

THESIS

FRUIT CLUSTER PRUNING IMPACTS ON YIELD AND QUALITY OF
THREE TOMATO CULTIVARS IN AN ORGANIC HIGH TUNNEL SYSTEM

Submitted by

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ABSTRACT

FRUIT CLUSTER PRUNING IMPACTS ON YIELD AND QUALITY OF THREE TOMATO CULTIVARS IN AN ORGANIC HIGH TUNNEL SYSTEM

The successful production of high-quality, high-yielding crops is important for fruit and vegetable producers, especially growers who use high tunnels. The valuable space within a high tunnel is well-suited to organic farming and can be used to grow many specialty crops. Fruit load management is practiced in tree fruit production (e.g. apples and peaches), but there is little consensus concerning the effectiveness of fruit cluster pruning on tomato (*Solanum lycopersicum*) when considering its impact on fruit yield, quality, and marketability. There is also no published research on tomato cluster pruning in certified organic systems or intensively-managed high tunnels (e.g. densely-planted, trellised, vegetatively pruned plants) on the Front Range of Colorado. The objective of this research was to address and add to the present knowledge of production techniques for cultivating indeterminate tomatoes in a high tunnel under intensive organic management. In 2016 and 2017, a randomized complete block design was used to test the effects of cluster pruning within a high tunnel on certified organic land at Colorado State University's Agricultural Research, Development, and Education Center, South (ARDEC S.). Two treatments and three cultivars of tomato were selected for the study; the treatment-cultivar combinations were replicated six times within a high tunnel. The treatments involved reducing fruit loads to three fruits and six fruits per cluster while plants with unpruned clusters, which developed up to ten fruits naturally, served as the control.

Tomato cultivars evaluated were 'Cherokee Purple', a widely-studied heirloom, and two hybrids: 'Jet Star' and 'Lola'. Parameters measured included total yield, individual fresh fruit weight, soluble solids content, marketable yield, and non-marketable yield. Averaged over two growing seasons, individual fresh fruit weight increased for both hybrids in the three-fruit treatment, but 'Cherokee Purple' did not respond to the cluster pruning treatments. There was no decrease in total yield between treatments and the unpruned control; however, cultivars performed differently with 'Jet Star' yielding more than the other two cultivars. In a complete analysis, soluble solids content and marketability measurements were more influenced by cultivar than cluster pruning treatments: 'Jet Star' had the highest marketable yields of all cultivars tested, while 'Cherokee Purple' produced larger non-marketable yields. In summary, cluster pruning produced larger organic tomatoes without reducing yield or quality for two of the three cultivars used in the study. Cultivar selection remains one of the largest factors in determining yield, quality, and marketability of a crop.

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1. INTRODUCTION

Small organic diversified farmers in Colorado grow numerous crops for seasonal, local markets. In 2012, Colorado had 290 farms cultivating fresh market tomatoes on 130 hectares of open field (USDA Census, 2012). Trends in the national fresh tomato market, specifically, indicate the increase in demand for both organically grown and heirloom types. Organic tomatoes are often sold at a 15-20% price premium over conventionally grown crops (O'Connell et al., 2012). The market for organic produce in general has shown strong growth over the last two decades and currently makes up 5.3% of total food sales of the United States (Organic Trade Association, 2018). There are many tactics to achieve the goals of growing high-quality, fresh produce for farmers markets, community-supported agriculture (CSA), and restaurants. One of the most successful tactics for growing high-quality, high-value, and high-yielding crops is the utilization of a high tunnel.

A high tunnel, also known as a hoop house or unheated greenhouse, may be single-span or multiple-span; temporary, movable, or semi-permanent structure; covered in polyethylene film, insect netting, shade cloth, or left bare. Typically, high tunnels are unheated and passively ventilated. Crops are usually planted directly in the soil within high tunnels, although artificial media is occasionally used. Colorado State University (CSU) in Fort Collins, Colorado has 557 m² of high tunnel space across seven structures that is dedicated to research in vegetable crop breeding, vegetable cropping systems, cover crops, and cyanobacterial fertilizer (Carey et al., 2009). A high tunnel provides multiple benefits for the grower over open field cultivation, including season extension, insect exclusion and reduced disease pressures, protection from

environmental damage such as hail avoidance, and higher marketable yields. Furthermore, high tunnels are an appropriate complement to organic farming, as high tunnels are energy efficient and can improve the quality and yield of vegetables over open field growing systems (Rogers and Wszelaki, 2012).

Tomatoes are the most popular plant for high tunnel growers and are a sound choice of crop due to their high value in the fresh market and the crop's ability to produce high yields. Growers of indeterminate tomatoes (tomatoes with a continuous growth habit that produce fruit throughout the season) can take unique advantage of the high tunnel infrastructure with trellising. They can produce fresh fruits throughout the growing season, allowing for a longer harvest season when protected by the microclimate created by the high tunnel (Rogers and Wszelaki, 2012). Indeterminate cultivars of tomato allow growers to consistently meet consumer demand at the farmers market, fill the CSA basket for investors each week for months, or fulfill an obligation to the local farm-to-table restaurant.

Fruit cluster pruning of tomatoes has been shown to influence total yield, marketability, individual fruit fresh weight, and various indicators of quality, e.g. dry matter and soluble solids content. Fruit cluster pruning is used to limit the number of fruits per cluster and reduce competition to increase individual fruit weight (Hanna, 2009). Cluster pruning has been found to significantly affect total yield, with an increased number of fruits providing the highest total yields (Maboko et al., 2011). However, the average fresh weight and quality has been shown to increase as the number of fruits per cluster decreases. Greenhouse studies in the Netherlands demonstrated that reducing the fruit number from six to three per cluster increased individual

fruit weight by 42% but decreased the marketable yield by 15-25% for the cultivar Cederico, grafted onto a 'Maxifort' rootstock (Fanasca et al., 2015). Researchers in Turkey cultivating 'Vivia' tomato plants in unheated low tunnels have recommended that the most appropriate number of fruits per cluster to be either of 4 or 6, with a 26% increase of average fruit fresh weight between six fruits and four fruits remaining per cluster (Saglam and Yazgan, 1999).

