Root Distribution and Proliferation of Field-grown Acorn Squash as Influenced by Plastic Mulch and Water

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Summary. Squash (*Cucurbita pepo* L. var. *pepo*) plants were grown on black polyethylene mulch or on bare ground, with trickle or furrow irrigation, and received only natural rainfall, or natural rainfall plus half or all of the estimated supplemental irrigation water required as determined by an irrigation scheduling program. The squash roots predominate in the upper 6 inches of soil throughout the season, with no less than 60% of the root mass located in this layer. The proliferation of roots increased as they extended horizontally from the vertical center line of the plant from 0 to 24 inches. Neither the irrigation treatments nor black polyethylene mulch had any influence on the pattern of root development. Water stress, however, reduced the size of the root system and the crop yield. Yields were not influenced by either furrow or trickle irrigation on the short rows that were used in this study. However, black polyethylene mulch and full irrigation offered the best chance of maximizing squash yields under the conditions of this study.

It is an advantage to know where roots are located, because water and fertilizer placed beyond the range of roots is of no benefit to the plant and results in wasted resources and possible groundwater pollution.

The purpose of this study was to follow the distribution pattern of the roots of a field-grown crop of acorn squash without restricting root growth with devices placed in the soil, such as root view-boxes, tubes, lysimeters, or rhizotrons (Meyer and Barrs, 1991), and to determine what effect irrigation and polyethylene mulch had on the size and distribution of root systems.

This research was conducted at the Horticulture Research Center, northeast of Fort Collins, Colo. The soil was classified as a Nunn clay loam (Aridic Arguistoll) with a water-holding capacity of 1.2 inches/ft. The ground was fertilized each year according to recommendation, which generally called for 100 lb of N and 100 lb of P₂O₅ per acre, broadcast and worked into the soil. Beds were made on 5-ft centers, and black polyethylene mulch (1 mil × 36 inches) was laid over designated beds. Four-inch-diameter circles were removed from the plastic to allow hand-planting. Acorn squash seeds ('Table King', Peto Seed Co., Saticoy, Calif.) were planted in hills 3 ft apart, with five seeds to each hill, on 23 May 1990; 23 May 1991; and 22 May 1992. Plots were irrigated after planting and thinned to a single plant when 6 inches high.

Treatments

There were six treatments each year, replicated four times. Half of these treatments were on black polyethylene mulch and the others were on bare ground. The irrigation treatments were natural rainfall and natural rainfall plus either half (0.5) or all (1.0) of the calculated water requirement. There was one treatment that compared furrow to trickle irrigation—both on black polyethylene. The plots consisted of three 30-ft rows with 10 squash plants in each row. One row was used for sampling plants at various growth stages throughout the season and two rows were used to measure yield.

Irrigations were scheduled with a program developed by the USDA (Kincaid and Heermann, 1974) and modified for vegetable vine crops (Ells et al., 1989). The program used me-

teorological data in conjunction with squash crop coefficients to determine the date and the amount of water that should be applied. This information was converted to gallons per plot, and either half (0.5) or all (1.0) of the calculated amount of water was metered to the plot. Where furrows were used, the water was impounded until it infiltrated into the soil. Where trickle tubes were employed, water was metered into the tubing until the required amount was applied. The trickle tubing was double-walled, plastic ribbon with holes every 6 inches.

Direction of root growth

The first objective was to determine if root growth was influenced by compass direction before taking extensive samples. On 2 July 1990, when the plants were 10 inches tall, soil samples were taken 6 and 12 inches from plant stems, and either 6 or 12 inches deep, in the north, east, south, and west quadrants, using a 2-inch-diameter soil-coring device. Once a plant was sampled it was not sampled again. Yields were taken from plants that were not root-sampled. Soil cores were bagged in the field, brought into the lab where they were first soaked in water, then agitated, settled briefly, then decanted, catching the roots on nylon screens, where they were allowed to dry. The dried roots were picked off the nylon screens and weighed. Root weights were multiplied by factors based on the volume of soil each sample represented. For example, if the soil core equaled 0.1 of the soil volume that it represented, then weight of the roots found in core would be multiplied by 10 to arrive at the estimated weight of roots in this volume. This procedure was used throughout the study.

Roots were found to be evenly distributed in the root zone about the stem of the plant, with each quadrant of the root zone having ≈25% of the roots (N, 28%; E, 25%; S, 27%; W, 20%—no significant difference). From this preliminary study, it was concluded that direction was not a factor in root distribution. Therefore, because the rows ran east and west, all samples were taken from the south side of the plant.

