The Pennsylvania State University

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EVALUATION OF PENN STATE TOMATO VARIETIES FOR FRUIT QUALITY AND COMMERCIAL PRODUCTION

A Thesis in

Horticulture

by

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ABSTRACT

The Pennsylvania State University's Tomato Breeding Program has reached a point in its development when it is trialing elite experimental hybrids throughout the state, country, and internationally. The purpose of this thesis project was to evaluate select number of Penn State fresh-market (FM) tomato hybrids (varieties) for fruit quality and other desirable characteristics, and compare them with a few commercial cultivars (varieties) of tomato commonly grown in Pennsylvania (PA). In 2017, preliminary yield and fruit quality trials were conducted at two locations in PA, using a large number of Penn State tomato hybrids with early blight (EB) resistance and other desirable characteristics. In 2018, the number of FM large tomato hybrids was reduced to elite ones, and new late blight (LB) resistant hybrids were included and evaluated. In 2019, a total of 12 elite Penn State FM hybrids and three popular commercial cultivars were visually evaluated in multi-location trials (MLTs). Four farmers in different locations in PA cooperated in visual evaluation of 15 hybrids, trialed in a randomized complete block design (RCBD) in each location. Traits for plant and fruit quality characteristics, including yield, disease resistance, maturity, fruit size and color, were scored and hybrids ranked. Various statistical analyses were conducted, including analysis of genotype main effects and mixed models for genotype (G), environment (E) (location), and G x E interactions. Analysis of variance (ANOVA) and pairwise multiple comparisons were performed for each of the genotypes and locations, to determine differences in performance among the 15 varieties within each location and differences in performance of each variety across multiple locations. The same 15 varieties were also field-evaluated and harvested from one site at the Penn State Russell E. Larson Agricultural Research Center, Pennsylvania Furnace (Rock Springs), PA, and additionally analyzed for pH, soluble solids content (SSC), % acidity, and fruit lycopene content (using spectrophotometry and image-based analysis). In 2017, yield potential was determined for all hybrids, including Penn State top

hybrids G49, G118, and G126, which produced estimated marketable yield of 51.0, 53.0, and 50.3 tonnes/ha, respectively. Across all hybrids trialed, the average marketable yield was 37.9 tonnes/ha. The top hybrids G118 and G126 also produced the largest fruit, with an average fruit weight of 0.67 and 0.64 lb/fruit, respectively, whereas G49 produced a larger number of fruit with an average weight of 0.54 lb/fruit. In 2019 MLTs, six PSU hybrids (G4, G49, G126, L37, L39, and L40) performed significantly better than all of the commercial cultivars based on the overall score; and G49 performed significantly better than each of Mt. Merit (MM) and Mt. Fresh + (MF) for yield score. For fruit firmness, all PSU hybrids but G83 performed significantly better than MM and MF; the commercial cv. Red Deuce (RD) performed as good as PSU hybrids for firmness. All PSU hybrids performed significantly better than commercial cultivars for internal fruit color with the exception of G118, which was not significantly different from RD. All PSU hybrids performed significantly better than MM and MF for external fruit color; and, three hybrids (G49, L37, L39) performed significantly better than RD. There were other variations and differences among Penn State and commercial varieties for other traits, as described in Chapter 3 of this thesis. Penn State G49 had the highest fruit lycopene estimate by whole fruit colorimeter measurements, 59.44 ug/g^{-1} fruit weight, and was significantly higher than estimates for G4, G9, G73, G81, G40, RD, MF, and MM. Overall, several PSU experimental hybrids show great potential for commercialization, including G4, G49, G118 and G126, based on overall scores, yield scores, and stability in farm locations.

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Chapter 1

Introduction

Tomato Taxonomy

The cultivated tomato, *Solanum lycopersicum* L., is a member of the Solanaceae family of plants consisting of more than 96 genera and more than 2,800 different species (Ashrafi and Foolad, 2007). It is among the *Solanum* genus also known as nightshade, which consists of approximately 2,300 different species of flowering plants. Two other popular crops contained in the *Solanum* genus include potato and eggplant, and pepper and tobacco are within the Solanaceae family as well. *Solanum* section *Lycopersic*on includes 13 different species, one of which is the cultivated tomato, *Solanum lycopersicum* L. The cultivated tomato is thought to be derived from two wild ancestor species, *Solanum pimpinellifolium* and *Solanum cerasiforme* (OECD, 2017). The 12 wild relatives (*Solanum arcanum, S. cheesmaniae, S. chilense, S. chmielewskii, S. corneliomulleri, S. galapagense, S. habrochaites, S. huaylasense, S. neorickii, S. pennellii, S. peruvianum, and S. pimpinellifolium*) embody a broad assortment of heritable phenotypic and genetic variation (Bedinger et al., 2011; OECD, 2017) and present great opportunity for breeding desirable traits into the cultivated tomato, including disease resistance, fruit shape and size, fruit quality, and color (OECD, 2017; Ranc et al., 2008).

Domestication and Distribution

The wild ancestors of the cultivated tomato originate in South America, specifically in the dry Andean coastal region of Peru, Ecuador, and Northern Chile, the center of species

diversity. Domestication is believed to have occurred in the Puebla and Vera Cruz areas of Mexico where the plant populated maize fields (Rubatzky and Yamaguchi, 1997); although, there is also a theory for Peruvian domestication. These regions remain the center of diversity for wild species (Bai and Lindhout, 2007; Robertson and Labate, 2007) Selection for desirable tomato variants progressed to an advanced stage before being brought to Europe in the 15th century, where intensive breeding began in the 18th and 19th centuries (Bai and Lindhout, 2007; Sims, 1980). Through plant breeding, scientists and researchers have created a broad array of cultivated tomato types varying in shape, color, size, taste and various other traits (Bai and Lindhout, 2007). Tomato is now grown increasingly throughout the world, but most production occurs in the Northern Hemisphere. Countries along the fortieth parallel account for the highest production values, where the top five countries produce more than 61% of total world production (FAOSTAT, 2019). The top ten producers for 2017 in descending order are: China, India, Turkey, U.S., Egypt, Iran, Italy, Spain, Mexico, and Brazil. In the Southern Hemisphere, Brazil stands alone as the largest producer of tomato with 2.3% of world production (FAOSTAT, 2019). In the past two decades, tomato production has doubled throughout the world. In that time, China has nearly quadrupled its production of tomato with approximately one-third of the world total in 2017 (FAOSTAT, 2019).

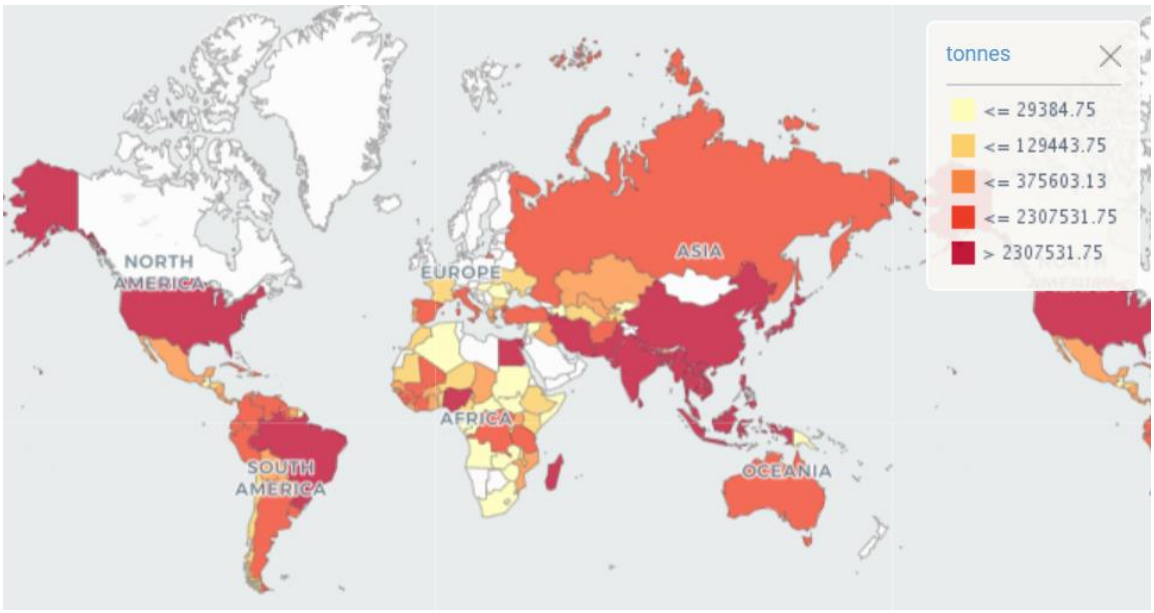

Figure 1-1: Tomato production throughout the world in 2017 (FAOSTAT, 2019).

Economy and Production

Tomato is the second most consumed vegetable crop in the world behind potato (FAOSTAT, 2019) with an $88 billion gross production value and approximately 182 million tonnes produced annually (FAOSTAT, 2019). Asia accounts for more than half of all production, while the Americas produce 18.1%, Europe 16.2%, Africa 12%, and Oceania 0.4% (FAOSTAT, 2019). China is the largest producer of tomato in the world, followed by India, Turkey, and the United States. In the United States, tomato is the most consumed vegetable crop with potato being second; and, tomato is third in crop production value behind only two agronomic crops, maize and soybean (FAOSTAT, 2019). In the U.S., approximately 12.5 million tonnes of tomato were harvested from 321,900 acres with a total farm value of 1.86 billion dollars in 2018 (USDA-NASS, 2019).

In the U.S., California and Florida remain the largest producers of tomato with two thirds of domestic field production. California accounts for 95% of processing tomato production, while

both California and Florida account for a large majority of domestic fresh market production. The next largest producers are Indiana, Michigan, New Jersey, North Carolina, Ohio, South Carolina, Tennessee, and Virginia (USDA-NASS, 2019). In Pennsylvania, there is about 4,000 acres in fresh market production with an annual value between $15 and $25 million dollars (Orzolek et al., 2006). The tomato area under protection in PA is estimated to be 10.91 hectares with total production of approximately 1,097 tonnes and $2.97 million dollar sale value (USDA-NASS, 2014). Processing production in PA amounts to approximately 465 hectares and a $15 million production value (Furmano, 2017).

Although production has continually increased throughout the world, the U.S. has experienced a continual decrease, a result of the fresh market industry and its demand being met by imports from primarily Mexico, Canada, and the Dominican Republic (Guan et al., 2017). In the U.S., only 40% of demand for fresh market tomatoes is met by domestic production (Guan et al., 2017). Figure 1-2 highlights the decrease in U.S. tomato production and the increase in tomato imports from 2000 to 2015. The period from 2002 to 2017 marks a 34% decrease in tomato production in the U.S. from 4.4 billion pounds to 2.9 billion pounds (FAOSTAT, 2019). One reason is increased competition from both Canada and particularly, Mexico, where lower labor costs and government policy has encouraged an increase in tomato production by Mexican growers (Guan et al., 2017).

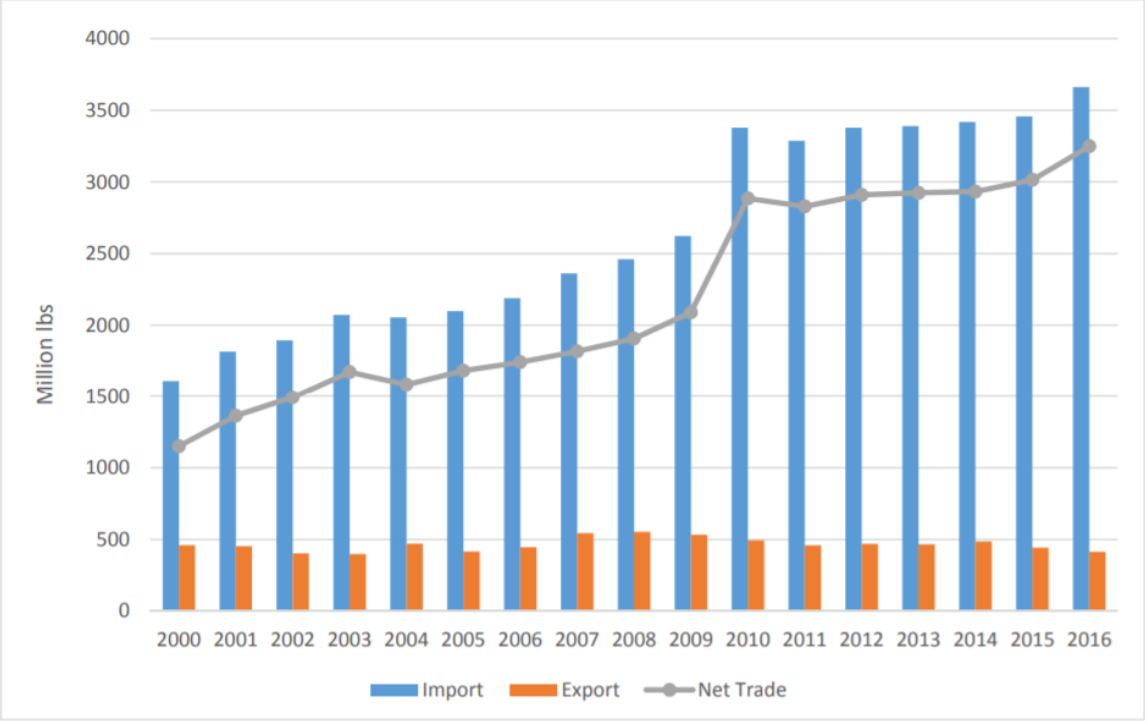

Figure 1-2: U.S. fresh market tomato trade 2000-2016. Source: U.S. Department of Commerce (Guan et al., 2017).

The U.S. tomato industry, and particularly the Florida Tomato Exchange, has petitioned the United States Department of Commerce (USDC) to intervene on behalf of domestic growers. Since 1996, the issue has been revisited every five years in an effort to prevent suppression and undercutting of the U.S. domestic market by setting floor prices for Mexican tomato imports (Guan et al., 2017). In the past two decades the Tomato Suspension Agreement has brought balance to the U.S. domestic market and has allowed consumers the variety of tomato products they see in grocery stores. In the past, the agreement has suspended investigations into the dumping of low-quality fruit into the U.S. market from Mexican imports; while The Florida Tomato Exchange has been in favor of terminating the suspension and re-opening investigations into dumping of low-quality fruit (Noble, 2019). There have also been anti-dumping investigations into tomato produce received from Canada (Cook and Calvin, 2005).

The Department of Commerce has developed a new Tomato Suspension Agreement that was signed in September of 2019 and continues to prevent suppression and undercutting, while putting in place more stringent mechanisms for inspection of tomato imports. Florida growers believe this is a step in the right direction for protection of the U.S. domestic fresh tomato market. Tomato importers and the USDA believe this is a step backwards. Mexican tomato imports have a large impact on the U.S. economy with 3.3 billion dollars in GDP and 33,000 jobs. The new agreement will require an estimated 200 million dollars of warehouse space that requires 50 million dollars in fees annually. According to the USDA, previous quality inspections of tomato imports has demonstrated a 99.76% pass rate and the new agreement enacts unnecessary inspections of tomato imports from Mexico (Karst, 2019).

Nutritional Value

Tomato does not rank high in nutritional value, but contributes significantly to human health in the U.S. because of its high per capita consumption, 93.6 pounds per year in 2017 (AGMRC, 2017). Processing tomato products contribute the greater majority of tomato in people's diets with 73.3 pounds per year. In this regard, tomato contributes important nutrients for human health in the form of vitamin A and C as well as essential minerals (Foolad et al., 2008; Rick, 1980), and it is the most abundant source of lycopene (Foolad et al., 2008; Nguyen and Schwartz, 1999), an antioxidant. Lycopene is an unsaturated carotenoid in fruits and vegetables such as tomato, watermelon, papaya, red grapefruits, and guava (Mozos et al., 2018), and is responsible for the red color, desirable for aesthetic and fruit quality as well as human health. Lycopene contributes benefits in the form of protection against reactive oxygen species, or oxidants, linked with various cancers (Foolad et al., 2008; Giovannucci, 1999), especially prostate cancer (Zu et al., 2014); and, it is efficacious in prevention of cardiovascular disorders

(CVD), contributing to primary and secondary prevention in patients exhibiting subclinical atherosclerosis, metabolic syndrome, hypertension, peripheral vascular disease, stroke and other cardiovascular diseases (Mozos et al., 2018). Consumers receive a majority of their lycopene through processed tomato products because of high consumption rates as well as the higher bioavailability of lycopene resulting from exposure to heat during processing, which releases lycopene from the fibrous cell structure matrix (Basu and Imhran, 2007; Burton-Freeman and Sesso, 2014; Mozos et al., 2018; Thies et al., 2012).

Cultivation: Fresh Market and Processing

Solanum section *Lycoperiscon* are perennials, but in commercial production the cultivated tomato is generally considered an annual. In warmer regions, particularly those with little to no days below freezing temperature, the plant will survive indeterminately. In cultivation, the plant is often treated as an annual, especially in field cultivation, in which the fruits are harvested and the plants are removed, destroyed, or plowed back into the soil at the end of the season. Cultivated in more controlled conditions (greenhouse/high-tunnel), the plant can be considered a semi-perennial, often grown for periods greater than 12 months and sometimes as long as 18 months, in which plant health is maintained and fruits continuously harvested.

The tomato industry consists of two main markets: fresh market and processing. The fresh market industry consists of large round, cherry, grape, and plum tomatoes, all grown either in the field or in controlled greenhouse settings and requiring substantial labor; while the processing industry consists solely of processing tomatoes for use in juice, sauce, paste, puree, and whole-peel products.

In the U.S., a majority of tomato production occurs in the warm season in field production. In California and Florida where a large majority of tomato production occurs,

growers can have two crops of tomatoes each year—Southern regions of California and throughout Florida. In California, seeds can be started as early as mid-January and again in March for early Summer and late Summer harvests. In Florida, the summer is too hot for tomatoes. Seeds are typically started in early February and again in September, for harvest in early Summer and late Fall/Winter harvest, respectively. In plant hardiness zones 5 to 7, tomatoes do not have more than one season, and sometimes the season is too short with late frosts in the Spring and early frosts in the Fall. Growers will often stagger their tomato crops in order to continuously produce fruit throughout the warm season. High-tunnel operations can help to extend the growing season in both early Spring and into Fall and early Winter at the end of the season, especially if tunnels are equipped with heating systems.

Hothouse, or greenhouse (plastic or glass housing) grown tomatoes are typically grown in the off-season, when field production has decreased and consumer demand for tomato is high. These tomatoes come at a higher price resulting from higher demand in the off-season and supports the increased energy expenditure required for heat, light, general maintenance to infrastructure, and labor during cultivation in the colder seasons.

In the United States, the processing industry makes up approximately 92% of total tomato production with 11 million tons harvested and only 1.05 million tons of fresh market tomatoes harvested in 2017 (USDA-NASS, 2019). In the U.S., the processing industry is valued at 906 million dollars and the fresh market industry at 772 million dollars in 2017 (USDA-NASS, 2019). Fresh market tomatoes have greater value per unit weight than processing tomatoes. Difference in value results from expensive labor inherent in the fresh market production, in which tomatoes are typically trellised, trimmed, and hand-harvested several times throughout the growing season. These practices can account for as much as 55% of the total production cost for fresh market tomatoes in Florida (Davis and Estes, 1993; Frasca et al., 2014). In the processing industry, plants

are grown on bare ground without need for trimming or trellising, then harvested once by machine toward the end of the crop's maturity.

In commercial field settings, fresh market tomato can be trellised in multiple ways, depending on the type of plant, the labor available for pruning and maintenance, and whether the fruits are vine-ripened or harvested at the mature green stage. One of the most common methods for determinate type, large size tomatoes is the Florida-weave, or basket-weave method, in which stakes are driven into the ground between every one to two plants. Stakes are four to seven-foot tall depending on how tall the plants can be expected to grow. Weather-resistant twine is secured to one end post, looped around each stake to the end of the row, and then looped around each stake back to the original post. The first string is added when transplants begin to flower (or about 10 inches tall before lodging occurs), and new string is added every 8-12 inches of new plant growth. This method is ideal for compact growth habit, determinate type varieties with the self-pruning gene (*SP*), homozygous for both alleles, producing plants with main stems ending in a terminal flower bud. This method is also appropriate for semi-determinate plant types with longer vegetative growth and is ideal in operations where pruning is not expected.

The stake-and-wire method is more appropriate for long, indeterminate type plants in the field and also in protected cultivation. This method requires tall wooden or steel posts driven into the ground every 20 feet. A long, tightly stretched line of tensile-strength wire is threaded through the top of the posts along the row, and twine is suspended from the wire and loosely tied (overhand knot) or attached to the base of each plant stem with a clip. One twine is intended for each vine, so pruning indeterminate type plants to one vine is necessary with consistent maintenance and removal of new suckers. If more than one vine is intended, then additional twine should be added. In protected cultivation, this method is similar. Instead of tensile-strength wire between posts, twine can be tied around a supportive housing frame or pipes contained as part of

the protective structure. Additional methods for greenhouse cultivation are included in the Protected Cultivation section.

The mature green fresh market industry has functioned in much the same way as the above Florida-weave concerning cultivation practices—several harvests per season, high crop inputs, and substantial labor requirements. Although, in recent years plant breeders and researchers have been making progress in the direction of one-time machine-harvested tomato. Instead of harvesting fruit at the orange or red vine-ripened stage, fruits harvested at the firmer, mature green stage are stored at 55-70 degrees Fahrenheit, treated with ethylene to enhance ripening, and shipped to market. At 55-58 degrees, fruits can be stored for three to five weeks before quality begins to decrease (Lerner, 2019).

The University of Florida and their tomato breeder, Sam Hutton, are especially interested in further developing CGH varieties suitable for machine harvest at the mature green stage, which would assist Florida growers in competing with the tomato import market from Mexico. In 2013, Florida ranked first in the U.S. for fresh market tomato production with a total production value of $455 million (Frasca et al., 2014). Many genes have been discovered for applications in machine-harvesting at the mature green stage; and studies are underway to determine the efficacy of different cultivation methods for developed CGH breeding lines, including single or double-row field production, plant and bed spacing, and nutrient regimens. Flowering, yield, and post-harvest fruit quality have been assessed within this experimental design to better understand optimal harvest time to achieve acceptable yield and fruit quality. Sam Hutton, Aline Coelho Frasca, Monica Ozores-Hampton, John Scott, and Eugene McAvoy have researched the efficacy of CGH, machine-harvested, mature green fruit at the University of Florida Institute of Food and Agricultural Sciences. In North Carolina, Syngenta and North Carolina State University have also done work on CGH.

There are two key characteristics that must be contained in varieties developed for this purpose. CGH cultivars must have the joint-less pedicel characteristic (*j or j-2*) for once over mechanical harvesting; and, similar to varieties in the processing industry, CGH fresh market varieties must have a concentrated fruit in which most of the fruit is ready for harvest at one time (Frasca et al., 2014). Additional genes important in the development of CGH varieties include the self-pruning (*SP*) gene for determinate plant type mentioned above, decumbens (*dec*) (Stubbe, 1959), procumbens-2 (*prc-2*) (Stubbe, 1960), and brachytic (*br*) (Barton et al., 1955), which play a role in plant growth habit and/or branching (Ozores-Hampton et al., 2013). Genes erecta-2 (*er-2*) (Clayburg et al., 1979), globiformis (*glf*) and globosa-2 (*glo-2*) (Clayburg et al., 1966) increase side-branching and reduce the apical dominance—the tendency for the main stem of the plant to grow more strongly than its side branches (Campbell and Nonnecke, 1974; Ozores-Hampton et al., 2013). The *br* gene is of particular importance for shortened internodes and side-branching. The overall amalgamation of these genes results in plants with low-growing, spreading habit with a 50-60% decrease in internode length (Ozores-Hampton et al., 2013).

Studies by North Carolina State University and Syngenta have determined that a NC CGH breeding line, NC 13G-1, produces 48% higher yield when planted in double-rows than a commercial cultivar, Mountain Spring in staked, upright cultivation; although, NC 13G-1 had lower individual fruit weight (Frasca et al., 2014). In the 2013 and 2014 season, the University of Florida conducted a study that found the best performing CGH line produced less yield than a Harris Moran variety, HM 8849, but more yield than the Florida average yield of 29.68 tonnes (Frasca et al., 2014). This result is promising for the development and commercialization of more CGH cultivars that can perform for yield in comparison to staked, upright varieties. Additionally, CGH lines thus far proved to require less fertilizer inputs, substantially less labor, and a 2-4-week shorter growing season (Frasca et al., 2014).

In the U.S., processing tomato varieties are grown almost exclusively on bare ground in field settings throughout the San Joaquin and Sacramento Valleys in Fresno, Yolo, San Joaquin, Kings, and Colusa Counties (Hartz et al., 2008). Variety characteristics are in large part determined by the processors who conduct extensive evaluation on fruit quality specific for end products (Hartz et al., 2008)—juice, sauce, paste, puree, and whole-peel products.

Growers select from a processor-approved list of varieties based on yield, earliness, concentrated ripening and with resistance in mind for nematodes and disease (Hartz et al., 2008). Processing varieties used to be direct seeded, but since 1990 there has been a transition to transplants for bed preparation, stand-establishment, reduced weed competition, and improved use of various weed control methods (Hartz et al., 2008), such as pre- and post-planting herbicides.

Beds are typically prepared in the Fall to avoid wet soil conditions in the Spring and to reduce soil compaction; and, growers have been increasingly experimenting with methods for improving soil quality by introducing minimum tillage practices and the uncommon use of winter cover crops in fields where tomatoes are planted year after year (Hartz et al., 2008). Rows are prepared at 60-66 inches center-to-center and seeding rates of 40,000 to 60,000 seed per acre with plants 9-12 inches apart in a row when direct-seeded. Transplanting is practiced in the range of 7,000 to 9,000 plants per acre, and planting is staggered from March through early June (Hartz et al., 2008). A variety of mechanical cultivation practices are used to control weeds, minimize large clods, maintain deep furrows, train or cut excessive vines, and smooth the bed surface for improved ease of mechanical harvest (Hartz et al., 2008).

Drip irrigation is becoming more prevalent among processing growers, though there are a variety of irrigation methods employed throughout the season—sprinkler irrigation for stand establishment, after which most farmers use furrow irrigation (Hartz et al., 2008). The increased

use of drip irrigation has proven useful for many reasons including improved crop yield and water efficiency. Drip has been effective in sloped fields, for soil characteristics prone to runoff or drainage issues, ease of fertilizer application, and for the presence of shallow saline water tables in some growing regions (Hartz et al., 2008). The typical suggested fertilizer application rates are 125-250 pounds of nitrogen, 40-120 pounds of P_2O_5 and 0-200 pounds of K_2O depending on the region (Hartz et al., 2008). Most soils in California maintain sufficient potassium (K), but with those soils containing less than 150 ppm of ammonium acetate-exchangeable K, application may be required (Hartz et al., 2008). This is the especially the case for tomatoes purposed for whole-peel processing, for which yellow-shoulder disorder can be exacerbated by insufficient K (Hartz et al., 2008).