In contrast, greenhouse studies in Louisiana, USA, have shown that pruning clusters to three fruits increased total marketable yield and individual fresh fruit weight, and reduced cull yield for three cultivars of tomato ('Geronimo', 'Quest', and 'Trust'). The author of these studies did not advise local growers to prune clusters to an exact number of fruit due to the conflicting reports about the optimum number of fruit required for higher yields and heavier fruit (Hanna, 2009). In disagreement with both previous studies, researchers hydroponically growing 'FA593' tomato plants under shade in South Africa found that the highest marketable yield was obtained from plants where no cluster pruning was performed, or when the cluster was pruned to six fruits versus four fruits. Additionally, fruit pruning to four or six fruits per cluster resulted in an increase in unmarketable yield in the study (Maboko et al., 2011). There are conflicting results on the efficacy of cluster pruning of tomatoes in various controlled environments and a lack of research on cluster pruning in intensively-managed organic systems, high tunnels, and the Front Range of Colorado. Table 1 summarizes the critical research on the cluster pruning of tomatoes.

Table 1- A summary of tomato fruit cluster pruning literature.

	Site	Growing Environment	Tomato Cultivar	Fruit No. Per Cluster
Saglam & Yazgan (1995)	Turkey	low tunnel	Vivia	4, 6, 8
Hanna (2009)	Louisiana, U.S.	greenhouse	Geronimo, Trust, Quest	3, 4
Maboko et al. (2011)	South Africa	hydroponic/shade	FA593	4, 6
Fanasca et al. (2015)	Netherlands	greenhouse	Cederico/Maxifort rtstk.	3, 6

Cultivar selection is a critical component for growers who are concerned about the maximization of yield, the fresh market appeal of their products, and the general performance (e.g. pest and disease resistance, physiological traits, and quality) of their crops. Growers should evaluate cultivars in terms of the desired fruit qualities, shelf life and storage characteristics, and potential yield (Hanna, 2009). While most hybrid cultivars of tomatoes have been bred for increased yield, visual appeal, and durability in transport, open-pollinated heirloom cultivars of tomatoes are valued for their unique colors, shapes, flavors, and legacies. However, heirloom tomatoes generally lack uniformity, have thinner skins, lack disease resistance, and have lower yields than most modern hybrid cultivars (O'Connell et al., 2012).

Soluble solids content, represented in °Brix, is a common measurement used by tomato growers and processors, and is gaining traction with fresh market growers as well. In the fresh market, soluble solids levels provide an approximation of how sweet the tomato may taste; however, there are many components that define the overall flavor of each tomato, including sugars, acids, volatiles, and other compounds. Still useful and quick, a °Brix measurement made using a refractometer is a reliable and inexpensive field test for quality. While measurements can be an early indication of sweetness and flavor, °Brix can fluctuate with many factors, such as crop, cultivar, maturity, growing environment, and storage conditions (Kleinhenz and

Bumgarner, 2015). A study in Wisconsin, USA, found that tomatoes had a higher SSC when grown in a high tunnel compared to open-field production (Healy et al., 2017).

Flavor is increasingly important to consumers and consequently for growers. Market growers serve local food systems, run CSA programs, participate in farmers markets, sell to restaurants, or work within co-ops. These farmers tend to be small-scale, diversified, and are certified organic or use organic techniques. For these local producers, quality is the most important trait for their markets. Flavor is a crucial component of quality and research is being conducted to better understand the genetics behind the flavor traits important to consumers. Essentially, components of flavor from heirloom tomatoes are being bred into modern hybrids to achieve an heirloom-like hybrid that retains positive characteristics of each type (Klee, 2017).

Tomato vegetative growth is pruned regularly when grown in greenhouses and often in high tunnels as well. Tomato plants have side shoots that develop in the leaf axil; these axillary shoots will continue to grow and produce leaves and fruit clusters if not removed. To maintain a single leader, the side shoots were removed, often repeatedly, as needed. The removal of side shoots and pruning to single leader are effective in maximizing the utilization of production space and can improve the yield and quality of tomatoes (Maboko et al., 2011). It is also common practice in intensive greenhouse operations to remove any leaves below the lowest ripening cluster. The leaves in the lower canopy receive little sunlight and are unnecessary to the continued growth or flowering of the plants. Additionally, the removal of superfluous leaves allows the plant to allocate more photosynthates to vertical growth and fruit development while also reducing disease pressure by maximizing air flow.

The overall objective of this study was to evaluate the differences between two tomato fruit cluster pruning treatments on three cultivars of indeterminate tomatoes. The three-fruit treatment reduced clusters to three fruits per cluster while the six-fruit treatment left six fruits remaining on each cluster. The control group was not cluster pruned and could develop naturally, producing up to ten fruits per cluster. The tomato cultivars evaluated were 'Cherokee Purple', a popular heirloom widely-used in research, 'Jet Star', an F1 hybrid cultivar previously trialed at Colorado State's CSA program, and 'Lola', an F1 hybrid cultivar bred for intensive greenhouse cultivation (but not necessarily high tunnel production). The hypotheses to be tested in this project were: 1) cluster pruning would decrease total yield, 2) cluster pruning would increase the quality of the organic tomatoes, and 3) cultivars would respond differently to the cluster pruning treatments for the parameters analyzed in the study. To test these hypotheses, evaluations of differences between cluster pruning treatments and cultivar performance were assessed in terms of total yield, fresh fruit weight, soluble solids content, marketable yield, and non-marketable yield.

2. MATERIALS AND METHODS

2.1 Site Description, High Tunnel Description, and Cultural Practices

This study was conducted in semi-permanent high tunnels on certified organic land at Colorado State University's Agricultural Research, Development, and Education Center, South (ARDEC S.) (40.610012, -104.993979, Altitude: 1523 m) in 2016 and 2017. The high tunnel soil at ARDEC S. is classified as a Nunn clay loam by the Natural Resources Conservation Service web soil survey (NRCS, 2018). Soil samples were collected at a depth of 20 to 30 cm each year before planting and analyzed at the CSU Soil, Water and Plant Testing Laboratory. Soil was analyzed for pH, salts, lime, texture, organic matter, and nutrient content to determine recommended pre-planting compost application and fertilizer rates during the growing season.

