AGRICULTURAL RESEARCH FOUNDATION
INTERIM REPORT FOR COMPLEMENTARY PROPOSALS
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TITLE: Improving irrigation efficiency and profitability in winter squash production in Western Oregon: The case for deficit irrigation.

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SUMMARY:

Over the past two decades, yields of Golden Delicious squash (*Cucurbita maxima*) have been declining. This cultivar is grown for both flesh and seed markets on approximately 4500 acres in the Willamette valley and traditionally has yielded > 25 tons of fruit/A. Now many farmers are only realizing 15 to 17 tons/A, and in some cases as low as 12 tons/A. Possible causes may be increased disease pressure due to short crop rotations, too much or too little irrigation, or a combination of both. This project sought to find the relationship between rotation, disease severity, and irrigation on yield (fruit and seed) and quality.

A field trial was setup at OSU's Vegetable Research farm in a field with a short (3 out of the last 4 years) and long rotation history (1 of 4 years) growing Golden Delicious to which five irrigation levels were established (105%, 90%, 60%, 45%, and 0% of crop evapotranspiration (ET)). Squash was direct seeded with 30-inch row spacing, and were thinned to 24 inch in-row plant spacing.

The overall disease severity based on root, crown, and vascular tissue ratings was greater in the short rotation treatment. As a result, average fruit yield across all irrigation treatments in the long rotation was 1.2x higher than in the short rotation (28 t/a vs. 23 t/a, respectively). Increasing irrigation amount increased disease pressure by creating moist soil conditions conductive to pathogen growth. Despite the direct relationship between disease and irrigation, the increase of fruit yield due to increasing irrigation amount far outweighed disease pressure.

The highest yields were obtained at the highest irrigation level (105% ET) regardless of rotation history. In the long rotation (lower disease pressure), there was no difference in yield when the irrigation level was ≥45% of ET. Therefore, these results indicate that irrigation amounts could likely be reduced without suffering a yield loss, but only when the disease pressure is low and when the soil has a high water holding capacity (finer textured) without root restrictive layers. When disease pressure is high, employing a deficit irrigation strategy may result in yield loss.

The results of this study highlight the need for long rotations out of squash to reduce soilborne diseases. When soilborne disease pressure is low, there is a potential to reduce irrigation quantity and costs (electricity and labor). Using a simple tool to track crop ET and schedule irrigations (e.g., Washington State University's Irrigation Scheduler), farmers can experiment with deficit irrigation to determine if this strategy is appropriate for their site-specific conditions.

OBJECTIVES:

Deficit irrigation study on fruit and seed yield (Peachey):

1. Determine the optimum irrigation amount and soil moisture level needed under overhead irrigation to maximize winter squash flesh and seed yield in Western Oregon.
2. Measure the effect of irrigation level on rooting depth of squash.

Variable rate irrigation on soilborne disease severity, flesh quality, and seed quality (Stone)

Evaluate the impact of variable rate irrigation applications and squash rotation history on:

1. The severity of root rot, crown rot, and vascular discoloration of Golden Delicious and the butternut variety Ultra.
2. Fruit quality (dry matter and Brix).
3. Seed maturity, yield, and size in Golden Delicious.

Both projects:

Use this project as a case study and educational opportunity to promote methods that both conserve water in squash and other vegetable production systems in western OR as well as reduce disease pressure.

PROCEDURES:

This study was conducted at OSU's Vegetable Research Farm in Corvallis, OR on a soil mapped as a Chehalis silty clay loam (sicl). Based on a particle size analysis using the hydrometer method, the soil texture to 4 ft was classified as a sicl (between 28 to 35% clay with clay content decreasing with depth). The top foot of soil had the following properties: pH 6.4, CEC= 24 meq/100g (sum of cations method), OM= 4.2% (LOI), 65 ppm Bray 1P, and 166 ppm K.

The field was separated into two sections: Short and Long rotation out of squash (Table 1). The Short rotation section of the field was planted to squash (var. Golden Delicious) 3 out of the 4 previous years, while the Long rotation was planted to squash in only one out of the previous 4 years. On June 2, squash (*C. maxima*, var. Golden Delicious, strain for seed production; and *C. moschata*, butternut var. Ultra for flesh processing) were planted at 8 inch in-row spacing on 30 inch rows, and 325 lbs of 12-10-10 was banded. The following day Reflex (12 oz/acre) was tractor-applied (30 gal/a), followed by a 1-inch irrigation. A lower-than-typical rate of Reflex was chosen than is often used to protect the butternut squash from injury. The field received a second irrigation on June 7 (0.66 inch). On June 14, the squash plants were thinned to an in-row spacing of approximately 2 feet, which is a plant stand consistent with (and at the high end of) grower practices (8700 plants/A). Weeds and volunteer squash from the previous year were managed through multiple tractor cultivations and intensive hand hoeing. As a result of intensive weed management, weed pressure was low and competition with the crop was minimal. On July 12, 50 lb urea-N/acre was side-dressed. Because the 0 ET treatment (discussed below) received no irrigation, the urea was never washed into the soil and the plants in that treatment had no access to the fertilizer.

To be able to adjust the irrigation amount across the field, a single overhead irrigation line was set up across the field to bisect the Short and Long rotation history sections (Fig. 1). To maximize uniformity, spray nozzles were spaced every 20 feet and irrigations were applied early in the morning to avoid wind. The experimental design was a line-source study (Hanks et al., 1980) with four replications for each irrigation treatment for Golden Delicious and one replicate for butternut Ultra. Line source designs are commonly used in irrigation experiments because they require less land than replicated overhead-irrigation designs. In line source studies, a single irrigation line is installed in the middle of a field and plots are established at specified distances perpendicular from the irrigation line to create a gradation of irrigation levels.

Irrigation treatments of 0, 50, 75, 100, and 125% of crop evapotranspiration (ET_c) were located perpendicular to the irrigation line based on the irrigation gradient. Washington State University's (WSU) Irrigation Scheduler (available here: http://weather.wsu.edu/) was used to estimate squash ET_c. This model uses weather data (reference ET_o for alfalfa) from OSU Hyslop Research Farm's Agrimet weather station. Based on the ET_c estimates, sufficient irrigation was applied to reach a target rate of 125% of ETc next to the irrigation line (blue line in Fig. 1).