Integrated Pest Management (IPM) should be employed for weed, insect, and disease management. Cultural methods for control include field cultivation and sanitation, good drainage, irrigation management to prevent consistently wet soils, and field scouting and identification of weed and insect pests (Hartz et al., 2008). There are several insect pests that can be problematic for processing growers, including garden symphylans (*Scutigerella immaculate*), flea beetles (*Epitrix* spp.), cutworms (*Peridroma* and *Agrotis* spp.), fruitworms (*Helicoverpa zea*), armyworms (*Spodoptera* spp.), russet mites (*Aculops lycopersici*), stink bugs (*Euschistus conspersus*, *Thyanta pallidovirens*, *Chlorochroa* spp., and *Nezara viridula*), potato aphids (*Macrosiphum euphorbiae*), and occasionally pinworms (*Keiferia lycopersicella*) more prevalent in San Joaquin Valley (Hartz et al., 2008). Crop rotation, resistant varieties, and avoiding saturated soils can be effective for controlling root knot nematodes (*Meloidogyne* spp.) and Phytophthora root rot (*Phytophthora parasitica and P. capsica*) (Hartz et al., 2008). Disease occurrence in California is stymied by the Mediterranean weather, but in cool rainy Springs bacterial speck (*Pseudomonas syringae*) and bacterial spot (*Xanthomonas campestris*) can occur

(Hartz et al., 2008). Bacterial speck-resistant varieties and copper sprays can be used to deter spread. In the Fall, chemical protectants can be used to prevent blackmold (*Alternaria alternata*) on fruit (Hartz et al., 2008). Late blight (*Phytophthora infestans*) also occurs in the late Spring and the Fall. Both late blight-resistant varieties and fungicide applications can be used to prevent disease establishment and reduce pathogen reproduction and spreading (Hartz et al., 2008).

Protected Cultivation

Protected cultivation consists of both plastic and glass greenhouses and both large and small plastic tunnels. There is a total of 1,612,380 hectares grown in controlled structures around the world (Peet and Welles, 2005). China maintains the largest area of plastic greenhouses with 55% of the world total. Europe contains 23%, primarily in Italy and Spain; and the Netherlands contains 25% of the 39,430-ha total glasshouse acreage worldwide (Peet and Welles, 2005).

The cost of greenhouse production is generally more expensive than field production for any given crop, determined by regular maintenance of structure and equipment, labor, energy for heating and lighting, and variable costs such as plant material, substrate, and fertilizer (Peet and Welles, 2005). In British Columbia (BC), Canada, direct capital investment for a high-tech greenhouse in 2003 amounted to $1.8 million dollars, excluding the cost of land (MAFF, 2003; Peet and Welles, 2005). In California, costs for greenhouse structure and equipment were estimated at $52/$m^2$ (Hickman, 1998; Peet and Welles, 2005) and when a hydroponics system is employed the cost can be as high as $90-100/$m^2$ (Jensen and Malter, 1995; Peet and Welles, 2005). In the Netherlands, the cost of a modern greenhouse with total climate-control capability, transportation, and fertilization is estimated at $75/$m^2$ (Peet and Welles, 2005; Woerden and Bakker, 2000). In BC, Canada, the primary operating costs are labor (25%), heating (28%), and marketing (25%) (Peet and Welles, 2005). Larger operations tend to be more feasible

economically, resulting from 9-10% lower heating and labor costs; and, the minimum economical greenhouse operation was estimated at 1.5 ha in the Netherlands (Peet and Welles, 2005; Woerden and Bakker, 2000).

Greenhouse production in North America used to be a niche market, but between the early 1990's and 2003 the area in which greenhouse tomatoes were grown increased by 596% with a total of 1,726 ha in 2003 (Cook and Calvin, 2005). Though, this rapid growth contributed to declining prices and commoditization of the greenhouse tomato market, and the dynamic between greenhouse grown and field grown tomatoes became more important to understand. While the food service industry has become reliant on and still favors the mature green fresh market grown in the field, high fruit quality and specialty varieties have become associated with greenhouse production that was continually becoming mainstream (Cook and Calvin, 2005). In 2003, the greenhouse share in tomato fresh market consumption in the U.S. was 17% with only half of this produce being covered by domestic production; however, in retail settings, greenhouse grown tomatoes accounted for about 37% of all sales in the U.S. (Cook and Calvin, 2005). This number is expected to be much higher now. Canada and Mexico also play an important role in the greenhouse market in North America. In Canada, greenhouse tomato production accounts for 89% of fresh tomato production, and the most growth in greenhouse production can be seen in Mexico which accounts for the largest growth area in North America, but with comparatively lower average yields (Cook and Calvin, 2005). See Figure 1-3 and Figure 1-4 for greenhouse acreage and production trends in North America.

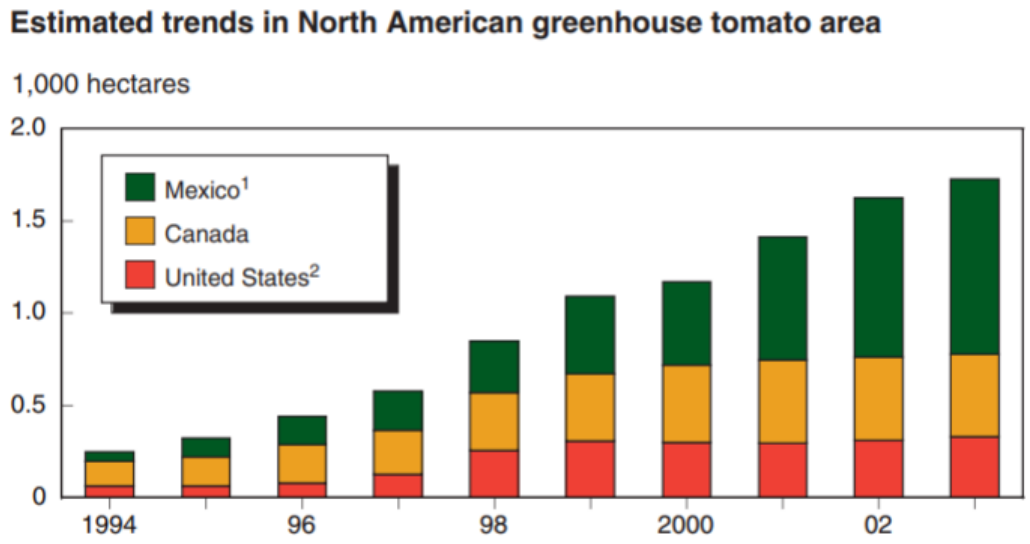

Figure 1-3. 1 excludes most shade-house area. 2 only large and medium size growers until 1998. Source: U.S. International Trade Commission; Asociacion Mexicana de Productores de Hortalizas en Invernaderos (AMPHI); Statistics Canada; and estimates by Cook and Calvin (Cook and Calvin, 2005).

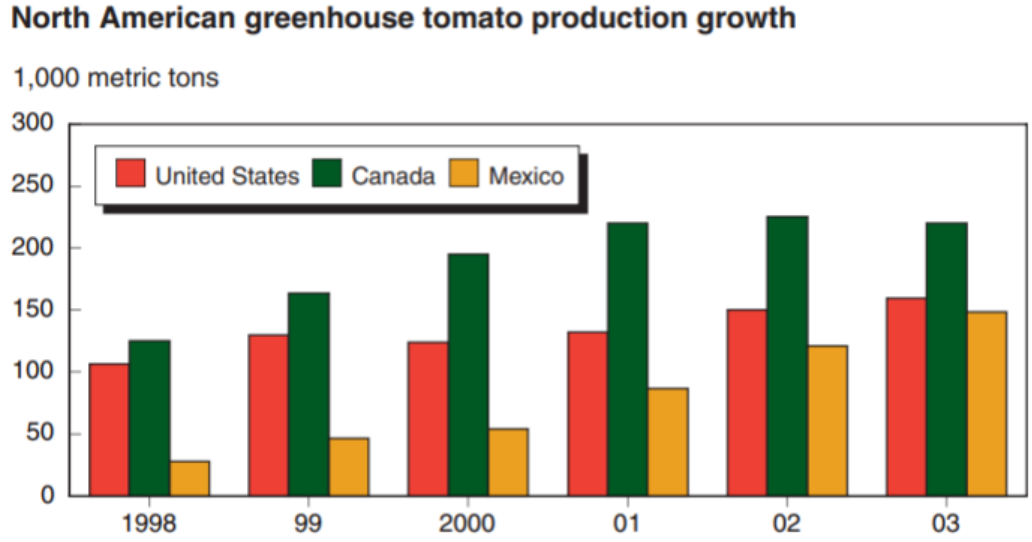

Figure 1-4. Sources: Statistics Canada; Ontario Greenhouse Vegetable Growers; British Columbia Vegetable Marketing Commission; and estimates by Cook and Calvin (Cook and Calvin, 2005).

Canada has dominated the greenhouse market in North America in terms of production. In the period from 1992 to 2003, fresh market field production decreased from 67% to 11% as growers transitioned to more profitable greenhouse operations (Cook and Calvin, 2005). Despite

Canada's clout in the market, individual growers in the U.S. tend to maintain operations three times as large, and in Mexico even larger individual operations exist (Cook and Calvin, 2005). Canadian production has embraced technology and management-based improvements in production for greenhouse operations and the favorable summer climate has allowed growers to produce tomatoes for exports nearly the whole year around (Cook and Calvin, 2005). Canada's yields boast a 494 tonne/ha average (Cook and Calvin, 2005). Mid-winter is the only time that Canada imports greenhouse grown tomatoes from both the U.S. and Mexico as well as several other countries (Cook and Calvin, 2005). Most production in Canada occurs in Ontario with 63% of the total and in British Columbia producing less than half the amount in Ontario (Cook and Calvin, 2005).

Generally, Mexico tends to have lower-technology protected cultivation in comparison to Canada and the United States, but it does have more area under protected cultivation (Cook and Calvin, 2005). Fresh market greenhouse yields in Mexico are about 156 tonnes/ha in comparison with the U.S. and Canada at about 500 tonne/ha (Cook and Calvin, 2005). This is partly a result of the lack of research and support to assist growers in determining which greenhouse technologies would be appropriate in different regions (Cook and Calvin, 2005). Additionally, 30% of production is devoted to lower yielding tomato on the vine (TOV) products (Cook and Calvin, 2005). Mexico's fresh market field production still dwarfs its greenhouse production with more than 12 times as much production occurring in the field, but protected cultivation can be found in half of its 31 states (Cook and Calvin, 2005). Most growers have allotted at least a portion of their land to some form of protected cultivation (Cook and Calvin, 2005). Plastic, instead of glass covering, is more common in Mexico, where heating is not a major concern as it is in Northern latitudes in the U.S. and Canada (Cook and Calvin, 2005). In particular, Sinaloa has more high-tech greenhouse operations than other regions with as many as 40 in 2003 (Cook

and Calvin, 2005). Major production regions include those along the coast such Baja California and Baja California Sur, Sinaloa, and Sonora, but also include areas in Central Mexico (Cook and Calvin, 2005). Mexico maintains the highest per capita consumption of tomato in North America, but it also accounts for 90% of U.S. tomato imports (Cook and Calvin, 2005). Mexico does have the advantage of producing fresh market tomatoes through the winter with no freezing days in some areas (Cook and Calvin, 2005).

In the U.S. in 2003, four large firms, totaling 205 ha of greenhouse space, accounted for 67% of total greenhouse production in the United States (Cook and Calvin, 2005). In total, the U.S. produced 159,664 tonnes of greenhouse fresh market tomatoes on 330 ha (Cook and Calvin, 2005). Some of these firms consolidated during tumultuous economic times and also relocated to different areas in order to optimize growing conditions and to access the appropriate markets year-round (Cook and Calvin, 2005). These larger firms generally turned to the South and Southwest in Arizona, New Mexico, Texas, and Mexico (Cook and Calvin, 2005). Northeastern firms were still successful and remained close to large urban centers, but they comprised only the seasonal market and could not grow year-round and remain profitable (Cook and Calvin, 2005). In the Southwest, growers could enjoy strong light levels, low humidity, high altitude, good water, and natural gas (Cook and Calvin, 2005). The negative aspects of the move include increased necessity of greenhouse cooling in the hottest summer months, adapting Dutch technology to new environmental conditions, and increased cost of transportation to markets (Cook and Calvin, 2005). In the U.S., high-technology is relatively uniform in medium and large size greenhouses, containing active climate control and hydroponic systems; and, smaller greenhouses generally operate with low- or medium-level technology (Cook and Calvin, 2005). Larger operations' technology tend to be similar to those seen in the Netherlands and BC, Canada (Cook and Calvin, 2005). Typically, greenhouses are made from glass to maximize light

transmission in the winter and for temperature control purposes (Cook and Calvin, 2005). In the U.S., large greenhouse fresh market operations yield an average of 534 tonnes/ha and can be as high as 700 tonnes/ha (Cook and Calvin, 2005). Greenhouse and high-tech controlled operations boast yields much higher than fresh market field tomatoes. For reference, in 2015, the average yield for fresh market field tomatoes in Florida was 32.3 tonnes/ha (Guan et al., 2017); and, in 2017, the national average for fresh market field and processing production was 88.2 tonnes/ha (AGMRC, 2017).

Apart from the plastic (rigid or film) and glass covering, structures can be built from a variety of materials. Frames are made from aluminum or galvanized steel and the ends of houses can sometimes be made from wood, especially when double-polyethylene plastic film is used (Peet and Welles, 2005). Double-poly consists of two layers of plastic between which a 10 cm layer of air is inflated. The two layers act as a buffer against wind and help to maintain structural integrity and temperature a few degrees warmer than a single layer. Additionally, double-poly houses prevent and disperse condensation on the inside of the structure that may result in dripping on crops, which can result in opportunity for disease.

Shapes of housing can vary according to different conditions such as expected snow-load, ventilation needs, housing that can be joined at the gutters, covering material (glass or plastic), growing system, and whether screen or artificial light is used (Peet and Welles, 2005). More modern greenhouses are typically taller (6 meters), allowing growth of taller crops, efficient use of space near the sidewalls, in addition to more climate-control equipment—fans, screens, lights, and heaters (Peet and Welles, 2005). Higher walls also increase the effectiveness of natural ventilation for open-roof configurations. Greenhouses are typically oriented in a North/South direction to optimize light, or depending on the natural climate wind is taken into consideration for temperature and ventilation purposes (Peet and Welles, 2005). For example, larger, connected

greenhouses with greater open space are more concerned with having perpendicular orientation to the wind to allow proper natural ventilation during the hottest time of the season (Peet and Welles, 2005).

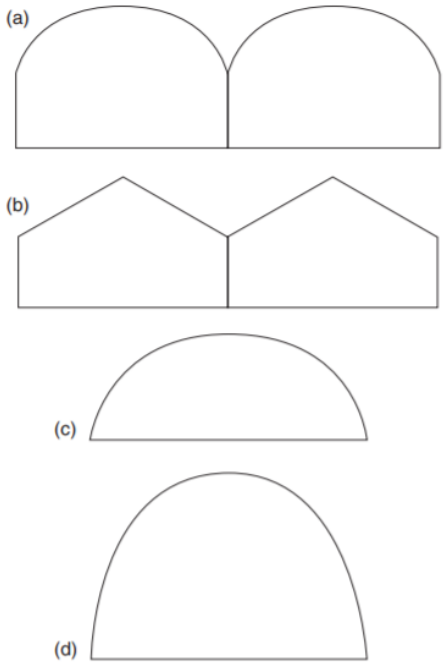

Figure 1-5. Greenhouse structures/shape: a) Gutter-connected straight sidewall with arch roof b) Gutter-connected straight sidewall with gable roof c) hoop style d) Gothic-arch frame. Source: (Peet and Welles, 2005)

The quality and yield of tomato in protected cultivation is largely determined by tomato type/variety, the technology employed, and the size of individual operations. Table 1-1 highlights the cost of production, yield, sale price received, labor, and energy consumption for both large, beefsteak and cluster type tomatoes of a single greenhouse operation in the Netherlands (Peet and Welles, 2005).

Table 1-1. Cost and perceived price received for two different types of greenhouse Grown tomatoes—cluster and beefsteak. Source: (N.S.P. de Groot, LEI, The Hague; Peet and Welles, 2005).

	Cluster	Beefsteak
Costs (US$/m^2)		
Labour	13.22	9.60
Depreciation and interest	4.62	4.18
Energy	6.31	5.94
Plant material	2.01	1.61
Other materials (excluding plants)	2.27	2.48
Delivery costs	1.11	2.81
Other costs	3.43	2.81
Total costs	32.98	29.43
Yield		
Fruit (kg/m^2)	46.7	53.4
Price received (US$/m^2)	31.94	30.00
Costs (US$/kg)		
Labour	0.26	0.18
Plants	0.04	0.03
Delivery	0.02	0.05
Total	0.70	0.54
Labour (h/m^2)	1.09	0.77
Fruit produced (kg/h labour)	45	71
Natural gas used (m^3/m^2)	60.8	56.9

Similar to field production, greenhouse growers will intercrop, or stagger tomato crops throughout the growing season in order to have a continuous supply to buyers throughout the season (Peet and Welles, 2005). Generally, greenhouse tomato growers will avoid competition with the field season, growing greenhouse crops in the Spring and Fall and maintaining empty houses for a month in mid-Summer and mid-Winter to prevent continuous infestation by any pests or diseases (Peet and Welles, 2005). During this time, growers will start and grow seedlings in separate houses that will later be transplanted into the larger growing areas (Peet and Welles, 2005). Though, in some cases growers prefer to keep their buyers and continue to grow tomato crops throughout the field season despite being less profitable (Peet and Welles, 2005).

In the 1970's and 1980's the primary cultivation method for greenhouse grown tomatoes was the "up and down system" (Peet and Welles, 2005). In this system plants are trained to twine

and upon reaching the top of the wire, vines drape down the other side. Plant spacing is usually about half a meter, or 19-20 inches. The problem with this method is that the apical meristem and the newest leaves becomes shaded within the lower parts of the plant, resulting in decreased yield (Peet and Welles, 2005). The most common cultivation method now is the "high-wire" system, which allows the leaning and lowering of the oldest parts of the plant; though, great caution should be taken to avoid any stem damage (Peet and Welles, 2005). High-wire maintains the newest growth at the highest part of the plant, maximizing sunlight and productive capacity of each plant (Peet and Welles, 2005). At the top of the wire, roller hooks are used to unwind twine. It is important to use stem clips and to wind twine around the lower stem to facilitate the lowering of the plant and giving extra support to avoid stem breakage (Peet and Welles, 2005). For those growers who wish to intercrop, this method also allows for younger seedlings to be started and planted within the trimmed canopy of older plants; allowing sufficient light to reach the new crop coming in (Peet and Welles, 2005). One row of older plants can also be removed to make room for new plants (Peet and Welles, 2005). For indeterminate plants, it is necessary to trim and remove suckers on a weekly basis with only one main stem producing fruit. If a plant becomes damage or is removed because of disease, a new stem on a neighboring plant can be allowed to grow, fill in the space, and become productive (Peet and Welles, 2005). This allows growers to maximize yield.

The single-truss method for greenhouse cultivation gained traction in the 1970's in Japan, when there was labor shortage and lack of interest from younger people to take over older growers' businesses (Okano, 2001). Though, single-truss was originally proposed by A.J. Cooper during the 1960's in the United Kingdom (Okano, 2001). In this method, main stems are pinched with only 2-3 leaves above the first truss. This allows higher density plant spacing and results in only 4-5 fruits per plant, while also substantially increasing the number of crops per year. This

system is also effective for its efficient use of light, space, nutrients, and water as well as better control in fruit uniformity. The single-truss cultivation method has several advantages. 1) Single-truss drastically reduces specialized labor necessary for training, pruning, and harvesting. 2) Elevated benches improve work posture. 3) Crop management is drastically simplified and allows the employment of regular workers at all times throughout the year for continuous tomato production and a reduction in seasonal labor peaks. 4) In controlled conditions with simple management, a focus on optimizing cultural conditions can contribute significantly to increased fruit quality. 5) There is a decrease in disease and pest incidence resulting from the relatively short growth cycle; and, this results in a decreased need for pesticide applications (Okano, 2001).

Single-truss cultivation employs a soilless culture with either nutrient film technique (NFT), rockwool, or deep flow technique (Okano, 2001). A simple, low-cost, hydroponics system is necessary for single-truss for which there are several frequent plantings per year (Okano, 2001). Researchers developed a custom closed, “wet-sheet culture” system, in which a water-retaining sheet made of non-woven fabric is used as the growing medium. The bed is made from styrene foam and does not have to be very strong as there is a low volume of nutrient-solution contained in the wells. Roots do not penetrate into the root-proof sheet, and the nutrient-solution water level is maintained automatically by a sensor connected directly to the water pump. Overflow from the system is drained into a reservoir that can be re-used later. When plants are removed and replaced, roots that have grown into the wells separate easily from the sheet.

Okano (2001) decided to re-assess the efficacy of this cultivation method to improve upon some of its weaknesses and present some alternatives. 1) Since planting density is increased, there is need for a large number of seed and nursery plants in comparison to multi-truss and indeterminate type growth habits typically practiced in greenhouse settings. 2) There is a high labor requirement for frequent replanting. 3) There is low fruit productivity for single-truss

tomatoes (Okano, 2001). One method to reduce the cost of seed in single-truss cultivation is to use plant cuttings, which can be successfully propagated in rockwool; however, propagation of commercial seed in this manner and the sale of any product may infringe on current laws (Okano, 2001). While sale of propagated cuttings is not allowed under current law, the use of cuttings by private growers is permitted (Okano, 2001). One cultivation issue with stem propagation is there is less uniformity among the plants in a single crop planting (Okano, 2001).

In addressing the high-labor requirements for frequent replanting for seedlings raised to the first flower stage, Okano suggests sowing seeds in rockwool, transferring germinated, young seedlings to ebb and flow benches for automatic supply of nutrients, and transferring seedlings to the culture bed at the true leaf stage (Okano, 2001). Additionally, to reduce the number of nursery plants by half, two-shoot training with a decreased plant density can be suitable for this single-truss system while maintaining comparable fruit quality (Okano, 2001). If multi-shoot training is performed there tends to be an increase in the incidence of blossom end rot (Okano, 2001).

Concerning low yield for single-truss systems, the researchers focused on experimental variables concerning yield as it relates to salt stress (EC determined by NaCl), soluble solids (BRIX%), fruit citrate content, and salt stress timing and optimization for improved fruit quality while avoiding incidence of blossom end rot (Okano, 2001). Yields were also improved with a change from a fixed bench system to a more uniformly spaced movable bench system, in which distance between plants can be increased and distance between benches can be decreased. The movable benches allow workers to move between benches when work is required (Okano, 2001). This allows the same number of plants in the same area to produce 25% more yield. There is potential for more yield if more compact varieties can be developed for adaptation in higher density planting. An early, compact, determinate variety fits best for single-truss cultivation. In this single truss system, there is potential for 10 tonnes/ha (Okano, 2001).

History of Tomato Breeding

Upon domestication in the Americas, tomato was transported to Europe in the 15th century and throughout the world, away from its origin and with increasingly low germplasm diversity. In a predominantly inbreeding species, genetic variation tends to decrease from generation to generation. Case in point: any one of the self-incompatible species of tomato (*S. chilense and S. peruvianum*) by itself contains more genetic variation than is contained within all of the other self-compatible species combined (Bai and Lindhout, 2007; Breto et al., 1993; Egashira et al., 2000; Miller and Tanksley, 1990; Sacks et al., 1997; Villand et al., 1998). The very narrow genetic diversity contained in germplasm brought back to Europe would ultimately result in ever-decreasing genetic diversity in cultivated tomato generations to come. Tomato domestication experienced a genetic bottleneck in which selection for single plants and subsequent progeny resulted in a cultivated tomato with extremely low genetic variation (Bai and Lindhout, 2007). Compared with the high genetic diversity in wild species, the cultivated tomato contains <5% of the genetic diversity present in wild species (Bai and Lindhout, 2007; Miller and Tanksley, 1990).

Although the tomato plant was domesticated before the Spanish arrived in South America, most breeding began more than 200 years ago in Europe, primarily in Italy (Foolad, 2007). Tomato breeding in the U.S. began in the 1870's with AW Livingston (Foolad, 2007; Stevens and Rick, 1986; Tigchelaar, 1986). Until the 1950's, there was little distinction between the fresh market and processing industries, and individual cultivars were developed for many needs (Foolad, 2007; Stevens and Rick, 1986; Tigchelaar, 1986). Now, there are two distinct industries containing either fresh market or processing cultivars, each with their own set of characteristics desirable for cultivation and consumption (Foolad, 2007). However, important breeding traits for both industries include: disease resistance, broad adaptability, early maturity,

ability to set fruit, resistance to cracking, tolerance to fruit rots, sufficient fruit cover by foliage, and fruit firmness among others (Foolad, 2007). In the processing industry there are particular traits of interest for one-time mechanical harvesting and processing purposes. These traits include concentrated fruit set and ripening, firmness, high SSC, total acidity, pH, color, and viscosity (Foolad, 2007). The fresh market industry includes tomato fruits of all different size, shape, and color. For large, slicing tomatoes, cultivars are developed for good firmness and shelf-life, uniformity of fruit size, shape, and ripening, free from blemishes and abnormalities, as well as taste and flavor (Foolad, 2007). There are many other fresh market types that include plum, cherry, grape, and most recently cocktail and specialty varieties. In addition to many of the traits described above such as yield, disease resistance, and firmness; these smaller tomato types are developed with the priority of having a sweet or unique flavor and good texture.

Developing cultivars with high yield has always been a top priority. In fact, if a tomato fruit has little else but high yield it can be considered an acceptable variety; however, preference for high fruit quality and taste is becoming more desirable in the last several decades. Increased yield has also become associated with many other selected traits. For example, high yield can be achieved by selecting for plants with high disease resistance (Foolad, 2007) and plant vigor, commonly found in more wild types. Other characteristics that may lead to higher yields include increased tolerance to abiotic stresses and earliness (Foolad, 2007) for increased number of crops per season and to avoid frost. The University of Florida has made heat tolerance a priority so that cultivars may continue to thrive and set fruit in hot and humid conditions (Foolad, 2007).

Breeding for disease resistance has also become a top priority, and is considered as important if not more important than developing cultivars with the highest yield (Foolad, 2007). This is absolutely necessary to combat extremely destructive diseases such as tomato yellow leaf curl virus and late blight. Most often, resistance genes come from exclusively wild type tomato

species (Foolad, 2007). Developing cultivars with a high level of disease resistance has typically been achieved through phenotypic selection in disease screening techniques through traditional breeding; however, transferring these characteristics from wild species to cultivated varieties is difficult and time-consuming (Foolad, 2007). Development of more modern techniques such as marker-assisted selection (MAS), gene identification, and mapping in the past four decades have contributed greatly to more precise and timelier introgression of important resistance genes (Foolad, 2007). Most contemporary commercial hybrid cultivars now contain as many as ten different disease resistance genes (Foolad, 2007). Many different genes have been discovered for host resistance in the cultivated tomato, including: *Pto*, *Prf*, and *Fen* for bacterial speck (*Pseudomonas syringae*) (Martin, 2003; Ronald et al., 1992; Salmeron et al., 1994), *Rx1*/*Rx2*/*Rx3* for bacterial spot (*Xanthomonas campestris*) (Wencai Yang, 2005), *Cf-2* for tomato leaf mold and root parasitic nematode (*Cladosporium fulvum* and *Globodera rostochiensis*, respectively) (Lozano-Torres et al., 2012), *Mi1*/*Mi2*/*Mi3* for root-knot nematode (*Meloidogyne incognita*) and *Ve1/Ve2* for Verticillium wilt (*Verticillium dahlia* and V. *albo-atrum*) (Soya and Tanyolac, 2010), *Tm-1*, *Tm-2*, *Tm-2*^{2} for tobacco/tomato (TMV/ToMV) mosaic virus (*Tobamovirus*) (Hall et al., 1979; Zhang et al., 2013), *Ty-1*/*Ty-2*/*Ty-3*/*Ty-4*/*Ty-5*/*Ty-6* for tomato yellow leaf curl virus (*Begomovirus*) (Yan et al., 2018), *I*/*I-2*/*I-3* for tomato Fusarium wilt (*Fusarium oxysporum*) (van der Does et al., 2018), and *Ph-1*/*Ph-2*/*Ph-3*/*Ph-5* for late blight pathogen (*Phytophthora infestans*) (Ohlson et al., 2018).

