Onion Response to Drip Irrigation Intensity and Emitter Flow Rate

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SUMMARY. Although an irrigation onset criterion for drip-irrigated onion (*Allium cepa*) has been determined, the optimal irrigation intensity has not been examined. Some authors have argued that very high irrigation frequencies with low amounts of water are needed to maximize crop responses. Long-day, sweet Spanish onions were grown on 44-inch beds with two double rows spaced 1.8 ft apart and a drip tape buried 4 inches deep in the bed center. Onions were submitted to eight treatments as a combination of four irrigation intensities (1/16, 1/8, 1/4, and 1/2 inch of water per irrigation) and two drip tape emitter flow rates (0.5 and 0.25 L·h⁻¹) on silt loam in 2002 and 2003. The 1/16-, 1/8-, 1/4-, and 1/2-inch irrigation intensities had irrigations scheduled up to eight times, four times, twice, or once per day, respectively, to replenish soil water potential to -20 cbar as needed. Each plot was independently and automatically irrigated if the soil water potential at 8-inch depth was equal to or lower than -20 cbar. This resulted in an average of 564, 269, 121, and 60 irrigations over 107 days for the 1/16-, 1/8-, 1/4-, and 1/2-inch irrigation intensities, respectively. Onions were harvested, stored, and evaluated for yield and grade after 75 days of storage. Averaged over irrigation intensities, the drip tape with 0.5 L·h⁻¹ emitters had significantly higher total yield, marketable yield, and colossal onion yield than the tape with 0.25 L·h⁻¹ emitters. Averaged over emitter type, the 1/2-inch irrigation intensity had higher total and marketable onion yields than the 1/16- and 1/8-inch intensities. Averaged over emitter type, the 1/2-inch irrigation intensity resulted in the highest super colossal and colossal onion yield. Onions grown with an irrigation intensity of 1/2 inch and drip tape with emitter flow rate of 0.5 L·h⁻¹ produced total yields of 50.0 ton/acre, marketable yields of 48.8 ton/acre, super colossal yield of 1.05 ton/acre, and colossal yield of 13.9 ton/acre. Interactions between irrigation intensities and emitter flow rates were nonsignificant for the number of irrigations, water applied, average soil water potential, or onion yield and grade. There was no significant difference in average soil water potential between treatments. There was no significant difference in total water applied plus precipitation between treatments, with, on average, 32.3 and 31.1 inches applied in 2002 and 2003, respectively. Onion evapotranspiration from emergence to onion lifting totaled 34.6 and 37.3 inches in 2002 and 2003, respectively.

The Treasure Valley of southeastern Oregon and southwestern Idaho annually produces 22,000 acres of sweet Spanish onions, classified as long day and medium-to-long storage (Shock et al., 2000a). Onions are marketed starting at harvest in August and out of storage through April, so maintaining quality during storage is indispensable. Onion growers in the Treasure Valley target the larger onion size classes (jumbo, colossal,

and super colossal) because of price premiums for the larger bulbs.

Past research at the Malheur Experiment Station in Ontario, Ore., on silt loam soils determined the ideal soil water potential (SWP) of -12.5 to -27 cbar for furrow-irrigated onion (Shock et al., 1998a) and of -10 to -17 cbar

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Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
1	cbar	kPa	1
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
2.5400	inch(es)	cm	0.3937
25.4000	inch(es)	mm	0.0394
1.1209	lb/acre	kg·ha ⁻¹	0.8922
6.8948	psi	kPa	0.1450
2.2417	ton/acre	Mg·ha ⁻¹	0.4461
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

with drip irrigation (Shock et al., 2000b) to maximize yield. Irrigation at the wet end of these ranges risks bulb decomposition in storage and aggravated nitrate leaching. Onions were shown to need frequent furrow irrigation, because the SWP at which yield started to decline was relatively high. With furrow irrigation, large amounts of water are unavoidably applied, leading to negative environmental consequences due to leaching and runoff. Drip irrigation can reduce the negative environmental consequences of irrigation by applying smaller amounts of water at a higher frequency. When investigating the ideal SWP for drip irrigated onions, we used low intensity, high frequency, automated irrigations based on SWP (Shock et al., 2000b). Onions were irrigated at different soil water potentials measured at 8-inch depth below onion rows up to eight times per day as needed. However, low intensity, high frequency drip irrigation on a farm scale might result in large water application disuniformity and inefficiencies, because of water losses from the frequent charging and drainage of the drip irrigation system. In addition, low intensity irrigation requires that growers allocate water nearly continuously to each field, yet a continuous water supply may not be practical.