The certified organic high tunnels were prepared each year by tilling the soil 0.15 to 0.30 m deep with a rototiller (Harvester 722; BCS, Portland, OR). All practices aligned with USDA guidelines for organic production. After tilling, 1.2 cubic m of plant-based compost (A-1 Organics, Eaton, Colorado) was incorporated into the topsoil; 1.5 cubic meters was used in 2017. Six lines of drip tape 13.7 m long were run lengthwise within the high tunnel, directly corresponding to blocking described below. The six lines of drip tape were attached to 1.9-centimeter black plastic irrigation headers at each end of the high tunnel. The drip tape emitted 500 liters per hour per 100 meters. The high tunnels were 6.1 m wide, 15.2 m in length, and had twin-walled polycarbonate end walls with a 1.8-meter square roll-up door on one side. Insect netting was used on both high tunnels and was attached with wiggle wire and

zip channels attached to the side boards and end bows. A four-channel data logger (HOBO U12 Outdoor/Industrial logger; Onset Computer Corporation, Bourne, MA) with four sensors was used to record temperatures at 0.61 meters from the ground both inside and outside the high tunnel, at 1.8 m from the ground at plant canopy height, and at 15 cm deep in the soil. The three ambient sensors were equipped with solar radiation shields. Temperature was recorded to capture information on unusual temperature events and to better understand the microclimate within the high tunnel.

The high tunnels had six metal cables running from the end bows that functioned as a trellising system. In 2017, extra metal cables were strung perpendicular to the six main trellis cables for additional support. Trellising spools with white twine and hooks on each end were used to train the single-leader tomatoes. Trellising clips were used to attach the plants to the twine and were added every 15 to 30 cm throughout the growing season. Tomato fruit cluster supports were used to redistribute fruit weights from plant stems to the trellis. The reduction of the number of fruits per cluster can dramatically increase fruit size and the weight of large fruits can cause damage to the cluster and stem. Cluster supports were added as needed as fruit matured (Figure 1).

Water was supplied to plants with a drip irrigation system. In 2016, fish emulsion fertilizer (Alaska Fertilizer 5-1-1; Pennington, Renton, WA) was used for supplemental nitrogen fertilization throughout the growing season, and occurred every 2 to 3 weeks from July to mid-Sept. In 2017, the same fertilizer was used from mid-June to mid-July. A different fish emulsion product (Drammatic "One" Plant Food 4-4-0.5; Dramm Corporation, Manitowoc, WI) was used



Figure 1- Photographs of a trellis clip and fruit cluster supports.

from August until mid-Sept. The fertilizer change was an economic decision; however, all treatments received the same rates of fertilizer in terms of nitrogen, phosphorous, and potassium. Organic fertilizers were applied through the irrigation system using a siphon injector or by hand with a watering can. In mid-July 2017, a small fertilizer injector (Dosatron, Clearwater, FL) replaced the previous system. Weed barrier was laid down to control weeds within the high tunnel. Weeds were pulled by hand or mowed in and around the high tunnel as needed; predominant weeds included bindweed, Canada thistle, and grasses.

Tomato seeds were sown in CSU's Horticulture Center in Fort Collins on 17 May 2016 and 13 Apr. 2017. The seedlings were hardened off in a shaded, protected outdoor space for a week before planting at ARDEC S. The seedlings were transplanted into high tunnel #5 on 14 June 2016 and into high tunnel #6 on 1 June 2017. All tomato plants were trained to have a single leader, or main stem, beginning on 8 July 2016 and 19 June 2017. Fruit clusters would often develop stems or leaves that would continue to grow and would obscure and possibly damage the cluster; this excessive vegetative growth was pruned off all plants in the study.

Leaves were removed throughout the growing season as they senesced, showed signs of disease, touched the soil or weed barrier (to preventatively manage disease transmission), or as they hampered data collection or harvest. Sufficient leaf cover was left to shade developing and ripening fruits and to prevent sunscald and uneven ripening. Nitrile gloves were worn while pruning the plants and a 70% ethanol solution was sprayed on the small pruners between plants in an effort towards good sanitation. It was necessary to prune side shoots, unnecessary leaves, and excess vegetative growth on fruit clusters once a week. A pollination wand (Garden Pollinator Model VBP-01; VegiBee, Maryland Heights, MO) was used to manage pollination; it was used on medium speed near each mature flower on the cluster and performed in the mornings every other day.

2.2 Experimental Design, Cluster Pruning Treatments, and Harvests

A randomized complete block design (RCBD) was used for this experiment (Figure 2). The high tunnels at ARDEC S. are oriented lengthwise east to west; in northern latitudes, east-west orientation is commonly used to maximize light interception. Six blocks ran from east to west; this blocking was used to compensate for known variability in the growing space within the high tunnel. There were 0.9-m spaces between blocks and from blocks to the sides of the high tunnel. Clusters were pruned to three fruits in one treatment and six fruits in the other treatment. Plants in the control had unpruned clusters that developed naturally (Figure 3). The two cluster pruning treatment groups and the control groups were randomly assigned within each block. Treatments within blocks were separated by a 1.2-m walkway. Within each treatment, four-plant groupings of the three indeterminate tomato cultivars ('Cherokee

High Tunnel 5 - 2016 Tomato Map



T2	Control	Control	T2	Control	T2
Lola F1 4 plants	Cherokee Purple 4 plants	Cherokee Purple 4 plants	Lola F1 4 plants	Cherokee Purple 4 plants	Jet Star 4 plants
Cherokee Purple 4 plants	Jet Star 4 plants	Lola F1 4 plants	Jet Star 4 plants	Lola F1 4 plants	Cherokee Purple 4 plants
Jet Star 4 plants	Lola F1 4 plants	Jet Star 4 plants	Cherokee Purple 4 plants	Jet Star 4 plants	Lola F1 4 plants