Tomato breeding for resistance to insect pests has received much less effort than breeding for disease resistance, despite there being many insects that cause devastating crop losses (Foolad, 2007). Insect species that affect tomato include mites, whiteflies, aphids, thrips, stink bug, cutworms, and numerous species within the genera Lepidoptera, Coleoptera, and Diptera (Foolad, 2007). *Solanum habrochaites* and *S. pennellii* are most notable for their insect resistance

(Foolad, 2007; Tigchelaar, 1986) with *S. habrochaites* being resistant to 16 different insect species (Foolad, 2007; Weston et al., 1989); and, several other wild types (*Solanum lycopersicum* var. *cerasiforme, S. pimpinellifolium, S. cheesmaniae, S. chmielewskii, S. peruvianum, S. peruvianum, and S. chilense*) have been reported to have resistance as well (Farrar and Kennedy, 1991; Foolad, 2007). Breeding for insect resistance is difficult because of linkage drag of undesirable traits (Foolad, 2007; Hartman and St Clair, 1998; Kohler and St Clair, 2005; Muigai et al., 2003; Tigchelaar, 1986).

Importance of Wild Species

Tomato like many other domesticated crops have developed domestication syndrome, defined by a crop's tendency to develop morphological and physiological traits associated with compact growth habit, increased earliness, reduction/loss of seed dispersal and dormancy, gigantism, and increased morphological diversity in fruits (Bai and Lindhout, 2007; Frary et al., 2003). Studies on domestication syndrome have elucidated that domesticated crops differ from their wild relatives for many traits and that these traits are governed by a relatively small number of genetic loci (Bai and Lindhout, 2007; Frary et al., 2003). Tomato and other Solanaceous crops such as pepper and eggplant share these common QTL's despite their independent domestication—loci associated with similar traits among these different crop species co-localize (Bai and Lindhout, 2007; Doganlar et al., 2002; Frary et al., 2003; Frary et al., 2000; van der Knaap et al., 2002). Naturally, humans have selected directly for large fruit as well as uniform germination and seedling vigor, while indirectly selecting for traits associated with seed size/weight and soluble solids content that result from pleiotropic effects: QTL's for seed weight, fruit weight, and soluble solids content are all in close proximity to each other (Bai and Lindhout, 2007; Doganlar et al., 2000; Tanksley, 2004). Fruits and seeds in domesticated crops became bigger, and plants perform more uniformly, but fruits contain less soluble solids. For example,

QTL *sw4-1*, contributes to seed weight variation and is likely the cause for both the variation for seed weight observed in wild types and uniformity in domesticated types (Bai and Lindhout, 2007; Doganlar et al., 2000).

It was not until 1940 that cultivated tomato known as landraces and heirlooms (cultivars procured and associated with particular areas or communities) were re-introduced with wild species. Dr. Charles Rick noted that when the cultivated tomato is crossed with wild species the progeny embodied a broad array of novel genetic variation. Dr. Rick organized expeditions to the Andes and collected thousands of accessions from various wild tomato species that are maintained at the Tomato Genetics Resources Center (Bai and Lindhout, 2007).

The Botanical and Experimental Garden in the Netherlands keeps the most expansive ex situ plant repository of non-tuberous *Solanaceae* species. They have also developed a mutation population, an isogenic tomato 'mutation library', produced from exposure to EMS (ethyl methane sulfonate) and fast neuron mutagenesis. These populations can serve to investigate gene function at the molecular level (Bai and Lindhout, 2007).

In total, about 83,000 different tomato accession exist in repositories around the world, including: The Tomato Genetic Resources Center (TGRC), the USDA-ARS Plant Genetic Resources Unit (PGRU), the World Vegetable Center (AVRDC), the Svalbard Global Seed Vault (SGSV), and European collections (Hopkin, 2008). Many more seed banks exist throughout the world for the purpose of conserving native and diverse wild germplasm of various species.

In addition to the collection and maintenance of tomato germplasm, the regions of northern Chile, Bolivia, Ecuador, and Colombia remain the center of species origin, where wild tomato species populations continue to inhabit and develop (Bai and Lindhout, 2007). It is of utmost importance to continually discover and maintain species diversity in these regions as they

represent the greatest asset for novel and exotic traits and for the reintegration of a diverse genome into the cultivated tomato.

Contemporary Breeding Methods and Challenges

Early in the 20th century, public institutes, primarily in the U.S., began to play a larger role in tomato breeding, specifically with more disease resistant varieties in the 1920's and 1930's (Bai and Lindhout, 2007). The advent of private seed companies marked a shift from open-pollinated to hybrid varieties. Hybrids combine desirable qualities from two different homozygous parental lines often with different genetic backgrounds that contain traits complementary to each other. Since the 1970's, emphasis has been placed on the development of hybrid varieties (Foolad, 2007). It has been reported that hybrid varieties have increased heterosis, or hybrid vigor, in which the hybrid outperforms each of its parents for its respective traits (Foolad, 2007). However, more importantly, hybrids make it possible to combine several different beneficial traits in one variety (such as multiple disease resistance) and also contribute to the protection of breeders' research investment (Foolad, 2007). Hybrid seed discouraged propagation of subsequent generations by growers since progeny would segregate and selection would be necessary; but, the advantages of hybrid varieties were so great that farmers were willing to buy new hybrid seed each season despite higher seed prices (Bai and Lindhout, 2007; Dorst, 1946). The first hybrid variety, 'Single Cross', was released in 1946 (Dorst, 1946).

It is in public institutions that researchers have been able to focus on long-term projects, specifically those regarding introgression of wild germplasm for traits such as disease resistance, increased soluble solids content (SSC), and increased fruit lycopene into the cultivated tomato.

There are more than 200 diseases that affect the cultivated tomato worldwide as a result of low genetic variation (Lukyanenko, 1991). Therefore, it has become a necessity to discover

genes inherent in the tomato genome that confer natural host resistance. Developing resistance varieties is an ongoing effort to battle against pests and diseases that adapt to plant resistance and control methods. For example, widespread use of pesticides creates a high pressure on pathogens in which they are able to adapt and overcome the control method, and eventually pathogens overcome plant host resistance. Integrated Pest Management (IPM) is a good way to balance out the control methods for pests and disease and reduce the pressure from any one method. IPM encourages the use of cultural practices such as proper field selection, crop rotation, soil and water tests, equipment sanitation, and removal of debris, in addition to use of several different pesticides with various modes of action. This is the case for when a grower wishes to protect against any of either weed, insect, bacterial, fungal, or nematode pests.

IPM and particularly the practice of developing natural resistance in crop varieties extends the time period in which pathogens may overcome the plant resistance, and is even more effective when there is cascading resistance, or resistance that is conferred from multiple genes within a single cultivar. Not only does this more effectively help to control pest infestation and outbreaks, but it also reduces the need for widespread and often excess use of chemical pesticides that have become cause for concern among consumers for health and environmental safety reasons.

In addition to breeding for disease host resistance, there is an increasing demand by consumers for better fruit quality associated with taste, texture, aroma, and color. Introgression of these traits presents considerable difficulty as their complexity often comes with pleiotropic effects, carrying undesirable horticultural traits via linkage drag (Chen et al., 1999). Wild species, *S. cheesmaniae* and *S. pimpinellifolium*, are two red-fruited wild species that are most advantageous for introgressing fruit quality traits into the cultivated tomato; although, their smaller fruit size can compromise yield potential. The more distantly related green-fruited species

such as S. *habrochaites*, *S. pennelli*, and *S. peruvianum* are less desirable for fruit quality characteristics (Chen et al., 1999). It is with the advent of Marker-Assisted Selection (MAS) and QTL mapping that fruit quality traits can be effectively introgressed with the reduction of undesirable pleiotropic effects (Chen et al., 1999).

Tomato Breeding at Penn State

During the domestication and early breeding of the large type tomatoes, the cultivated tomato has developed a narrow genetic base resulting from a few genetic bottlenecks as well trait selection by breeders and distributors, primarily in relation to increased shelf-life, shipping, and large, deep fruit for slicing purposes. This selection practice has compromised the quality and nutrition of large type tomato fruit in the market. Breeding for traits such as increased yield, durable disease resistance, increased nutritional content, and fruit quality is of great importance for future food security, sustainable farm practices, and human health. It remains a constant effort to improve upon existing crop varieties in achieving these goals. More recently, there have been efforts to improve upon fruit quality while maintaining previously selected traits. Yield and fruit size traits will always be important in a tomato breeding program; however, an increasing importance is now placed on developing tomatoes with wider genetic diversity. Utilizing related wild species as one part of a breeding program is effective in this respect and often it contributes to more durable disease resistance, increased nutritional content, and fruit quality. In the PSU Tomato Breeding Program, initiated in the late 1990s, Dr. Majid Foolad and his team have made diligent efforts to identify genetic sources of desirable traits, including resistance/tolerance to biotic and abiotic stresses, fruit quality, early maturity and high yield, within the related wild species of tomato. The long-term goal of the program has been to develop superior new breeding lines and hybrid cultivars of tomato suitable for commercial production in PA and the US NE.

Plant breeding programs can spend 10-15 years selecting plant germplasm for superior phenotypic traits in the field. Plant material with variable traits are selected in different generations and self-pollinated to maintain beneficial qualities and reduce variability into the next generation. This long process eventually culminates in procuring superior inbred lines for use in hybrid production. One of the main goals of the PSU tomato breeding program has been to combine lines with complementary qualities—those qualities acquired by introgression from wild types (e.g. disease resistance and high fruit lycopene content) with other lines containing exceptional horticultural characteristics such as determinate, compact plant type, and high yield. Hybrid production can combine the best of both parental lines and produce a commercially competitive tomato with increased heterosis (hybrid vigor). Due to dominance and epistatic effects, traits in hybrid cultivars may be enhanced. Interactions between alleles of distantly related tomato species (i.e. wild type and cultivated tomato) are known to produce effects for loci controlling fruit weight, locule number, fruit firmness, soluble solid content, sugars, and acidity (Causse et al., 2007). Hybrid crosses may result in a tomato plant that not only contains the best characteristics of each of its parents but also enhanced qualities that outperform both parents for their respective beneficial traits. For these reasons, the PSU tomato breeding program is developing many experimental hybrids with the hope of identifying those which would be commercially competitive and marketed.

Since 1999, The Pennsylvania State University Tomato Breeding and Genetics Program, led by Dr. Majid R. Foolad, has worked on developing tomato fresh market and processing lines for the development of hybrid tomato varieties. The program has focused on developing cultivated tomato adapted to Pennsylvania and the Northeast for both high fruit quality, increased fruit lycopene content, and disease resistance to both early blight and late blight diseases.

First, fresh market and processing tomato lines were developed over many years prior to production of hybrids. These lines were developed much in the same way described above. Briefly, for large type, determinate fresh market germplasm (slicers), plants are selected on an individual basis. Fruits are harvested from that plant, processed, stored, and planted the next year in the field for another round of evaluation. Selections are continuously made year after year and records are taken to keep track of pedigree. After 4-5 generations of selection, the lines contain a high level of homozygosity (87.5% to 93.75%, respectively) appropriate for assessment as potential parents for use in production of experimental hybrids. Beginning in early generations, plants are selected for high yield, high harvest index, compact growth habit, plant vigor, fruit coverage, disease resistance, fruit firmness, large fruit size, uniformity of fruit shape/size/ripening, resistance to biotic and tolerance to abiotic stresses, resistance to cracking and raincheck, and reduced occurrence of physiological fruit disorders/abnormalities such as sunscald, zippering, yellow shoulder, blockiness, catfacing, and large, apparent scars on the stem and blossom ends. Fruits are cut open and assessed for locule distribution, pericarp and wall thickness, grey wall and white tissue, internal color, and taste.

Two key areas of focus in the Penn State Tomato Breeding Program have been the development of tomato lines with high-fruit quality (specifically increased fruit lycopene content) and greater resistance to early blight (EB) late blight (LB) diseases. For example, in a screening of ~300 accessions of the wild tomato species *S. pimpinellifolium*, one accession (LA2093) was identified for having seven-fold higher fruit lycopene content than commercial cultivars (Hyman et al., 2004). In subsequent genetic mapping studies, two QTLs responsible for increased fruit lycopene content were identified and mapped and found to be on chromosomes 7 and 12, termed *lyc7.1* and *lyc12.1* (Ashrafi et al., 2012). Since *S. pimpinellifolium* can be easily hybridized with the cultivated tomato, a series of backcrosses were performed in order to introgress the high-

lycopene genes into cultivated tomato lines for each of cherry, grape, plum, processing, and large fresh market lines, and advanced elite breeding lines were developed (MR Foolad, unpublished data). These lines were also improved for many other desirable horticultural characteristics. Most recently, select elite lines have been used to produce experimental hybrids for commercial evaluation.

Several genes have been identified and deployed in different tomato breeding programs for increasing fruit lycopene content, including *hp-1 and hp-2* (high pigment) and *ogc* (old gold crimson). All these genes were identified from spontaneous mutations. The *ogc* gene is the most commonly used in production of commercial tomato cultivars and contributes approximately 25% increase in lycopene concentration in the homozygous condition (Ronen et al., 2000). The *hp* genes are lycopene enhancers that are involved in the light-signaling pathway (Kinkade and Foolad, 2013). There are often undesirable pleiotropic effects observed in the *hp* mutations that result in linkage drag of undesirable genomic background traits into the target tomato cultivar. In a more recent study, the *lyc12.1* QTL for increased fruit lycopene concentration was identified and genetically mapped using early filial (e.g. F2, F3, F4) and advanced generations (i.e., in recombinant inbred lines, RILs) (Ashrafi et al., 2012). *Lyc12.1* has no known pleiotropic effects and is therefore very desirable for producing inbred lines to be used in tomato breeding programs. *Lyc12.1* was identified in *S. pimpinellifolium* accession LA2093 (Ashrafi et al., 2012). This QTL significantly increases fruit lycopene content in both heterozygous and homozygous conditions with no significant difference in concentration between the two (Kinkade and Foolad, 2013). This suggests that the contributing allele from the wild parent, LA2093, has dominance effects and can be more easily transferred to breeding lines. *Lyc12.1* contributed a remarkable 52-70% increase in fruit lycopene content (Kinkade and Foolad, 2013).

The late blight (LB) disease, caused by *Phytophthora infestans*, represents a dire threat to tomato growers, especially in the Northeastern U.S. Its destructive nature is such that once it has become established in a tomato field, it can destroy a crop in 5-7 days. In tomato, several LB resistance genes have been discovered, including *Ph-1*, *Ph-2*, and *Ph-3*. However, it is a perpetual effort to continue developing LB resistance. *Ph-1* has become largely ineffective to the spread of LB as a result of the pathogen's ability to sexually reproduce when two or more mating types are present in one area. New LB pathogen types have emerged in the last several decades that have overcome *Ph-1* host resistance. *Ph-2* also used to be effective for LB control, but now its resistance is characterized only by its ability to slow the spread of the disease. *Ph-3* is the most effective resistance gene against LB, and it is currently present in several commercial varieties. Further, resistance to LB is more effective when *Ph-3* is combined with *Ph-2*. A relatively new LB resistance gene, *Ph-5*, has been discovered in the tomato breeding program at Penn State, but has yet to be commercialized in any varieties. *Ph-5* was determined to confer as much LB resistance as *Ph-2*/*Ph-3* combined. At Penn State, many processing and FM tomato lines have been developed with LB resistance, and many experimental hybrids containing *Ph-5*, *Ph-5*/*Ph-2*, *Ph-5*/*Ph-3*, and *Ph-5*/*Ph-3*/*Ph-2* have been developed.

Starting in 2013, the Penn State tomato breeding program has developed hundreds of large type, experimental FM hybrids. Hybrid seed production in our program has primarily occurred in the greenhouse during the Winter/Spring months prior to the summer field season. Manual crosses are performed by collecting the pollen from one parent (designated as male contributor) and emasculating (removal of anther cone) the flower on a uniquely different chosen parent (designated as the female contributor). The resulting pollination and fertilization produce a fruit that contains hybrid seed. Once ripening begins, the seed inside the fruit are mature and the fruit can be cut open and the seed extracted. Seed are fermented for 2-3 days to facilitate the

break-down of seed gels and improve germination rates. Then, the seed is treated and cleaned in a 10% bleach solution for 15 minutes, and later heat-treated for the killing of any potential bacteria or viral pathogen.

F1 hybrid plants are often highly heterozygous and an F1 hybrid variety a homogenous population resulting from the combination of its two homozygous parental genotypes. Hybrids are assessed in a manner similar to the above-stated selection of traits for inbred lines. Once hybrids are evaluated, breeders can determine which parents are most compatible and which parents are less useful for further hybrid production. Parents that produce many good hybrids with many other parental lines have good general combinability; whereas parents that produce good hybrids with only a few other parents have good specific combining ability. Both parents can be useful for further production of new hybrids in additional unique crosses; however, those parents with high general combining ability are more desirable as they are more likely to produce a greater number of high-performing hybrids.

In 2013, the Penn State tomato breeding program produced and evaluated more than 300 large type FM hybrids. Hybrids were developed from high-lycopene lines combined with lines containing early blight (EB) resistance. Beginning in 2017, newly developed *Ph-5* lines were used in crosses for experimental hybrids containing high-lycopene, EB resistance, and LB resistance with one, few, or several LB resistance genes. Several hybrids evaluated in this thesis project are more recently produced in 2018 along with nine other elite 2016 experimental hybrids.

Thesis Objectives

The purpose of this thesis project was to evaluate select number of Penn State fresh-market tomato hybrids for fruit quality and other desirable horticultural characteristics across several locations in Pennsylvania, and compare them with a few commercial cultivars of tomato commonly grown in Pennsylvania.

Chapter 2

Materials and Methods

Overview of Projects

In the Summer of 2017, 22 Penn State advanced large type FM hybrids were selected from among hundreds of hybrids for evaluation. These hybrids were evaluated for fruit quality and yield in a replicated trial at the Russell E. Larson Agricultural Research Center in Rock Springs (Pennsylvania Furnace), Centre County, PA. In 2017, hybrid variety trials were also conducted at PSU Southeast Research Center, Landisville, PA. In the Winter and Spring of 2018, many more crosses were made with newly developed LB resistant lines and new hybrids developed. In Summer 2018, 18 of the previous 22 varieties were evaluated, but only a limited amount of data was collected due to torrential rains and severe flooding in the field. In 2019, we narrowed down the number of Penn State hybrids to 12, expanded trials to several cooperating farms in Pennsylvania, and included a few Penn State top-performing LB-resistant hybrids side by side with three standard commercial cultivars. The 2019 trials included four farms locations in PA, in addition to the main research farm at Rock Springs. At five sites total, 15 varieties (12 PSU experimental hybrids and 3 commercial standards) were visually evaluated in three replications at each farm, using a split-plot design with randomized complete block design.

In all three years at the Penn State research center (Rock Springs), seed was sown in the greenhouse in late April and provided with Jack's high-phosphorous (N-P-K—9-45-15) starter fertilizer. One week prior to transplanting in the field, all seedlings were treated with fungicide and insecticide for initial protection against pathogens and pests. Deep and chisel-plowing were performed in early and mid-May weather-permitting, and in mid to late-May raised beds with matte black plastic were prepared at 7-feet center to center. At 5-6-week-old, seedlings were

transplanted in to the field during the first week of June (June 7th—2017, June 1st—2018, June 3rd—2019), and fertigated with Jack's General Purpose 20-20-20 fertilizer upon transplanting and on weekly basis afterward (5 lbs/acre/week) for six weeks. Plant spacing in the field was 36 inches to accommodate individual plant evaluation and selection work in other parts of the field. As plants began to mature and become bushy with many trusses of young green fruit, nutrients were switched to Peters Excel 15-5-15 Cal-Mag Special fertilizer on a weekly basis (5 lbs/acre/week) until about half the fruit on plants became ripe. Cal-Mag Special fertilizer was applied beginning on July 15th until August 19th. When plants were mature with at least half the fruit ripe, fungicide applications were applied on a weekly basis in an alternating fashion to prevent disease infestation in the field in the latter portion of the season. Fungicide products included: combination of Tanos and Bravo in one application and Pervicur Flex and Bravo in the subsequent application.

2017 Preliminary Yield and Fruit Quality Trials

Preliminary yield and fruit quality trials were conducted for 22 large type FM (slicers) PSU experimental hybrids (coded as PSFH-16) in the field at Russell E. Larson Agricultural Research Center. Eighteen of the hybrids were planted in two replications across the field, and four hybrids were planted in only one replication (due to insufficient seed) and so were not included in yield estimates. Each plant in the 6-plant plots were harvested at the red-ripe stage a total of six times throughout the season. In few plots, there were only 4-5 plants. Yield per hectare was determined by first obtaining single plant production for each hybrid and multiplying it by the number of plants expected to be in a hectare based on our field setting—7-feet center to center rows and 3-feet plant spacing (5,125 plants/ha). Fruit were graded and sized according to USDA standards 1, 2, and 3. Grade 1 fruit were perfect tomatoes with no blemishes. Grade 2 fruit were those with one minor blemish, and grade 3 fruit were those with several blemishes (e.g.

diseases or physiological disorders). Grades 1 and 2 were considered marketable fruit, and all grade 3 and small fruit (<2.25 inches) were considered culls. All marketable fruit were counted and weighed, and all culls were counted and weighed separately to obtain unmarketable yield. Medium size fruit were 2.25-2.50 inches in diameter. Large size fruit were 2.50-2.75 inches in diameter. Extra-large size fruit were 2.75-3.50 inches in diameter. Jumbo size fruit were greater than or equal to 3.50 inches in diameter. All diameter measurements were taken across the equator of the fruit. At the PSU Southeast Research Center, 11 experimental hybrids were planted in 4-5 replications in a completely randomized design. One hybrid contained only one rep and was not included in the analysis. Fruit were harvested and evaluated for USDA standards, defects, and marketable and unmarketable fruit weight were measured.

2018 Replicated Yield and Fruit Quality Trials

The 2018 trials included 18 of the previous 22 hybrids in three randomized replications throughout different parts of the field to account for soil variability and micro-environments. Before the first harvest, Pennsylvania in general, and particularly Centre County, received record rainfall amounts with the highest precipitation ever recorded in State College, PA. Precipitation amounted to 63.73 inches by the end of the year, surpassing the 1996 record of 59.30 inches, and was well above the annual average precipitation of 39.64 inches. As a result, our tomato field was flooded and very little data was collected.

2019 Multi-Location Visual Evaluation

For visual evaluation of multi-location trials (MLTs) in 2019, seed for 15 varieties were sent to two growers, and transplants were prepared in the same manner as stated above for two other growers. Growers were instructed to cultivate the plants in the same way that they typically performed on their farm. Farm locations were selected based on growers' interest in participating

and to represent several geographical locations in Pennsylvania. At all farms, we conducted visual evaluations for various traits.

For trials in 2019, the number of Penn State hybrids was reduced to 12, which included several from the previously-chosen 18 hybrids plus a few new hybrids, which were deemed very desirable based on our own evaluations as well as data obtained from seed companies. In addition, three new LB-resistant hybrids produced in 2018 (coded: PSFH-LBR-18) were included in MLTs as they showed good potential based on the limited visual evaluation conducted in the less-damaged part of the field in 2018. Thus, nine PSFH-16, three PSFH-LBR-18, and three popular commercial cultivars (Red Deuce, Mt. Fresh +, Mt. Merit) were visually evaluated for various traits in three randomized replications at each of the five locations in PA. The visual evaluation included characteristics for qualitative notes as well as quantitative traits that were given a visual score of 1-5. Traits scored qualitatively with remarks included: plant type (determinate, semi-determinate, indeterminate), plant habit (prostrate, upright), plant size (small, medium, large), green shoulder vs. uniform ripening, cluster size, fruit size (small, medium, large, extra-large, jumbo), fruit shape (flat, round-flat, round, round-globe, globe, deep-globe), and maturity (early, mid, late). These data are valuable for breeding purposes, but are not included in the results presented here. Traits evaluated based on scores of 1-5 (1-worst, 5-best) included: plant disease resistance, fruit disease resistance, estimated yield, stem end size/quality, blossom end size/quality, firmness (by feel), internal fruit color (visual evaluation of degree of redness), external fruit color (visual evaluation of degree of redness), uniformity fruit size, taste, and an overall calculated score from the average of all scored traits. In addition to the research center at Rock Springs, the four other farms located in PA included Altoona in Blair County, Berwick in Columbia County, Homer City in Indiana County, and York in York County. Each location was evaluated on one date: Rock Springs (August 19th), Altoona (August 14th), Berwick (August 16th), Homer City (high-tunnel, October 4th), York (August 29th).

2019 Fruit Quality Evaluation

Five tomato fruit were collected for each of the 15 varieties in 2019 replicated trial at the Russell E. Larson Agricultural Research Center. Fruit were evaluated for quality characteristics: pH, soluble solids content (SSC), and % acidity. The same fruit were analyzed using a spectrophotometer on whole fruit and puree samples to estimate lycopene content according to equations derived in a study previously performed in our program, in which transformation of spectrophotometric data was correlated with measurements of lycopene by HPLC. Previous research in the tomato program at Penn State had indicated that estimating lycopene from the a^{*4} transformation of a* value for puree obtained from chromaticity values (L*, a*, b*, C*, h*) showed an R^2 value of 0.945, indicating a good predictor of lycopene content based on chromaticity values (Hyman et al., 2004). Similarly, estimation of lycopene based on whole fruit transformation of $(a^*/b^*)^{2.5}$ correlated with lycopene measurements with an R^2 value of 0.736 (Hyman et al., 2004). Equations for estimating lycopene based on puree and whole fruit chromaticity transformations are provided below.

$$\text{Puree model: Lycopene (ug/g)} = 5.8 + 3.735 \times 10^{-5}\, a^{*4} \qquad R^2 = 0.945$$

$$\text{Whole fruit model: Lycopene (ug/g)} = -0.4 + 53.5\, (a^*/b^*)^{2.5} \qquad R^2 = 0.736$$

Image analysis was performed on the same samples of fruit used in lycopene estimation as stated above. Pictures were taken of both the inside and the outside of tomato fruits and analyzed using Tomato Analyzer 4.0 developed by Ohio State University's van der Knaap Laboratory. Chromaticity values were obtained from image data, and similar lycopene estimation was performed using equations derived from a study in which correlation between lycopene estimates based on chromaticity values obtained from image analysis and lycopene measurement rendered high R^2 values. Although these equations were derived from image analysis for whole

fruits, we used them to estimate lycopene based on chromaticity values for both internal and external images of fruit. These equations are used to estimate lycopene for chromaticity values obtained from image analysis and are provided below (Saad et al., 2016):

$$\text{Lycopene (ug/g)} = 22.809\ (a^*/b^*) + 13.846 \qquad R^2 = 0.91$$

$$\text{Lycopene (ug/g)} = -31.139\ \ln (h^*) + 148.96 \qquad R^2 = 0.82$$

At the Penn State research station (Rock Springs), five ripe fruit were harvested from each of 45 plots. Samples were stored in 34 degrees Fahrenheit cold-storage until analysis one week later. First, all fruits were washed of any soil and plant debris, and fruits were dried before any analysis was performed. All stages of analysis were performed on each sample before moving on to the next sample. Whole fruit colorimeter values were collected using a handheld Konica Minolta Chroma Meter CR-400. Three readings were taken on the outside each of the five fruit to account for any variation in ripening. A photobooth was setup with a black background and consistent lighting. Whole fruit pictures were taken for three of the five fruit. Fruits were then cut open and pictures were taken of the slice cross section (equatorial cut). The bottom halves of all five fruit were then homogenized in a blender and three puree colorimeter measurements were taken through plastic petri dishes. The puree was mixed to obtain representative sample of the tomato puree prior to measurements, and additional puree was poured into 50 ml BD Falcon polypropylene conical tubes. Thermo Scientific Sorvall Legend RT+ Centrifuge was set at 4,000 RPM and 25 degrees Celsius for 15 minutes to separate tomato puree layers. The transparent supernatant layer was used to measure pH, soluble solids content (Brix), and % acidity. The SympHony SP70P was used to measure pH of each sample, and an ATAGO PAL-BX | ACID F5 was used for measuring Brix and % acidity. Brix was measured with a 200 ul sample of supernatant. The sample was then diluted 50X for acidity measurement.