Root length vs. root weight

Because the dried roots were brittle, they were difficult to straighten

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Fig. 1. Distribution of roots by percentage in three root zones centered around a field-grown acorn squash plant, 2 July 1990. Each value represents four samples from eight plants.

out and measure with accuracy. On the other hand, they could be weighed quite accurately with a high-sensitivity electronic scale. Nevertheless, a comparison of the two methods was made with both measured and weighed roots from zones A, B, and C, showing r values of 0.44, 0.62, and 0.84, respectively. The A zone was composed of a cylinder of soil 6 inches deep with a 7-inch radius (Fig. 1). The B zone was situated around the A zone and was also 6 inches deep, and had a 13-inch radius. The C zone was situated directly beneath the A zone and was the same size as the A zone. The poor correlation ($r = 0.44$) between the length and weight of roots in zone A may be explained by the fact that the diameter of roots varied greatly, some being several times as thick as others. As distances from the plant crown increased, the diameter of the roots decreased, and when all roots approached a uniform diameter the correlation between length and weight increased.

The developing root system

On 2 July 1990, 81% of the roots were found in the top 6 inches of soil (Fig. 1, zones A and B). At that time, the plants were 10 inches tall, and it was expected that most of the roots would be in the top 6-inch soil layer.

Roots were sampled three times a year for 2 years (1990 and 1991) during mid-July, mid-August, and mid-September (Table 1). The number of

zones (as shown in Fig. 1) was increased from three to six for the mid-July sampling to keep up with root growth. This was done by taking additional soil cores 6 inches further from the plant center, and 6 inches deeper. Each of these cores represented roots in an additional zone. Zones were increased to 10 for the mid-August and mid-September sampling. There was no logic in sampling any further than 30 inches from the plant because the rows were 60 inches apart, and the sampling point would then be nearer the adjacent row, with most of the roots coming from plants in that row.

In all cases, the percent root weight increased with the distance from the plant, and decreased with depth. This indicated that dichotomous branching was taking place during horizontal root growth, resulting in proliferation of roots at the periphery (Table 1).

Table 1. Acorn squash roots distribution through the matrix of the soil expressed in percent of total dry weight, 1990 and 1991.

Depth from surface (inches)	Distance from plant center (inches)	1990		1991		Mean	
		Zone	Total	Zone	Total	Zone	Total
July							
0-6	0-6	22		14		18	
	>6-12	22		25		24	
	>12-18	22	66	29	68	25	67
>6-12	0-6	7		10		9	
	>6-12	25	32	17	27	20	30
>12-18	0-6	2	2	5	5	3	3
			100		100	1	100
August							
0-6	0-6	10		8		9	
	>6-12	13		16		15	
	>12-18	18		19		18	
	>18-24	24	65	16	59	20	62
>6-12	0-6	5		5		5	
	>6-12	8		11		10	
	>12-18	15	28	15	31	15	30
>12-18	0-6	2		3		3	
	>6-12	3	5	5	8	4	6
>18-24	0-6	2	2	2	2	2	2
			100		100		100
September							
0-6	0-6	11		14		13	
	>6-12	18		21		19	
	>12-18	19		20		20	
	>18-24	22	70	12	67	17	69
>6-12	0-6	3		6		5	
	>6-12	8		9		8	
	>12-18	13	24	10	25	11	24
>12-18	0-6	1		3		2	
	>6-12	3	4	3	6	3	5
>18-24	0-6	2	2	2	2	2	2
			100		100		100

Effect of treatment on root systems

As was expected, there was a difference between the weight of the young root system in July and the mature root system in August and September. This occurred in 1990 (treatments 2 and 5 of Fig. 2) and again in 1991 (treatments 3, 4, 5, and 6 of Fig. 3). Roots were not sampled in 1992. After the August sampling, the plants either stopped producing roots or produced them at the same rate that the older roots were decaying, because there was no case where there were more roots in September than in August. There was, however, one case (Fig. 3, treatment 4) where the root system was smaller in September than in August, giving credence to the theory that root decay sometimes exceeds root production toward the end of the season.

The size of the root system was influenced by irrigation treatment; however, the distribution of roots was not affected, because the pattern for every profiled root system looked alike. Using the Sept. 1990 sampling as a typical example (Table 2), the nonirrigated plants had almost the same root percentage distribution among the four depth zones as the squash that was irrigated, even though, with irrigation, four times as much root mass was produced.

Yield, fruit number, and water-use efficiency

These values are expressed in terms of percent of the average to make it easier to compare performances over the 3 years. The actual yields were in the range of 12 tons/acre of marketable fruit, which is probably lower than a grower would like; however, only one harvest was made, and this came after the vines had been killed by frost. In addition, the research center is not located in an area where commercial squash is produced.