Control	T2	T1	T1	T2	T1
Jet Star 4 plants	Cherokee Purple 4 plants	Lola F1 4 plants	Jet Star 4 plants	Jet Star 4 plants	Jet Star 4 plants
Cherokee Purple 4 plants	Jet Star 4 plants	Jet Star 4 plants	Lola F1 4 plants	Lola F1 4 plants	Cherokee Purple 4 plants
Lola F1 4 plants	Lola F1 4 plants	Cherokee Purple 4 plants	Cherokee Purple 4 plants	Cherokee Purple 4 plants	Lola F1 4 plants

T1	T1	T2	Control	T1	Control
Cherokee Purple 4 plants	Jet Star 4 plants	Lola F1 4 plants	Cherokee Purple 4 plants	Lola F1 4 plants	Cherokee Purple 4 plants
Jet Star 4 plants	Cherokee Purple 4 plants	Jet Star 4 plants	Lola F1 4 plants	Jet Star 4 plants	Jet Star 4 plants
Lola F1 4 plants	Lola F1 4 plants	Cherokee Purple 4 plants	Jet Star 4 plants	Cherokee Purple 4 plants	Lola F1 4 plants

Figure 2- A map of the experimental design within a high tunnel in 2016. The design was completely re-randomized in a different high tunnel in 2017.



Figure 3- A visual representation of the cluster pruning treatments in the study. Clockwise from top left: three-fruit treatment, six-fruit treatment, and an unpruned cluster as a control.

Purple', 'Jet Star', 'Lola') were randomly assigned. Plants within treatments were spaced 0.3 meters apart. In 2017, the experimental design was the same, but in an immediately adjacent high tunnel that was used to ensure an adequate rotation. The three treatments were re-randomized within six blocks; the three cultivar sub-samples were rerandomized within each treatment.

Fruits were pruned from clusters when they were marble-sized (Maboko et al., 2011). The fruits most proximal to the plant stems were selected to remain on the cluster and distal fruits were removed when a choice was available. Efforts were made to identify and remove king fruits (i.e. the result of two or more flowers fusing together) from clusters. King fruits are often the first fruit that develops and are frequently larger than average, misshapen, and unmarketable in most contexts. King fruits were particularly an issue with 'Cherokee Purple' in this study. Cluster pruning was done once a week throughout the growing season, from 29 July to 28 Sept. 2016 and 7 July to 27 Sept. 2017.

Harvests were conducted in a manner that emulated a grower harvesting ripe and near-ripe fruits for the local fresh market. In 2016, there were eleven harvests, with the first harvest occurring on 30 Aug. 2016 and the final harvest taking place on 7 Oct. 2016. In 2017, there were fourteen harvests, with the first harvest occurring on 31 July 2017 and the last harvest taking place on 6 Oct. 2017. The data collected for each fruit included the block number, treatment, plant number within treatment and cultivar, cluster number proximal to distal, tomato number and position on each cluster, whether the fruit was marketable or not marketable, notes on physiological disorders or damage, and fruit fresh weight. Marketability was determined using a combination of the United States Standards for Grades of Fresh Tomatoes and local market standards (USDA, 1991).

On 23 Sept. 2016 and 8 Sept. 2017, harvests were conducted to assess the soluble solids contents (SSC) of fruits using the °Brix scale. Fruits were collected during the peak of harvest season, a standard practice when measuring SSC. Two to four representative fruits were

harvested, one from each plant within an experimental unit. The samples were sealed in plastic bags and stored in a freezer. The fruits, once thawed, were mashed and combined to attain an aggregate measure. The pulp was strained with cheesecloth and the juice was assessed using a refractometer. SSC was measured in °Brix and recorded for each of the fifty-four experimental units each year. An acceptable range for fresh market tomatoes in Colorado is 3.5 - 5.3. The °Brix scale is used to assess harvest readiness, determine quality in the field and in processing, and represents a product's potential sweetness and flavor. (Kleinhenz and Bumgarner, 2015)

2.3 Statistical Analyses

A two-way factorial treatment structure with subsampling was used in this study. Basic assumptions for the statistical analyses were met (homoscedacity, normal distribution of residuals, independent simple random sampling, and appropriate sample size). Analyses explored differences in years, the main effects of treatment and cultivar, and interactions between treatment and cultivar. If an interaction was found to be significant at $\alpha = 0.05$, further tests were conducted. The separate linear models included block, year, treatment, and cultivar as categorical variables and allowed interaction between the main effects of treatment and cultivar. Response variables were total yield, individual fresh fruit weight, soluble solids content measured in °Brix, marketable yield, and non-marketable yield. Blocks were treated as a random effect while year, treatment, and cultivar were treated as fixed effects in the model. The experimental unit consisted of 4-plant groupings by cultivar that represented each treatment and cultivar combination. Years were combined for a total of twelve replications for the study; the same three treatments and three cultivars were used both years.

All data were analyzed using R statistical software (R Core Team, 2016) and R Studio (Version 1.0.136). R packages "car", "lme4", "lme4Test", "pbkrtest", "lsmeans", "plyr", "XLConnect", and "gplots" were used in the analyses. Yields were assessed by taking the mean yield for the plants in each experimental unit. Fresh fruit weights were calculated by taking the mean yield of the individual fruits from each plant and then taking the average mean fruit weight for the entire sub-sample. Soluble solids content was calculated as described previously. An analysis of variance (ANOVA) and pairwise comparisons were used to compare the differences in the least squared means of the response variables. T-tests used Satterthwaite approximations to degrees of freedom while the Type III ANOVA used the Kenward-Roger approximation for degrees of freedom. Pairwise comparisons were used to separate least squared means by treatment and cultivar and results were averaged over year. Default p-value adjustments for pairwise comparisons were made using the Tukey method for comparing a family of three estimates. The significance level was set at 0.05 for all results.

3. RESULTS AND DISCUSSION

3.1 Total Yield

There was a significant main effect of cultivar ($p < 0.01$) on total yield as the three cultivars performed differently averaged over year and treatment (Figure 4).