Lycopene estimation was performed for chromaticity values with equations provided by Hyman et. al (2004) as stated above for both whole fruit and puree colorimeter readings. Data was compiled and transformations were performed as appropriate for estimating lycopene according to Hyman et al. (2004). Lycopene estimation was also performed for chromaticity values obtained from image analysis of whole fruit and sliced fruit with equations developed by Saad et al. (2016). Before image analysis in Tomato Analyzer 4.0, images were cropped and enhanced to 500 dots per inch (DPI) and converted from JPG to TIF files. Tomato Analyzer 4.0 software was developed to automatically sense the perimeter of tomato fruits; however, few fruit in some samples were not recognized. The perimeter of fruit was then re-drawn to exclude light shine due to excess light and shadow in order to obtain a representative and relatively uniform area of each whole fruit. For sliced fruit, this was more difficult, as the wetness of tomato slices was difficult to avoid. The software was then used to analyze chromaticity values for which lycopene estimation is performed. Chromaticity values are: L* (lightness/luminescence), a* (intensity red + / green –) values, b* (intensity yellow + / blue –) values, C* (chroma = sqrt(a^{*2} + b^{*2})), and h* (hue = arctan (b* / a*)).

Statistical Analyses

All data were recorded in Microsoft Excel 2016. Basic analysis was performed in Excel to obtain averages, standard deviations, histograms for 2017 yield and fruit quality, charts for lycopene estimation and other fruit quality characteristics (BRIX, % acidity, pH), and to create suitable data formats for further analysis in SAS Studio University Edition 9.4. The 2019 MLTs were analyzed in SAS using various functions, including, PROC MIXED, PROC GLIMMIX, PROC GLM, and PROC SGPLOT. Further, PROC MIXED and PROC GLM were used for analysis of variance, in which CLASS variables included genotype, environment (location), and replication nested within location. The models for each of MIXED, GLIMMIX, and GLM

included genotype main effects and genotype x location (G x E) interactions with replication nested in location for each trait observed. PROC MIXED has the advantage of being able to analyze data sets with missing values, so initial analysis used PROC MIXED in combination with PROC GLIMMIX for multiple comparisons to further parse out the data for individual interactions using the SLICEDIFF statement. In PROC GLIMMIX, the SATTERTH option approximates the denominator degrees of freedom based on the linear mixed model (trait = G Env G*Env Rep(Env)); and, LSMEANS and SLICEDIFF statements were used to determine if there were any significant interactions between genotype or location for a given trait (alpha = 0.01). PROC GLM was used to obtain ANOVA tables and F-values for the model for all traits observed, and to determine significance for genotype main effects for all traits with LINES TUKEY in the MEANS statement. PROC SGPLOT was used to visualize the mixed model in boxplot formats, which effectively depicted hybrid performance and potential G x E interactions for hybrids in difference locations. PROC GLM was also used for analyzing fruit quality between genotypes for each of fruit lycopene content, BRIX, % acidity, and pH. The MEANS statement in PROC GLM was used with LINES TUKEY (genotype main effects, alpha = 0.05) statement to visualize significant differences and produce classes of significance for all experimental hybrids.

Chapter 3

Results and Discussion

2017 Preliminary Yield and Fruit Quality Trials

At the Russell E. Larson Agricultural Research Center, the two replications were not randomized throughout the field, but instead were planted side by side. Therefore, it was possible that hybrids performed better on one side of the field, resulting from more favorable conditions such as higher elevation or better soil qualities. Hybrids PSFH-16-2, -7, -8 and -10 were located at a lower point in the field where there was occasionally standing water during the season. These hybrids tended to be earlier with no fruit harvested on the last harvest date. It is also worth noting that there were groups of hybrids close to one another that shared the same maternal parent. For example, hybrids -2 to -19 shared a maternal parent, hybrids -46 to -49 shared a maternal parent, hybrid -85 did not share a maternal parent with any other hybrids, and hybrids -114 to -126 shared a maternal parent. The general trend of the bar chart indicated that there was a possibility that yield was increasing across the length of the field due to either field position, soil characteristics, or commonality between hybrids for the maternal parent. Therefore, statistics were not performed to find any significant differences among experimental hybrids for yield estimate. However, hybrids PSFH-16-49, -65, -85, -115, -117, -118, -121, and -126 demonstrated above average for the estimated yield, and hybrids -49, -118, and -126 were perceived to stand out among the others for both demonstrated marketable yield, and relatively lower proportion of estimated cull weight.

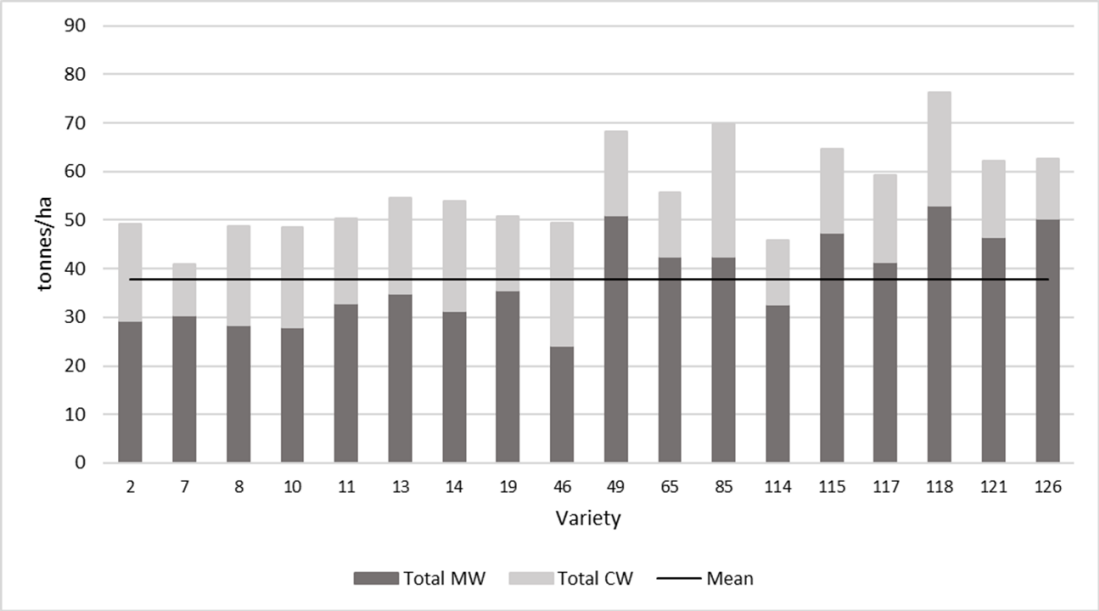

Figure 3-1. PSFH-16 experimental hybrid yield trial at Russell E. Larson Agricultural Research Center (Rock Springs) 2017. Dark grey bars represent estimated marketable weight (MW) and stacked light grey bars represent estimated cull weight (CW). Line represents the estimated mean marketable weight across all hybrids (37.9 tonnes/ha)

Figure 3-2 represents the number of fruit harvested for each hybrid in two replications. Hybrids for which there were less than two replications and plots that contained less than six plants were not included as these results represented raw data for marketable fruit number and fruit size. All of the PSU hybrids produced fruit that were primarily extra-large and jumbo size; though PSFH-16-118, -121, and -126 produced the largest proportion of jumbo size fruit. Hybrids -49, -65, and -115 produced a large proportion of extra-large fruit with -115 actually producing more large size fruit than it does jumbo fruit. These three hybrids also produced the most total fruit. Table 3-1 shows the average fruit weight for all 22 hybrids. This data may be more useful as it represents fruit weight rather than size category that is based on the diameter of the fruit across the equator. Therefore, hybrids with flatter fruit may be overly represented with larger fruit size in Figure 3-2. Hybrids PSFH-16-118, -121, and -126 had the highest average fruit weight (0.67, 0.64, 0.64 lbs, respectively). The mean average fruit weight for all varieties is 0.55 lbs/fruit.

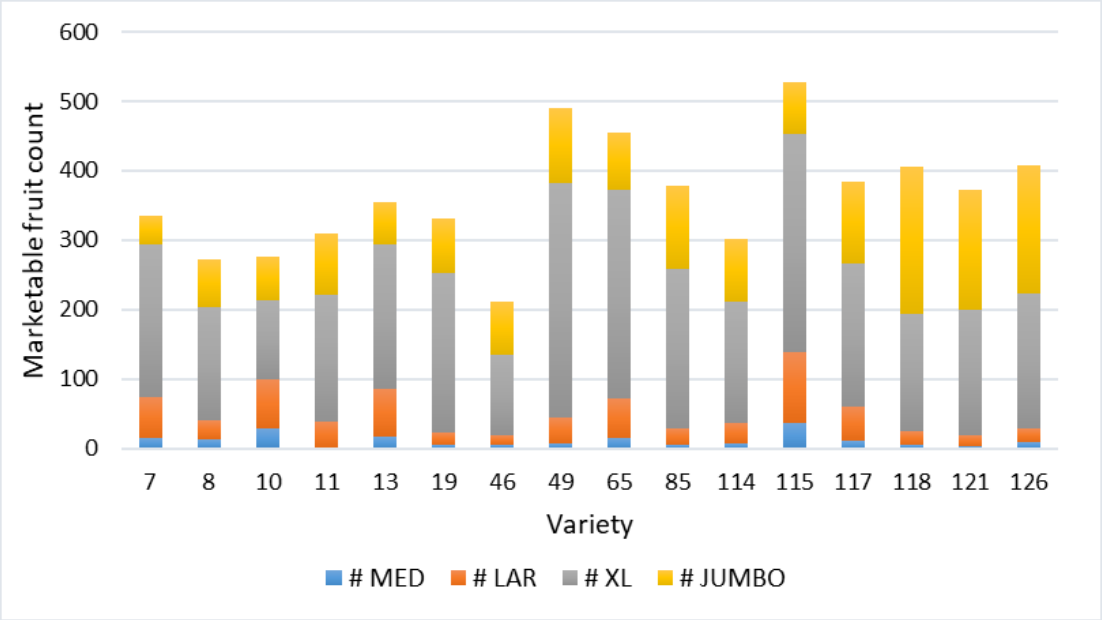

Figure 3-2. Fruit size for each of 16 PSFH-16 hybrids with yellow (jumbo), grey (extra-large), orange (large), and blue (medium) categories. Number of marketable fruits is represented on the y-axis based upon 12 plants for each experimental hybrid. Fruits were harvested from a total of 12 plants for each hybrid.

Table 3-1. Average fruit weight for all 22 PSFH-16 hybrids.

Hybrid	Fruit weight (lbs/fruit)
2	0.53
7	0.47
8	0.54
10	0.52
11	0.55
13	0.51
14	0.53
19	0.55
33	0.53
35	0.50
46	0.59
49	0.54
65	0.48
85	0.58
99	0.58
100	0.58
114	0.56
115	0.46
117	0.56
118	0.67
121	0.64
126	0.64
AVG	0.55

ANOVA was performed on yield data for PSFH-16 hybrid trials at Penn State Southeast Research Center (Landisville, PA) with $p = 0.2588$, indicating no significant differences. Figure 3-3 represents yield data for Landisville for hybrids with similar performance; however, it is worth noting that yields were much lower (with an average of ~ 20 tonnes/ha) than in the Rock Springs trial (with an average of 37.9 tonnes/ha). In particular, hybrids planted at both locations performed differently, with PSFH-16-2, -7, -8, -10, -13, and -14 yielding an estimated 30 tonnes/ha at Rock Springs. PSFH-16-118 did not perform well for the estimated marketable yield

(12.77 tonnes/ha) compared with trials at Russell E. Larson Agricultural Research Center (53 tonnes/ha). This may be due to the incidence of bacterial canker (caused by bacterium *Clavibacter michiganensis* subsp. *Michiganensis*) in Landisville, which did not occur at the main research site in Rock Springs. PSFH-16-118 showed the potential for equally high total yield in Landisville, but clearly had a greater proportion of cull weight, and so it might be disproportionately affected by bacterial canker. Also, many of the hybrids that performed below average in Rock Springs performed above average in Landisville; though this could be due to the lack of top-performing hybrids in Landisville which were planted only in Rock Springs. Disparity in performance between sites indicated the need for more legitimate experimental setups and geographically well-distributed variety trials to determine which hybrids perform better in a wide variety of locations.

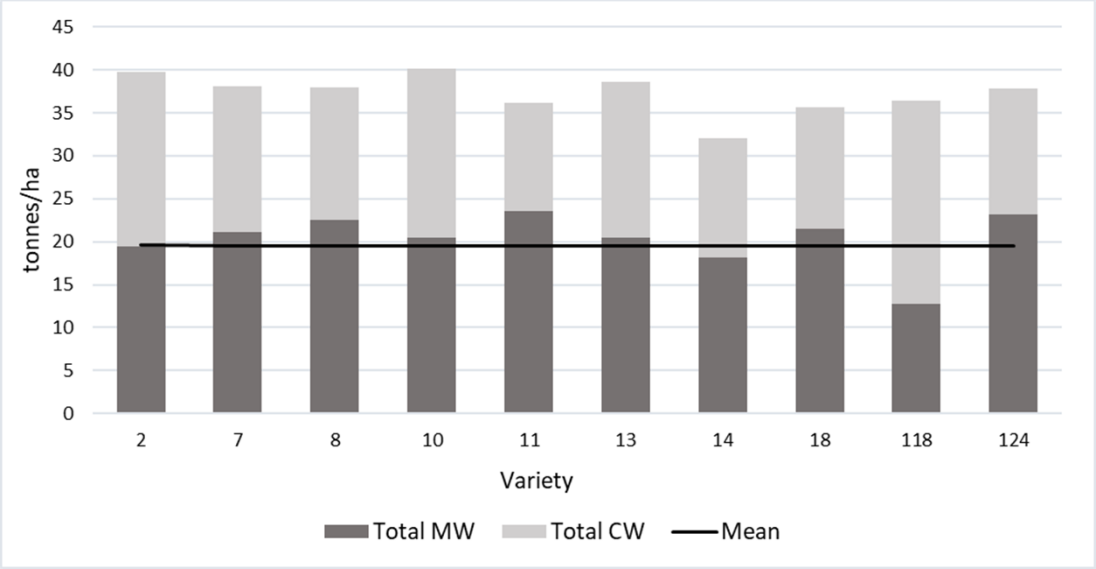

Figure 3-3. PSFH-16 hybrid yield trial at PSU Southeast Research Center (Landisville) 2017. Dark grey bars indicate marketable weight (MW) and stacked light grey bars indicate cull weight (CW).

2019 Multi-Location Visual Evaluation

All hybrids in the 2019 trials were visually scored for numerous characteristics. In Figures 3-4 through 3-15, variety main effects are presented in vertical bar graphs with significant differences represented by letter class; or in the case of no significant difference, no letter class is shown. There were significant differences in mean overall scores among varieties ($p < 0.0001$). The ANOVA output for overall score is presented in Table 3-2. All PSU experimental hybrids performed significantly better than commercial cultivars Mt. Fresh + (MF) and Mt. Merit (MM). Each of PSFH-16-4, -49, -126 (G4, G49, G26) and PSFH-LBR-18-37, -39, -40 (L37, L39, L40) performed significantly better than Red Deuce (RD); and RD performed significantly better than both MF and MM.

There were significant differences in mean yield scores among varieties ($p = 0.0106$). The individual trait yield had few significant differences, with PSU experimental hybrid G49 performing significantly better than each of MF and MM. The ANOVA output is presented in Table 3-3. Hybrid yield scores are presented in Figure 3-5. None of the other PSU hybrids or the commercial cultivars RD, MF, and MM performed significantly different from each other for yield.

There were no significant differences for variety main effects in scores for plant disease resistance. Disease resistance scores are presented in Figure 3-6 and the ANOVA results in Table 3-4. There were few disease issues in the trials. In Berwick, there was substantial bacterial canker incidence throughout the trial, and in York there was little bacterial canker with few varieties being more affected than others. In Homer City high-tunnel trials, there was a high degree of powdery mildew and grey leaf mold affecting all varieties as well as insect damage on foliage caused by thrips. Insect damage on fruit at Homer City was primarily due to stink bugs. Insect damage was specific to Homer City, and that data is not presented here. All farms had at least some incidence of early blight, and a small degree of late blight was detected in Rock Springs.

There was also no significant difference among varieties for fruit disease resistance scores. The ANOVA output is presented in Table 3-5 and the disease fruit scores are presented in Figure 3-7. The only farm that had fruit disease problems was at the Berwick site and only minimal incidence of fruit black mold due to recent deterioration of plant health by bacterial canker, which resulted in exposed fruit.

There were significant differences in mean stem end scores among varieties ($p < 0.0001$). The ANOVA output is presented in Table 3-6. The stem end scores are presented in Figure 3-8. One commercial cultivar, Red Deuce, had an excellent stem end despite having very large, jumbo size fruit. As fruit size increases, the stem end tends to get bigger. RD had significantly better stem end than 10 PSU hybrids—G4, G49, G73, G74, G81, G83, G18 (PSFH-16-118), L37, L39, and L40. RD was significantly different than two other commercial cultivars, MF and MM, but RD was not significantly different than one PSU hybrid, G26 (PSFH-16-126). G26 performed significantly better than MF and MM; and, G9 and G49 performed significantly better than MF.

There were significant differences in mean blossom end scores among varieties ($p = 0.0021$). The ANOVA output for the blossom end trait is presented in Table 3-7. Blossom end scores are presented in Figure 3-9. There was only one significant difference for blossom end between varieties RD and L37. Overall, all PSU hybrids and commercial cultivars had a good blossom end.

There were significant differences in mean fruit firmness scores among varieties ($p < 0.0001$). The ANOVA output for fruit firmness is presented in Table 3-8. Fruit firmness scores are presented in Figure 3-10. All PSU hybrids and RD performed better than the commercial cultivar, MM. This same group performed significantly better than MF with the exception of G83, which was scored higher but was not significantly different than MF.

There were significant differences in mean internal fruit color scores among varieties ($p < 0.0001$). The ANOVA output is presented in Table 3-9. The internal fruit color scores are

presented in Figure 3-11. All PSU hybrids with the exception of G18 (PSFH-16-118) scored significantly better than all of the commercial cultivars. G18 scored significantly higher than MF and MM, but not better than RD. RD performed better than MF, but not better than MM.

Table 3-10 contains the ANOVA output for the main effects of variety for external fruit color ($p < 0.0001$), and Figure 3-12 presents the data for external fruit color score. PSU experimental hybrids, G49, L37, and L39, performed significantly better than all of the commercial cultivars, RD, MF, and MM. The nine other PSU hybrids did not perform significantly different from RD, but they did perform better than MF and MM.

The ANOVA output for the main effect of variety for locule distribution are presented in Table 3-11 ($p < 0.0001$), and the locule distribution scores are presented in Figure 3-13. All PSU hybrids performed significantly better than the commercial cultivars with the exception of G9, G74, G81, G83, G18, and G26, which did not perform significantly better than RD. RD performed significantly better than MF and MM.

The ANOVA output for the main effect of variety for taste are presented in Table 3-12 ($p < 0.0001$) and the taste scores are presented in Figure 3-14. None of the PSU hybrids performed significantly different from each other for taste. Two PSU hybrids, L37 and L40, tasted significantly better than all of the commercial cultivars. The 10 other PSU hybrids did not taste significantly different from RD; and RD received significantly higher scores in comparison to MM, but was not significantly different from MF.

The ANOVA output for the main effect of variety for uniformity of fruit size are presented in Table 3-13 ($p < 0.0001$) and the scores are presented in Figure 3-15. All PSU hybrids and MM performed significantly better for uniformity of fruit size in comparison with MF.

Table 3-2. ANOVA output for Variety Main Effects (Overall) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	8.0277229	0.57340878	10.56	<.0001
Error	190	10.319265	0.05431192		
Corrected Total	204	18.34698791			

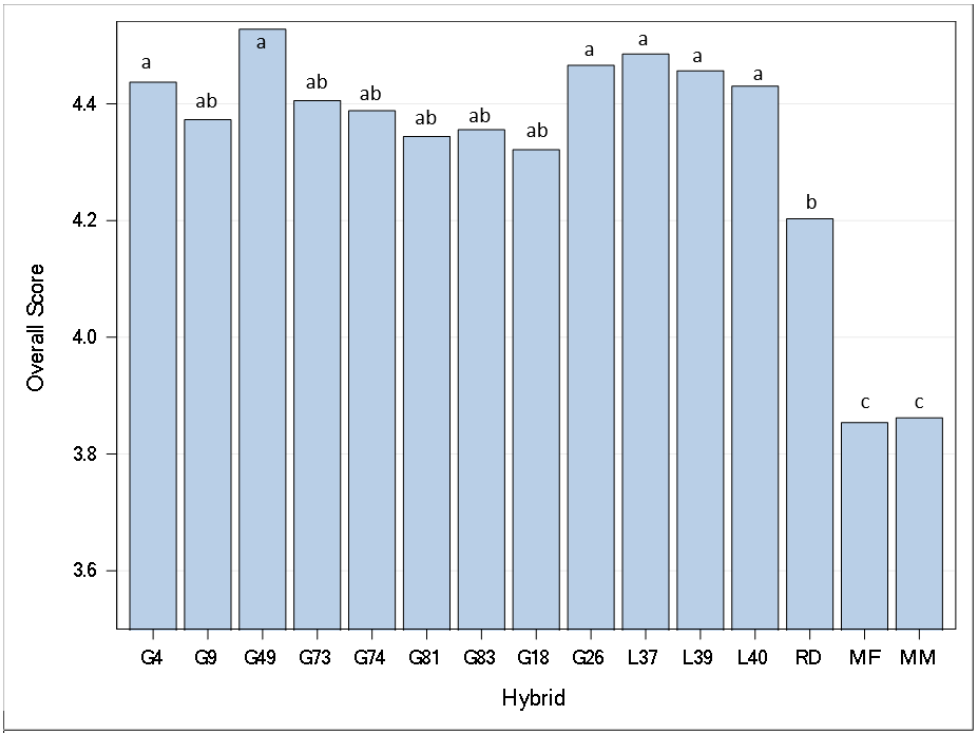

Figure 3-4. Overall scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype). Overall scores were calculated from the average of all trait scores observed for each of three replications at each farm location. Homer City was the only location in which 2 replications were evaluated.

Table 3-3. ANOVA output for Variety Main Effects (Yield) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	5.01374966	0.35812498	2.16	0.0106
Error	190	31.47527473	0.16565934		
Corrected Total	204	36.48902439			

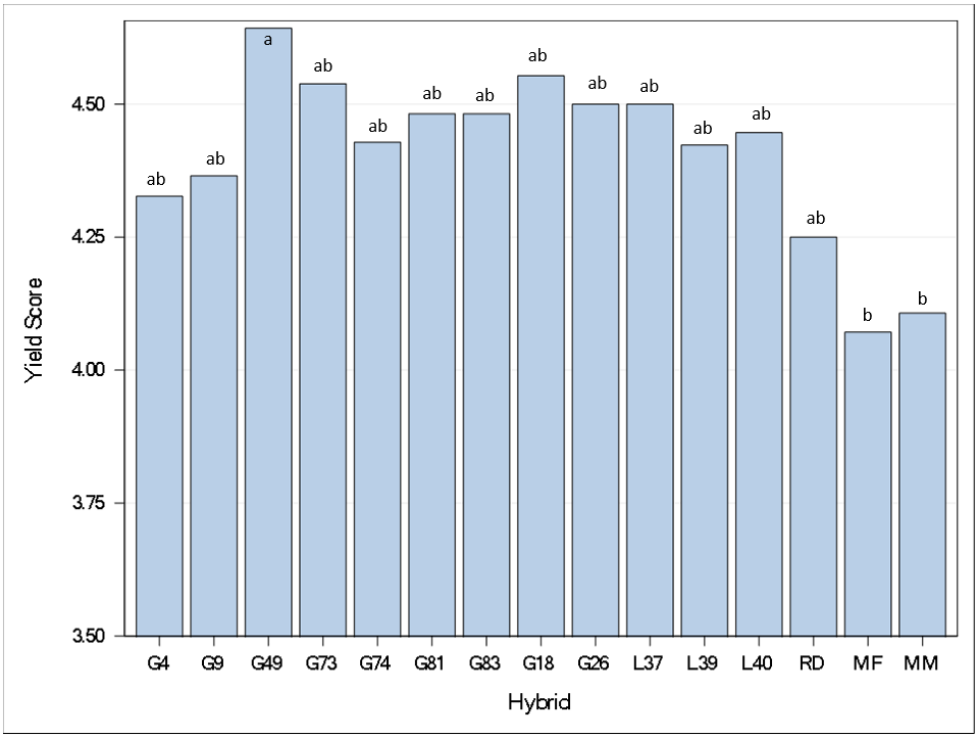

Figure 3-5. Yield scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

Table 3-4. ANOVA output for Variety Main Effects (Plant Disease Resistance) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	8.7763356	0.6268811	0.58	0.878
Error	191	206.1411401	1.079273		
Corrected Total	205	214.9174757			

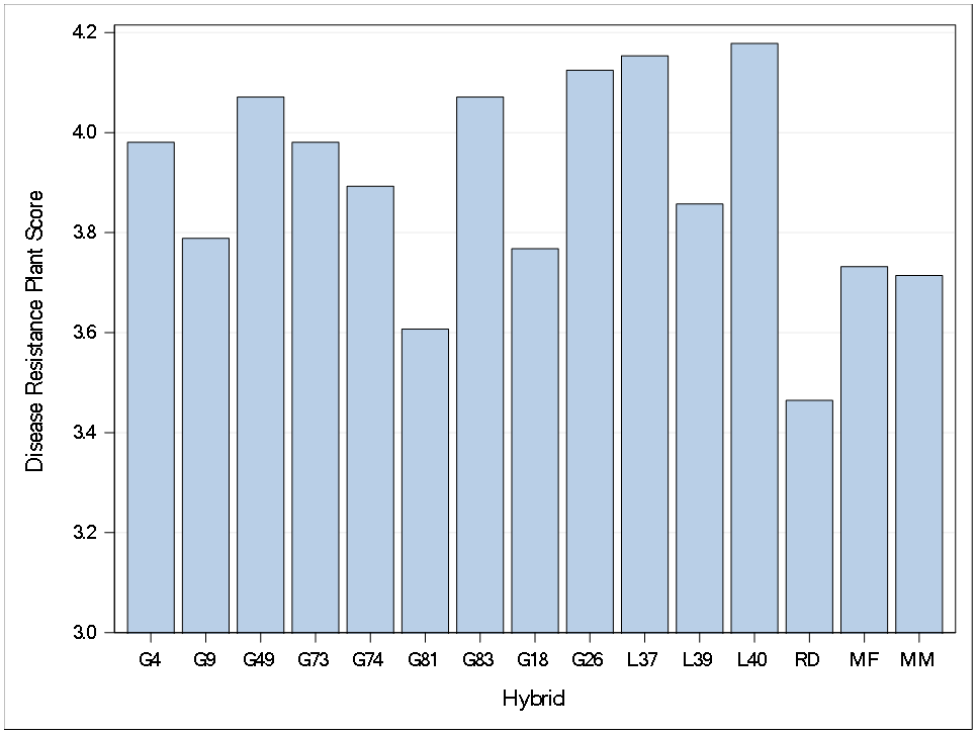

Figure 3-6. Plant disease resistance scores for all PSU hybrids and commercial cultivars. ANOVA did not indicate any significant differences between varieties.