High frequency, low intensity irrigation has been championed as the ideal irrigation strategy for maximizing plant growth (Phene and Beale, 1976; Phene et al., 1992; Rawlins and Raats, 1975). Few studies have examined the effect of small irrigation intensities and irrigation frequencies higher than once-per-day on crop yield under field conditions. Phene et al. (1992) found higher yields of processing tomato in California with high frequency drip irrigation (crop irrigated after each 0.04 inch of evapotranspiration was measured) than with low frequency drip irrigation (crop irrigated after each 0.99 inch of evapotranspiration was measured) on clay loam.

Few studies have examined drip irrigation frequency in relation to onion yield. Bucks et al. (1981) found higher onion yield with daily compared to weekly drip irrigation on a loam in Arizona. Ellis et al. (1986) found no difference in onion yield between drip irrigation frequencies of three times weekly or weekly on clay loam in Colorado. Kannan and Mohamed (2001) found onion yield and average

bulb weight to be highest with an irrigation frequency of 6 d compared to 10, 14, and 18 d. Hanson et al. (2003) compared onion yield with drip irrigation frequencies of twice per day, once per day, twice per week, and once per week on a sandy loam in California. They found onion yields to be significantly lower only for the once per week irrigation frequency.

Drip tapes with lower water application rates make uniform application of lower intensity, higher frequency irrigation more feasible. New drip tape emitters with lower flow rates have been recently developed. The drip tape previously used at the Malheur Experiment Station had emitters spaced 12 inches apart with emitter flow rate of $0.5 \text{ L} \cdot \text{h}^{-1}$. An emitter with a flow rate of $0.25 \text{ L} \cdot \text{h}^{-1}$ is available and is being promoted by drip irrigation dealers. Dealer claims include improved wetting pattern uniformity which could improve onion size uniformity. Assouline et al. (2002) showed that reducing emitter flow rate can reduce water loss from the crop root zone without reducing crop yield. If irrigation intensity is increased and the frequency is reduced (i.e., larger amounts of water applied at each irrigation), a lower emitter flow rate might help mitigate the deep percolation that could result from the higher irrigation intensities necessary with lower irrigation frequencies. Favorable responses to lower flow rates could be soil type specific.

The current study tested the effect of two emitter flow rates and water applications of 1/16, 1/8, 1/4, and 1/2 inch with irrigation scheduling up to eight times, four times, twice, or once per day, respectively, conditional on SWP being drier than -20 cbar. The lowest applied amounts would result in vastly more irrigation events. The hypotheses were that larger amounts of applied water would be less efficient and result in lower yields and that lower emitter flow rates would improve yield and grade.

Materials and methods

The trials were conducted in 2002 and 2003 at the Malheur Experiment Station, Ontario, Ore., on Owyhee silt loam (coarse-silty, mixed, mesic, Xerollic Camborthids) previously planted to wheat (*Triticum aestivum*). An analysis of a composite soil sample of the top foot taken in mid-May each year showed 2.1% and 1.4% organic