The field was divided into four 45 ft by 140 ft long blocks for Golden Delicious and one 45 ft by 140 ft block for Ultra. Each block was divided into two sections: the Short rotation and the Long rotation (see map). Within each block, the five irrigation treatments were established in both the Long and Short rotation sections along the moisture gradient for a total of 50 plots (5 replicates x 5 irrigation rates x 2 rotations). Tipping buckets (raised as the plants grew so that the top of the bucket was level with the crop canopy) connected to a datalogger were used to measure the quantity of irrigation applied at each irrigation level. We also placed buckets at each irrigation level, which we manually measured after each irrigation. As the canopy height increased, these buckets were raised by placing them on raised platforms. **The measured quantities of irrigation water applied for the treatments were 0, 45, 60, 90, and 105% of ET; these values (and not the predicted values of 0, 50, 75, 100, and 125%) will be used through this paper.**

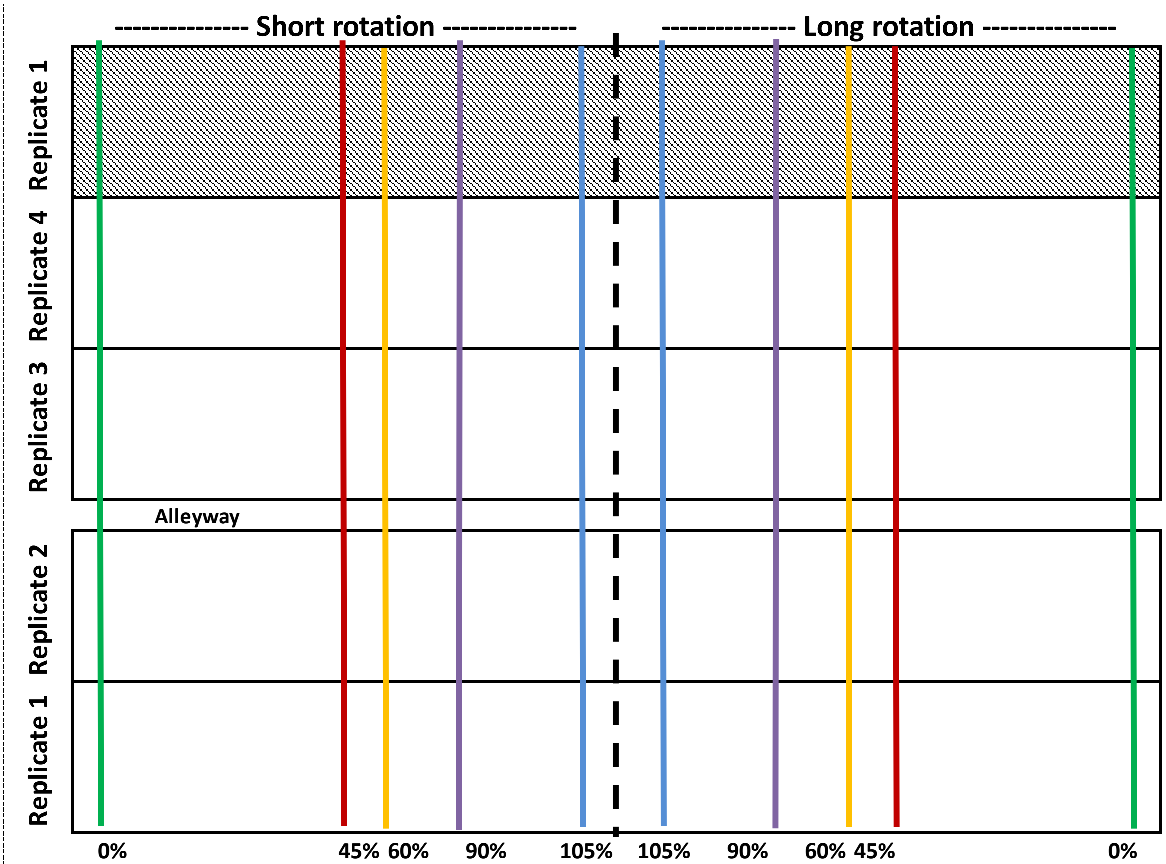

Figure 1. Plot layout. The field is split in half by the irrigation line (dashed line), with the Short rotation history on the left side and the Long on the right. The colored lines represent the irrigation level (% of ETc) and the shaded area was planted with butternut whereas the rest of the field was planted with Golden Delicious.

Allowable depletion of available soil water is the amount of water that the plant can use from the total available before experiencing drought stress. Total available water is the amount of water between field capacity and permanent wilting point. For squash, the allowable depletion is approximately 50% of total available soil water (Maughan et al., 2015). Using the WSU Irrigation scheduler, irrigation was applied when the model estimated that the soil was between 40 to 67% of total available soil water. We chose not to use data from soil moisture monitoring equipment to make irrigation decisions for the following reason: by the time the matric potential reached 80 centibars (equivalent to kPa, see below for more information on equipment used), multiple early morning irrigations would have been required to replenish soil water; this would have been difficult to accomplish.

On one edge of the field outside the study area, an unreplicated deficit irrigation trial was set up. In this trial, no irrigation was applied until fruit set/flowering (some fruits were at the size of softballs). The first irrigation occurred on July 22. Another section received its first irrigation on August 4. The objective of this was to look at the relationship between irrigation timing and yield, with the goal of answering the following question: what is the effect on yield of withholding water until fruit set?

Table 1. Rotation history. Year field was in squash highlighted in grey

Year	Short	Long
2015	**squash**	Fallow
2014	**squash**	beets/beans
2013	corn/wheat	cabbage, beets/corn/wheat
2012	**corn/squash**	**squash**
2011	tomatoes/peas	peas/beans
2010	onions/peppers/corn	beans
2009	fallow	Fallow
2008	Hazelnut removal	Hazelnut removal

<u>Soil moisture monitoring</u>

Changes in soil moisture were monitored using Watermark sensors (Irrometer Company, Inc.) and a neutron probe (CPN 503 Elite Hydroprobe). The Watermark sensors are solid-state electrical resistance sensing devices that are used to measure soil water tension. In these sensors, electrodes are embedded within a granular matrix through which a current is applied. Based on the measured resistance and a conversion formula, the resistance is then converted to matric potential (centibars or kPa). At each irrigation level three Watermarks were installed at 12 and 24 inches according to manufacturer specifications. Two replicates were connected to CR10X dataloggers (Campbell Scientific) set to record every three hours. One replicate was manually read and recorded using a handheld meter (Watermark soil moisture meter).

The neutron probe has a radioactive source that emits neutrons. Emitted neutrons are reflected by water molecules, and a sensor records how many are reflected back to hit the sensor. Based on an in-field calibration curve, the amount of neutrons recorded can be converted to a volumetric water content. Soil access tubes were augured to four feet, and a thin-walled PVC tube was inserted. There was no need for backfilling as the auger hole and access tube were exactly the same diameter, and the tubes fit snuggly in the hole. Only two replicates for each moisture treatment were installed. Readings were taken before and after each irrigation at 6, 12, 24, 36, and 48 inches.

