of growth stage), individual irrigations often exceeded 3 cm. The inherent inefficiency in this practice is apparent for early season irrigations, since ETc would be substantially less than ETo.

Even in the period immediately before harvest when ETc may exceed ETo, application of >3 cm through the drip tape undoubtedly resulted in substantial leaching. In most low organic matter mineral soils, surface drip irrigation wets only a portion of the bed; the furrows remain dry. Indeed, this characteristic wetting pattern is perceived to be one of the beneficial aspects of drip irrigation, in that it allows nearly unlimited access to the field for pesticide application, harvesting or other operations. However, this water distribution limits the amount of water that can be held in the top 30 cm of soil, from which shallow-rooted vegetable crops like celery draw most heavily (Feigin et al., 1982a). In the trial fields the raised portion of the soil beds was ≈60 cm wide. The effective lateral wetting from the tape was usually limited to ≈30–40 cm, not extending into the bottom of the furrow. The available water holding capacity of these soils ranged from ≈10% to 20% by volume (Table 1). Given that no more than 20% to 40% of available water depletion is advisable for stress-sensitive vegetable crops (Hartz, 1996), only 0.6–1.9 cm of cumulative ETc would be desirable between drip irrigations. Individual applications in excess of that amount would be progressively less efficient, with a high leaching fraction. This irrigation inefficiency explained the undesirably low SWT, reduced yield, and increased pithiness in treatments that, based on seasonal irrigation volume alone, should not have experienced significant water stress.

In fields 1, 6, 7, and 8 celery receiving the grower irrigation practice exhibited significant petiole pithiness. All were late spring or summer fields, located in areas of relatively high ETo. The only other summer field (#3) was located near the coast where marine influence limited maximum temperatures and ETo (mean daily ETo of 0.41 cm in the

month before harvest compared to a combined mean of 0.48 cm for fields 1, 6, 7, and 8). By contrast, the fall fields, none of which had significant levels of pithiness, averaged <0.30 cm daily ETo and seldom had SWT <-30 kPa. In fields 1 and 8, all irrigation treatments had equivalent pithiness incidence, suggesting that a major stress factor was the relatively infrequent irrigation (6–7 d between irrigations on some occasions). In fields 6 and 7, incidence of pithiness declined with increasing irrigation volume. In field 6, the grower management resulted in consistently low SWT; both increased irrigation frequency and increased irrigation volume late in the season would have been appropriate.

The grower of field 7 maintained an every other day irrigation schedule and consistently applied at 20% to 100% more than ETo, yet SWT fell below -30 kPa on four occasions, and 20% of plants exhibited pithiness. The reduced pithiness in plots receiving higher irrigation volume suggested that the higher flow tape developed a wider wetting pattern, or that slow drainage of the extra gravitational water maintained root zone soil moisture for an extended period. The appropriate response in this field would have been daily irrigation rather than increasing application volume on an every other day schedule.

This study suggested that substantial improvement in commercial drip irrigation management was possible. The uncertainty with which these growers approached drip irrigation management was highlighted by the fact that one or more sprinkler irrigations were applied after the initiation of drip irrigation in four of the trial fields. In fields 3 and 4, this was done due to grower concern over the relatively small wetted zone maintained by the drip tape; in the other two fields (fields 1 and 8) the growers reinstalled sprinklers as a 'rescue' treatment when a high incidence of pithiness was detected several weeks before harvest. Similarly, the large range of N application rates encountered among fields suggested that growers remain uncertain about appropriate N fertility management with drip irrigation. The very high N fertigation rates used in fields 7 and 9 presented a substantial N leaching hazard, particularly given the high rate of irrigation.

In the California industry, where it is common for a farm manager to supervise the production of dozens of fields of various crops simultaneously, it is impractical for that individual to devote the time necessary to optimize drip irrigation management on a field by field basis. However, this study suggests that commercial drip irrigation management of celery could be significantly improved simply by applying a few basic principles. Those principles are: 1) more frequent irrigation; 2) lower volume per irrigation; and 3) more closely matching irrigation volume to ETo and crop growth stage.

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