matter and pH 7.8 and 7.7 in 2002 and 2003, respectively. In the fall preceding the trials the fields were plowed, roller harrowed twice, fumigated with dichloropropene and chloropicrin (77.9% 1,3-dichloropropene + 16.5% chloropicrin, Telone C-17; Dow AgroSciences, Indianapolis) at 24 gal/acre and bedded. Onion seeds (cultivar Vaquero; Nunhems, Parma, Idaho) were planted in two double rows per 44-inch bed in late March each year. The onion double rows were spaced 18 inches apart. Each double row consisted of two onion rows spaced 3 inches apart. Onions were planted at 150,000 seeds/acre. Drip tape (T-tape; T-Systems International, San Diego) was installed in each bed at the same time as planting at 4-inch depth between the two double rows. The tape had emitters spaced 12 inches apart and either of two emitter flow rates: $0.5 \text{ L} \cdot \text{h}^{-1}$ (low flow) or $0.25 \text{ L} \cdot \text{h}^{-1}$ (ultra-low flow). The tape flow rates were: 0.22 gal/min per 100 ft for the low flow emitters and 0.11 gal/min per 100 ft for the ultra-low flow emitters. The field was minisprinkler-irrigated until seedling emergence. Seedling emergence occurred on 18 Apr. 2002 and 7 Apr. 2003.

Weeds were controlled with an application of pendimethalin (Prowl; BASF, Florham Park, N.J.) at 1 lb/acre a.i. on 2 May 2002 and on 21 Apr. 2003. Approximately 0.4 inch of water was applied through the minisprinkler system to incorporate the pendimethalin. Subsequently, weeds were controlled with low rate herbicide applications as needed until early July, when onion foliage growth precluded further tractor traffic. Herbicides included bromoxynil (Buctril; Bayer CropScience, Research Triangle Park, N.C.), oxyfluorfen (Goal; Dow AgroSciences), and sethoxydim (Poast; Micro Flo Co., Memphis, Tenn.).

The experimental design was a randomized complete block with four replicates. The onions were submitted to eight treatments consisting of a combination of two drip tape emitter flow rates and four irrigation intensity treatments (Table 1). The onions in each plot (four double rows by 50 ft) were submitted to one irrigation intensity and one emitter flow rate. The maximum irrigation frequencies were limited by the daily time interval by which the datalogger (CR10; Campbell Scientific, Logan, Utah) checked the

Table 1. Effect of four irrigation intensities and two drip tape emitter flow rates on onion yield and size in 2002 and 2003.