<u>Yield and quality of flesh and seeds</u>

On Sept. 26, fruit yield was evaluated from either a 5 ft by 30 ft (treatments 45, 60, and 105%) or 7.5 ft by 30 ft (0 and 90%). The harvest area straddled the row where the irrigation treatment was designated. A string line was stretched across the plot, and any fruit within the area collected. If the string touched a squash and more than 50% of the squash was in the plot, we included it in the sample. Each squash was individually weighed.

From each harvested area, 7 squash were selected that represented the range of fruit sizes. The fruits were weighed and the seeds were extracted, fermented for several days (to facilitate removal of placental tissue), and dried at 60^{o}C. The dried seeds were then weighed and counted. Flesh samples were taken from 4 randomly selected fruit (of the 7 from which seed were extracted); subsamples were frozen for Brix analysis and dried for dry matter analysis. After thawing, degrees Brix was evaluated with a digital refractometer. The relationship between seed weight and fruit weight was calculated for both the Long and Short rotation data sets. The regression models for each of these data sets were then used to calculate predicted seed weights for all fruit per plot (not just the subsample of fruits from which seed was extracted). Seed yields were calculated from these predicted values. This calculation is necessary as 1) Golden Delicious fruit weights are highly variable, 2) the subsample of fruits from which seeds were extracted represents fruit size range but not fruit size distribution, and 3) the relationship between fruit yield and seed yield is not linear; small fruits contain proportionately more seed on a weight basis than large fruits (Stone, historic data).

<u>Disease evaluation</u>
On Sept. 27, the number of plants in the row was counted (45') for each replicate x rotation x irrigation plot (50 total). Each plot had an average of 21 plants (range 19 to 24). The plants were considered dead when crowns were fully brown (and in some cases rotting). Plants with yellow or green stems were counted as living. Up to 10 living plants per plot were harvested. If a row had less than 10 living plants, all were collected. If a row had more than 10 living plants, 10 were randomly collected from the row. Roots were washed and then evaluated for severity of root and crown rot and vascular tissue were rated for discoloration on a 1 to 4 scale (Fig. 2). Presence or absence of sclerotia (the resting bodies of the white mold pathogen, *Sclerotinia sclerotiorum*) was noted.

Figure 2. Rating scale (1 to 4) for stem vascular tissue symptom severity.

<u>Rooting depth evaluation</u>
On October 12 (16 days after harvest), four soil pits were dug to a depth of 36" with an excavator (two in 0% ET and two in 105% ET). The pits were dug between the rows next to a squash plant that had a live crown. Unfortunately, most of the roots had begun to decay and a quantitative measurement of root density was not possible; for this reason, the roots were evaluated qualitatively.

SIGNIFICANT ACCOMPLISHMENTS:
Results from this study suggest that when disease severity is low (i.e., when squash is grown in a long rotation sequence), irrigation water applied can be reduced without suffering a significant yield loss. However, this will depend on soil properties (water holding capacity and depth to a restrictive layer) of a given field. Farmers may be able to realize cost savings (electricity to pump water and labor) by decreasing irrigation frequency and duration without suffering a yield loss. Results and discussion are presented in Appendix A.

Key findings for the variety Golden Delicious:

- Washington State University's Irrigation Scheduler is a farmer friendly, easy to use irrigation decision making tool, which can be used to guide deficit irrigation decisions. There is a mobile as well as web based application.
- Across all irrigation treatments, average fruit yield was 23 t/a for the short rotation (3 out of the last 4 years in squash) vs. 28 t/a for the long (1 out of 4 years in squash), a 22% increase in fruit yield.
- There was a positive relationship between the quantity of irrigation applied and root rot severity (i.e., more water, more disease).
- Overall, disease severity (root, crown, and vascular discoloration) was lower and fruit and seed yields were higher in the Long rotation than in the Short rotation plots.
- Across all irrigation treatments, average seed yield was 1242 lbs/a for the Short rotation compared to 1466 lbs/a for the Long rotation, an 18% increase in seed yield.
- There was a positive relationship between irrigation amount and root disease (i.e., more water, more disease). However, irrigation amount was the factor controlling yield, not disease severity.
- Delayed irrigation also appeared to be a viable deficit irrigation strategy. For plots receiving no irrigation until fruit set (fruit as large as softballs) followed by irrigations of 100% of ET through fruit development, yield was not much different than those of the high irrigation treatments. Irrigation quantity was reduced by 40% compared to applying 100% of ET. This strategy not only has the potential to reduce irrigations costs, but may reduce weed seed germination and competition.
- There were no significant irrigation treatment differences in seed yield in Golden Delicious planted in the long rotation section of the field – a startling finding. In contrast, seed yield increased linearly with increased irrigation applied in Golden Delicious planted in the Short rotation section of the field; mean seed yield was 65% higher in the highest irrigation treatment compared to the no additional irrigation applied treatment.
- Seed yield was 44% higher in the Long than in the Short rotation treatments when no additional irrigation was applied. At the highest irrigation level, there was no difference in seed yield in Golden Delicious planted in the Long rotation and the Short rotation sections of the field.

Some key findings for the butternut variety Ultra:

- There was no difference in disease severity between the short and long rotation treatments, as well as no relationship between disease and irrigation level.
- There was little difference in yield for all irrigation treatments (even the no irrigation treatment). However, butternut plots were unreplicated.

BENEFITS & IMPACT:

A soilborne disease is significantly affecting yields of Golden Delicious in the Willamette Valley. This study shows that there is a significant benefit of increasing rotation length when growing Golden Delicious for flesh or confectionary seed.

This study also suggests that there is potential to reduce water use in Golden Delicious production, though this will vary depending on the soil (water holding capacity, depth to restricting layer, compaction, etc) and soilborne disease severity. By doing so, irrigation costs may be reduced (electricity to pump, and labor) and the water saved could be used to irrigate other crops, stored in the ground for future use, or kept in the rivers. Additional research in different locations and soil types would be required to better understand the relationships between irrigation applied and Golden Delicious fruit yield, flesh quality, and seed yield. However, even without further study, the results of this study may inspire some farmers to experiment with deficit irrigation in an effort to reduce the cost and environmental impact of Golden Delicious production.

ADDITIONAL FUNDING RECEIVED DURING PROJECT TERM: None

References:

Maugham, T., D. Drost, and L. Allen. 2015. Vegetable Irrigation: Squash and Pumpkin. Department of Horticulture, Utah State University.

Appendix A. Results and discussion

<u>Soil Moisture</u>

Cumulative ETc in 2016 from emergence to the final irrigation was estimated to be 12.7 inches. Using the same time period and weather station, estimated ETc in 2015 was 14.2. This is expected? given that 2015 was hotter than 2016 (mean daily air temperature of 69 vs. 64F and mean daily high temperature of 86 vs. 78F). Figure A1 shows the estimated root zone water deficit for the 90% of ETc treatment. We were aiming for 100% replenishment of soil water lost through ET (the 90% ET treatment was supposed to be 100%), which would have brought the root zone water deficit to 0 after irrigations. However, due to the limitations with irrigation timings to take advantage of zero wind (for uniform irrigation distribution), this target was not achieved.