Yield. On the basis of the 1990 yield (Fig. 4), the squash grown on black polyethylene mulch exceeded the production from squash grown on bare ground by 35% (bars 1–3 vs. bars 4–6). There was no yield difference due to irrigation method (bars 1 and 2). There was no difference between the 1.0 and 0.5 irrigation levels on mulch (bars 1 and 2) or on bare ground (bars 3 and 4). However, when the plants only

Fig. 2. Effect of sampling date on total dry weight of acorn squash roots for six irrigation/mulch treatments, 1990. Bar grouping/treatment: 1) Plastic mulch, trickle irrigation, 0.5-irrigation level; 2) plastic mulch, furrow irrigation, 0.5-irrigation level; 3) plastic mulch, furrow irrigation, 1.0-irrigation level; 4) bare ground, furrow irrigation, 0.5-irrigation level; 5) bare ground, furrow irrigation, 1.0-irrigation level; 6) bare ground, furrow irrigation, 0.0-irrigation level. Each group of three bars represents samplings in July, August, and September. Each bar represents an average of four values. Treatment 6 was sampled only in September. Bars within a group having different letters are different at $P = 0.95$.

Fig. 3. Effect of sampling time on total dry weight of acorn squash roots for six irrigation/mulch treatments, 1991. Bar grouping/treatment: 1) Plastic mulch, trickle irrigation, 0.5-irrigation level; 2) plastic mulch, furrow irrigation, 0.5-irrigation level; 3) plastic mulch, furrow irrigation, 1.0-irrigation level; 4) bare ground, furrow irrigation, 0.5-irrigation level; 5) bare ground, furrow irrigation, 1.0-irrigation level; 6) bare ground, furrow irrigation, 0.0-irrigation level. Each group of three bars represents samplings in July, August, and September. Each bar represents an average of four values. Bars within a group having different letters are different at $P = 0.95$.

Table 2. Comparison of acorn squash roots from two treatments: Bare ground with no irrigation and standard irrigation (1.0), Sept. 1990.²

Depth (inches)	Root wt (g/plant)		Percent of total	
	Nonirrigated	1.0 irrigation	Nonirrigated	1.0 irrigation
0-6	4.9	19.9	76	73
>6-12	1.3	6.3	20	23
>12-18	0.3	0.7	3	3
>18-24	0.1	0.4	1	1
Total	6.6	27.3	100	100

²Nonirrigated and 1.0-irrigated plots received 4.7 inches of water (rain) and 18.1 inches of water (irrigation plus rain), respectively, during the season.

Fig. 4. Weight of marketable acorn squash as influenced by six irrigation/mulch treatments, 1990, 1991, and 1992. Bar grouping/treatment: 1) Plastic mulch, trickle irrigation, 0.5-irrigation level; 2) plastic mulch, furrow irrigation, 0.5-irrigation level; 3) plastic mulch, furrow irrigation, 1.0-irrigation level; 4) bare ground, furrow irrigation, 0.5-irrigation level; 5) bare ground, furrow irrigation, 1.0-irrigation level; 6) bare ground, furrow irrigation, 0.0-irrigation level. Each group of three bars represents samplings in July, August, and September. Each bar represents an average of eight values. Bars in a group bearing different letters are different at $P = 0.95$.

received rain, the yield was only 57% of average. At the 1.0-irrigation level, the plots received 13.4 inches of water by furrow, plus 4.7 inches of rain, for a total of 18.1 inches. At the 0.5-irrigation level, the plots received 6.7 inches of water by furrow or trickle, plus rain, for a total of 11.5 inches. The nonirrigated plots received only 4.7 inches of rain, which was not enough to produce an average yield. The lack of yield difference between furrow and trickle irrigation was observed in an earlier study on onions (Ells et al. 1986).

The following year (1991), the greatest yield was obtained with squash grown on polyethylene mulch with full (1.0) irrigation applied in furrows (Fig. 4, 1991, bar 3). When half the

estimated water requirement was applied (0.5) to the mulched plots (bars 1 and 2), the yields were the same as the bare ground plots that received full (1.0) irrigation (bar 5), suggesting that additional water compensated for evaporative losses from unmulched plots. Squash yields on bare ground were 95% of average yield (bar 4) when they received only half the amount of irrigation (0.5) and only 75% of the average yield (bar 6) when they received no irrigation.

During the final year (Fig. 4, 1992), all squash on polyethylene mulch produced alike (bars 1-3). The yield for plants receiving full irrigation on polyethylene mulch exceeded those receiving full irrigation on bare ground

(bars 3 and 5), whereas the squash on bare ground that received only rain (bar 6) produced the lowest yield, equal to only 60% of average. Bar 4 was dropped from the 1992 set because, after 2 years of testing, it was apparent that half the level of irrigation water on bare ground was not a viable treatment.