Emitter flow rate (L·h ⁻¹) ^z	Irrigation intensity ^y (inches) ^x	Irrigation frequency ^w (h)	Irrigations (no.)	Total water applied ^v (inches)	Avg soil water potential (cbar) ^u	Total yield	Marketable yield				
							Total	Super	Colossal	Jumbo	Medium
								colossal			
----- ton/acre ^t -----											
2002											
0.5	1/16	3	498	32.7	-20.3 ± 3.1	52.1	51.4	0.3	11.9	38.2	1.0
0.5	1/8	6	245	32.2	-19.9 ± 3.4	49.3	48.5	0.6	9.6	36.9	1.5
0.5	1/4	12	124	32.6	-20.3 ± 3.5	52.0	51.4	0.5	9.6	40.0	1.4
0.5	1/2	24	60	31.5	-18.8 ± 4.1	52.6	51.4	0.8	14.4	35.4	0.8
Avg			222	32.3	-19.8	51.5	50.7	0.5	11.4	37.6	1.2
0.25	1/16	3	496	32.6	-19.8 ± 2.9	48.5	47.6	0.7	9.3	36.8	0.9
0.25	1/8	6	236	31.2	-21.2 ± 3.9	49.7	48.6	0.2	9.5	37.5	1.4
0.25	1/4	12	125	32.9	-19.8 ± 4.2	48.9	47.9	0.5	8.9	37.3	1.2
0.25	1/2	24	229	32.1	-19.9 ± 5.4	52.0	51.3	0.6	10.7	38.9	1.2
Avg					-20.2	49.8	48.9	0.5	9.6	37.6	1.2
Avg over emitter types	1/16	3	497	32.7	-20.0	50.3	49.5	0.5	10.6	37.5	1.0
	1/8	6	241	31.8	-20.4	49.5	48.5	0.4	9.6	37.2	1.5
	1/4	12	124	32.7	-20.1	50.5	49.6	0.5	9.3	38.6	1.3
	1/2	24	60	31.5	-19.4	52.4	51.4	0.7	12.8	36.9	1.0
2003											
0.5	1/16	3	523	35.6	-18.0 ± 2.7	43.0	42.3	0.9	8.2	32.5	0.9
0.5	1/8	6	233	32.2	-19.4 ± 3.0	44.0	42.3	0.5	10.6	30.5	0.8
0.5	1/4	12	116	32.1	-18.9 ± 3.3	45.1	44.7	0.3	9.7	33.9	0.9
0.5	1/2	24	53	29.7	-17.4 ± 4.5	47.4	46.3	1.3	13.4	30.8	0.8
Avg			232	32.4	-18.4	44.9	43.9	0.7	10.4	31.9	0.9
0.25	1/16	3	460	31.8	-18.9 ± 2.8	42.5	41.7	0.1	6.9	33.6	1.0
0.25	1/8	6	229	31.7	-18.9 ± 2.4	40.3	39.3	0.8	7.5	29.9	1.1
0.25	1/4	12	141	38.2	-19.6 ± 3.3	47.0	45.0	0.3	9.3	34.6	0.9
0.25	1/2	24	55	30.4	-18.7 ± 4.1	44.1	43.0	0.7	9.8	31.5	1.0
Avg			221	33.0	-19.0	43.5	42.3	0.5	8.4	32.5	1.0
Avg over emitter types	1/16	3	492	33.7	-18.5	42.8	42.0	0.5	7.5	33.0	0.9
	1/8	6	231	31.9	-19.2	42.1	40.8	0.6	9.0	30.3	1.0
	1/4	12	129	35.1	-19.2	46.0	44.9	0.3	9.5	34.2	0.9
	1/2	24	54	30.1	-18.1	45.7	44.6	1.0	11.7	31.1	0.9
2002-03 Avg											
0.5	1/16	3	515	34.6	-18.8	47.6	46.9	0.6	10.1	35.3	0.9
0.5	1/8	6	238	32.2	-19.6	46.6	45.4	0.5	10.1	33.7	1.2
0.5	1/4	12	120	32.3	-19.5	48.6	48.0	0.4	9.7	36.9	1.2
0.5	1/2	24	55	30.3	-17.9	50.0	48.8	1.1	13.9	33.1	0.8
Avg			228	32.4	-18.9	48.2	47.3	0.6	10.9	34.8	1.0
0.25	1/16	3	472	32.1	-19.2	45.5	44.6	0.4	8.1	35.3	1.0
0.25	1/8	6	231	31.5	-19.6	44.3	43.3	0.5	8.3	33.2	1.2
0.25	1/4	12	136	36.4	-19.7	47.9	46.5	0.4	9.1	36.0	1.1
0.25	1/2	24	56	30.8	-19.1	47.5	46.5	0.6	10.2	34.6	1.1
Avg			224	32.7	-19.4	46.3	45.3	0.5	8.9	34.8	1.1
Avg over emitter types	1/16	3	494	33.4	-19	46.5	45.8	0.5	9.1	35.3	1.0
	1/8	6	235	31.9	-19.6	45.5	44.5	0.5	9.3	33.5	1.2
	1/4	12	127	34.2	-19.6	48.3	47.3	0.4	9.3	36.5	1.1
	1/2	24	56	30.5	-18.5	48.8	47.8	0.9	12.2	33.8	0.9
LSD _(0.05) Emitter type (E)			NS	NS	NS	1.5	1.4	NS	1.5	NS	NS
LSD _(0.05) Irrigation intensity (I)			17	NS	NS	2.0	1.9	0.3	2.1	1.6	NS
LSD _(0.05) Year (Y)			NS	NS	NS	1.5	1.4	NS	NS	1.1	0.2
LSD _(0.05) E × I			NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD _(0.05) E × I × Y			NS	NS	NS	NS	NS	0.6	NS	NS	NS

^z 1 L·h⁻¹ = 0.2642 gal/h.^y Amount of water applied per irrigation.^x 1 inch = 25.4 mm^w Time interval used by datalogger for checking sensors and making irrigation decisions.^v Includes precipitation (0.93 inch in 2002, 2.81 inches in 2003) and microsprinkler irrigation (2 inches in 2002, 1.39 inches in 2003).^u 1 cbar = 1 kPa.^t 1 ton/acre = 2.2417 Mg·ha⁻¹.