For squash, the allowable depletion is approximately 50% of total available soil water before plant stress occurs (Maughan et al., 2015). Using the WSU Irrigation scheduler, irrigation was applied when the model estimated that the soil was between 40 to 67% of total available soil water.

Changes in soil moisture are given in Figs. A1 and A2. For 105% ET, the soil was saturated to a depth of 48 inches after each irrigation as indicated by a matric potential of 0 kPa as measured by Watermark sensors (Fig. A2), and changes in volumetric water content as measured by a neutron probe to a depth of 48 inches (Fig. A2). For the 90% ET, Watermark data showed that irrigations often wet the soil to 24 inches, though not always to saturation (Fig. A2), but this was not recorded using the neutron probe. Soil moisture ≤36 inches showed more soil water than 45 and 60% ET, either due to water moving from above via capillary action, or due to less need to exploit deeper water into the soil.

For treatments 45 and 60% ET, free soil water was never recorded at or below 24 inches (i.e., soil was never wet to a depth of ≥24 inches). Irrigation amounts were typically enough to saturate the soil to a depth of 6 inches, but not always to 12 inches. However, this irrigation was enough so that the plant likely did not have to utilize as much water deeper in the profile (Fig. A2 36 and 48 inches).

Irrigation treatments ≤60% ET started to draw down/utilize soil water ≤36 inches at the same time, but 90% ET was delayed by approximately 2 weeks. There are three possible explanations for this: 1) water was moving into the lower depths via capillary action from above, keeping the soil moist, 2) root growth into the lower depth for plants in 90% ET was delayed because adequate moisture was available in the surface 24 inches, or 3) roots had penetrated deeper than 24 inches, but the due to adequate soil moisture in the surface, the roots did not need to uptake as much water from deeper in the soil. For 0 and 45% ET, they began to draw down water at 24 inches at the same time (~7/9; Fig. A2), but uptake was delayed by ~10 days for ≥60% ET.

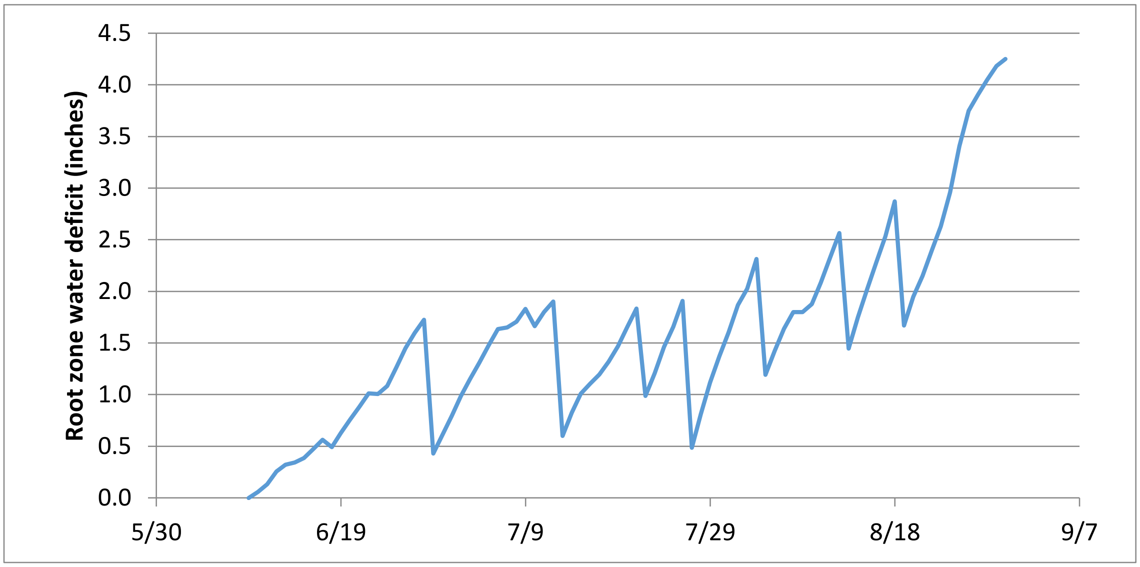

Figure A1. Estimated root zone water deficit for the 90% of ETc irrigation treatment from WSU's Irrigation Scheduler. This is estimated based on the available moisture storage capacity of the soil, rooting depth of the crop during the growing season, irrigations applied, and ETc.

