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VISUALIZATION OF WATER MOVEMENT IN MULCHED BEDS WITH INJECTIONS OF DYE WITH DRIP IRRIGATION

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Abstract. **Adequate water, fertilizer, and fumigant management in plasticulture production systems requires an understanding of water movement in mulched beds. Soluble blue dye and controlled irrigation conditions were used to visualize the wetting pattern of several common drip tapes on three Florida sandy soils. On an Orangeburn fine sandy loam near Quincy, Fla., the wetted zone reached the 10-inch-deep impermeable layer between 60 and 120 gal/100 ft (2 to 4 hours at 30 gal/100 ft per hour; 12-inch emitter spacing). With greater irrigation volumes, lateral water movement occurred. On a 15-ft deep Lakeland fine sandy soil near Live Oak, Fla., increasing irrigation volume from 24 to 192 gal/100 ft (1 to 8 hours at 24 gal/hour per 100 ft; 12-inch emitter spacing) significantly increased depth (D), width (W), and emitter-to-emitter coverage (L) of the water front. The wetting front passed the bottom of the root depth (12 inches) after an irrigation volume of approximately 72 gal/100 ft (3 hours). After 8 hours, W did not exceed 15 inches. Complete emitter-to-emitter coverage was reached after approximately 3-hours irrigation (72 gal/100 ft). Therefore, the highest volume of irrigation water that can be applied in this soil type when no leaching is expected is 72 gal/100 ft (3 hours). On a Boca sand soil with a spodic layer at the 18 inch depth in Hendry County, Fla., the water front reached the impermeable layer after 96 gal/100 ft (4 hours at 24 gal/hour per 100 ft; 18-inch emitter spacing). Lateral, then upwards vertical movement occurred with greater irrigation volumes. In Live Oak, W did not exceed 30% of the bed width, confirming that complete wetting of 32-inch-wide beds cannot be achieved with a single drip tape. The presence of an impermeable layer in Quincy and LaBelle would allow for greater W once the entire profile has been wetted. Using the drip line to deliver fumigants may impact preplant fertilizer movement, thereby requiring an adjustment of the fertility program.**

Scheduling irrigation for vegetables consists of knowing when and how much water to apply in a way that satisfies crop water needs, maintains soil water tension between field capacity and 15 kPa at the 12-inch depth, and prevents nutrient leaching (Simonne et al., 2002). Because of the low water holding capacity of the sandy soils of Florida (approximately 10%, v:v), proper irrigation management requires an estimate of crop water use, a tool to monitor soil moisture status, and a guideline for splitting irrigation events (Simonne et al., 2002). Splitting irrigation events is necessary when the amount of water to be applied is larger than the water holding capacity of the wetted zone. For a sandy soil, a 1 ft^2 vertical section of a 100-ft-long raised bed can hold approximately 24 gal of water (Simonne et al., 2002). However, this amount may change based on soil texture, bed compaction, and actual root depth (Clark and Smajstrla, 1993). In practice, splitting irrigation has to be a compromise between two constraints. On one side, the more frequent the irrigation, the less likely soluble nutrients are to be leached below the root zone. On the other side, frequent and short irrigations may waste water and reduce irrigation uniformity due to a large portion of the irrigation cycle used for system charge and flush. In addition, each irrigation cycle has to deliver enough water to ensure complete wetting between two adjacent emitters to maintain crop uniformity, especially when the plants are small.

A direct knowledge of how much water can be stored in the root zone can be gained by visualizing water movement in the soil. Visualizing the effect of irrigation volume on water movement in the root zone of vegetable crops is naturally difficult because of where this process occurs. Often, wetted soil looks much like dry soil, and observing wetting patterns in the root zone requires extensive digging. Yet, precise knowledge of where irrigation water goes has direct implications on not only irrigation management, but also on fumigant application (Hochmuth et al., 2002) and fertilizer leaching (Simonne et al., 2003a). Irrigation, fertilization, and fumigant management are at the center of Best Management Practices for vegetables (Simonne et al., 2003b). A blue dye and controlled irrigation conditions were used to visualize the wetting pattern of drip irrigation using different drip tapes on soils from three vegetable producing areas of Florida. The main objectives of this project were to (1) describe the shape of the wetting zone for several water volumes applied by drip irrigation, (2) determine vertical, lateral, and longitudinal movements of irrigation for these water volumes, (3) quantify the relative volume of the wetted raised bed, and (4) provide guidelines for splitting irrigation.