Table 3-5. ANOVA output for Variety Main Effects (Fruit Disease Resistance) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	0.4911081	0.03507915	0.42	0.967
Error	191	15.92788462	0.08339207		
Corrected Total	205	16.41899272			

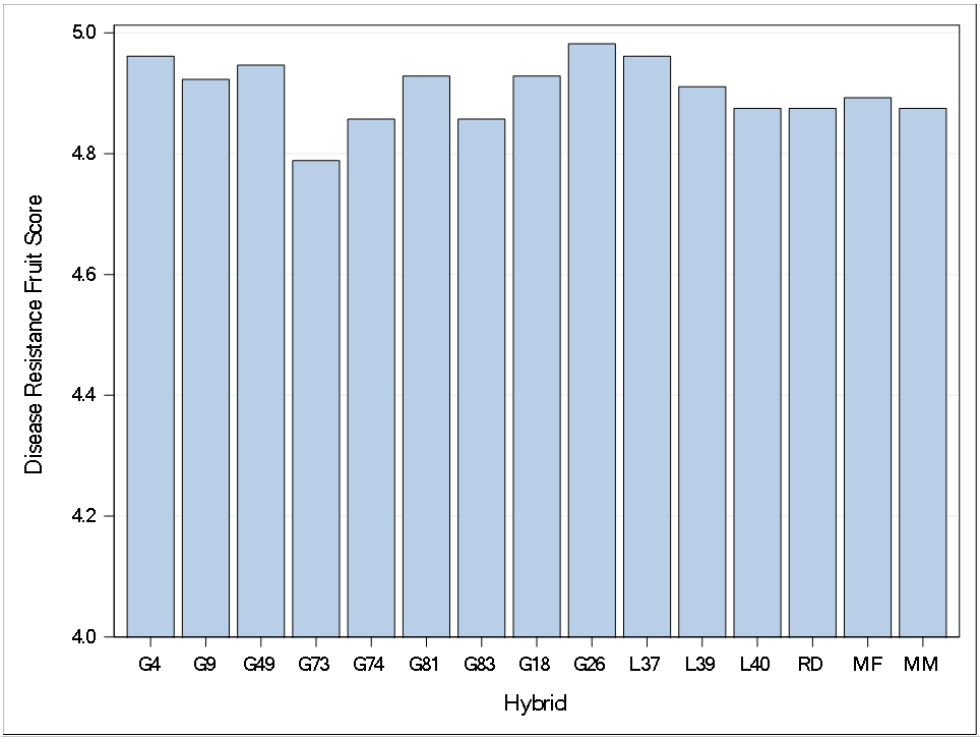

Figure 3-7. Fruit disease resistance scores for all PSU hybrids and commercial cultivars. ANOVA did not indicate any significant differences between varieties.

Table 3-6. ANOVA output for Variety Main Effects (Stem End) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	11.19048397	0.79932028	4.86	<.0001
Error	191	31.44574176	0.16463739		
Corrected Total	205	42.63622573			

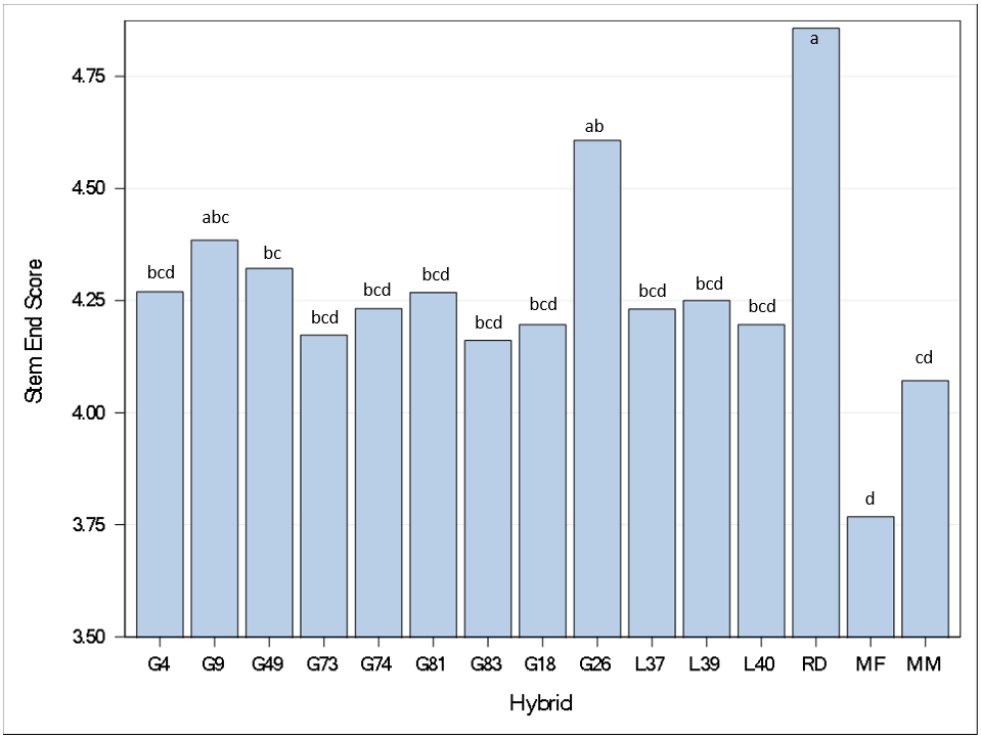

Figure 3-8. Stem end scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

Table 3-7. ANOVA output for Variety Main Effects (Blossom End) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	3.62469327	0.25890666	2.56	0.0021
Error	191	19.29429945	0.10101727		
Corrected Total	205	22.91899272			

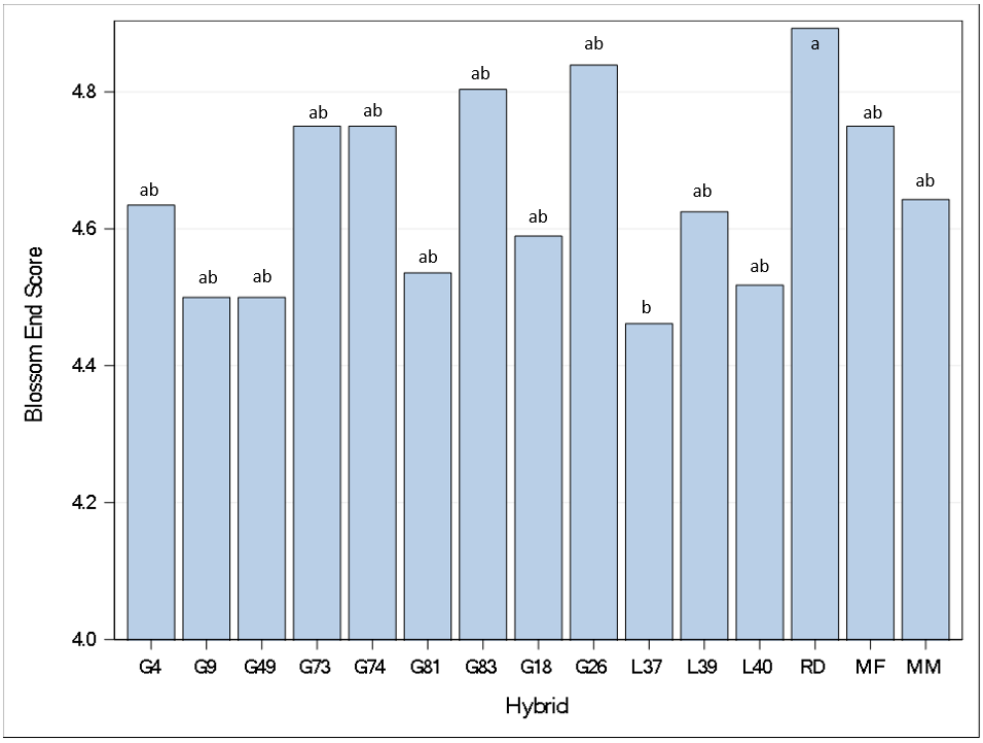

Figure 3-9. Blossom end scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

Table 3-8. ANOVA output for Variety Main Effects (Firmness) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	27.55063274	1.96790234	10.58	<.0001
Error	188	34.97830815	0.18605483		
Corrected Total	202	62.52894089			

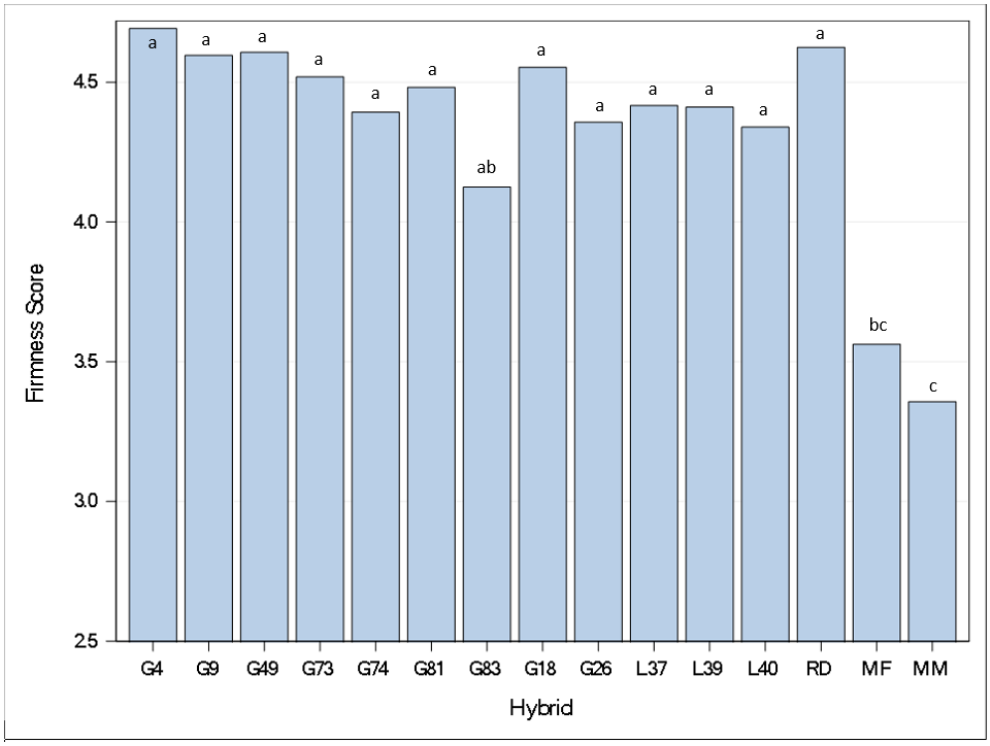

Figure 3-10. Fruit firmness scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

Table 3-9. ANOVA output for Variety Main Effects (Internal Fruit Color) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	51.50965091	3.67926078	24.02	<.0001
Error	188	28.80254121	0.15320501		
Corrected Total	202	80.31219212			

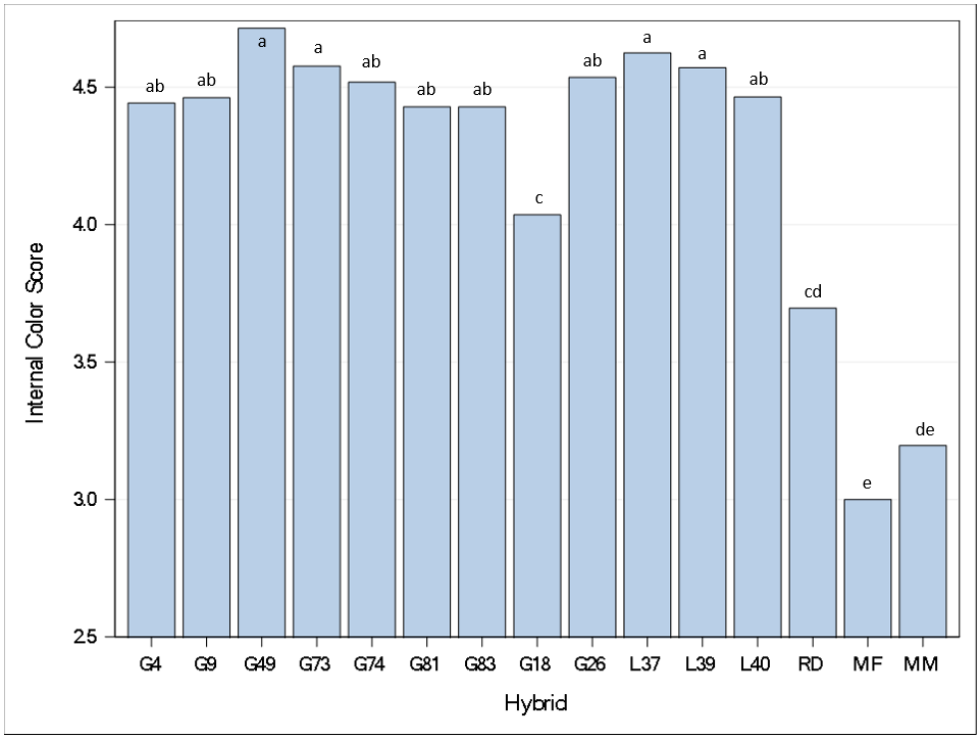

Figure 3-11. Internal fruit color scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

Table 3-10. ANOVA output for Variety Main Effects (External Fruit Color) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	12.49666067	0.89261862	8.04	<.0001
Error	188	20.87156593	0.11101897		
Corrected Total	202	33.3682266			

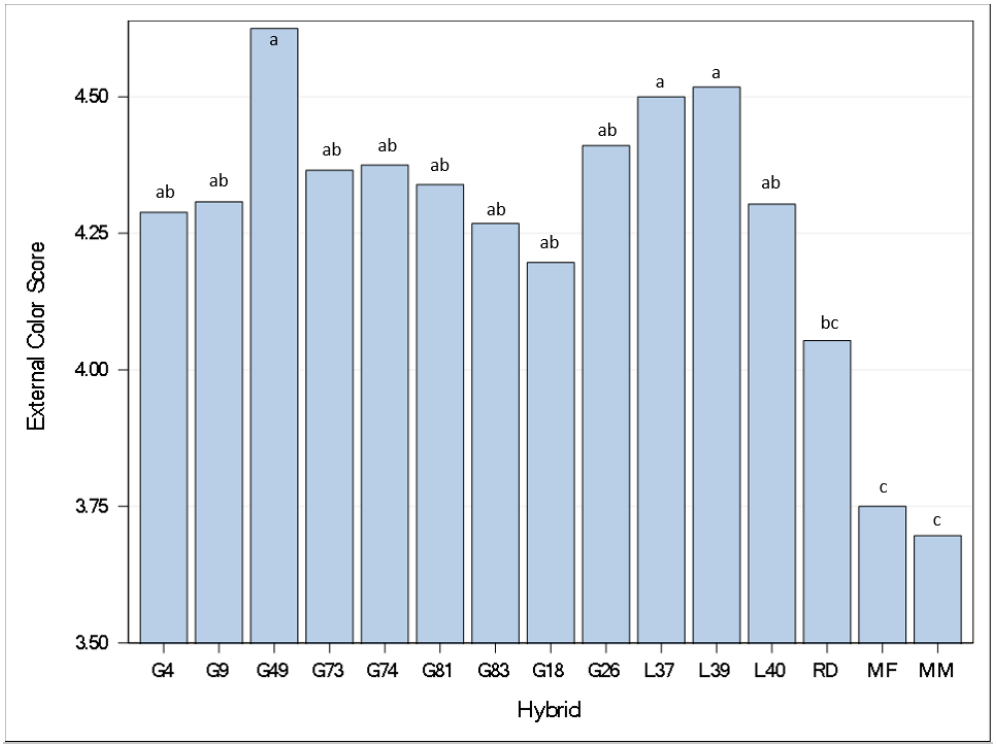

Figure 3-12. External fruit color scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

Table 3-11. ANOVA output for Variety Main Effects (Locule Distribution) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	22.33798952	1.59557068	11.73	<.0001
Error	189	25.69877518	0.13597236		
Corrected Total	203	48.03676471			

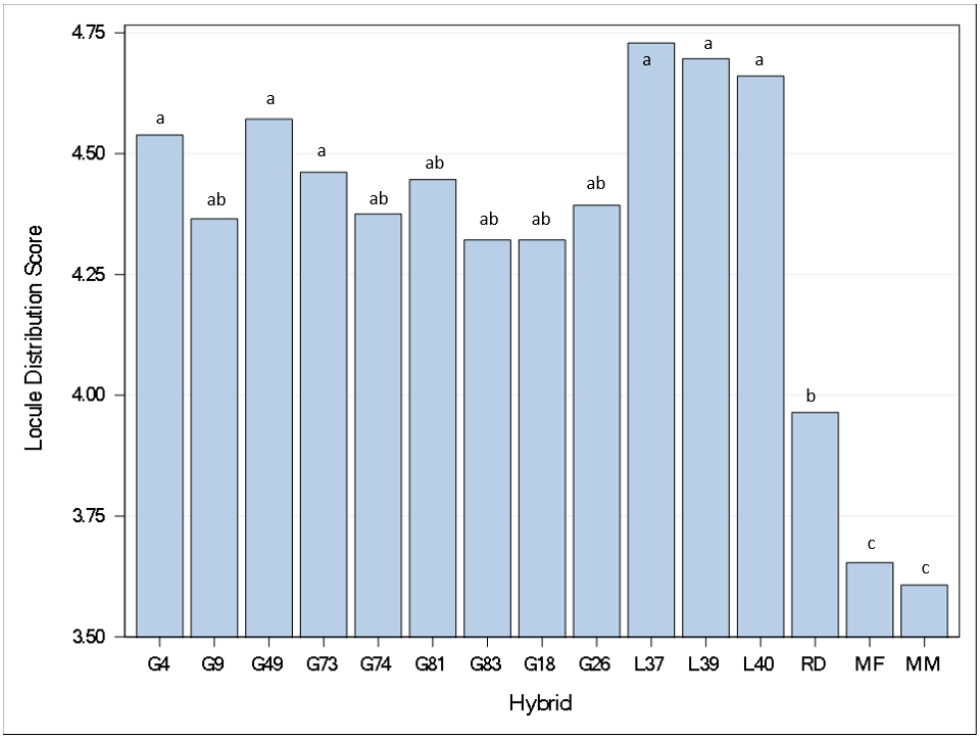

Figure 3-13. Fruit locule distribution scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

Table 3-12. ANOVA output for Variety Main Effects (Taste) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	25.66038667	1.83288476	10.09	<.0001
Error	188	34.14503205	0.18162251		
Corrected Total	202	59.80541872			

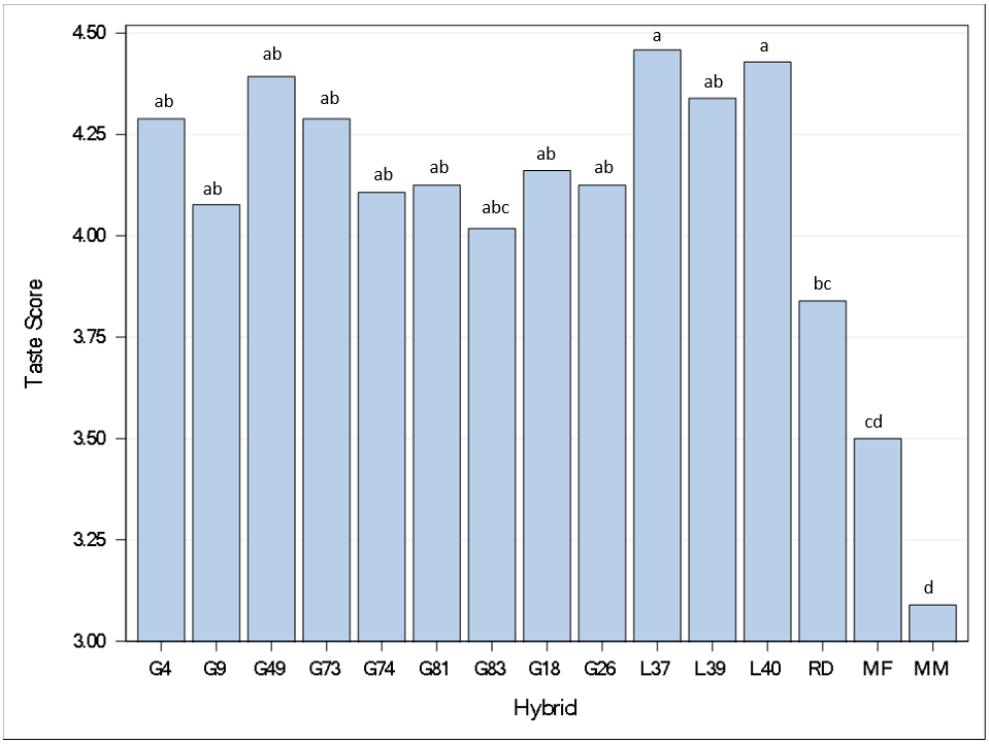

Figure 3-14. Taste scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

Table 3-13. ANOVA output for Variety Main Effects (Uniformity Fruit Size) by PROC GLM, SAS University 9.4.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr > F
Model	14	8.75735024	0.62552502	3.52	<.0001
Error	158	28.09886364	0.17784091		
Corrected Total	172	36.85621387			

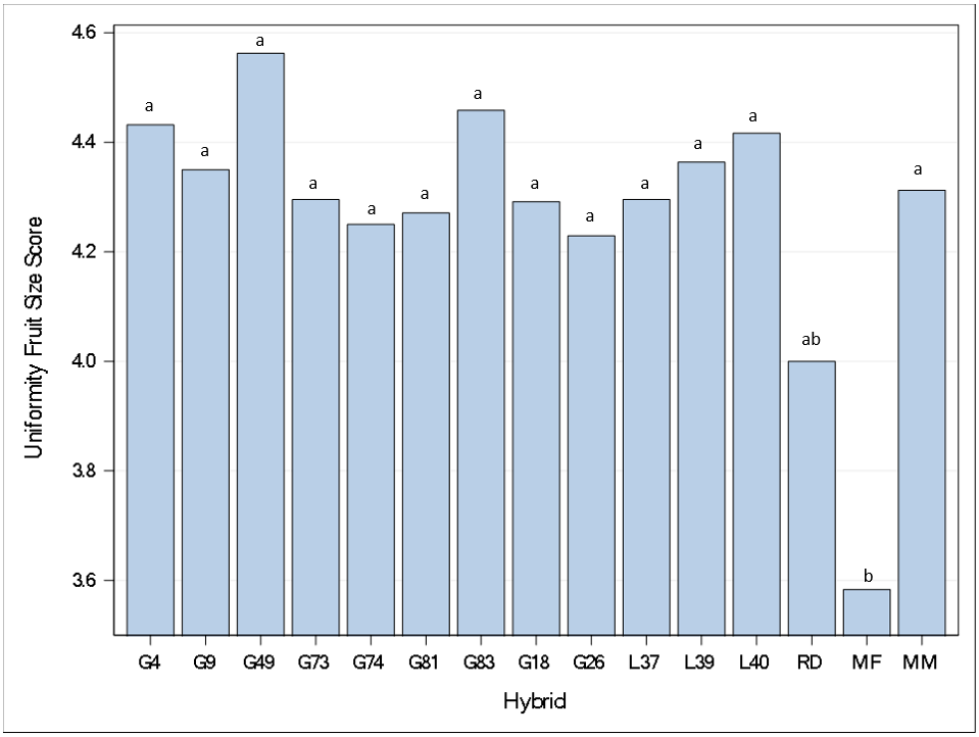

Figure 3-15. Uniformity fruit size scores for all PSU hybrids and commercial cultivars. Significance levels were produced by Tukey's HSD at alpha = 0.05 in an ANOVA analysis for main effect of variety (genotype).

ANOVA was performed for mixed models for all traits, and the GLIMMIX 'SLICEDIFF' procedure was performed for multiple comparisons to analyze all combinations of pairwise comparisons of variety at each farm. The ANOVA mixed model for overall score is presented in Table 3-14, and the significant differences for multiple comparisons for overall score of variety by location are presented in Table 3-15 ($p < 0.01$).

Table 3-14. ANOVA for mixed model overall score.

Type 3 Tests of Fixed Effects for Overall				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	121	20.93	<.0001
En	4	8.84	10.41	0.0021
G*En	56	121	1.93	0.0014

Table 3-15. Significant differences of multiple comparisons for overall score by location.