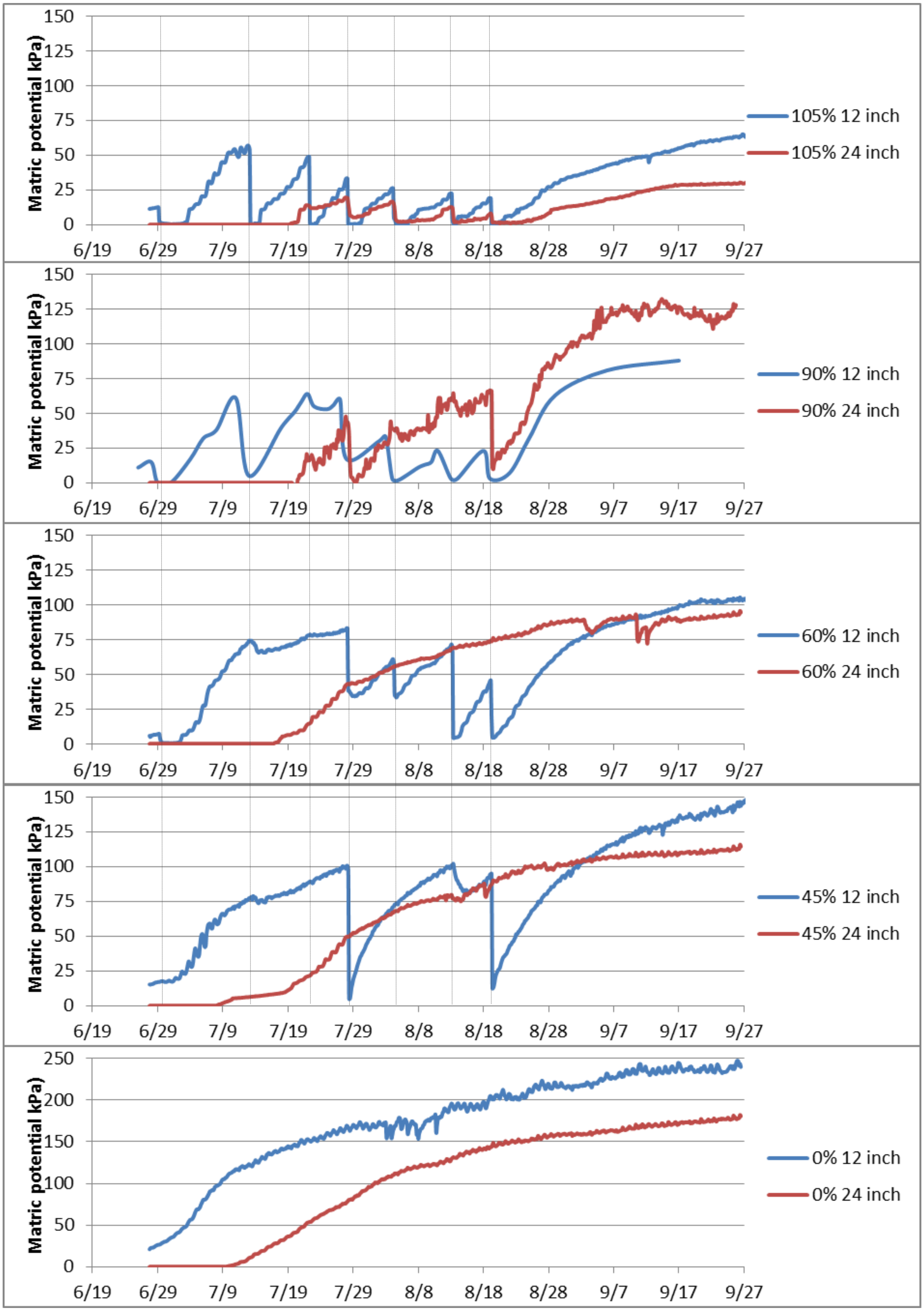

Figure A2. Soil matric potential measured using Watermark sensors placed at 12 and 24 inches. Dotted lines represent irrigations. kPa = centibars

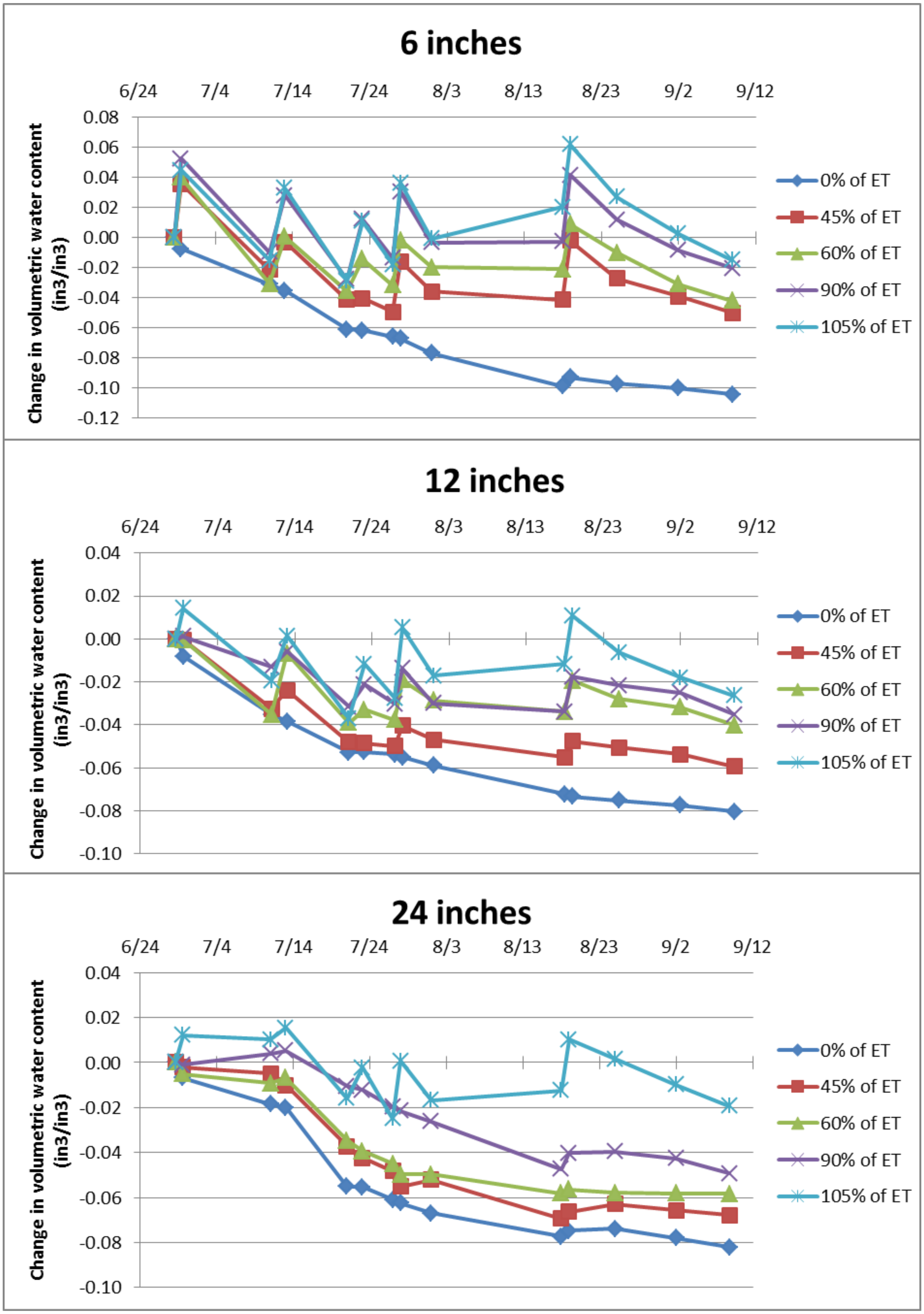

Figure A3. Change in volumetric water content by depth as measured by a neutron probe before and after irrigation. Readings for irrigations on 8/4 and 8/13 were not recorded.