sensors and made irrigation decisions. Each plot was irrigated independently when the average SWP at 8-inch depth below the onion rows reached -20 cbar. The irrigation durations for the 1/16-, 1/8-, 1/4-, and 1/2-inch irrigation intensities were, respectively, 1, 2, 4, and 8 h for the low flow emitters and 2, 4, 8, and 16 h for the ultra-low flow emitters. All treatments had the capacity to deliver a maximum of 1/2 inch/d of water if irrigated at every possible time. The highest onion evapotranspiration recorded in 2002 and 2003 was 0.43 inch/d.

Soil water potential in the onion root zone was measured and recorded every three hours with four granular matrix sensors [GMS (Watermark Soil Moisture Sensors Model 200SS; Irrrometer Co., Riverside, Calif.)] in each plot. The GMS were installed at 8-inch depth below the center of one of the middle two double onion rows. In addition, each plot had a GMS installed at 18-inch depth below an onion row. Sensors had been calibrated to SWP determined by tensiometers with pressure transducers in the same soil (Shock et al., 1998b). The GMS were connected to a datalogger (CR10; Campbell Scientific) via multiplexers (AM 416; Campbell Scientific). The irrigations to each plot were controlled by the datalogger through a controller (SDM16; Campbell Scientific) using a solenoid valve. The pressure in the drip lines was maintained at 10 psi by pressure regulators in each plot. The automated drip irrigation system was started on 22 May each year. The amount of water applied to each plot was recorded daily at 0800 HR from a water meter installed downstream of the solenoid valve in each plot. The total amount of water applied included uniform sprinkler irrigations applied at emergence, water applied with the drip irrigation system, and precipitation from emergence through the final irrigation on 30 Aug. 2002 and 2 Sept. 2003.

Onion evapotranspiration (ET_c) was calculated by the Pacific Northwest Cooperative Agricultural Weather Network (AgriMet; U.S. Bureau of Reclamation, Boise, Idaho) from data collected at the Malheur Experiment Station by an AgriMet weather station using crop coefficients and a modified Penman equation (Wright, 1982). AgriMet estimates crop evapotranspiration (ET_c) by first modeling refer-

ence evapotranspiration (ET_o) from observed weather conditions at each weather station. AgriMet uses alfalfa (*Medicago sativa*) as its reference crop. The ET_o is then multiplied by a crop coefficient (K_c) that varies through the season depending on the growth stage of the crop. Onion ET_c was estimated and recorded from crop emergence until lifting of the crop each year.

The adequacy of plant nutrients was based on root tissue sample analysis (Sullivan et al., 2001; J. Taberna, personal communication). The roots from 25 onion plants taken from plot border rows representative of the field were washed with deionized water and analyzed for nutrient content. Necessary fertilizer was applied through the drip tape. In 2002, the following fertilizers were applied: nitrogen (N) at 50 lb/acre and phosphorus (P) at 96 lb/acre as ammonium phosphate on 12 June; N at 25 lb/acre and P at 48 lb/acre as ammonium phosphate on 19 and 27 June; zinc (Zn) at 0.25 lb/acre as zinc chelate, copper (Cu) at 0.2 lb/acre as copper chelate, and boron (B) at 0.1 lb/acre as boric acid on 13 June; magnesium (Mg) at 5 lb/acre as magnesium sulfate on 20 June; Mg at 5 lb/acre as magnesium sulfate and Cu at 0.2 lb/acre as copper chelate on 3 July. In 2003, the following fertilizers were applied: N at 25 lb/acre as ammonium sulfate on 30 May; N at 25 lb/acre as urea ammonium nitrate solution on 5, 16, and 25 June; and Zn at 0.25 lb/acre as zinc chelate and Cu at 0.2 lb/acre as copper chelate on 25 June.