The GLIMMIX Procedure for Overall, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G18	MM	0.5303	0.1373	120.9	3.86	0.0002
En Altoona	G26	MM	0.5909	0.1373	120.9	4.31	0.0001
En Altoona	G4	MM	0.5985	0.1373	120.9	4.36	0.0001
En Altoona	G49	MF	0.4336	0.1541	122.2	2.81	0.0057
En Altoona	G49	MM	0.6515	0.1373	120.9	4.75	0.0001
En Altoona	G73	MM	0.6061	0.1373	120.9	4.42	0.0001
En Altoona	G74	MM	0.4545	0.1373	120.9	3.31	0.0012
En Altoona	G81	MM	0.4848	0.1373	120.9	3.53	0.0006
En Altoona	G83	MF	0.4033	0.1541	122.2	2.62	0.01
En Altoona	G83	MM	0.6212	0.1373	120.9	4.53	0.0001
En Altoona	G9	MM	0.5606	0.1373	120.9	4.08	0.0001
En Altoona	L37	MF	0.4147	0.1541	122.2	2.69	0.0081
En Altoona	L37	MM	0.6326	0.1373	120.9	4.61	0.0001
En Altoona	L39	MM	0.5758	0.1373	120.9	4.19	0.0001
En Altoona	L40	MF	0.426	0.1541	122.2	2.76	0.0066
En Altoona	L40	MM	0.6439	0.1373	120.9	4.69	0.0001
En Berwick	G49	MF	0.3864	0.1373	120.9	2.81	0.0057
En Homer	G18	MF	0.9886	0.1681	120.9	5.88	0.0001
En Homer	G18	MM	0.9886	0.1681	120.9	5.88	0.0001
En Homer	G26	G81	0.4773	0.1681	120.9	2.84	0.0053
En Homer	G26	MF	1.2386	0.1681	120.9	7.37	0.0001
En Homer	G26	MM	1.2386	0.1681	120.9	7.37	0.0001
En Homer	G26	RD	0.5455	0.1681	120.9	3.24	0.0015
En Homer	G4	MF	0.9659	0.1681	120.9	5.75	0.0001
En Homer	G4	MM	0.9659	0.1681	120.9	5.75	0.0001
En Homer	G49	MF	0.9773	0.1681	120.9	5.81	0.0001
En Homer	G49	MM	0.9773	0.1681	120.9	5.81	0.0001
En Homer	G73	L39	-0.4432	0.1681	120.9	-2.64	0.0095
En Homer	G73	MF	0.8523	0.1681	120.9	5.07	0.0001
En Homer	G73	MM	0.8523	0.1681	120.9	5.07	0.0001
En Homer	G74	MF	1.1932	0.1681	120.9	7.1	0.0001
En Homer	G74	MM	1.1932	0.1681	120.9	7.1	0.0001
En Homer	G74	RD	0.5	0.1681	120.9	2.97	0.0035

En Homer	G81	L39	-0.5341	0.1681	120.9	-3.18	0.0019
En Homer	G81	MF	0.7614	0.1681	120.9	4.53	0.0001
En Homer	G81	MM	0.7614	0.1681	120.9	4.53	0.0001
En Homer	G83	MF	0.9091	0.1681	120.9	5.41	0.0001
En Homer	G83	MM	0.9091	0.1681	120.9	5.41	0.0001
En Homer	G9	MF	1.0341	0.1681	120.9	6.15	0.0001
En Homer	G9	MM	1.0341	0.1681	120.9	6.15	0.0001
En Homer	L37	MF	1.125	0.1681	120.9	6.69	0.0001
En Homer	L37	MM	1.125	0.1681	120.9	6.69	0.0001
En Homer	L39	MF	1.2955	0.1681	120.9	7.71	0.0001
En Homer	L39	MM	1.2955	0.1681	120.9	7.71	0.0001
En Homer	L39	RD	0.6023	0.1681	120.9	3.58	0.0005
En Homer	L40	MF	0.8977	0.1681	120.9	5.34	0.0001
En Homer	L40	MM	0.8977	0.1681	120.9	5.34	0.0001
En Homer	MF	RD	-0.6932	0.1681	120.9	-4.12	0.0001
En Homer	MM	RD	-0.6932	0.1681	120.9	-4.12	0.0001
En Rock	G18	MF	0.4621	0.1373	120.9	3.37	0.001
En Rock	G18	MM	0.4697	0.1373	120.9	3.42	0.0008
En Rock	G26	MF	0.5606	0.1373	120.9	4.08	0.0001
En Rock	G26	MM	0.5682	0.1373	120.9	4.14	0.0001
En Rock	G4	MF	0.5909	0.1373	120.9	4.31	0.0001
En Rock	G4	MM	0.5985	0.1373	120.9	4.36	0.0001
En Rock	G49	MF	0.7349	0.1373	120.9	5.35	0.0001
En Rock	G49	MM	0.7424	0.1373	120.9	5.41	0.0001
En Rock	G73	MF	0.6136	0.1373	120.9	4.47	0.0001
En Rock	G73	MM	0.6212	0.1373	120.9	4.53	0.0001
En Rock	G74	MF	0.5152	0.1373	120.9	3.75	0.0003
En Rock	G74	MM	0.5227	0.1373	120.9	3.81	0.0002
En Rock	G81	MF	0.5455	0.1373	120.9	3.97	0.0001
En Rock	G81	MM	0.553	0.1373	120.9	4.03	0.0001
En Rock	G83	L37	-0.3712	0.1373	120.9	-2.7	0.0078
En Rock	G83	L40	-0.3939	0.1373	120.9	-2.87	0.0048
En Rock	G83	MF	0.4015	0.1373	120.9	2.93	0.0041
En Rock	G83	MM	0.4091	0.1373	120.9	2.98	0.0035
En Rock	G9	MF	0.4924	0.1373	120.9	3.59	0.0005
En Rock	G9	MM	0.5	0.1373	120.9	3.64	0.0004
En Rock	L37	MF	0.7727	0.1373	120.9	5.63	0.0001
En Rock	L37	MM	0.7803	0.1373	120.9	5.69	0.0001
En Rock	L39	MF	0.7576	0.1373	120.9	5.52	0.0001

En Rock	L39	MM	0.7651	0.1373	120.9	5.57	0.0001
En Rock	L40	MF	0.7955	0.1373	120.9	5.8	0.0001
En Rock	L40	MM	0.803	0.1373	120.9	5.85	0.0001
En Rock	MF	RD	-0.5076	0.1373	120.9	-3.7	0.0003
En Rock	MM	RD	-0.5151	0.1373	120.9	-3.75	0.0003
En York	G18	MF	0.5379	0.1373	120.9	3.92	0.0001
En York	G18	MM	0.4091	0.1373	120.9	2.98	0.0035
En York	G26	MF	0.6894	0.1373	120.9	5.02	0.0001
En York	G26	MM	0.5606	0.1373	120.9	4.08	0.0001
En York	G4	MF	0.6818	0.1373	120.9	4.97	0.0001
En York	G4	MM	0.553	0.1373	120.9	4.03	0.0001
En York	G49	L39	0.3771	0.1373	120.9	2.75	0.0069
En York	G49	MF	0.8636	0.1373	120.9	6.29	0.0001
En York	G49	MM	0.7348	0.1373	120.9	5.35	0.0001
En York	G49	RD	0.4015	0.1373	120.9	2.93	0.0041
En York	G73	MF	0.7879	0.1373	120.9	5.74	0.0001
En York	G73	MM	0.6591	0.1373	120.9	4.8	0.0001
En York	G74	MF	0.7349	0.1373	120.9	5.35	0.0001
En York	G74	MM	0.6061	0.1373	120.9	4.42	0.0001
En York	G81	MF	0.6212	0.1373	120.9	4.53	0.0001
En York	G81	MM	0.4924	0.1373	120.9	3.59	0.0005
En York	G83	MF	0.7121	0.1373	120.9	5.19	0.0001
En York	G83	MM	0.5833	0.1373	120.9	4.25	0.0001
En York	G9	MF	0.547	0.1373	120.9	3.99	0.0001
En York	G9	MM	0.4182	0.1373	120.9	3.05	0.0028
En York	L37	MF	0.7273	0.1373	120.9	5.3	0.0001
En York	L37	MM	0.5985	0.1373	120.9	4.36	0.0001
En York	L39	MF	0.4865	0.1373	120.9	3.54	0.0006
En York	L40	MF	0.6818	0.1373	120.9	4.97	0.0001
En York	L40	MM	0.553	0.1373	120.9	4.03	0.0001
En York	MF	RD	-0.4621	0.1373	120.9	-3.37	0.001

A visual representation for overall score of each variety in all locations is presented in Figure 3-16. In Altoona, PSU experimental hybrids, G18, G26, G4, G49, G73, G74, G81, G83, G9, L37, L39, and L40, all performed significantly better than MM for overall score; and G49, G83, L37, and L40 performed significantly better than MF for overall score. In Berwick, there

was only one significant difference with G49 performing significantly better than MF. In Homer City, G18, G26, G4, G49, G73, G74, G81, G83, G9, L37, L39, and L40 all performed significantly better than MF and MM. G26, G74, and L39 performed better than RD for overall score. G26 and L39 performed significantly better than G81; and L39 performed significantly better than G73. RD performed significantly better than each of MF and MM. In Rock Springs, all 12 PSU hybrids performed significantly better than MF and MM. L37 and L40 performed significantly better than G83; and RD performed significantly better than MF and MM. In York, all PSU hybrids performed significantly better than each of MF and MM with the exception of L39, which performed significantly better than MF, but not MM. G49 was the only PSU hybrid that performed significantly better than RD, and G49 also performed significantly better than L39. RD performed significantly better than MF.

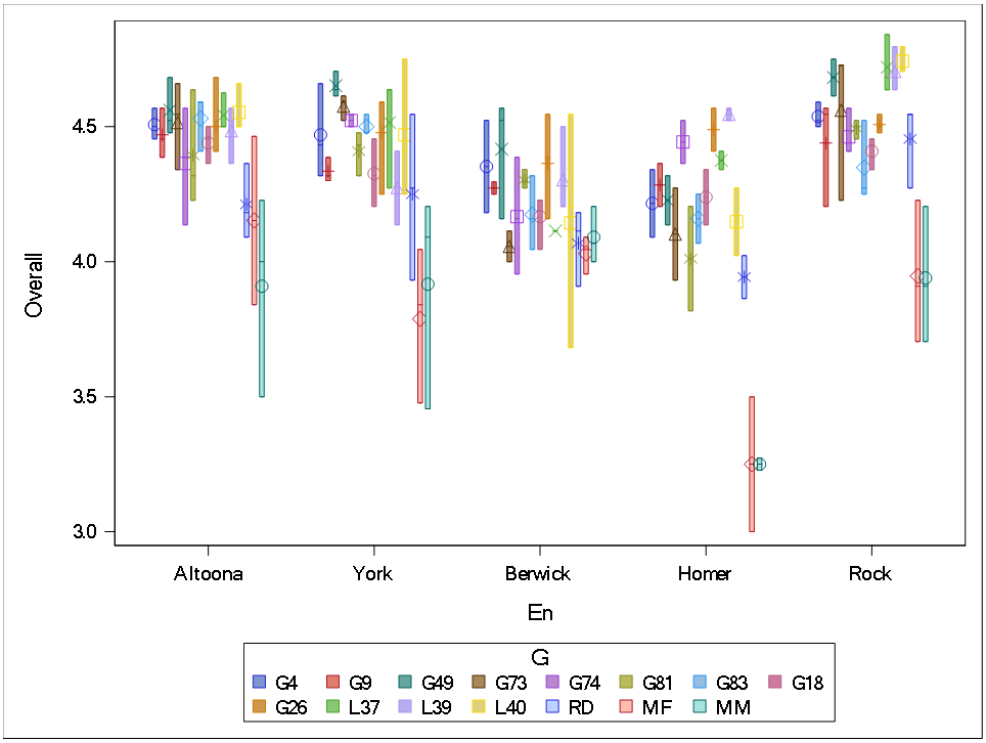

Figure 3-16. Overall score for each PSU hybrid and commercial cultivar in each farm location. Significant differences presented in multiple comparisons Table 3-16 (alpha = 0.01).

The ANOVA mixed model for yield score is presented in Table 3-16, and the significant differences for multiple comparisons for yield score of variety by location are presented in Table 3-17 ($p < 0.01$).

Table 3-16. ANOVA for mixed model yield score.

Type 3 Tests of Fixed Effects for Yld				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	121	4.47	<.0001
En	4	8.97	7.38	0.0065
G*En	56	121	1.84	0.0027

Table 3-17. Significant differences of multiple comparisons for yield score by location.

The GLIMMIX Procedure for Yield, p < .01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G73	MF	0.6667	0.2541	121	2.62	0.0098
En Berwick	G18	MM	0.6667	0.2541	121	2.62	0.0098
En Berwick	G49	G73	0.8692	0.2854	122.5	3.05	0.0028
En Berwick	G49	G74	0.6667	0.2541	121	2.62	0.0098
En Berwick	G49	MF	0.6667	0.2541	121	2.62	0.0098
En Berwick	G49	MM	0.8333	0.2541	121	3.28	0.0014
En Homer	G18	MF	0.875	0.3112	121	2.81	0.0057
En Homer	G18	MM	1.625	0.3112	121	5.22	0.0001
En Homer	G18	RD	1.25	0.3112	121	4.02	0.0001
En Homer	G26	G4	0.875	0.3112	121	2.81	0.0057
En Homer	G26	MF	1.125	0.3112	121	3.62	0.0004
En Homer	G26	MM	1.875	0.3112	121	6.03	0.0001
En Homer	G26	RD	1.5	0.3112	121	4.82	0.0001
En Homer	G4	G74	-1	0.3112	121	-3.21	0.0017
En Homer	G4	MM	1	0.3112	121	3.21	0.0017
En Homer	G49	MF	0.875	0.3112	121	2.81	0.0057
En Homer	G49	MM	1.625	0.3112	121	5.22	0.0001
En Homer	G49	RD	1.25	0.3112	121	4.02	0.0001
En Homer	G73	MF	1	0.3112	121	3.21	0.0017
En Homer	G73	MM	1.75	0.3112	121	5.62	0.0001
En Homer	G73	RD	1.375	0.3112	121	4.42	0.0001

En Homer	G74	MF	1.25	0.3112	121	4.02	0.0001
En Homer	G74	MM	2	0.3112	121	6.43	0.0001
En Homer	G74	RD	1.625	0.3112	121	5.22	0.0001
En Homer	G81	MF	1	0.3112	121	3.21	0.0017
En Homer	G81	MM	1.75	0.3112	121	5.62	0.0001
En Homer	G81	RD	1.375	0.3112	121	4.42	0.0001
En Homer	G83	MM	1.5	0.3112	121	4.82	0.0001
En Homer	G83	RD	1.125	0.3112	121	3.62	0.0004
En Homer	G9	MM	1.375	0.3112	121	4.42	0.0001
En Homer	G9	RD	1	0.3112	121	3.21	0.0017
En Homer	L37	MM	1.375	0.3112	121	4.42	0.0001
En Homer	L37	RD	1	0.3112	121	3.21	0.0017
En Homer	L39	MM	1.5	0.3112	121	4.82	0.0001
En Homer	L39	RD	1.125	0.3112	121	3.62	0.0004
En Homer	L40	MM	1.375	0.3112	121	4.42	0.0001
En Homer	L40	RD	1	0.3112	121	3.21	0.0017
En York	G83	MF	0.6667	0.2541	121	2.62	0.0098
En York	L37	MF	0.6667	0.2541	121	2.62	0.0098

A visual representation for yield score of each variety in all locations is presented in Figure 3-17. In Altoona, there was only one significant difference for yield scores with PSU experimental hybrid G73 performing significantly better than MF. In Berwick, G18 performed significantly better than MM; and G49 performed significantly better than G73, G74, MF, and MM. In Homer, PSU hybrids, G18, G26, G49, G73, G74, and G81 performed significantly better than MF. All PSU hybrids performed significantly better than MM. All PSU hybrids with the exception of G4 performed significantly better than RD. Additionally, G26 and G74 performed significantly better than G4. In York, PSU hybrids G83 and L37 performed significantly better than MF for yield score.

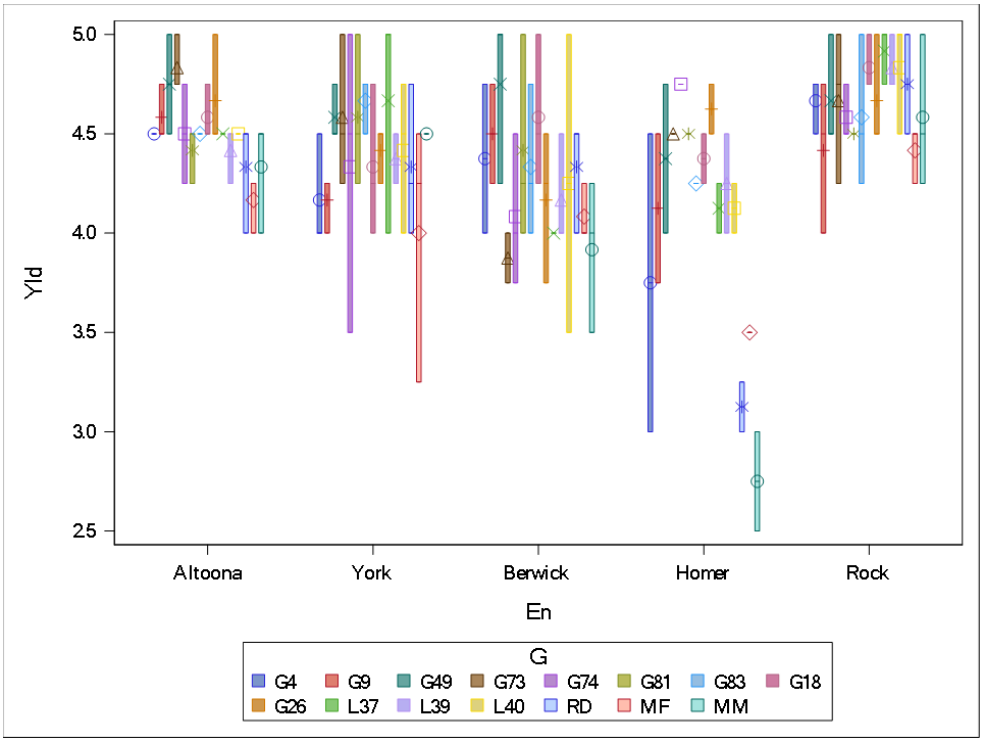

Figure 3-17. Yield score for each PSU hybrid and commercial cultivar in each farm location. Significant differences presented in multiple comparisons Table 3-17 (alpha = 0.01).

Figure 3-16 and Figure 3-18 represent the entirety of the MLTs summarized in one boxplot graph. The boxplots include means and variance in performance for each variety in three replications at each farm (Two replications in Homer City). The visual range of the boxplots give a good indication of the mean performance of varieties in each location and their consistency within and across locations. In Figure 3-16, the 15 different varieties were clustered at each farm location; and in Figure 3-18, the scores for each individual variety were clustered together with boxplot color representing the farm. This allowed visual observation of an individual variety's performance and variation at a given farm site, which allows researchers to see which locations presented the best or worst conditions based on the collective performance of an individual location. It also allows researchers to see instances in which a specific variety had excellent/poor

performance in a certain location despite having a lower/higher main overall effect across all locations, respectively.

For nearly all PSU hybrids, it is apparent that the three replications performed consistently, with relatively low variation in Altoona; and commercial cultivar RD performed well with relatively low variation. On the contrary, boxplots for the commercial cultivars MF and MM show more variability between replications in Altoona, where three PSU hybrids performed significantly better than MF, and all PSU hybrids performed significantly better than MM. In York and Rock Springs, the same trend is observed for each of MF and MM—relatively lower scores and higher variation in performance between replications. In Homer, MF has relatively high variation and low scores, whereas MM had low variation and low scores. RD performed more consistently in individual locations than MF and MM except for in York, where it had relatively higher variation between replications. Similarly, there was generally lower variation between replications in individual locations for PSU hybrid performance for overall score; however, L40 in Berwick had the most variation among any PSU hybrid or commercial cultivar. L40 also had relatively higher variation in performance in York in comparison with all other varieties. G73, G74, and G81 had relatively higher variation in Altoona. G4, G26, and L37 had relatively higher variation than other PSU hybrids in York; and G4, G49, G74, and G26 had relatively higher variation between replications in Berwick in comparison to other PSU hybrids. The same scenario was apparent for G73 and G81 in Homer City and for G9 and G73 in Rock Springs.

In Figure 3-16, it is also apparent that there were some farms in which there were little or no variation for high-scoring PSU hybrids: G4, G9, G49, G83, G18, L37, L39, and L40 in Altoona; G49, G73, G74, and G83 in York; G4 and G81 in Berwick; G74, G26, L37, and L39 in Homer City; and G4, G49, G74, G81, G18, G26, L37, L39, and L40 in Rock Springs.

Table 3-18 represents significant pairwise comparisons of locations for each variety for overall score ($p < 0.01$); and Figure 3-18 represents a visual boxplot for overall scores of varieties in different locations. G49 performed significantly better in Rock Springs and York in comparison to its performance in Homer City. G73 performed significantly better in Altoona, Rock Springs, and York than it does in Berwick; and G73 performed significantly better in Rock Springs and York than it does in Homer City. G81 performed significantly better in Rock Springs than it does in Homer City. L37 performed significantly better in Rock Springs than it does in Berwick. L39 performed significantly better in Rock Springs than it does in Berwick and York. L40 performed significantly better in Altoona and Rock Springs than it does in Berwick; and, L40 performed significantly better in Rock Springs than it does in Homer City. MF performed significantly better in Altoona, Berwick, Rock Springs, and York than it does in Homer City. MM performed significantly better in Altoona, Berwick, Rock Springs, and York than it does in Homer City. RD performed significantly better in Rock Springs than it does in Berwick and Homer City.

Table 3-18. Significant differences of multiple comparisons for overall score by variety.

The GLIMMIX Procedure for Overall Score, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G G49	Homer	Rock	-0.4545	0.162	113.5	-2.81	0.0059
G G49	Homer	York	-0.4242	0.162	113.5	-2.62	0.01
G G73	Altoona	Berwick	0.4298	0.161	120.6	2.67	0.0087
G G73	Berwick	Rock	-0.4752	0.161	120.6	-2.95	0.0038
G G73	Berwick	York	-0.4904	0.161	120.6	-3.05	0.0029
G G73	Homer	Rock	-0.4583	0.162	113.5	-2.83	0.0055
G G73	Homer	York	-0.4735	0.162	113.5	-2.92	0.0042
G G81	Homer	Rock	-0.4811	0.162	113.5	-2.97	0.0036
G L37	Berwick	Rock	-0.5775	0.161	120.6	-3.59	0.0005
G L39	Berwick	Rock	-0.4015	0.1449	113.5	-2.77	0.0065

G L39	Rock	York	0.4301	0.1449	113.5	2.97	0.0037
G L40	Altoona	Berwick	0.4091	0.1449	113.5	2.82	0.0056
G L40	Berwick	Rock	-0.5985	0.1449	113.5	-4.13	0.0001
G L40	Homer	Rock	-0.5947	0.162	113.5	-3.67	0.0004
G MF	Altoona	Homer	0.877	0.1766	119.7	4.97	0.0001
G MF	Berwick	Homer	0.7803	0.162	113.5	4.82	0.0001
G MF	Homer	Rock	-0.697	0.162	113.5	-4.3	0.0001
G MF	Homer	York	-0.5379	0.162	113.5	-3.32	0.0012
G MM	Altoona	Homer	0.6591	0.162	113.5	4.07	0.0001
G MM	Berwick	Homer	0.8409	0.162	113.5	5.19	0.0001
G MM	Homer	Rock	-0.6894	0.162	113.5	-4.25	0.0001
G MM	Homer	York	-0.6667	0.162	113.5	-4.11	0.0001
G RD	Berwick	Rock	-0.3864	0.1449	113.5	-2.67	0.0088
G RD	Homer	Rock	-0.5114	0.162	113.5	-3.16	0.002

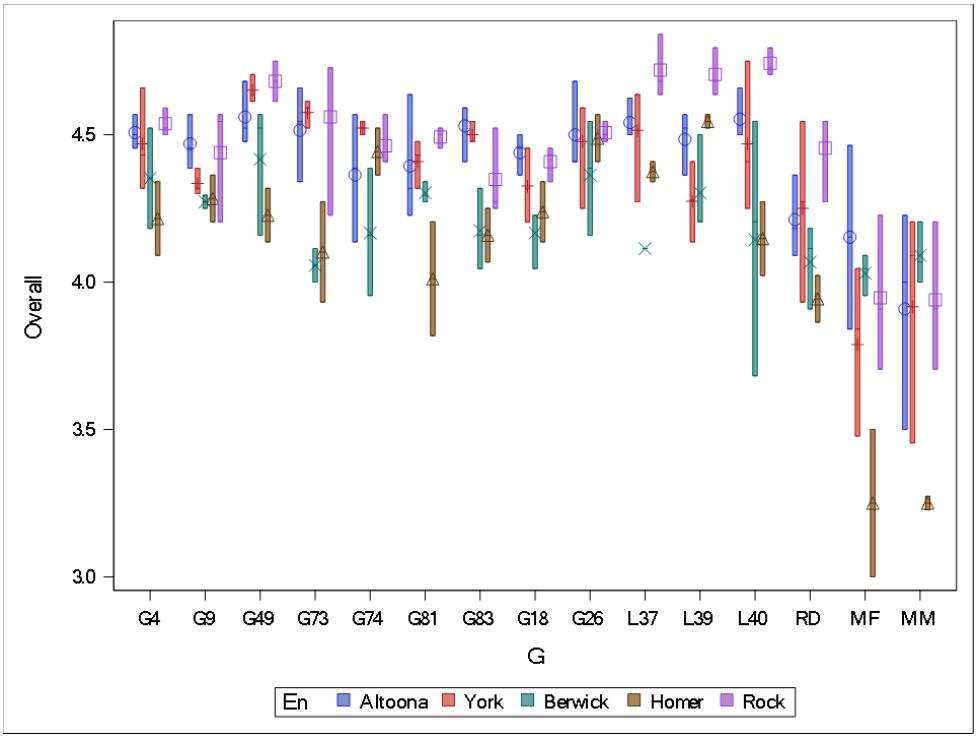

Figure 3-18. Variety overall scores are clustered together in order to more easily observe differences of an individual's performance throughout all five locations. Significant differences presented in multiple comparisons Table 3-18 (alpha = 0.01).

Table 3-19 represents significant pairwise comparisons of locations for each variety for yield score ($p < 0.01$); and Figure 3-19 represents a visual boxplot for yield scores of varieties in different locations. G4 performed significantly better for yield in Rock Springs than it does in Homer City. G73 performed significantly better in Altoona and Rock Springs than it does in Berwick. L37 performed significantly better in Rock Springs than it does in Berwick and Homer City. MF performed significantly better in Rock Springs than it does in Homer City. MM and RD performed significantly better in Altoona, Berwick, Rock Springs, and York than in Homer City.

Table 3-19. Significant differences of multiple comparisons for yield score by variety.