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Materials and Methods

Three dye tests were conducted at the North Florida Research and Education Center (NFREC)—Quincy in Quincy, Fla. on 6 June 2002 on an Orangeburg fine sandy loam soil, at the NFREC—Suwannee Valley near Live Oak, Fla. on 3 Mar. 2002 on a Lakeland fine sand, and in a commercial field near LaBelle in Hendry County, Fla. on 6 and 7 Feb. 2002 on a Boca sand soil. Treatments were irrigation volume applied. Plots consisting of 150-ft-long sections of raised beds were established with typical plastic mulch layer equipment.

At each location, the dye tests consisted of injecting the dye, irrigating with the selected volume of water, digging longitudinal and transverse sections of the raised beds, and taking measurements. Drip irrigation systems consisted of a water source, a pump, a back-flow prevention device, a fertilizer injector (model DI16-11, Dosatron, Clearwater, Fla.), a 150-mesh screen filter, a 10-psi pressure regulator, and drip tubing. After pressurizing the drip irrigation system, a soluble blue dye (Terramark SPI High Concentrate, ProSource One, Memphis, Tenn.) was injected at a 1:49 (v:v) dye:water dilution rate. After dye injection, clear water was injected according to treatments.

The drip tape most commonly used by the industry was selected at each location. In Quincy, beds were 36 inches wide. The drip tape used had a flow rate of 30 gal/100 ft per h and a 12-inch emitter spacing (Chapin Watermatics, Watertown, N.Y.). Irrigation times were 1, 2, 4, and 6 h, which created water application rates of 30, 60, 120, and 180 gal/100 ft, respectively. An impermeable clay layer was present in the field at the 10-inch depth. In Live Oak, beds were 28 inches wide. The drip tape used had a flow rate of 24 gal/100 ft per h and a 12-inch emitter spacing (Roberts Ro-Drip, San Marcos, Calif.). Irrigation times were 1, 2, 4, and 8 h, which created water application rates of 24, 48, 96 and 192 gal/100 ft, respectively. The thickness of the sand layer at the test site varied between 12 and 15 feet. In LaBelle, beds were 36 inches wide and had already been planted with a squash crop (*Cucurbita pepo* L.) whereas the beds used in Quincy and Live Oak were new and had not been cropped previously. The drip tape used had a 24 gal/100 ft per h flow rate and an 18-inch emitter spacing (Netafim USA, Fresno, Calif.). An impermeable marl layer was present in the field at a depth ranging between 10 and 17 inches. Because of scheduling reasons, the last 2 and 4 h of the 6- and 8-h injection times, respectively, were performed the next day.

Digging was done immediately after completion of the longest irrigation treatment in Live Oak and LaBelle. However, the field had to drain for 24 h before digging was possible in Quincy. For each treatment, a 12-ft-long longitudinal and at least one transverse section were dug. Hence, measurements were made on approximately 6 to 8 emitters. Wetting patterns were described qualitatively and quantitatively. The shape of the wetting pattern and whether and when the water movement was affected by the presence of an impermeable layer were noted. The shape of the wetted area on the longitudinal and cross sections were described as 'round' (circular), 'elongated' (true elliptic), 'triangular' (narrow top, wide base due to lateral movement), 'rectangular' (modified elliptic shapes due to the joining of the wetting pattern of two adjacent emitters), and 'irregular' (when none of the above descriptions applied). For the quantitative description of the wetted pattern, vertical depth (V), width (W), and length (L) were measured as the longest vertical distance from the drip tape to the bottom of the blue ring, the horizontal length perpendicular to the bed axis at the widest point of the wetted zone, and the horizontal length parallel to the bed axis at the widest point of the wetted zone, respectively. Actual wetting measurements were transformed into relative wetting measurements based on the greatest possible wetting lengths imposed by bed width for W and emitter spacing for L. Values for W were limited by bed width and Wmax values were 36, 28, and 36 inches for Quincy, Live Oak, and LaBelle, respectively. Values for L were limited by the emitter spacing of the drip tape used and Lmax values were 12, 12, and 18 inches for Quincy, Live Oak, and LaBelle, respectively. Values for V may be limited by the presence of an impermeable layer and Vmax values were 10 and 17 inches for Quincy and LaBelle, respectively. In the absence of an impermeable layer in Live Oak, the Vmax value was set at the 12-inch tillage depth. This depth was selected because for most vegetables, the root zone is limited to the tillage depth. At each location, V, W, and L responses to water application rates were analyzed using ANOVA and Duncan's Multiple Range Test. Orthogonal contrasts were used to test the significance of linear and quadratic responses.