The onions were lifted to cure on 10 Sept. 2002 and 11 Sept. 2003. After 10 d, onions in the central 40 ft of the middle two double rows in each plot were topped, bagged, and placed into storage. The storage was automated to maintain an air temperature of approximately 34 °F by using a large fan to move outdoor air into the storage building as needed. The onions were graded out of storage in mid-December. Bulbs were separated according to quality: bulbs without blemishes (No. 1s), split bulbs (No. 2s), and diseased bulbs. The No. 1 bulbs were graded according to diameter as generally marketed from this production area: small ($<2\text{--}1\frac{1}{4}$ inches), medium ($2\text{--}1\frac{1}{4}$ to 3 inches), jumbo (3 to 4 inches), colossal (4 to $4\text{--}1\frac{1}{4}$ inches), and super colossal ($>4\text{--}1\frac{1}{4}$ inches). Bulb counts per 50 lb of super colossal onions were

determined for each plot by weighing and counting all super colossal bulbs during grading. Marketable onions were considered perfect bulbs in the medium, jumbo, colossal, and super colossal size classes.

Data on the number of irrigations, water applied, SWP, and onion yield and grade were subjected to the general linear model analysis of variance (ANOVA) procedure of NCSS statistical software (Hintze, 2000). Treatment means with differences greater than the corresponding protected $LSD_{(0.05)}$ were considered to be different.

Results

Only super colossal bulb yield showed an interaction between emitter flow rate, irrigation intensity and year, so the results for all other parameters are analyzed and discussed as the average over the 2 years. Emitter flow rate did not have an effect on the number of irrigations required to maintain the SWP at -20 cbar (Table 1). Averaged over emitter flow rates and years, there was a significant increase in the number of irrigations during the season with decreasing irrigation intensity. Averaged over emitter flow rates and years, 445, 223, 110, and 57 irrigations were run from mid-May to 31 Aug. for the 1/16-, 1/8-, 1/4-, and 1/2-inch irrigation intensities, respectively. Averaged over emitter flow rates and years, 4.2 irrigations/d, 2.1 irrigations/d, 1.1 irrigations/d, and one irrigation every 1 to 2 d, were run from mid-May to 31 Aug. for the 1/16-, 1/8-, 1/4-, and 1/2-inch irrigation intensities, respectively.

There was no significant difference in total water applied between treatments, with, on average, 32.2 and 32.7 inches applied in 2002 and 2003, respectively (Table 1). Onion ET_c from emergence to lifting totaled 34.6 and 37.3 inches in 2002 and 2003, respectively. Accumulated water applications by all treatments closely accompanied accumulated ET_c (Figs. 1–2), suggesting that even at the highest irrigation intensity used in this trial, water loss to deep percolation was probably minimal. The total amount of water applied included 2.00 and 1.39 inches of water applied with the minisprinkler system after emergence, and 0.93 and 2.81 inches of precipitation, in 2002 and 2003, respectively. There was no significant difference in average SWP at 8-inch depth between treatments

Fig. 1. Onion evapotranspiration (ET_c) and total water applied (includes precipitation) over time for two drip emitter flow rates and four drip irrigation intensities (amount of water applied per irrigation) in 2002 ($1 \text{ L}\cdot\text{h}^{-1} = 0.2642 \text{ gal/h}$, $1 \text{ inch} = 25.4 \text{ mm}$).

Fig. 2. Onion evapotranspiration (ET_c) and total water applied (includes precipitation) over time for two drip emitter flow rates and four drip irrigation intensities (amount of water applied per irrigation) in 2003 ($1 \text{ L}\cdot\text{h}^{-1} = 0.2642 \text{ gal/h}$, $1 \text{ inch} = 25.4 \text{ mm}$).

(Table 1, Figs. 3–6). The standard deviation of the SWP increased with higher intensity irrigation, reflecting the higher amplitude of SWP oscillation around the -20 cbar criterion. There was no significant difference in average SWP at 18-inch depth between treatments (data not shown). Soil water potential at 18-inch depth remained close to SWP at 8-inch depth during the season.

All irrigations were interrupted briefly in 2002 (Figs. 3–4). In 2003, the transformer powering the solenoid valves failed, stopping irrigations to all plots from 24 to 26 June (Figs. 5–6).