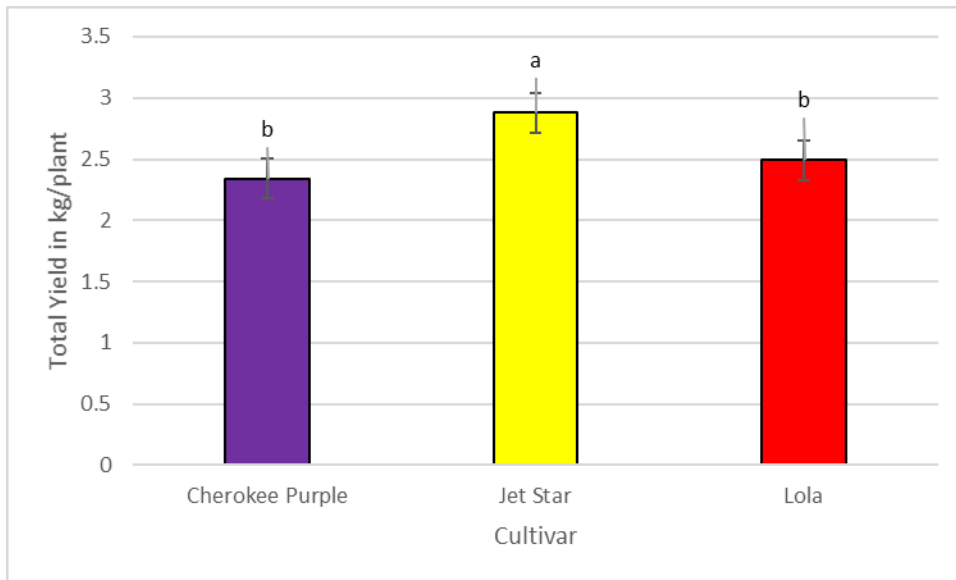


Figure 4- The main effect of cultivar for total yield. Dissimilar letters represent differences at $\alpha = 0.05$. Results are averaged over treatment, year, and block.

There was no interaction between treatment and cultivar, and no treatment main effect observed for total yield in this experiment. However, there was a difference in total yield between years with a 14% reduction in total yield in 2017 compared to 2016.

It is interesting to note that cultivar had more impact on total yield than a reduction in the fruit load per cluster. The difference in total yield between years of the study can likely be attributed to weather, temperature, or minor differences between high tunnels, since

treatments, cultivars, and management practices were consistent. Despite its compact yet indeterminate growth habit, 'Jet Star' consistently produced highly acceptable fruit irrespective of treatment, and outperformed both cultivars in terms of total yield, depending on the treatment. 'Jet Star' was a clear winner among the three cultivars and proved to be a good selection for organic high-tunnel production in this study, as it demonstrated in the context of total yield and marketability measurements.

3.2 Individual Fresh Fruit Weight

An interaction between treatment and cultivar was found in the responses for individual fresh fruit weight ($p < 0.01$) (Figure 5).

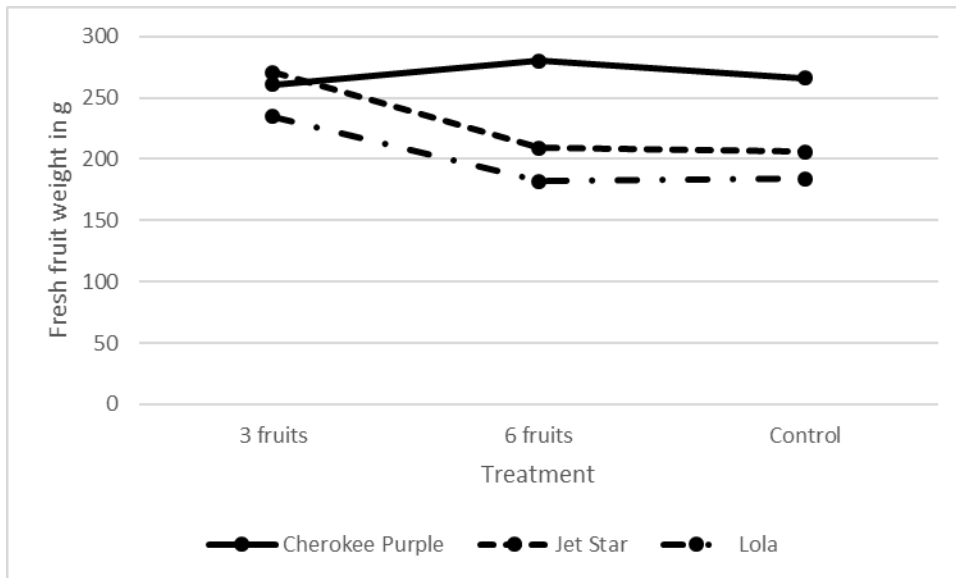


Figure 5- An interaction for individual fresh fruit weight. Note: lines are used to demonstrate interaction and do not represent a continuous response of the variable.

Significant differences were also found for both the main effect of treatment ($p < 0.01$) and cultivar ($p < 0.01$). Both hybrid tomato cultivars, 'Jet Star' and 'Lola', produced larger individual fruit with three-fruit clusters than with six-fruited or unpruned clusters.

'Jet Star' individual fresh fruit weight in the three-fruit treatment was 32% larger than the control and 31% larger than the six-fruit treatment. The individual fresh fruit weight for 'Lola' in the three-fruit treatment was 27% larger than the control and 29% larger than the six-fruit treatment. There were no differences in the fresh fruit weight of 'Cherokee Purple' tomatoes among treatments (Figure 6).