Results and Discussion

In all three tests, because the dye was injected first followed by clear water, the dye patterns in the soil appeared as a 1-inch-thick blue ring surrounding an uncolored section of soil. If the dye was continuously injected with all the irrigation water, the entire wetted section would appear colored. The dye was easily distinguishable in the soil, but the contrast between the soil color and the blue ring was improved by allowing a 1- to 2-h drying period after digging. Improved contrast was necessary for increasing quality of wetting patterns especially when large water volumes that diluted the dye in the soil were used. Because the drip tapes used were new in Quincy and Live Oak, the uniformity of water application was high as reflected by low coefficient of variations (CV) observed for V, W, and L (all CV ranged between 4% and 11%). In LaBelle, where the drip tape had already been used, some clogging was observed. For this study, data were not collected on totally or partially clogged emitters. However, emitter clogging affects irrigation uniformity, which in turn would also affect fertilizer and fumigant distribution.

The relative position of the wetting patterns and colored rings showed that the dye moved with the water front for all injection times in Quincy and Live Oak, and for the 0.5- to 4-h injection times in LaBelle. Therefore, under these conditions, dye position was a reliable indicator of water movement in the soil. However, it was visible on the dry beds in LaBelle that the dye did not move any further when the remaining 2 and 4 h of the 6- and 8-h injection times were done the next day (This was taken into account in making measurements for the 6- and 8-h injection times in LaBelle). This observation emphasizes the importance of continuous injection to ensure that the dye stays in solution and does not get adsorbed onto the soil. Free movement of the dye in the soil profile is essential for the reliability of this kind of test. The reason for dye adsorption in LaBelle soil has not been determined.

The shapes of the wetting zones were affected by location, irrigation volume, and the presence of an impermeable layer

Table 1. Qualitative and quantitative description of wetted area observed on three Florida soils as affected by irrigation volume.

Vol. (gph/100 ft)	Time (h)	Depth of impermeable layer (inch)	Transverse shape[z]	Longitudinal shape[z]	Vertical depth (inch)	Width (inch)	Lateral movement	Length (inch)	Emitter to emitter overlap	Relative vertical depth (%)[y]	Relative width (%)[x]	Relative length (%)[w]
					Orangeburg Fine Sandy Loam (NFREC-Quincy)							
30	1.0	10	Rectangular	Rectangular	6.5 c[u]	9 b	No	10 c	No	72	25	83
60	2.0	10	Rectangular	Rectangular	7.5 b	10 b	No	11 b	Yes	83	28	92
120	4.0	10	Irregular	Rectangular	10 a	18 a	Yes	12 a	Yes	100	50	100
180	6.0	10	Irregular	Rectangular	10 a	20 a	Yes	12 a	Yes	100	56	100
Significance[v]					L*	L*, Q*		L*, Q*				
					Lakeland Fine Sand (NFREC-SV)							
24	1.0	None	Round	Round	8.5 c	8 c	No	7 c	No	75	28	58
48	2.0	None	Elongated	Elongated	11.4 b	9 c	No	9 b	No	100	32	75
96	4.0	None	Elongated	Irregular	16.4 a	12 b	No	12 a	Yes	125	42	100
192	8.0	None	Elongated	Rectangular	18.8 a	15 a	No	12 a	Yes	158	54	100
Significance					L*	L*		L*, Q*				
					Boca Sand Soil (Hendry County, Fla.)							
12	0.5	17	Round	Round	6.9 e	6 e	No	6 e	No	41	17	33
24	1.0	17	Elongated	Elongated	9.1 d	7 d	No	7 de	No	54	19	39
36	1.5	17	Elongated	Elongated	10.2 d	8.5 c	No	7.7 de	No	60	23	43
48	2.0	17	Elongated	Elongated	10.2 d	8.75 c	No	8.3 cd	No	60	24	46
72	3.0	17	Elongated	Elongated	12 c	9.5 ab	No	10.7 b	No	71	26	59
96	4.0	17	Irregular	Elongated	17.2 a	9 bc	Yes	14.3 a	No	100	25	80
144	6.0	15	Triangular	Elongated	15.3 b	10/15 a[t]	Yes	10/18 bc[t]	Yes	n/a	n/a	n/a
192	8.0	13	Triangular	Rectangular	12.6 c	10/25 a[t]	Yes	9/18 cd[t]	Yes	n/a	n/a	n/a
Significance					L*, Q*	L*, Q*		L*, Q*				

[z]Shape of the wetted area: 'round' = circular; 'elongated' = true elliptic; 'triangular' = narrow top, wide base due to lateral movement; 'rectangular' = modified elliptic shapes due to the joining of the wetting pattern of two adjacent emitters; and 'irregular' = when none of the above descriptions applied.

[y]Values for vertical movement (V) may be limited by the presence of an impermeable layer and Vmax values were 10 and 17 inches for Quincy and LaBelle, respectively. In the absence of an impermeable layer in Live Oak, Vmax value was set at the 12-inch tillage depth.

[x]Values for width (W) are limited by bed width and Wmax values were 36, 28, and 36 inches for Quincy, Live Oak, and LaBelle, respectively.