Given the data presented, the best method for maximizing squash yield was to use black polyethylene mulch with the full irrigation level.

Squash number. The number of squash harvested during the first year were greatest from the plots covered with black polyethylene mulch (Fig. 5, 1990, bars 1-3), with no differences due to method of application (furrow or trickle) or irrigation amount (0.5 or 1.0). Squash grown on bare ground with irrigation produced 20% fewer fruit than squash grown on polyethylene mulch with irrigation (bars 1-3 vs. 4 and 5). The squash plants that received only rain (bar 6) produced 30% fewer fruit than their irrigated counterparts (bars 4 and 5).

The following year (1991), the greatest number of fruits was produced by squash plants grown on polyethylene mulch with the highest level of irrigation (bar 3). Squash plants without mulch that received the full amount of water (Bar 5) produced the same number of fruit as squash plants grown on polyethylene that received half the estimated water requirement (bars 1 and 2). Finally, the nonirrigated squash plants produced only 37% of average (Fig. 5, 1991, bar 6).

In 1992, all treatments produced the same amount of fruit, except the nonirrigated treatment, which produced only 68% of the average (Fig. 5, 1992, bar 6).

Fruit number is not usually as important as yield by weight; however, these data suggest that both fruit number and weight yield can be maximized by the use of black polyethylene mulch with the full estimated water requirement (Fig. 5).

Water-use efficiency. Water-use efficiency (WUE) is a measure of how efficiently irrigation water is being used. It is expressed in units of production per unit of water, such as tons of squash produced per acre-inch of water. WUE becomes more important with increasing irrigation costs. However, it generally is used to determine the preference between two equally

Fig. 5. Number of marketable acorn squash as influenced by six irrigation/mulch treatments, 1990, 1991, and 1992. Bar grouping/treatment: 1) Plastic mulch, trickle irrigation, 0.5-irrigation level; 2) plastic mulch, furrow irrigation, 0.5-irrigation level; 3) plastic mulch, furrow irrigation, 1.0-irrigation level; 4) bare ground, furrow irrigation, 0.5-irrigation level; 5) bare ground, furrow irrigation, 1.0-irrigation level; 6) bare ground, furrow irrigation, 0.0-irrigation level. Each group of three bars represents samplings in July, August, and September. Each bar represents an average of eight values. Bars in a group bearing different letters are different at $P = 0.95$.

Fig. 6. Water-use efficiency of acorn squash as influenced by mulching, irrigation method, and irrigation level, 1990, 1991, and 1992. Bar grouping/treatment: 1) Plastic mulch, trickle irrigation, 0.5-irrigation level; 2) plastic mulch, furrow irrigation, 0.5-irrigation level; 3) plastic mulch, furrow irrigation, 1.0-irrigation level; 4) bare ground, furrow irrigation, 0.5-irrigation level; 5) bare ground, furrow irrigation, 1.0-irrigation level; 6) bare ground, furrow irrigation, 0.0-irrigation level. Each group of three bars represents samplings in July, August, and September. Each bar represents an average of eight values. Bars in a group bearing different letters are different at $P = 0.95$.

effective irrigation treatments. The treatment selected will be the one with the higher WUE.

In 1990, the three most-efficient treatments were the two polyethylene mulch treatments (Fig. 6, 1990, bars 1 and 2), which received half the calculated water requirement, and the bare ground treatment (Bar 6), which received only rain. Because the yields were quite low on the nonirrigated plots (Fig. 4), preference has to be given to the polyethylene trickle or furrow treatments (Fig. 6, 1990, bars 1 and 2). Squash produced on polyethylene mulch produced the same yield and some number of fruit whether irrigated by trickle or furrow (Figs. 4 and 5).

The following year (1991), the two most water-efficient treatments were the polyethylene mulch treatments that received half the estimated water requirement (Fig. 6, 1991, bars 1 and 2). There were no differences between trickle and furrow irrigation for either weight or number of fruit (Figs. 4 and 5).

In 1992, the squash grown on the two polyethylene-mulched plots receiving half the estimated water requirement (Fig. 6, 1992, bars 1 and 2) had the highest WUE. No other treatment produced greater weight or more fruit (Figs. 4 and 5). Because squash irrigated by either furrow or trickle irrigation had equal yields and WUEs, the decision on which method to use must be based on factors other than yield.

Based on data presented for these 3 years, WUE was highest when 0.5 level of irrigation was used on squash grown on polyethylene mulch, with no preference noted for either trickle or furrow irrigation.

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