The GLIMMIX Procedure for Yield, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G G4	Homer	Rock	-0.9167	0.2993	114.8	-3.06	0.0027
G G73	Altoona	Berwick	0.9525	0.2976	121.4	3.2	0.0018
G G73	Berwick	Rock	-0.7859	0.2976	121.4	-2.64	0.0094
G L37	Berwick	Rock	-0.9109	0.2976	121.4	-3.06	0.0027
G L37	Homer	Rock	-0.7917	0.2993	114.8	-2.64	0.0093
G MF	Homer	Rock	-0.9167	0.2993	114.8	-3.06	0.0027
G MM	Altoona	Homer	1.5833	0.2993	114.8	5.29	0.0001
G MM	Berwick	Homer	1.1667	0.2993	114.8	3.9	0.0002
G MM	Homer	Rock	-1.8333	0.2993	114.8	-6.12	0.0001
G MM	Homer	York	-1.75	0.2993	114.8	-5.85	0.0001
G RD	Altoona	Homer	1.2083	0.2993	114.8	4.04	0.0001
G RD	Berwick	Homer	1.2083	0.2993	114.8	4.04	0.0001
G RD	Homer	Rock	-1.625	0.2993	114.8	-5.43	0.0001
G RD	Homer	York	-1.2083	0.2993	114.8	-4.04	0.0001

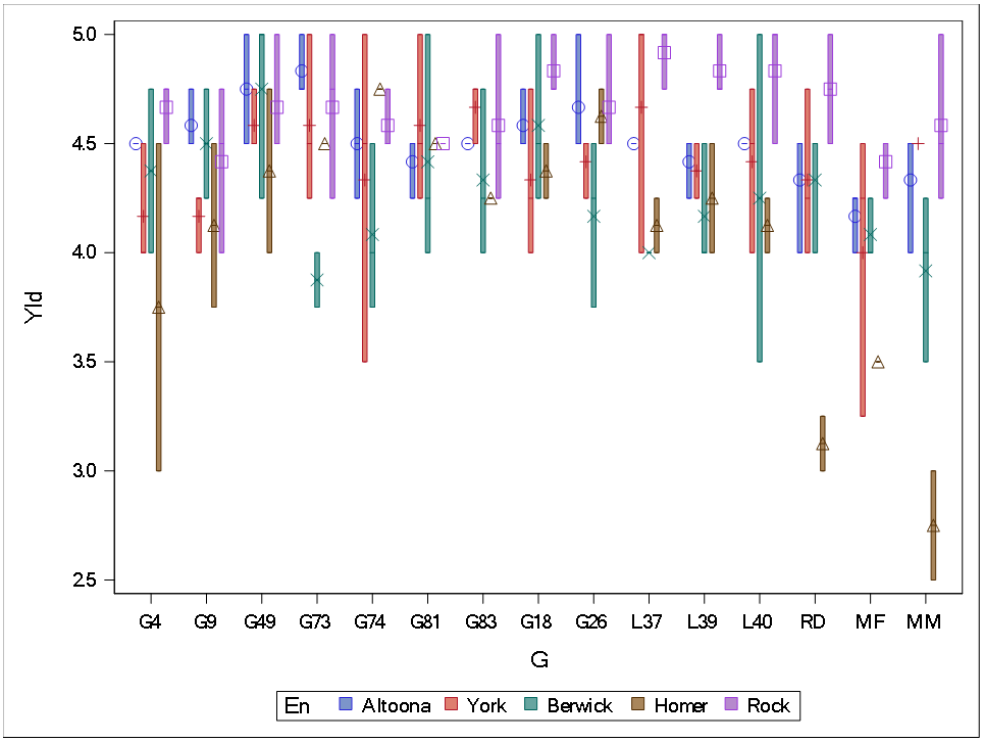

Figure 3-19. Variety yield scores are clustered together in order to more easily observe differences of an individual's performance throughout all five locations. Significant differences presented in multiple comparisons Table 3-19 (alpha = 0.01).

Disease resistance plant scores are presented in Figure 3-20, and multiple comparisons significant differences are presented in Table B-1 and C-1 in Appendix B and Appendix C, respectively. Multiple comparisons significance values do not reflect the incidence of any one particular disease for a given combination of varieties, but merely the overall disease present in the plots observed; so, the many significant differences in disease scores between varieties are not describe here. Instead, the farm locations are described for relevant disease incidence, and boxplots are observed for variety responses at each farm location. Altoona and Rock Springs both performed fairly well for plant disease resistance. At each farm there was varying degrees of early blight present. Additionally, at Rock Springs there was grey mold, bacterial speck, bacterial spot, and little late blight identified toward the end of the season. In York, there was a moderate degree

of bacterial canker and varieties were observed to be affected in varying degrees. In Berwick, there was a high degree of bacterial canker and substantial defoliation for many varieties at the time of evaluation. In Homer City high-tunnel plots, there was primarily incidence of powdery mildew and grey leaf mold, and minor degree of insect damage from thrips (on foliage) and stink bugs (on fruit). Insect damage was noted and scored, but was not included in the analysis as it remained specific to only the Homer City trial.

In York, G4, and especially L39 were heavily affected by bacterial canker, while G49, G73, G74, G83, G26, L37, and L40 were only moderately/slightly affected by disease incidence. The commercial cultivar, RD, performed among the best for disease resistance in York. In Homer City, there were several PSU hybrids that were observed to be less affected by the heavy incidence of powdery mildew and grey leaf mold throughout the plots. These hybrids include G4, G74, G83, G26, L37, L39, and L40, which all performed better than the commercial cultivars for plant disease resistance in Homer City. Rock Springs performed relatively uniformly for plant disease resistance with G49, G26, L37, L39, and L40 perhaps performing the best. One PSU hybrid, G9, seemed to be disproportionately affected by disease in the research field at Rock Springs.

In discussions with farmers, bacterial canker has become more of a problem with tomato crops in recent years. While the data presented here is not absolutely indicative of genetically conferred plant disease resistance, it presents the opportunity to further explore potential disease resistance in screenings with more controlled environmental settings. Additionally, the trials at Homer City indicate the potential for competitive PSU hybrids for cultivation within high-tunnel cultivation based on both the yield score performance presented in Figure 3-17 and the plant disease resistance in Figure 3-20.

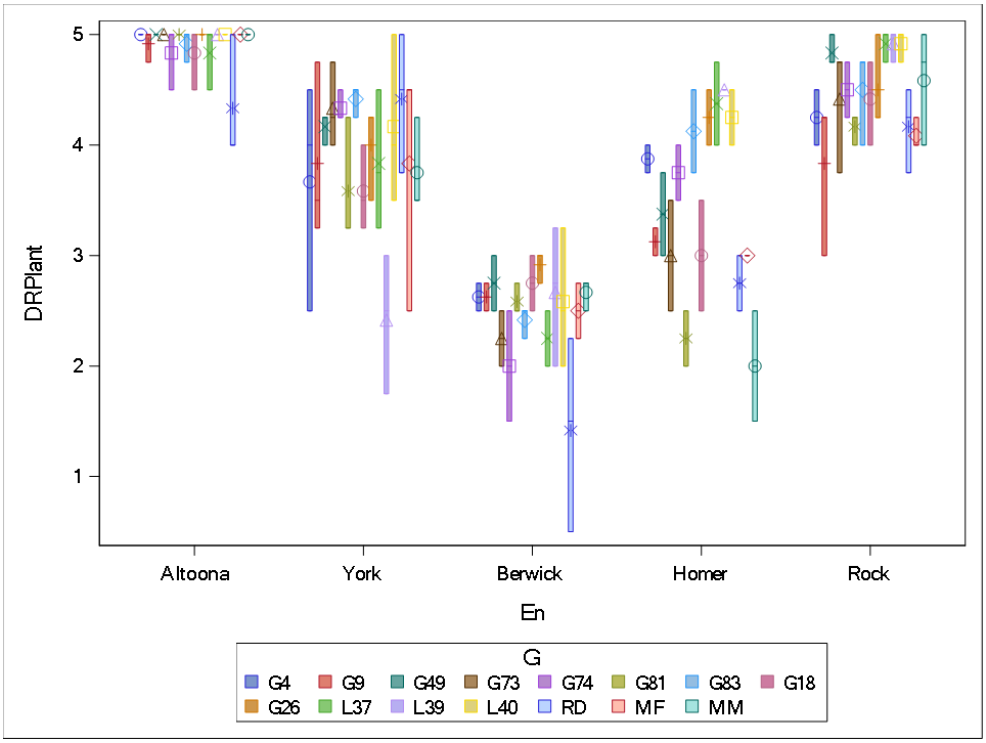

Figure 3-20. Plant disease resistance score for each PSU hybrid and commercial cultivar in each farm location. Significant differences for multiple comparisons are not discussed, but are presented in Table B-1 and C-1 in Appendices B and C for reference.

Since there were 1,740 possible interactions among varieties in all pairwise comparisons of locations for all traits; and there were 6,195 possible interactions for pairwise comparison of varieties in location for all traits, analysis for multiple comparisons was limited to overall and yield anlysis in Figure 3-16, Figure 3-17, Figure 3-18, and Figure 3-19. Significant interactions for multiple comparisons of all other traits are provided in Appendices B and C.

There were no significant differences for variety overall main effects between any of the 12 PSU hybrids; however, from a breeder's perspective, the six varieties in the 'a' signifiance class in Figure 3-4 for overall scores were significantly different from all of the commercial cultivars evaluated. Therefore, these six varieties (G4, G49, G26, L37, L39, L40) represent potential for competing with current commercial standards and should be further assessed for

genotype*location (G x E) interactions and variety stability. The overall means of the populations in each farm location were calculated independently of these six selected varieties, and locations were ordered in ascending order of overall means (calculated from the remaining 9 varieties) from left to right in Figure 3-21. G4 (blue line) did not exhibit any interaction with farm locations (see Table 3-18 for signifcant G*E interactions). G49 overall performance was significantly different between Homer City and each of Rock Springs and York. G126 was not significantly different for overall performance between any farm location. G37 (L37) was significantly different between Berwick and Rock Springs. L39 was significantly different for overall score between Rock Springs and each of Berwick and York. L40 performed significantly different for overall score between each of Altoona and Berwick, Berwick and Rock Springs, and Homer and Rock Springs. Based on these results and the relative performance of these six PSU hybrids, Figure 3-22 compares G4, G37, and G126 with each of the commercial cultivars. Each of MM and MF had four significant genotyope-location interactions between Homer City and each of the other farm locations. If we were to remove Homer City (the only high-tunnel cultivation), both MM and MF would be stable across the four other environments; however, RD was significantly different between Berwick and Rock Springs, indicating genotype-location interaction. G49 also had no genotype-location interactions for overall score if Homer City was removed from analysis.

Similarly in Figure 3-23, three PSU hybrids were selected for further anlysis for yield to assess genotype-location interactions and comparison with commercial cultivars. Significant multiple comparisons for variety by pairwise comparison of farm location are presented in Table 19. G49 and G118 had no significant interactions for yield between different farm locations. G73 was significantly different between Berwick and each of Altoona and Rock Springs, making it less desirable. For MF, the only significant interaction was between Homer City and Rock Springs. Each of MM and RD have four significant yield score-location interactions between

Homer City and each of the other four farm locations. If Homer City (high-tunnel) was removed from analysis, the commercial cultivars had no significant location interactions for yield score.

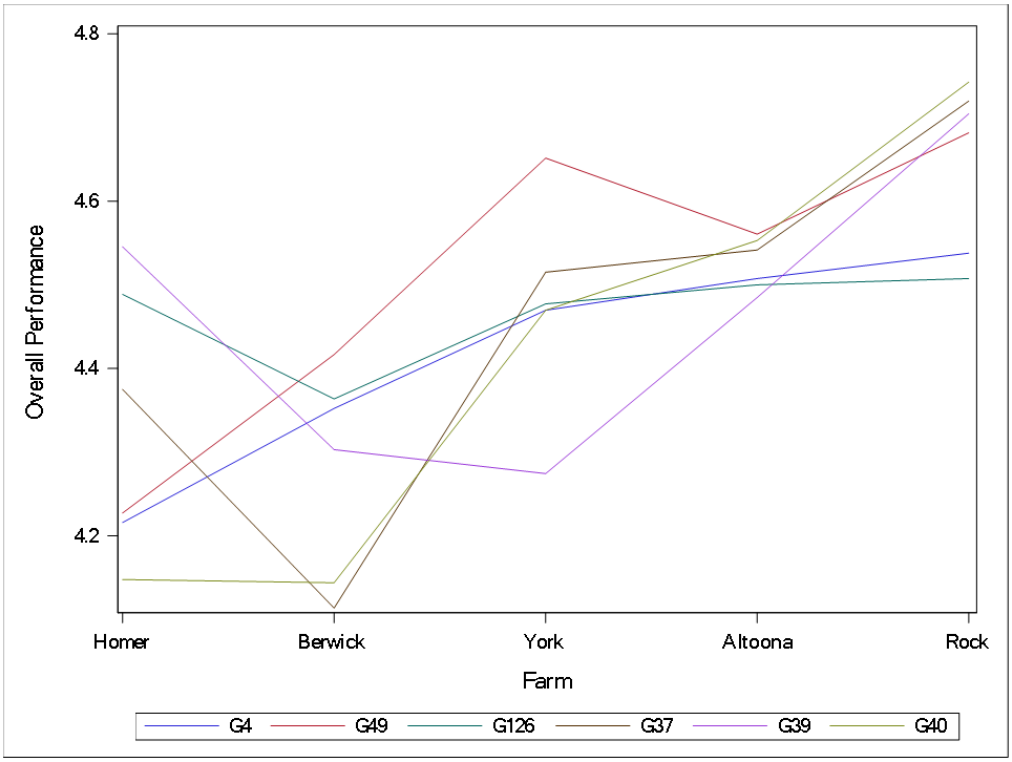

Figure 3-21. Line plot for overall score of six selected PSU experimental hybrids in five farm locations. Farms ranked in ascending order of overall means of population from left to right with six varieties independent of farm overall population means. Multiple comparisons least squares means significant differences for $p < 0.01$ are presented in Table 3-18.

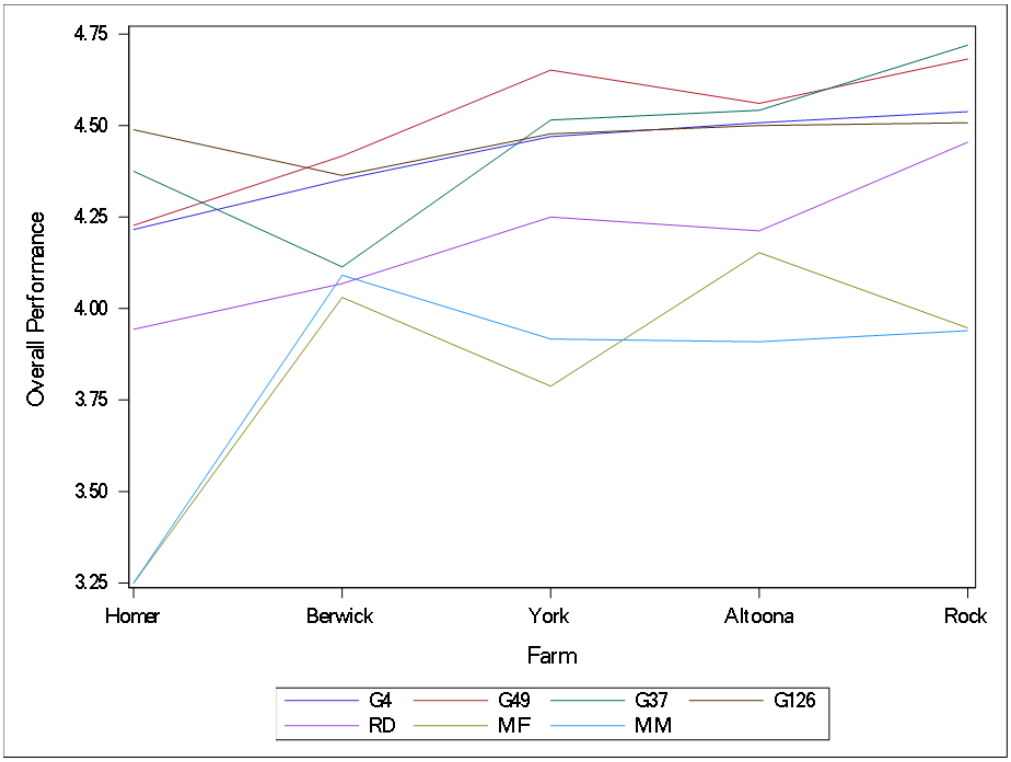

Figure 3-22. Line plot for overall score for four selected PSU hybrids in comparison to the commercial cultivars to assess differences in performance by variety across locations and significant genotype-location interactions. Multiple comparisons least squares means significant differences for $p < 0.01$ are presented in Table 3-18.

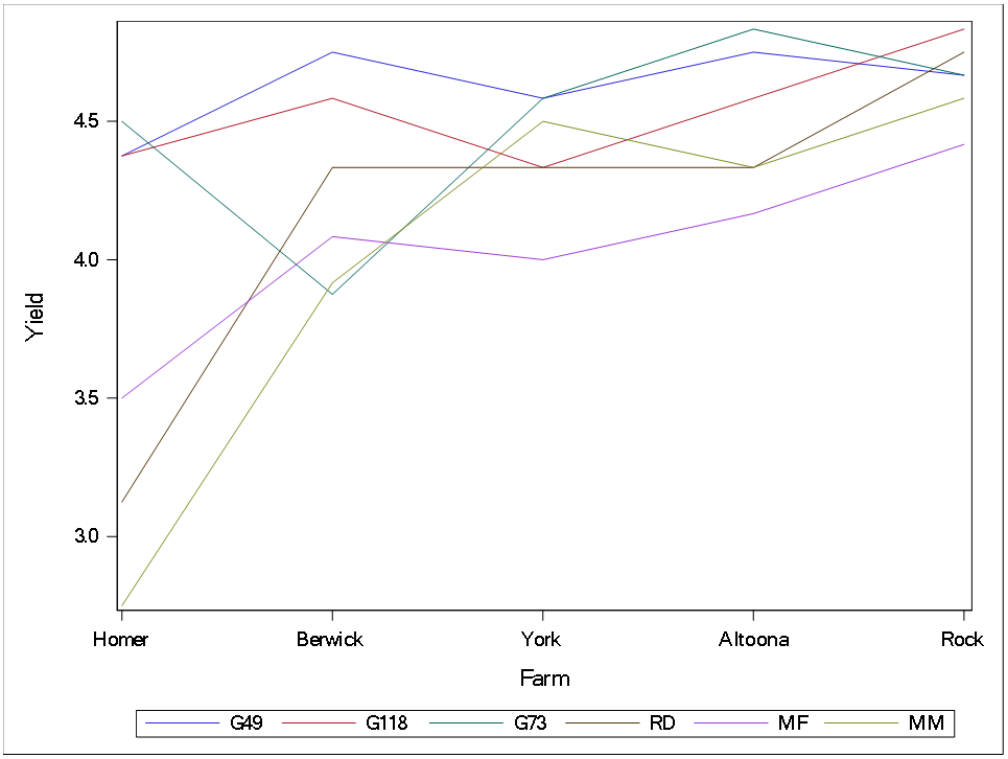

Figure 3-23. Line plot for yield score of three PSU hybrids in comparison to the commercial cultivars to assess differences in performance by variety across locations and significant genotype-location interactions. Multiple comparisons least squares means significant differences for $p < 0.01$ are presented in Table 3-19.

Fruit Quality and Lycopene Estimation

In conjunction with the fruit lycopene estimates performed, Brix, pH and % acidity were also measured for fruit collected from three replications at the Rock Springs location of the 2019 MLTs. These measurements and relevant significant differences are presented in Table 3-20. For Brix, there was no significant difference between any of the PSU hybrids or commercial cultivars, and all remained in the normal range for Brix for large slicing tomatoes. Brix measurements ranged from 4.4 (low—RD and G81) to 5.1 (high—MF). G126 had the highest Brix among PSU hybrids with a value of 5.0.

For % acidity measurement, there was only one significant difference between L39 (52.00%) and G83 (39.67%) with each measurement being the highest and lowest, respectively.

For pH, there were only two significant differences between MF and RD, and MM and RD, but all of the pH values remained in the normal range for large size tomatoes, 4.1-4.6.

Table 3-20. Brix, pH, and % acidity measurements.

Hybrid	Brix		% Acidity		pH	
4	ns	4.6	ab	47.67	ab	4.4
9	ns	4.5	ab	47.67	ab	4.3
49	ns	4.9	ab	47.67	ab	4.3
73	ns	4.4	ab	41.67	ab	4.4
74	ns	4.5	ab	42.50	ab	4.4
81	ns	4.4	ab	44.33	ab	4.3
83	ns	4.7	b	39.67	ab	4.4
118	ns	4.7	ab	41.67	ab	4.3
126	ns	5.0	ab	48.67	ab	4.4
37	ns	4.9	ab	48.33	ab	4.3
39	ns	4.8	a	52.00	ab	4.4
40	ns	4.7	ab	40.33	ab	4.3
Red Deuce	ns	4.4	ab	41.00	b	4.2
Mt. Fresh +	ns	5.1	ab	46.67	a	4.5
Mt. Merit	ns	4.9	ab	46.67	a	4.5

In Table 3-21, all lycopene estimates are presented for each of the spectrophotometric, colorimeter values, and color values obtained from image analysis with Tomato Analyzer 4.0. Lycopene estimates for the transformed a^{*4} value of colorimeter measurements were not significantly different among varieties and also seemed to underestimate the lycopene content compared to other estimation methods. Despite performing calibration through the plastic Petri dish in which puree measurements were taken, the obtained values are believed to be inaccurate and not reflect an accurate estimation of fruit lycopene content.

The lycopene estimates for transformed $(a^*/b^*)^{2.5}$ whole fruit colorimetric data were more within the range of normal values expected for large type, fresh market tomatoes, and there were

significant differences among varieties. G49 had the highest lycopene estimate with 59.44 ug/g, and was significantly greater than G4, G9, G73, G81, G40, RD, MF, and MM. G37 (57.37 ug/g) was significantly different from G81 and RD. RD had the lowest lycopene estimate with 40.87 ug/g.

Lycopene estimates for each of the external and internal color value were calculated using either h* or a/b* values. Although, the equations derived by Saad were derived using exclusively color values obtained from image analysis on the external portion of the fruit, the increased redness of PSU tomato germplasm on the inside portion of the fruit warranted lycopene estimation of sliced tomatoes as well.

There were many internal image (a*/b*) lycopene estimates that were significantly different among varieties. The two highest estimates for lycopene were for PSU hybrids G74 (45.70 ug/g) and L40 (45.16 ug/g), which were significantly greater than G118, RD, MF and MM. PSU hybrids G49 (44.93 ug/g) and G83 (45.07 ug/g) were significantly different from G118, RD and MF. G9 (44.88 ug/g) and G73 (44.85 ug/g) were significantly different from each of RD and MF. G4, G81, G126, G37 and G39 were significantly different from RD. RD had the lowest fruit lycopene estimate for internal (a*/b) image analysis with 40.73 ug/g; and MM had the highest lycopene estimate among the commercial cultivars with a value of 42.30 ug/g.

Internal image (h*) lycopene calculations tended to estimate values much lower than for the a*/b* estimates, but there were also many significant differences that were almost synonymous with significant differences for a*/b*. G9 was the only hybrid that was placed into a different significance class, making it significantly different from G118, RD and MF. G74 still had the highest fruit lycopene estimate with a value of 37.71 ug/g, and RD had the lowest value with 33.82 ug/g.

External image lycopene estimates for each of a*/b* and h* values had no significant differences between PSU hybrids or commercial cultivars. External fruit lycopene estimates were

generally lower than those estimates for internal fruit lycopene for each respective calculation (a*/b* or h*).

Since the correlation between whole fruit lycopene estimation and lycopene measurement by HPLC by Hyman et al. (2004) was $R^2 = 0.736$, and correlation between image lycopene estimation and lycopene measurement by Saad (2016) was $R^2 = 0.91$; internal image analysis based on Saad's equation for external image lycopene estimation may be a more accurate method for lycopene estimation in this trial. In addition, whole fruit colorimeter lycopene estimates from Hyman (2004) overestimated fruit lycopene content on average 13 ug/g.

Table 3-21. Lycopene estimates calculated from transformed color values for whole fruit and puree spectrophotometry and for color values obtained from image analysis of whole and sliced tomato fruit.

Hybrid	Colorimeter Puree Lycopene (ug/g)		Colorimeter Whole Lycopene (ug/g)		Internal Image (a*/b*) Lycopene (ug/g)		Internal Image (h*) Lycopene (ug/g)		External Image (a*/b*) Lycopene (ug/g)		External image (h*) Lycopene (ug/g)	
4	ns	14.39	bc	47.52	abcd	44.34	abcd	36.69	ns	41.67	ns	34.61
9	ns	15.24	bc	46.40	abc	44.88	ab	37.11	ns	41.37	ns	34.38
49	ns	15.97	a	59.44	ab	44.93	ab	37.15	ns	42.75	ns	35.47
73	ns	14.78	bc	47.12	abc	44.85	abc	37.09	ns	41.13	ns	34.21
74	ns	15.84	abc	52.12	a	45.70	a	37.71	ns	41.78	ns	34.70
81	ns	17.22	c	40.79	abcd	44.63	abcd	36.90	ns	40.80	ns	33.91
83	ns	15.24	abc	50.43	ab	45.07	ab	37.23	ns	42.12	ns	34.95
118	ns	16.14	abc	50.09	cde	42.12	cde	34.94	ns	41.80	ns	34.70
126	ns	19.04	abc	56.09	abcd	44.61	abcd	36.89	ns	42.86	ns	35.56
37	ns	17.91	ab	57.37	abcd	44.17	abcd	36.56	ns	42.03	ns	34.91
39	ns	15.71	abc	51.46	abcd	44.63	abcd	36.91	ns	41.52	ns	34.49
40	ns	17.59	bc	45.99	a	45.16	a	37.31	ns	41.71	ns	34.64
Red Deuce	ns	13.68	c	40.87	e	40.73	e	33.82	ns	40.93	ns	34.01
Mt. Fresh +	ns	16.34	bc	46.44	de	41.98	de	34.84	ns	41.55	ns	34.51
Mt. Merit	ns	17.15	bc	47.57	bcde	42.30	bcde	35.10	ns	42.01	ns	34.89

Chapter 4

Conclusion and Future Prospects

The main objective of the experiments conducted in this thesis project was to determine competitiveness of the PSU Tomato Breeding Program's large type FM experimental tomato hybrids. In this research, we conducted yield trials in 2017 to estimate yield potential in two locations and assess fruit size and quality attributes in one location in Rock Springs. Visual evaluations in Rock Springs over several years, and company evaluations from around the United States and internationally, have also determined which hybrids were most competitive in multiple years and in different locations. Thorough visual evaluations were conducted at multiple farm locations in 2019 with a reduced number of PSU hybrids side by side with a few commercial cultivars, and fruit quality assessment for pH, SSC, % acidity, and lycopene estimation were performed on the same varieties.

The results of the 2017 and 2019 trials have identified several excellent hybrids for more advanced trials. In 2017, hybrids G49, G118, and G126 demonstrated desirable yield potential, fruit size, and fruit quality characteristics, and were included for further analysis in 2018 and 2019. In 2019, hybrids G4, G49, G126, L37, L39 and L40 performed significantly better than all three commercial cultivars for overall scores across the five farm locations; these hybrids were not significantly different from the six other PSU hybrids in the experiments. G49 performed significantly better than commercial cultivars MF and MM for yield score, but not better than RD; and G49 was not significantly different from any PSU hybrids for visual yield score. G4 and G126 did not show any significant interactions by farm location; and when the Homer City high-tunnel operation was excluded, none of G49, MM or MF showed any interactions with farm

location. After final analysis, there were several PSU experimental hybrids that showed great potential for commercialization, including G4, G49, G118 and G126. G73 and L37 showed good potential as well, but exhibited more significant interactions with farm location (other than Homer City) for yield score; and L40 results showed significant interactions with farm location for overall score.

Fruit lycopene estimation has shown significant differences in fruit lycopene content between many PSU hybrids and commercial cultivars, especially for G49 that was estimated to have significantly higher lycopene content than each of Red Deuce, Mt. Fresh+ and Mt. Merit for one lycopene estimation method, and significantly higher lycopene than each of RD and MF for two estimation methods. G74 was significantly higher than all commercial cultivars for two lycopene estimation methods. G83 was significantly higher than RD and MF for two lycopene estimation methods; and G9 was significantly higher than RD and MF for one method. L40 was significantly higher than all commercial cultivars for two lycopene estimation methods.