[w]Values for length (L) are limited by the emitter spacing of the drip tape used and Lmax values were 12, 12, and 18 inches for Quincy, Live Oak, and LaBelle, respectively.

[v]Significance: L* and Q* = significant (5% level) linear and quadratic contrast, respectively.

[u]Means followed by different letters are significantly different (5% level) according to Duncan's Multiple Range Test.

[t]Due to partial adsorption of the dye to the soil, the water front moved ahead of the dye ring. The first/second numbers reflect the position of the dye and that of the water front, respectively.

(Table 1). In Live Oak, where the vertical water movement was not restricted, the wetted zones were round after 1 h and became elongated thereafter. Complete emitter-to-emitter coverage was first observed with the 96 gal/100 ft (4-h) rate. In Quincy and LaBelle, the presence of the impermeable layer resulted in two different wetted zone shapes. First, water moved by gravity as long as the impermeable layer was not reached, which occurred between 60 and 120 gal/100 ft (2 to 4 h) in Quincy and between 72 and 96 gal/100 ft (3 to 4 h) in LaBelle. The shape of the wetting zone was round and elongated. When the water front reached the impermeable layer, lateral water movement occurred, followed by a subsequent upward vertical movement. In Quincy, blue dye was visible on the soil surface between the raised beds after applying an irrigation volume of 180 gal/100 ft (6 h). This suggests that in Quincy irrigation volumes greater than 120 gal/100 ft (4 h) may carry soluble fertilizer into the alleys, away from the crop and within reach of the weeds. This also suggests that lateral water movement may be beneficial to increase bed area treated with fumigants. Because an 18-inch emitter spacing was used in LaBelle, complete emitter-to-emitter coverage did not occur even when the water front reached the impermeable layer (96 gal/100 ft; 4 h). These observations suggest that a 12-inch emitter spacing was adequate in Live Oak and Quincy to rapidly wet the soil between adjacent emitters. This is important when crops are small, thereby reducing the risk of having plants outside the wetted zone. In LaBelle, the entire wetting of the soil below the drip tape only occurred between 96 and 144 gal/100 ft (4 to 6 h). Because of the wide emitter spacing used, the goal of current irrigation practices is to maintain somewhat of a perched water table with drip irrigation. Therefore, excessive irrigation must be made when plants are small to adequately irrigate the ones that are planted between two emitters. In addition, upward vertical water movement may result in the accumulation of nutrients at the tops of the wetted zone, thereby increasing the risk of salt burn. It is likely that using drip tapes with 12-inch emitter spacings would allow for smaller irrigation volumes, especially at the beginning of the growing season, and would reduce the risk of salt damage and uneven water application.

Irrigation volume significantly affected D, W, and L (Table 1). In Live Oak, where the vertical movement of water was not restricted, D increased by 0.10 inch for every gal/100 ft applied for irrigation volumes ranging between 24 and 96 gal/100 ft (1 to 4 h), whereas D increased only by 0.03 inch for every gal/100 ft applied for volumes ranging between 96 and 192 gal/100 ft (4 to 8 h). Irrigation management is especially important in soils where the vertical water movement of the water is not restricted by an impermeable layer. For fertilizer and water management, over irrigation in Quincy was negative (field saturation delaying digging, softening of the bed, lateral water movement of the water), while in LaBelle it increased emitter-to-emitter coverage due to the 18-inch emitter spacing used. However, in Live Oak, while excessive irrigation did not have negative horticultural consequences, it is more likely to have negative environmental impact (Simonne et al., 2003a). These data suggest that an irrigation event should not exceed 120 gal/100 ft on an Orangeburg fine sandy loam and 60 gal/100 ft on a Lakeland fine sand. The range of irrigation volumes tested in LaBelle and the 18-inch emitter spacing did not allow the establishment of a similar threshold for a Boca fine sand.

At all three locations, W ranged between 6 to 15 inches when the water moved only by gravity. This illustrates the poor lateral movement of water on coarse-textured soils in the absence of an impermeable layer. Poor lateral movement seldom affects crop water uptake since seeds or transplants are usually placed within 6 to 8 inches of the drip tape (Maynard and Olson, 2002). The most important implication of a limited lateral water movement is for fumigant application. Total bed wetting is necessary for the uniform application of fumigants that stay in the water phase such as potassium N-methyldithiocarbamate (K-Pam) and sodium N-methyldithiocarbamate (VaPam) and is desirable for the application of fumigants that may be effective in the gas phase such as the 1-3 dichloropropene (Telone EC, InLine) products (Hochmuth et al., 2002). The presence of the impermeable layer in Quincy and LaBelle together with large irrigation applications (>120 gal/100 ft) would enhance fumigant distribution.

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