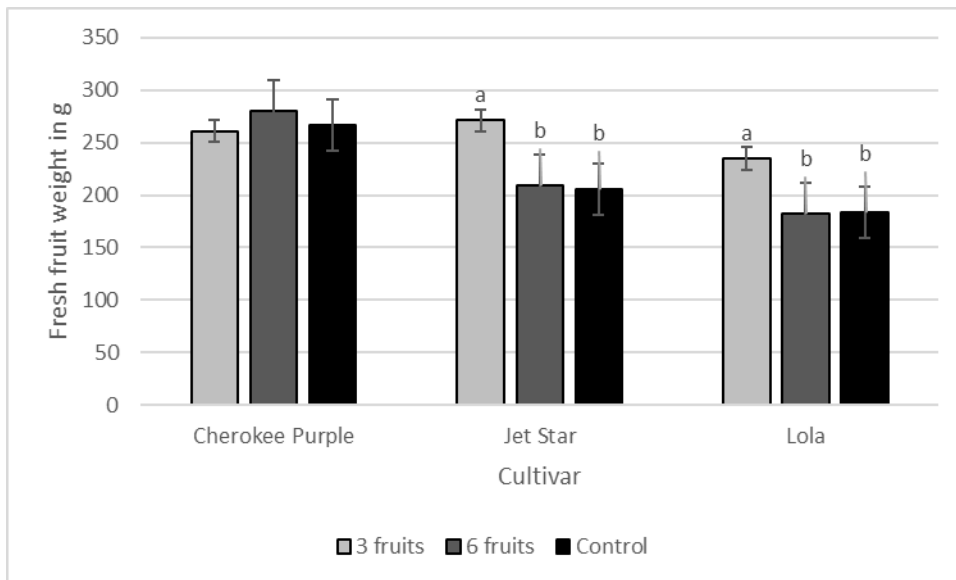


Figure 6- The main effect of treatment for individual fresh fruit weight. Dissimilar letters represent differences at $\alpha = 0.05$. Results are averaged over year and block.

For the main effect of cultivar, 'Cherokee Purple' plants with unpruned clusters produced larger fruits ($p < 0.01$) than both 'Jet Star' (23% smaller) and 'Lola' (31% smaller). Results were similar for the six-fruit treatment: 'Cherokee Purple' produced larger individual fruits than both hybrids ($p < 0.01$). With six-fruit clusters, 'Cherokee Purple' fresh fruit weight was 34% higher than 'Jet Star' and 54% higher than 'Lola'. Under the three-fruit cluster pruning treatment, 'Jet Star' produced a fresh weight measurement 16% higher than 'Lola' ($p < 0.01$).

‘Cherokee Purple’ clusters with three fruits almost produced larger fruits than ‘Lola’ in the same treatment ($p < 0.07$), but results were not significant at $p = 0.05$ (Table 2).

Table 2- Cultivar main effect for individual fresh fruit weight.

Cultivar	Fresh Fruit Weight (g)		
	3 fruits	6 fruits	Control
Cherokee Purple	261 ab	280 a	266 a
Jet Star	271 a	209 b	206 b
Lola	235 b	182 b	184 b

* Dissimilar letters within columns are different at $\alpha = 0.05$

Like the results from previously published studies, pruning clusters to three fruits significantly increased fruit weight for two of the three cultivars in this study (Hanna, 2009; Maboko et al., 2011; Saglam and Yazgan, 1999). The hybrid cultivars, ‘Jet Star’ and ‘Lola’, demonstrated a strong response to the three-fruit treatment, producing fruits that were one-third larger than both the six-fruit treatment and the control. Clearly, cultivar and fruit number per cluster affect individual fresh fruit weight. Cluster pruning likely reduces competition for plant resources and thus increases fruit weight (Hanna, 2009).

‘Cherokee Purple’ showed no response to the cluster pruning treatments in terms of fresh fruit weight. The fruits produced by this heirloom tomato cultivar were often very large, irrespective of the number of fruits per cluster. ‘Cherokee Purple’ with unpruned clusters produced larger fruits than both hybrids, which is likely explained by their proclivity for producing large fruits. The response was similar with the six-fruit treatment; often, clusters did not produce more than three or four fruits, so there was little difference between the six-fruit treatment and the control plant groups.

3.3 Soluble Solids Content

There was no interaction between treatment and cultivar in terms of soluble solids content. There was no significant main effect of treatment; SSC was not affected by the cluster pruning treatments. However, there was a significant main effect of cultivar ($p < 0.01$) (Figure 7).

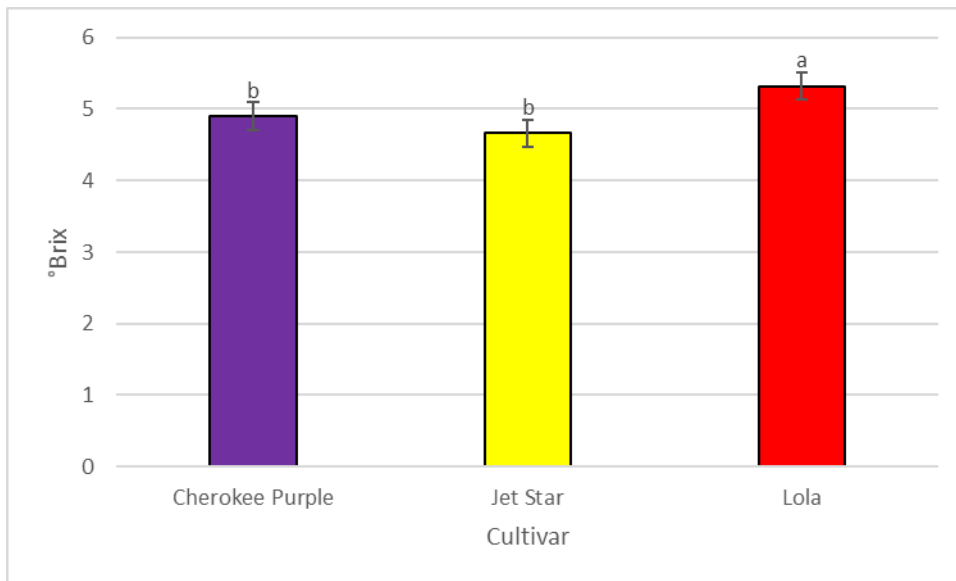


Figure 7- The main effect of cultivar for soluble solids content. Dissimilar letters represent differences at $\alpha = 0.05$. Results are averaged over treatment, year, and block.