Averaged over emitter flow rate, the $1/2$ -inch irrigation intensity had among the highest total and marketable onion yields (48.8 and 47.8 ton/acre,

respectively, Table 1). Averaged over emitter flow rate, the $1/2$ -inch irrigation intensity resulted in the highest super colossal and colossal onion yield (0.85 and 12.2 ton/acre, respectively). The low flow emitter at the $1/2$ -inch irrigation intensity in 2003 resulted in among the highest yield of super colossal onions (1.3 ton/acre).

Averaged over irrigation intensities and years, the drip tape with low flow emitters had significantly higher total yield, marketable yield, and colossal onion yield than the tape with ultra-low flow emitters (Table 1).

Discussion

Marketable yield averaged 49.8 and 43.1 ton/acre in 2002 and 2003, respectively, compared to average

county yields of 32.3 and 30.4 ton/acre in 2002 and 2003, respectively. While the yields are above the county average, they are similar to those realized by growers using drip irrigation (J. Klauzer, personal communication). In the analysis of variance, the year effect was significant for total, marketable, jumbo, and medium onion yields, which were higher in 2002 compared to 2003. The yield of the larger bulb size classes was limited in these trials by the high plant population (Shock et al., 2004). Lower plant populations are needed to optimize colossal and super colossal onion production.

The results of this study suggest that the drip tape with ultra-low flow emitters should not be recommended for onion production on silt loam in

Fig. 3. Soil water potential at 8-inch (20.3 cm) depth over time in 2002 for onions drip irrigated at four intensities with an emitter flow rate of $0.5 \text{ L}\cdot\text{h}^{-1}$ ($1 \text{ L}\cdot\text{h}^{-1} = 0.2642 \text{ gal/h}$, $1 \text{ inch} = 25.4 \text{ mm}$).

Fig. 4. Soil water potential at 8-inch (20.3 cm) depth over time in 2002 for onions drip irrigated at four intensities with an emitter flow rate of $0.25 \text{ L}\cdot\text{h}^{-1}$ ($1 \text{ L}\cdot\text{h}^{-1} = 0.2642 \text{ gal/h}$, $1 \text{ inch} = 25.4 \text{ mm}$).

the Treasure Valley, since onion yield and size were slightly lower and there were no apparent irrigation benefits. Assouline et al. (2002) showed that reducing emitter flow rate can reduce deep percolation and result in higher soil water content in the crop root zone, but the SWP was the same in the present study, irrespective of emitter flow rate. In the study by Assouline et al. (2002), irrigation scheduling was fixed and all treatments were irrigated equally regardless of actual soil moisture. In our present study, irrigation scheduling was flexibly based on soil moisture feedback. In addition, in the study by Assouline, the conventional emitter had a flow rate of 0.53 gal/h and a spacing of 19.7 inches and was compared with an emitter that had a flow rate of 0.07 gal/h and a spacing of 9.8 inches . This resulted in a much bigger difference in water application rates between emitter types than in our study. The smaller difference in flow rates between the two emitter types in our study would lessen the probability of a crop yield response or

of reductions in water application or water percolation loss.

The results of this study suggest that there is no benefit to reducing irrigation intensities below $1/2 \text{ inch}$ per irrigation for onions drip irrigated to maintain a SWP of -20 cbar on silt loam. An irrigation intensity of $1/2 \text{ inch}$ in our study corresponded to an irrigation frequency of approximately every 1 to 2 d depending on the time of season. Our results agree with Bucks et al. (1981), but disagree with Hanson et al. (2003). The study by Bucks et al. (1981), where only two irrigation frequencies were tested, leaves unanswered whether a frequency between daily and weekly would have been optimal. It is difficult to compare our results with those of Ellis et al. (1986) and Kannan and Mohamed (2001), because these studies did not test irrigation frequencies higher than three times per week. The study by Kannan and Mohamed (2001) leaves unanswered whether a frequency higher than every 6 d would have been optimal. The studies by Bucks et al. (1981),