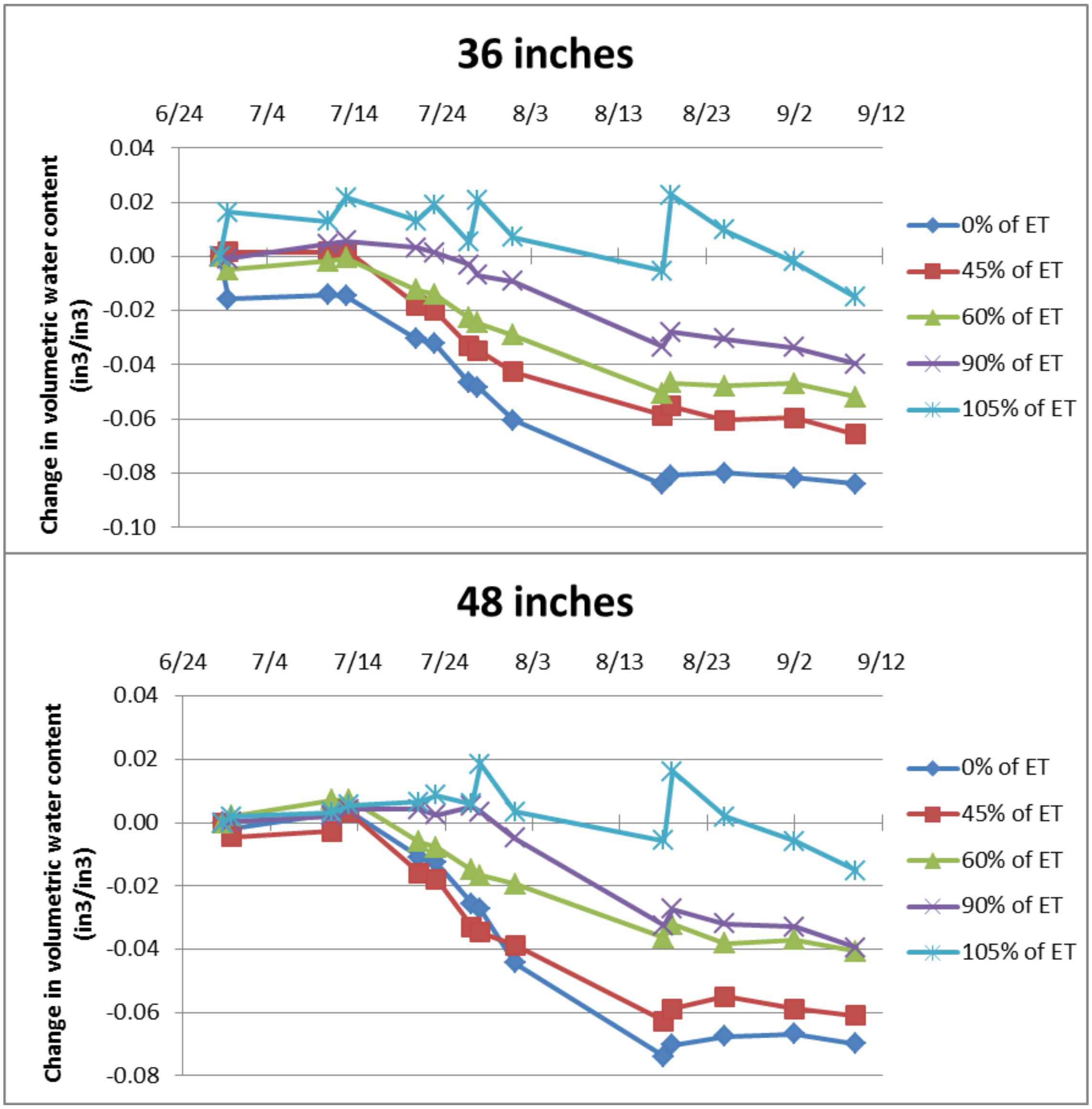

Figure A3 (cont.). Change in volumetric water content by depth as measured by a neutron probe before and after irrigation. Readings for irrigations on 8/4 and 8/13 were not recorded.

Deficit irrigation effects on yield and disease

Overall disease rating (average of crown, stem, and root ratings) is given in Table A1. For both treatments there was a trend of increasing disease severity with increasing irrigation amount. Higher irrigation treatments resulted in wetter soil conditions that lasted longer (Fig. A2), and most soilborne diseases are exacerbated by high soil moisture. Disease severity was higher in Golden Delicious grown in the Short than in the Long rotation sections of the field. This is expected because squash had been grown in the field in 3 of the last 4 years, and soilborne pathogen populations were likely higher.

The difference in disease severity in the Long and Short rotation field sections resulted in lower yields in the Short compared to the Long rotation treatment (22.9 vs. 28.1 ton/acre fruit yield; 1242 lbs/a vs. 1466 lbs/a seed yield).

Despite the positive relationship between disease severity and irrigation water applied, fruit yield was positively related to irrigation water applied in both the Long and the Short rotation sections of the field. For the Long rotation, irrigation could be reduced up to 45% without suffering a fruit yield loss, but for the short rotation treatment, the impact of deficit irrigation on fruit yield was variable. More water may be required when disease severity is high due to a decreased ability of the plant to exploit water resources. For seed yield, there was no impact of irrigation water applied on seed yield in the Long rotation section of the field. In contrast, seed yield increased linearly with increased irrigation applied in the Short rotation section of the field; mean seed yield was 65% higher in the 105% irrigation treatment compared to the 0% irrigation treatment.

The interaction between irrigation and rotation suggests that the response to irrigation is different depending on inoculum pressure (Table 3), which is demonstrated by the difference in the slope of the lines in Fig. A3. For example, when disease severity is greater, the loss in yield will be greater for each increment of water withheld from the plant (slope of the line in Fig. A3).

Reducing the amount of irrigation applied increased both degrees Brix and seed yield. The magnitude of the increase was higher for dry matter than for Brix. While overall, Brix and dry matter were numerically slightly lower in the short than in the long rotation, there was no significant effect of rotation length on Brix or dry matter.

Table A1. Effect of deficit irrigation level effects on squash yield, disease severity, fruit quality.

Rotation interval (since last squash crop)	ET	Fruit yield			Plant disease ratings (Sept 27)						Seed yield			
		Fruit yield	Fruit number	Avg fruit wt	Vascular	Crown	Root	Overall	Dead at harvest	Whole squash wt.	Seed wt.	Seed yield	Seed count	Brix reading
		t/A	*no/A*	*kg*	*--------- 0-4 (dead)---------------*				*avg.*	*g*	*g/fruit*	*lbs/A*	*Avg ct/fruit*	*Avg. (n=16)*
Long	0	23.9	8228	2.5	2.1	2.2	2.5	2.2	0	2660	64	1162	348	5.8
Long	45	28.3	8712	2.8	2.4	2.6	2.9	2.6	11	2862	85	1634	393	5.6
Long	60	28.0	8422	3.1	2.7	2.8	3.0	2.8	42	3125	85	1574	359	5.8
Long	90	29.8	8228	3.7	2.7	2.9	3.0	2.9	49	3577	92	1670	394	5.5
Long	105	30.5	8277	3.4	2.7	2.9	3.0	2.9	33	3221	74	1341	359	5.0
Short	0	16.4	8228	1.9	2.6	2.8	3.1	2.8	32	2016	46	831	284	6.1
Short	45	21.4	8857	2.3	2.2	3.0	3.0	2.7	82	2391	67	1299	387	5.3
Short	60	25.2	9075	2.5	3.4	3.8	3.9	3.7	84	2477	75	1504	346	4.8
Short	90	24.4	6921	2.8	2.8	3.4	3.6	3.2	72	2812	75	1149	337	5.3
Short	105	27.0	8567	3.1	2.8	3.3	3.4	3.2	70	3209	77	1444	377	4.9
Rotation		0.0070	0.88	<.0001	0.13	<.0001	0.004	0.001	<.0001	<.0001	<.0001	-	0.16	0.18
Irrigation level (ET)		0.0038	0.08	<.0001	0.01	0.043	0.01	0.004	<.0001	<.0001	<.0001	-	0.03	0.01
R x T		0.3951	0.29	0.21	0.36	0.5788	0.5085	0.3653	0.004	0.23	0.53	-	0.12	0.32