Soluble solids content is an indicator of fruit quality and, in a ratio with acidity and including volatile compounds, comprises the flavor profile. It is used in the field as a quick but efficient indication of crop quality. One might expect a larger tomato, from a three-fruit cluster for example, to have higher water content and reduced sugars compared to a cluster with more fruits. However, when fruit load and competition for plant resources are reduced and the sink-to-source ratio decreases, more photosynthates, acids, and other compounds are available for the remaining fruits (Fanasca et al., 2015).

3.4 Marketable Yield

No interaction was found between treatment and cultivar for the response of marketable yield. There was not a significant main effect of treatment and marketable yield did not differ between the two growing seasons. However, in terms of marketability, there was a significant main effect of cultivar and notable differences between the three cultivars (Figure 8). 'Jet Star' produced significantly higher marketable yields than 'Lola', which, in turn, produced significantly higher marketable yields than 'Cherokee Purple'. In this study, cultivar selection was the most important factor in determining marketable yield.

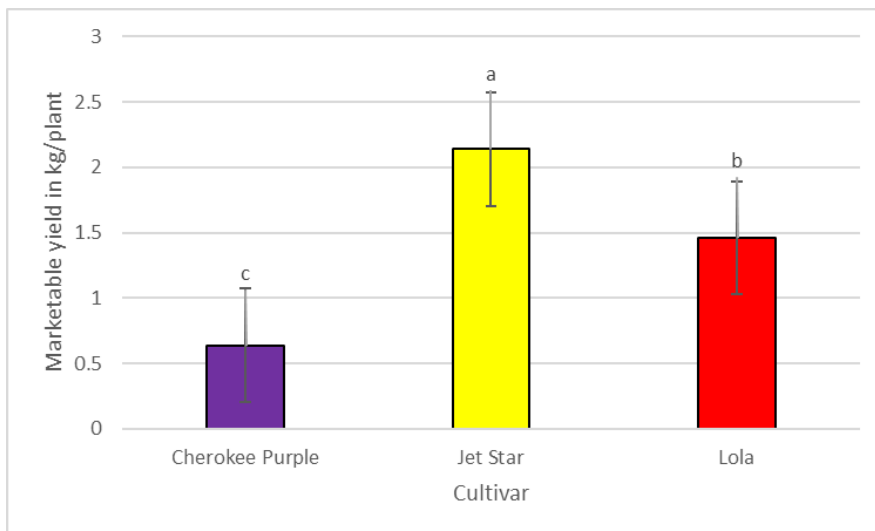


Figure 8- The main effect of cultivar for marketable yield. Dissimilar letters represent differences at $\alpha = 0.05$. Results are averaged over treatment, year, and block.

3.5 Non-marketable Yield

An interaction was found between cluster pruning treatments and cultivar for non-marketable yield ($p = 0.04$) (Figure 9). The main effect of cultivar was also significant at $p < 0.01$. Exploring the main effect of cultivar with post-hoc pairwise comparisons, a significant difference ($p = 0.04$) was found between the three-fruit and six-fruit treatments for 'Lola'. The

six-fruit treatment reduced non-marketable yield by 34% compared to the three-fruit treatment; therefore, the three-fruit cluster treatment increased the non-marketability of fruits compared to six-fruit cluster pruning treatment (Figure 10).

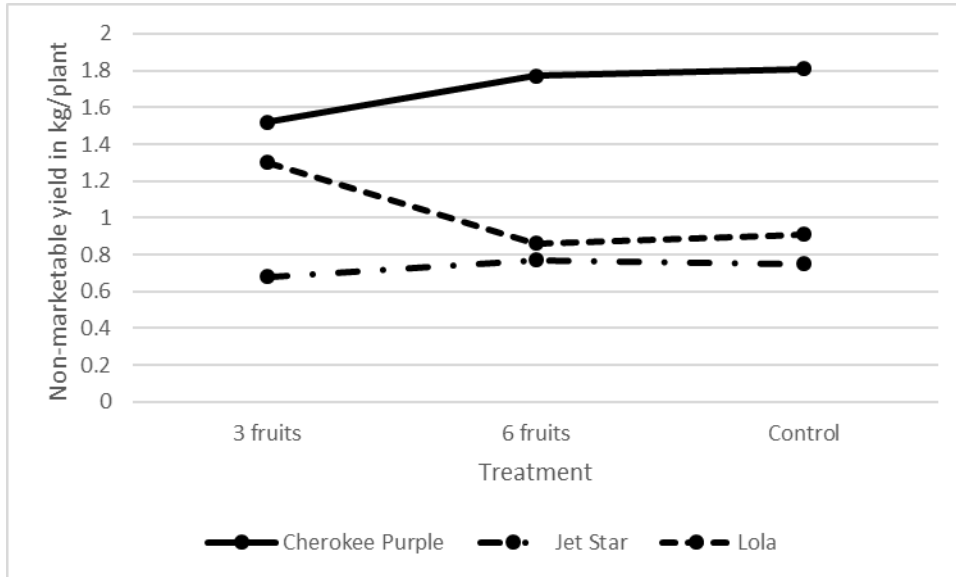


Figure 9- An interaction for non-marketable yield. Note: lines are used to demonstrate interaction and do not represent a continuous response of the variable.