and Kannan and Mohamed (2001) tested winter onions which would be expected to require less frequent irrigation than summer onions. The study by Bucks et al. (1981) used a seeding rate of $216,000 \text{ plants per acre}$, considerably higher than ours of $150,000 \text{ plants/acre}$. The study by Hanson et al. (2003) was with processing onion, which usually is planted at a higher population and does not require the larger bulb sizes for marketing as in our study. With these two studies probably using higher plant populations than our study, total or marketable onion yield could have been limited more by plant space and less by water. The study by Ellis et al. (1986) used an onion stand thinned to a low plant population of $66,451 \text{ plants/acre}$, which might have limited total onion yield response to water. The plant population used by Ellis et al. (1986) was substantially lower than our plant population and could be a factor in their highest total onion yield (15.3 ton/acre with drip irrigation three times per week) being substantially lower than our highest

Fig. 5. Soil water potential at 8-inch (20.3 cm) depth over time in 2003 for onions drip irrigated at four intensities with an emitter flow rate of $0.5 \text{ L}\cdot\text{h}^{-1}$ ($1 \text{ L}\cdot\text{h}^{-1} = 0.2642 \text{ gal/h}$, 1 inch = 25.4 mm).

Fig. 6. Soil water potential at 8-inch (20.3 cm) depth over time in 2003 for onions drip irrigated at four intensities with an emitter flow rate of $0.25 \text{ L}\cdot\text{h}^{-1}$ ($1 \text{ L}\cdot\text{h}^{-1} = 0.2642 \text{ gal/h}$, 1 inch = 25.4 mm).

total yield (48.8 ton/acre) with a frequency of once every 1 to 2 d.

The studies by Bucks et al. (1981), Kannan and Mohamed (2001), and by Hanson et al. (2003) only report total marketable onion yield without regard to the yield of different bulb size classes, which can greatly affect crop value (Shock et al., 2000b, 2004). The study by Ellis et al. (1986) measured jumbo as the largest size class. For the Idaho–eastern Oregon onion marketing order, there are colossal and super colossal size classes larger than the jumbo size. Colossal onion yield is more sensitive to irrigation criteria than total yield (Shock et al., 2000b). In the present study, the lowest total onion yield was 93% of the highest total onion yield, averaged over years and emitter type. In contrast, the lowest super colossal onion yield was 47% of the highest super colossal yield and the lowest colossal onion yield was 74% of the highest colossal yield.

The studies by Bucks et al. (1981), Ellis et al. (1986), Kannan and Mo-

hamed (2001), and by Hanson et al. (2003) used a fixed irrigation frequency regardless of soil moisture. The present study used a flexible frequency which was a result of basing applications on SWP, which was reached at different times for different irrigation intensities. Crop growth and yield is directly related to plant water potential, which is directly related to SWP (Rawlins and Raats, 1975). Although the studies by Ellis et al. (1986), Kannan and Mohamed (2001), and Hanson et al. (2003) adjusted the water applied at each irrigation according to ET_c estimates, and the study by Bucks et al. (1981) having adjusted irrigation amounts according to soil gravimetric sampling, these procedures may not have continuously maintained the ideal SWP. With a flexible frequency drip irrigation system as used in the present study, the irrigation intensity will influence temporarily how wet the soil gets during an irrigation and the depth of water percolation loss, if any.

The reason for the small increase

in production of the larger bulb sizes with the highest irrigation intensity is unknown. Perhaps larger pulses of water could have a small effect in moving sodium and chloride salts beyond the onion row, favoring better onion performance. We have shown that onions will respond to SWP higher than -20 cbar with increased bulb yield and size, but higher SWP can also increase storage losses (Shock et al., 1998a, 2000b). However, there were no significant differences in season-long average SWP at the 8-inch depth between irrigation intensities. It is unknown whether the 1/2-inch irrigation intensity could have kept part of the soil profile wetter, on average.

In a flexible frequency irrigation system as ours, as the irrigation intensity increases, the water use efficiency could start to decline because of increasing deep percolation. The results of this study leave unanswered whether irrigation intensities higher than 1/2 inch and hence lower frequencies would reduce or increase sweet Span-

ish onion yield, size, or storage quality on silt loam in Treasure Valley. Higher irrigation intensities risk increased leaching losses.

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