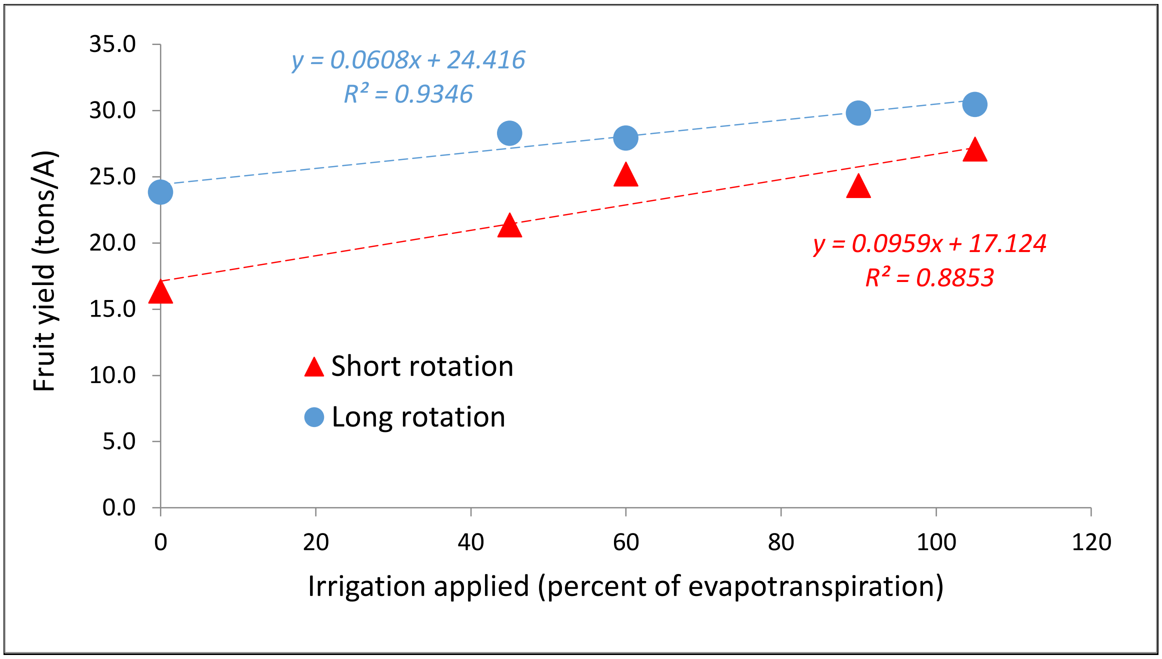

Figure A4. Effect of irrigation level on squash fruit yield in Short and Long rotations plots.

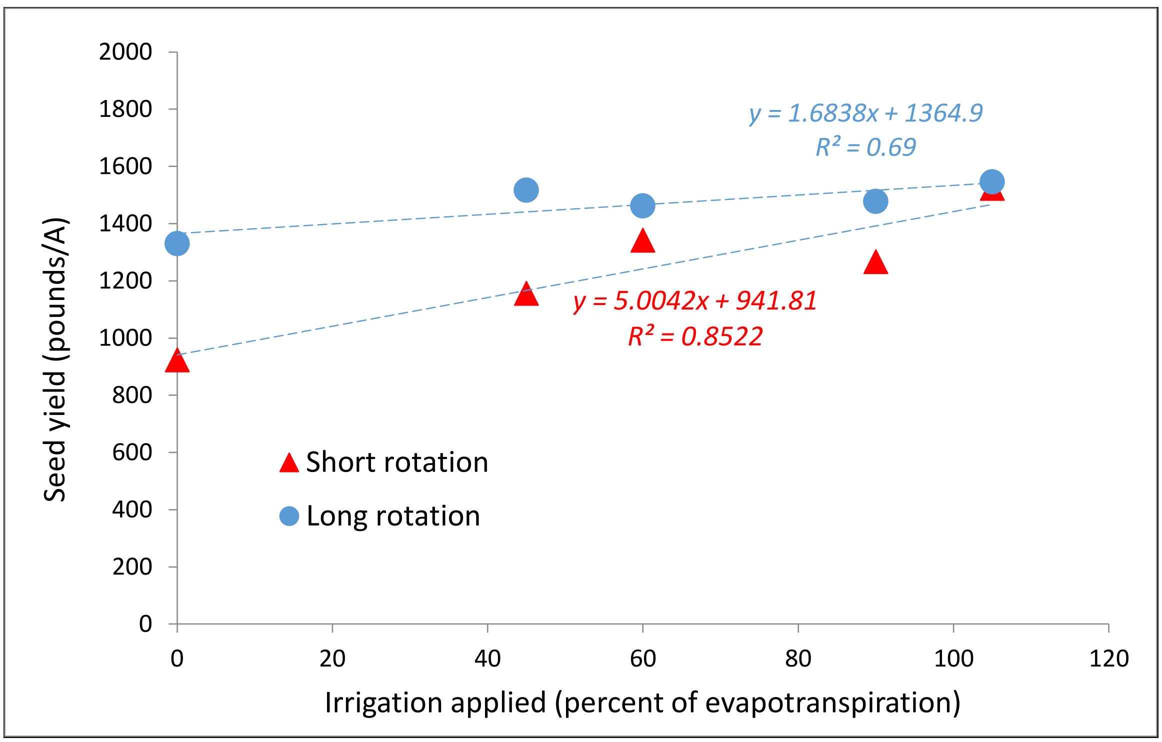

Figure A5. Effect of irrigation level on seed yield in Short and Long rotation plots.