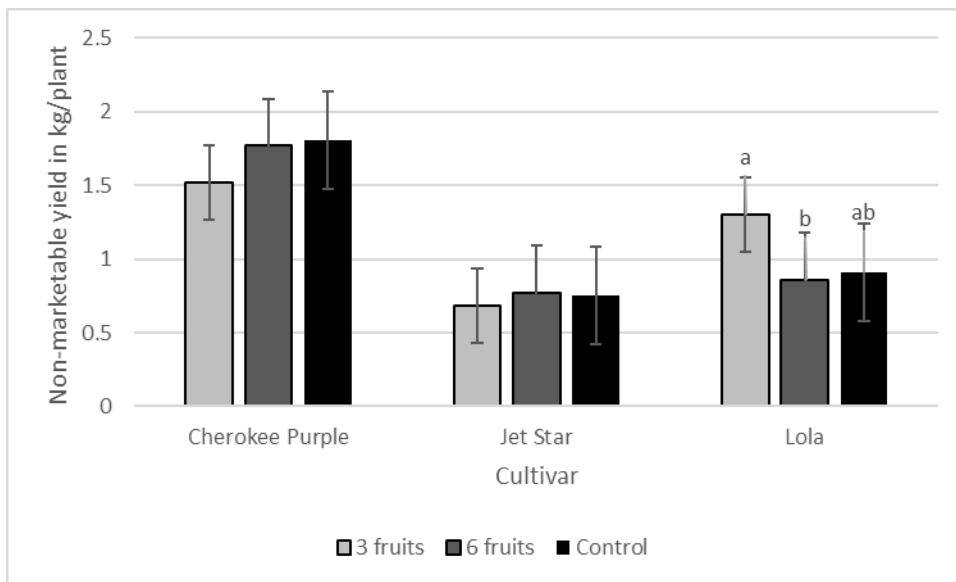


Figure 10- The main effect of cultivar for non-marketable yield. Dissimilar letters represent differences at $\alpha = 0.05$. Results are averaged over year and block.

Non-marketable yield, or cull yield, is an important factor to consider when developing production methods and choosing cultivars to grow. 'Cherokee Purple' produced fruits that were prone to cracking in various ways and had developmental problems like "cat-facing" and irregular shaping. 'Lola' fruits increased in size under the three-fruit treatment and frequently developed large radial cracks; these cracks would host fungal infections and render the fruit unmarketable while still on the vine (Figure 11). 'Jet Star' produced the smallest non-marketable yields and only showed physiological problems after periods of rain, as in the 2017 growing season, when many ripening fruits split before harvest.



Figure 11- Radial cracking of 'Lola' in 2016.

4. CONCLUSION

The purpose of this study was to determine if cluster pruning would improve the yield and quality of three different cultivars of tomato grown in an organic high tunnel. Cluster pruning did not increase or decrease total yield; organic high tunnel growers could reduce fruit loads per cluster and maintain yield, dependent on cultivar selection. 'Jet Star' produced higher total yields, averaged over treatment, than both 'Cherokee Purple' and 'Lola'. Individual fresh fruit weights increased for the two hybrid cultivars in the three-fruit treatment.

Cultivar had an impact on soluble solids content, with 'Lola' having an overall higher SSC than the other two cultivars. Marketability and non-marketability were determined largely by cultivar attributes, weather conditions, and insect and disease pressure, and less by treatment, as observed and noted in other studies. 'Lola', a hybrid cultivar bred for commercial greenhouse production, did not perform well in the context of the experiment: fruit did not ripen in a timely manner and non-marketable yields increased under the three-fruit treatment.

In summary, larger tomatoes were produced in this study by cluster pruning without a reduction in yield or quality for two of the three cultivars tested. Cultivar selection remains one of the largest factors in determining yield, quality, and marketability of a crop. Future studies could explore the genetics in tomato that would respond best to cluster pruning under intensive organic management in a high tunnel.

5. REFERENCES

- Carey, E. E., L. Jett, Lamont, Jr., W.J., T. T. Nennich, M. D. Orzolek, and K. A. Williams. 2009. Horticultural Production in High Tunnels in the United States: A Snapshot. *HortTechnology* 19(1):37-43.
- Fanasca, S., A. Martino, E. Heuvelink, and C. Stanghellini. 2007. Effect of electrical conductivity, fruit pruning, and truss position on quality in greenhouse tomato fruit. *The J. of Hort. Sci. and Biotechnol.* 82(3):488-494.
- Hanna, H.Y. 2009. Influence of cultivar, growing media, and cluster pruning on greenhouse tomato yield and fruit quality. *HortTechnology* 19:395-399.
- Healy, G.K., B.J. Emerson, and J.C. Dawson. 2017. Tomato variety trials for productivity and quality in organic hoop house versus open field management. *Renewable Agr. And Food Systems* 32(6):562-572.
- Klee, H.J. 2017. A chemical genetic roadmap for producing a better tasting tomato. Presentation. 13 Nov. 2017, Colo. State University, Fort Collins.
- Kleinhenz, M.D. and N.R. Bumgarner. 2015. Using Brix as an indicator of vegetable quality: instructions for measuring Brix in cucumber, leafy greens, sweet corn, tomato and watermelon. *Ohio State Univ. Ext.* 18 Sept. 2015. <<https://ohioline.osu.edu/factsheet/HYG-1651>>.
- Maboko, M.M., C.P. Du Plooy, and S. Chiloane. 2011. Effect of plant population, fruit and stem pruning on yield and quality of hydroponically grown tomato. *African J. of Agr. Res.* 6(22):5144-5148.
- NRCS. Web soil survey of Larimer County area, Colorado. 24 Feb. 2018. <<https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>>.
- O'Connell, S., C. Rivard, M.M. Peet, C. Harlow, and F. Louws. 2012. High tunnel and field production of organic heirloom tomatoes: yield, fruit quality, disease, and microclimate. *HortScience* 47(9):1283-1290.
- Organic Trade Association. 2018. Organic Trade Association's 2017 Organic Industry Survey. 14 Mar. 2018. <<https://www.ota.com/news/press-releases/19681>>.
- R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 16 Jan. 2018. <<https://www.R-project.org/>>.

Rogers, Mary A. and Annette L. Wszelaki. 2012. Influence of high tunnel production and planting date on yield, growth, and early blight development on organically grown heirloom and hybrid tomato. *HortTechnology* 22:452-462.

Saglam, N. and A. Yazgan. 1999. Effect of fruit number per truss on yield and quality in tomato. *Acta Hort.* 491:261-264.

U.S. Department of Agriculture. 2012. USDA Census of Agr., Volume 1, Chapter 1: State Level Data – Colorado. 17 May 2017. <https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1_Chapter_1_State_Level/Colorado/>.

U.S. Department of Agriculture. 1991. U.S. Standards for Grades of Fresh Tomatoes. 12 Mar. 2018. <https://www.ams.usda.gov/sites/default/files/media/Tomato_Standard%5B1%5D.pdf>.