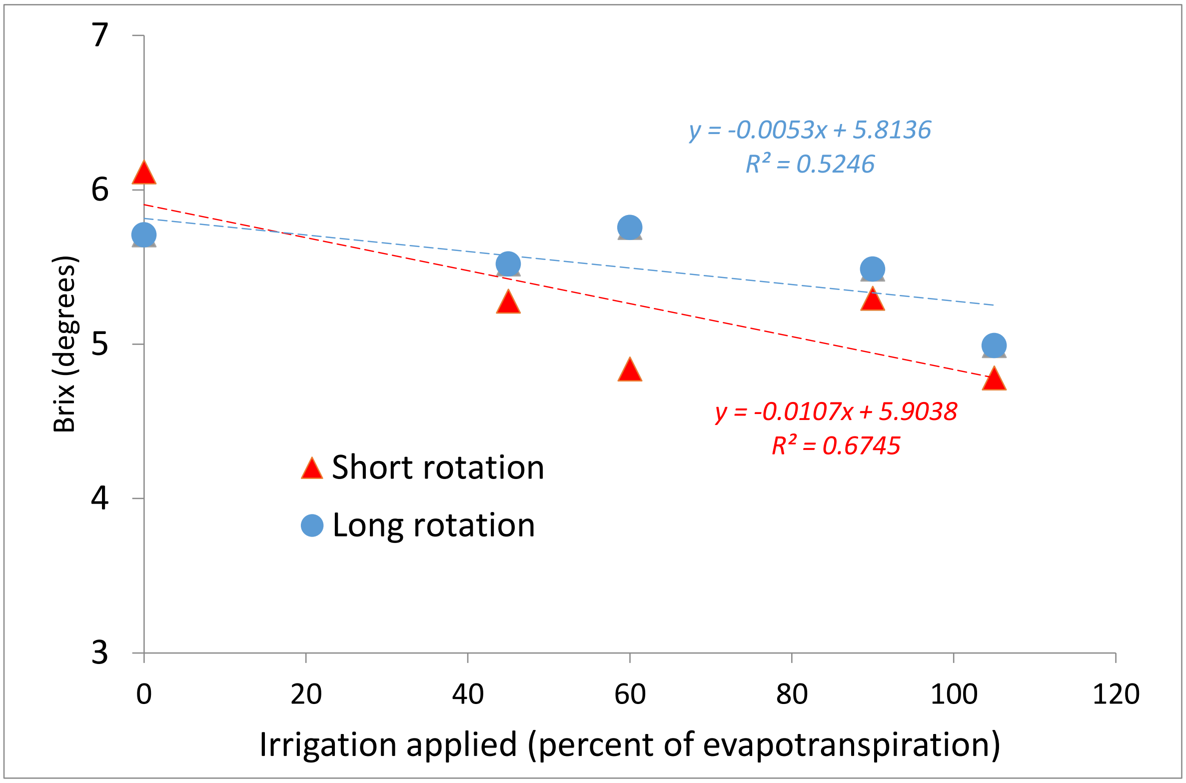

Figure A6. Effect of irrigation level on Brix of squash fruit in Long and Short rotation plots.

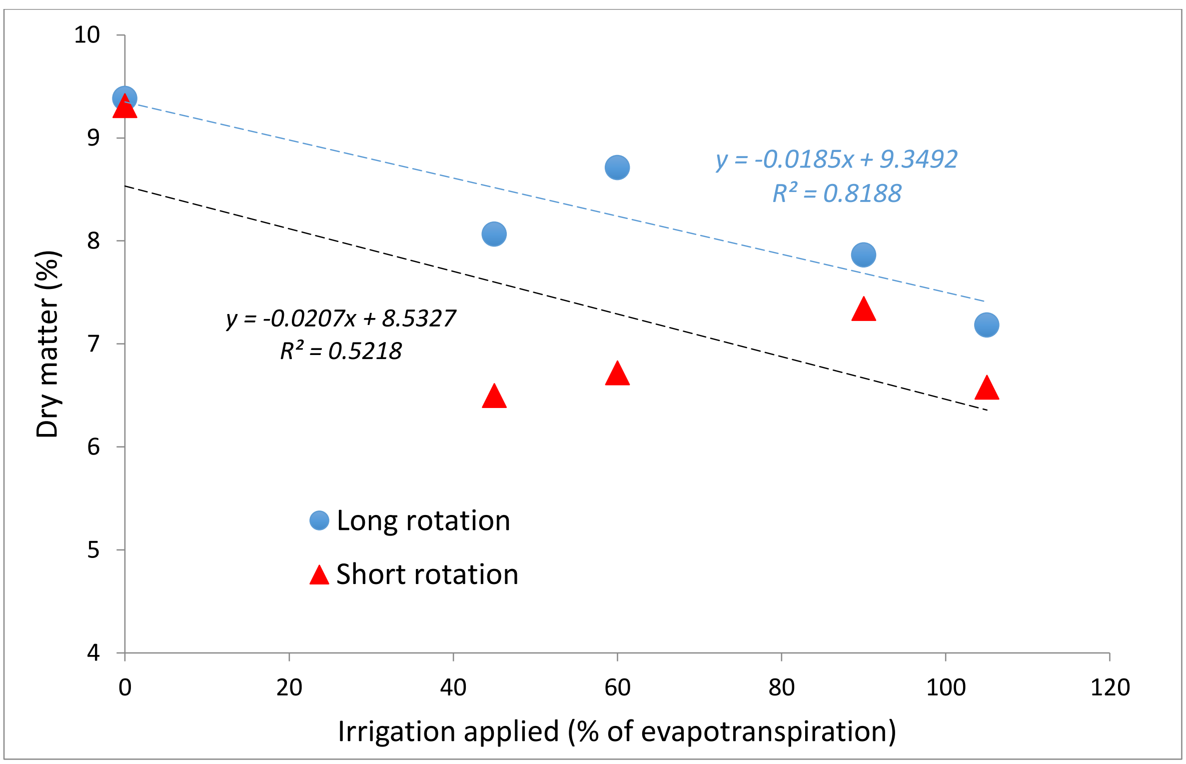

Figure A7. Effect of irrigation level on dry matter content of squash fruit in Long and Short rotation plots.

Table A5. Effect of irrigation level on Butternut yield in short and long rotation plots (1 block only)

Trt (% of ET)	Short rotation	Long rotation	Avg
0	13.2	22.4	17.8
45	21.9	25.5	23.7
60	25.8	23.4	24.6
90	21.2	21.7	21.4
105	23.7	20.3	22.0
Avg	21.2	22.6	21.9

<u>Qualitative root evaluation</u>

Pictures of roots in the top 8 inches of soil are shown in Fig. A5. In the 0% ET treatment, roots did not start until 4 to 5 inches. The roots were yellow and decaying, likely because moisture in the surface layers were depleted early in the season and the roots began to die. In contrast, roots extended to surface in the 105% ET treatment and showed little yellowing and decay.

Although water was the limiting factor affecting plant growth, reduced growth could have also been due to reduced nutrient availability to the plants. Plant essential nutrients are concentrated in the surface 12 inches of soil. As the soil dries, these nutrients become unavailable because water is necessary to transport these nutrients to the roots. Also, urea was banded urea next to the plants, but due to no irrigation or rain, the urea was never washed into the soil and the plants in the 0% ET could not access the applied nitrogen. There was no visual difference in root density deeper in the profile.

Figure A8. Roots to 9 inch depth in the 0% ET (left) and 105% ET (right).