Several growers have already indicated their interest in participating in larger yield trials for one or more PSU hybrids in the next season. Trials in Homer City also indicated there might be some PSU varieties that have potential in high-tunnel or greenhouse settings, though this must be explored further as there was only one high-tunnel operation in this experiment. Hybrids that were favored for more vigorous, continuous growth habits included G126, several late blight resistant hybrids, and G74, which performed particularly well in high-tunnel cultivation, though it had a more compact growth habit.

Future projects include further reducing the number of competitive PSU hybrids for larger yield trials in commercial settings, and getting PSU tomato seed in the hands of interested growers throughout PA. It is also of interest to examine PSU tomato hybrids in more controlled systems and greenhouse settings where indeterminate plants are desired (unlike determinate plants for field tomato production), and to design experiments to evaluate for greenhouse

production (e.g. hydroponic systems, plant nutrition), resistance/tolerance to common greenhouse diseases (powdery mildew, grey leaf mold), insect pests, and physiological disorders.

Currently, work is underway for the development of tightly-linked genetic marker(s) for a high-lycopene QTL (*lyc12.1*), which was identified at Penn State, and to test its presence in all PSU lines and hybrids. After a preliminary analysis and comparison of the processing tomato cultivar Heinz 1706 reference genome sequence with PSLP 125 (original source of the high lycopene QTL, *lyc12.1*), the coding and non-coding regions appeared to have no functional difference between accessions. We believe that the reason for higher lycopene content in PSLP 125 (and our derived lines and hybrids) may be due to SNPs or structural differences in the promoter region upstream of *lyc12.1,* which would result in upregulation of lycopene expression. Future projects also include accurate measurement of lycopene content by HPLC for many of the hybrids examined in this study, in which cultivation will be carried out in a more controlled greenhouse setting to avoid issues associated with variation in field settings.

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Appendix

A. ANOVA mixed model for each trait

Appendix A-1 ANOVA for Mixed Model Plant Disease Resistance Score

Type 3 Tests of Fixed Effects for DRPlant				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	122	4.21	<.0001
En	4	8.87	98.59	<.0001
G*En	56	122	3.2	<.0001

Appendix A-2 ANOVA Mixed Model Fruit Disease Resistance Score

Type 3 Tests of Fixed Effects for DRFruit				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	122	1.62	0.0828
En	4	8.9	6.85	0.0084
G*En	56	122	1.47	0.0395

Appendix A-3 ANOVA Mixed Model Stem End Score

Type 3 Tests of Fixed Effects for StemEnd				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	122	6.46	<.0001
En	4	8.99	3.13	0.0719
G*En	56	122	1.18	0.2239

Appendix A-4 ANOVA Mixed Model Blossom End Score

Type 3 Tests of Fixed Effects for BlosEnd				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	122	3.43	0.0001
En	4	8.95	5.58	0.0155
G*En	56	122	0.95	0.5746

Appendix A-5 ANOVA Mixed Model Fruit Firmness Score

Type 3 Tests of Fixed Effects for Firm				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	120	22.9	<.0001
En	4	9.54	18.43	0.0002
G*En	56	120	2.59	<.0001

Appendix A-6 ANOVA Mixed Model Internal Fruit Color

Type 3 Tests of Fixed Effects for ClrIn				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	119	30.29	<.0001
En	4	8.86	0.57	0.6933
G*En	56	119	1.78	0.0045

Appendix A-7 ANOVA Mixed Model External Fruit Color

Type 3 Tests of Fixed Effects for ClrOut				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	119	10.81	<.0001
En	4	8.34	8.69	0.0046
G*En	56	119	1.29	0.1227

Appendix A-8 ANOVA Mixed Model Locule Distribution Score

Type 3 Tests of Fixed Effects for Loc				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	121	16.24	<.0001
En	4	9.15	2.76	0.0941
G*En	56	120	1.57	0.0205

Appendix A-9 ANOVA Mixed Model Taste Score

Type 3 Tests of Fixed Effects for Taste				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	119	13.33	<.0001
En	4	9.13	0.94	0.4824
G*En	56	119	1.45	0.0466

Appendix A-10 ANOVA Mixed Model Uniformity Fruit Size

Type 3 Tests of Fixed Effects for Unifrsz				
Effect	Num DF	Den DF	F-Value	Pr > F
G	14	105	4.28	<.0001
En	3	7.74	4.35	0.0445
G*En	42	105	1.49	0.0523

B. Significant differences of multiple comparisons for trait score by location

Appendix B-1 Significant Differences of Multiple Comparisons for Plant Disease Resistance Score by Location

The GLIMMIX Procedure for Plant DR, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Berwick	G18	RD	1.3333	0.3403	121.9	3.92	0.0001
En Berwick	G26	G74	0.9167	0.3403	121.9	2.69	0.0081
En Berwick	G26	RD	1.5	0.3403	121.9	4.41	0.0001
En Berwick	G4	RD	1.1766	0.3821	123.7	3.08	0.0026
En Berwick	G49	RD	1.3333	0.3403	121.9	3.92	0.0001
En Berwick	G81	RD	1.1667	0.3403	121.9	3.43	0.0008
En Berwick	G83	RD	1	0.3403	121.9	2.94	0.0039
En Berwick	G9	RD	1.1766	0.3821	123.7	3.08	0.0026
En Berwick	L39	RD	1.25	0.3403	121.9	3.67	0.0004
En Berwick	L40	RD	1.1667	0.3403	121.9	3.43	0.0008
En Berwick	MF	RD	1.0833	0.3403	121.9	3.18	0.0018
En Berwick	MM	RD	1.25	0.3403	121.9	3.67	0.0004
En Homer	G18	G26	-1.25	0.4168	121.9	-3	0.0033
En Homer	G18	G83	-1.125	0.4168	121.9	-2.7	0.0079
En Homer	G18	L37	-1.375	0.4168	121.9	-3.3	0.0013
En Homer	G18	L39	-1.5	0.4168	121.9	-3.6	0.0005
En Homer	G18	L40	-1.25	0.4168	121.9	-3	0.0033
En Homer	G26	G73	1.25	0.4168	121.9	3	0.0033
En Homer	G26	G81	2	0.4168	121.9	4.8	0.0001
En Homer	G26	G9	1.125	0.4168	121.9	2.7	0.0079
En Homer	G26	MF	1.25	0.4168	121.9	3	0.0033
En Homer	G26	MM	2.25	0.4168	121.9	5.4	0.0001
En Homer	G26	RD	1.5	0.4168	121.9	3.6	0.0005
En Homer	G4	G81	1.625	0.4168	121.9	3.9	0.0002
En Homer	G4	MM	1.875	0.4168	121.9	4.5	0.0001
En Homer	G4	RD	1.125	0.4168	121.9	2.7	0.0079
En Homer	G49	G81	1.125	0.4168	121.9	2.7	0.0079
En Homer	G49	L39	-1.125	0.4168	121.9	-2.7	0.0079

En Homer	G49	MM	1.375	0.4168	121.9	3.3	0.0013
En Homer	G73	G83	-1.125	0.4168	121.9	-2.7	0.0079
En Homer	G73	L37	-1.375	0.4168	121.9	-3.3	0.0013
En Homer	G73	L39	-1.5	0.4168	121.9	-3.6	0.0005
En Homer	G73	L40	-1.25	0.4168	121.9	-3	0.0033
En Homer	G74	G81	1.5	0.4168	121.9	3.6	0.0005
En Homer	G74	MM	1.75	0.4168	121.9	4.2	0.0001
En Homer	G81	G83	-1.875	0.4168	121.9	-4.5	0.0001
En Homer	G81	L37	-2.125	0.4168	121.9	-5.1	0.0001
En Homer	G81	L39	-2.25	0.4168	121.9	-5.4	0.0001
En Homer	G81	L40	-2	0.4168	121.9	-4.8	0.0001
En Homer	G83	MF	1.125	0.4168	121.9	2.7	0.0079
En Homer	G83	MM	2.125	0.4168	121.9	5.1	0.0001
En Homer	G83	RD	1.375	0.4168	121.9	3.3	0.0013
En Homer	G9	L37	-1.25	0.4168	121.9	-3	0.0033
En Homer	G9	L39	-1.375	0.4168	121.9	-3.3	0.0013
En Homer	G9	L40	-1.125	0.4168	121.9	-2.7	0.0079
En Homer	G9	MM	1.125	0.4168	121.9	2.7	0.0079
En Homer	L37	MF	1.375	0.4168	121.9	3.3	0.0013
En Homer	L37	MM	2.375	0.4168	121.9	5.7	0.0001
En Homer	L37	RD	1.625	0.4168	121.9	3.9	0.0002
En Homer	L39	MF	1.5	0.4168	121.9	3.6	0.0005
En Homer	L39	MM	2.5	0.4168	121.9	6	0.0001
En Homer	L39	RD	1.75	0.4168	121.9	4.2	0.0001
En Homer	L40	MF	1.25	0.4168	121.9	3	0.0033
En Homer	L40	MM	2.25	0.4168	121.9	5.4	0.0001
En Homer	L40	RD	1.5	0.4168	121.9	3.6	0.0005
En Rock	G49	G9	1	0.3403	121.9	2.94	0.0039
En Rock	G9	L37	-1.0833	0.3403	121.9	-3.18	0.0018
En Rock	G9	L39	-1.0833	0.3403	121.9	-3.18	0.0018
En Rock	G9	L40	-1.0833	0.3403	121.9	-3.18	0.0018
En York	G18	L39	1.1667	0.3403	121.9	3.43	0.0008
En York	G26	L39	1.5833	0.3403	121.9	4.65	0.0001
En York	G4	L39	1.25	0.3403	121.9	3.67	0.0004
En York	G49	L39	1.75	0.3403	121.9	5.14	0.0001
En York	G73	L39	1.9167	0.3403	121.9	5.63	0.0001
En York	G74	L39	1.9167	0.3403	121.9	5.63	0.0001
En York	G81	L39	1.1667	0.3403	121.9	3.43	0.0008
En York	G83	L39	2	0.3403	121.9	5.88	0.0001

En York	G9	L39	1.4167	0.3403	121.9	4.16	0.0001
En York	L37	L39	1.4167	0.3403	121.9	4.16	0.0001
En York	L39	L40	-1.75	0.3403	121.9	-5.14	0.0001
En York	L39	MF	-1.4167	0.3403	121.9	-4.16	0.0001
En York	L39	MM	-1.3333	0.3403	121.9	-3.92	0.0001
En York	L39	RD	-2	0.3403	121.9	-5.88	0.0001

Appendix B-2 Significant Differences of Multiple Comparisons for Fruit Disease Resistance Score by Location

The GLIMMIX Procedure for Fruit DR, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Berwick	G18	G73	0.9976	0.1558	122.4	6.4	0.0001
En Berwick	G26	G73	1.2476	0.1558	122.4	8.01	0.0001
En Berwick	G26	G74	0.5833	0.1384	121.9	4.21	0.0001
En Berwick	G26	G83	0.5833	0.1384	121.9	4.21	0.0001
En Berwick	G26	L40	0.5	0.1384	121.9	3.61	0.0004
En Berwick	G26	MF	0.4167	0.1384	121.9	3.01	0.0032
En Berwick	G26	MM	0.5	0.1384	121.9	3.61	0.0004
En Berwick	G26	RD	0.5	0.1384	121.9	3.61	0.0004
En Berwick	G4	G73	1.1844	0.1726	123.1	6.86	0.0001
En Berwick	G4	G74	0.5201	0.1558	122.4	3.34	0.0011
En Berwick	G4	G83	0.5201	0.1558	122.4	3.34	0.0011
En Berwick	G4	L40	0.4367	0.1558	122.4	2.8	0.0059
En Berwick	G4	MM	0.4367	0.1558	122.4	2.8	0.0059
En Berwick	G4	RD	0.4367	0.1558	122.4	2.8	0.0059
En Berwick	G49	G73	1.081	0.1558	122.4	6.94	0.0001
En Berwick	G49	G74	0.4167	0.1384	121.9	3.01	0.0032
En Berwick	G49	G83	0.4167	0.1384	121.9	3.01	0.0032
En Berwick	G73	G74	-0.6643	0.1558	122.4	-4.26	0.0001
En Berwick	G73	G81	-0.9976	0.1558	122.4	-6.4	0.0001
En Berwick	G73	G83	-0.6643	0.1558	122.4	-4.26	0.0001
En Berwick	G73	G9	-0.9344	0.1726	123.1	-5.41	0.0001
En Berwick	G73	L37	-1.125	0.1695	121.9	-6.64	0.0001
En Berwick	G73	L39	-0.9143	0.1558	122.4	-5.87	0.0001
En Berwick	G73	L40	-0.7476	0.1558	122.4	-4.8	0.0001

En Berwick	G73	MF	-0.831	0.1558	122.4	-5.33	0.0001
En Berwick	G73	MM	-0.7476	0.1558	122.4	-4.8	0.0001
En Berwick	G73	RD	-0.7476	0.1558	122.4	-4.8	0.0001
En Berwick	G74	L37	-0.4607	0.1558	122.4	-2.96	0.0037
En Berwick	G83	L37	-0.4607	0.1558	122.4	-2.96	0.0037

Appendix B-3 Significant Differences of Multiple Comparisons for Stem End Score by Location

The GLIMMIX Procedure for Stem End, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G74	RD	-0.8333	0.3013	122.1	-2.77	0.0066
En Altoona	L39	RD	-0.8333	0.3013	122.1	-2.77	0.0066
En Altoona	MM	RD	-1	0.3013	122.1	-3.32	0.0012
En Berwick	G18	RD	-1	0.3013	122.1	-3.32	0.0012
En Berwick	G4	RD	-0.9088	0.3382	123.9	-2.69	0.0082
En Berwick	G73	RD	-0.9934	0.3382	123.9	-2.94	0.0039
En Berwick	G74	RD	-0.9167	0.3013	122.1	-3.04	0.0029
En Berwick	G81	RD	-0.9167	0.3013	122.1	-3.04	0.0029
En Berwick	G83	RD	-1	0.3013	122.1	-3.32	0.0012
En Berwick	G9	RD	-1.0338	0.3382	123.9	-3.06	0.0027
En Berwick	L39	RD	-1	0.3013	122.1	-3.32	0.0012
En Berwick	L40	RD	-1.0833	0.3013	122.1	-3.6	0.0005
En Berwick	MF	RD	-0.8333	0.3013	122.1	-2.77	0.0066
En Berwick	MM	RD	-1.0833	0.3013	122.1	-3.6	0.0005
En Homer	G18	MF	1.125	0.3691	122.1	3.05	0.0028
En Homer	G18	RD	-1.125	0.3691	122.1	-3.05	0.0028
En Homer	G26	G4	1	0.3691	122.1	2.71	0.0077
En Homer	G26	G73	1.25	0.3691	122.1	3.39	0.001
En Homer	G26	G83	1	0.3691	122.1	2.71	0.0077
En Homer	G26	L37	1.25	0.3691	122.1	3.39	0.001
En Homer	G26	MF	2	0.3691	122.1	5.42	0.0001
En Homer	G4	MF	1	0.3691	122.1	2.71	0.0077
En Homer	G4	RD	-1.25	0.3691	122.1	-3.39	0.001
En Homer	G49	MF	1.25	0.3691	122.1	3.39	0.001
En Homer	G49	RD	-1	0.3691	122.1	-2.71	0.0077
En Homer	G73	G9	-1	0.3691	122.1	-2.71	0.0077

En Homer	G73	RD	-1.5	0.3691	122.1	-4.06	0.0001
En Homer	G74	MF	1.5	0.3691	122.1	4.06	0.0001
En Homer	G81	MF	1.5	0.3691	122.1	4.06	0.0001
En Homer	G83	MF	1	0.3691	122.1	2.71	0.0077
En Homer	G83	RD	-1.25	0.3691	122.1	-3.39	0.001
En Homer	G9	L37	1	0.3691	122.1	2.71	0.0077
En Homer	G9	MF	1.75	0.3691	122.1	4.74	0.0001
En Homer	L37	RD	-1.5	0.3691	122.1	-4.06	0.0001
En Homer	L39	MF	1.625	0.3691	122.1	4.4	0.0001
En Homer	L40	MF	1.25	0.3691	122.1	3.39	0.001
En Homer	L40	RD	-1	0.3691	122.1	-2.71	0.0077
En Homer	MF	MM	-1.5	0.3691	122.1	-4.06	0.0001
En Homer	MF	RD	-2.25	0.3691	122.1	-6.1	0.0001
En Rock	G4	MF	0.8333	0.3013	122.1	2.77	0.0066
En Rock	MF	RD	-0.9167	0.3013	122.1	-3.04	0.0029
En York	G26	G83	0.8333	0.3013	122.1	2.77	0.0066
En York	G26	MF	1.4167	0.3013	122.1	4.7	0.0001
En York	G4	MF	0.8333	0.3013	122.1	2.77	0.0066
En York	G49	MF	1.0833	0.3013	122.1	3.6	0.0005
En York	G74	MF	0.8333	0.3013	122.1	2.77	0.0066
En York	G81	MF	0.8333	0.3013	122.1	2.77	0.0066
En York	G9	MF	0.9167	0.3013	122.1	3.04	0.0029
En York	L37	MF	0.9167	0.3013	122.1	3.04	0.0029
En York	L39	MF	0.8333	0.3013	122.1	2.77	0.0066
En York	MF	MM	-0.8333	0.3013	122.1	-2.77	0.0066
En York	MF	RD	-1.1667	0.3013	122.1	-3.87	0.0002

Appendix B-4 Significant Differences of Multiple Comparisons for Blossom End Score by Location

The GLIMMIX Procedure for Blossom End, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G83	L37	0.6667	0.2342	122	2.85	0.0052
En Altoona	L37	RD	-0.75	0.2342	122	-3.2	0.0017
En Homer	G49	G74	-0.875	0.2869	122	-3.05	0.0028
En Homer	G49	RD	-0.875	0.2869	122	-3.05	0.0028

En Homer	G73	L40	0.875	0.2869	122	3.05	0.0028
En Homer	G74	L40	1	0.2869	122	3.49	0.0007
En Homer	L40	RD	-1	0.2869	122	-3.49	0.0007

Appendix B-5 Significant Differences of Multiple Comparisons for Fruit Firmness Score by Location

The GLIMMIX Procedure for Fruit Firmness, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G18	MF	1.675	0.3507	124.4	4.78	0.0001
En Altoona	G18	MM	1.3333	0.2468	119.6	5.4	0.0001
En Altoona	G26	MF	1.3416	0.3507	124.4	3.83	0.0002
En Altoona	G26	MM	1	0.2468	119.6	4.05	0.0001
En Altoona	G4	G83	0.6667	0.2468	119.6	2.7	0.0079
En Altoona	G4	MF	1.7583	0.3507	124.4	5.01	0.0001
En Altoona	G4	MM	1.4167	0.2468	119.6	5.74	0.0001
En Altoona	G49	MF	1.5083	0.3507	124.4	4.3	0.0001
En Altoona	G49	MM	1.1667	0.2468	119.6	4.73	0.0001
En Altoona	G73	MF	1.3416	0.3507	124.4	3.83	0.0002
En Altoona	G73	MM	1	0.2468	119.6	4.05	0.0001
En Altoona	G74	MF	1.175	0.3507	124.4	3.35	0.0011
En Altoona	G74	MM	0.8333	0.2468	119.6	3.38	0.001
En Altoona	G81	MF	1.175	0.3507	124.4	3.35	0.0011
En Altoona	G81	MM	0.8333	0.2468	119.6	3.38	0.001
En Altoona	G83	MF	1.0916	0.3507	124.4	3.11	0.0023
En Altoona	G83	MM	0.75	0.2468	119.6	3.04	0.0029
En Altoona	G9	MF	1.5083	0.3507	124.4	4.3	0.0001
En Altoona	G9	MM	1.1667	0.2468	119.6	4.73	0.0001
En Altoona	L37	MF	1.2626	0.3714	123	3.4	0.0009
En Altoona	L37	MM	0.9209	0.2764	121.8	3.33	0.0011
En Altoona	L39	MF	1.3416	0.3507	124.4	3.83	0.0002
En Altoona	L39	MM	1	0.2468	119.6	4.05	0.0001
En Altoona	L40	MF	1.425	0.3507	124.4	4.06	0.0001
En Altoona	L40	MM	1.0833	0.2468	119.6	4.39	0.0001
En Altoona	MF	RD	-1.5083	0.3507	124.4	-4.3	0.0001
En Altoona	MM	RD	-1.1667	0.2468	119.6	-4.73	0.0001

En Berwick	G49	L40	0.6667	0.2468	119.6	2.7	0.0079
En Homer	G18	MF	2	0.3022	119.6	6.62	0.0001
En Homer	G18	MM	1.75	0.3022	119.6	5.79	0.0001
En Homer	G26	MF	2	0.3022	119.6	6.62	0.0001
En Homer	G26	MM	1.75	0.3022	119.6	5.79	0.0001
En Homer	G4	MF	1.75	0.3022	119.6	5.79	0.0001
En Homer	G4	MM	1.5	0.3022	119.6	4.96	0.0001
En Homer	G49	MF	1.75	0.3022	119.6	5.79	0.0001
En Homer	G49	MM	1.5	0.3022	119.6	4.96	0.0001
En Homer	G73	MF	1.75	0.3022	119.6	5.79	0.0001
En Homer	G73	MM	1.5	0.3022	119.6	4.96	0.0001
En Homer	G74	MF	1.875	0.3022	119.6	6.2	0.0001
En Homer	G74	MM	1.625	0.3022	119.6	5.38	0.0001
En Homer	G81	MF	1.875	0.3022	119.6	6.2	0.0001
En Homer	G81	MM	1.625	0.3022	119.6	5.38	0.0001
En Homer	G83	G9	-0.875	0.3022	119.6	-2.9	0.0045
En Homer	G83	MF	1.25	0.3022	119.6	4.14	0.0001
En Homer	G83	MM	1	0.3022	119.6	3.31	0.0012
En Homer	G83	RD	-1.25	0.3022	119.6	-4.14	0.0001
En Homer	G9	MF	2.125	0.3022	119.6	7.03	0.0001
En Homer	G9	MM	1.875	0.3022	119.6	6.2	0.0001
En Homer	L37	MF	1.875	0.3022	119.6	6.2	0.0001
En Homer	L37	MM	1.625	0.3022	119.6	5.38	0.0001
En Homer	L39	MF	2	0.3022	119.6	6.62	0.0001
En Homer	L39	MM	1.75	0.3022	119.6	5.79	0.0001
En Homer	L40	MF	1.5	0.3022	119.6	4.96	0.0001
En Homer	L40	MM	1.25	0.3022	119.6	4.14	0.0001
En Homer	L40	RD	-1	0.3022	119.6	-3.31	0.0012
En Homer	MF	RD	-2.5	0.3022	119.6	-8.27	0.0001
En Homer	MM	RD	-2.25	0.3022	119.6	-7.45	0.0001
En Rock	G18	G83	0.75	0.2468	119.6	3.04	0.0029
En Rock	G18	MF	1.1667	0.2468	119.6	4.73	0.0001
En Rock	G18	MM	1.75	0.2468	119.6	7.09	0.0001
En Rock	G26	G4	-0.6667	0.2468	119.6	-2.7	0.0079
En Rock	G26	MF	0.75	0.2468	119.6	3.04	0.0029
En Rock	G26	MM	1.3333	0.2468	119.6	5.4	0.0001
En Rock	G4	G74	0.6667	0.2468	119.6	2.7	0.0079
En Rock	G4	G83	1	0.2468	119.6	4.05	0.0001
En Rock	G4	MF	1.4167	0.2468	119.6	5.74	0.0001

En Rock	G4	MM	2	0.2468	119.6	8.11	0.0001
En Rock	G49	G83	0.6667	0.2468	119.6	2.7	0.0079
En Rock	G49	MF	1.0833	0.2468	119.6	4.39	0.0001
En Rock	G49	MM	1.6667	0.2468	119.6	6.75	0.0001
En Rock	G73	G83	0.6667	0.2468	119.6	2.7	0.0079
En Rock	G73	MF	1.0833	0.2468	119.6	4.39	0.0001
En Rock	G73	MM	1.6667	0.2468	119.6	6.75	0.0001
En Rock	G74	MF	0.75	0.2468	119.6	3.04	0.0029
En Rock	G74	MM	1.3333	0.2468	119.6	5.4	0.0001
En Rock	G81	G83	0.6667	0.2468	119.6	2.7	0.0079
En Rock	G81	MF	1.0833	0.2468	119.6	4.39	0.0001
En Rock	G81	MM	1.6667	0.2468	119.6	6.75	0.0001
En Rock	G83	G9	-0.8333	0.2468	119.6	-3.38	0.001
En Rock	G83	L37	-0.75	0.2468	119.6	-3.04	0.0029
En Rock	G83	L39	-0.6667	0.2468	119.6	-2.7	0.0079
En Rock	G83	L40	-0.6667	0.2468	119.6	-2.7	0.0079
En Rock	G83	MM	1	0.2468	119.6	4.05	0.0001
En Rock	G83	RD	-0.6667	0.2468	119.6	-2.7	0.0079
En Rock	G9	MF	1.25	0.2468	119.6	5.07	0.0001
En Rock	G9	MM	1.8333	0.2468	119.6	7.43	0.0001
En Rock	L37	MF	1.1667	0.2468	119.6	4.73	0.0001
En Rock	L37	MM	1.75	0.2468	119.6	7.09	0.0001
En Rock	L39	MF	1.0833	0.2468	119.6	4.39	0.0001
En Rock	L39	MM	1.6667	0.2468	119.6	6.75	0.0001
En Rock	L40	MF	1.0833	0.2468	119.6	4.39	0.0001
En Rock	L40	MM	1.6667	0.2468	119.6	6.75	0.0001
En Rock	MF	RD	-1.0833	0.2468	119.6	-4.39	0.0001
En Rock	MM	RD	-1.6667	0.2468	119.6	-6.75	0.0001
En York	G18	MF	1.25	0.2468	119.6	5.07	0.0001
En York	G18	MM	1.25	0.2468	119.6	5.07	0.0001
En York	G26	MF	1.1667	0.2468	119.6	4.73	0.0001
En York	G26	MM	1.1667	0.2468	119.6	4.73	0.0001
En York	G4	MF	1.4167	0.2468	119.6	5.74	0.0001
En York	G4	MM	1.4167	0.2468	119.6	5.74	0.0001
En York	G49	MF	1.4167	0.2468	119.6	5.74	0.0001
En York	G49	MM	1.4167	0.2468	119.6	5.74	0.0001
En York	G73	MF	1.3333	0.2468	119.6	5.4	0.0001
En York	G73	MM	1.3333	0.2468	119.6	5.4	0.0001
En York	G74	MF	1.25	0.2468	119.6	5.07	0.0001

En York	G74	MM	1.25	0.2468	119.6	5.07	0.0001
En York	G81	MF	1.25	0.2468	119.6	5.07	0.0001
En York	G81	MM	1.25	0.2468	119.6	5.07	0.0001
En York	G83	MF	1.1667	0.2468	119.6	4.73	0.0001
En York	G83	MM	1.1667	0.2468	119.6	4.73	0.0001
En York	G9	MF	1.25	0.2468	119.6	5.07	0.0001
En York	G9	MM	1.25	0.2468	119.6	5.07	0.0001
En York	L37	MF	1.1667	0.2468	119.6	4.73	0.0001
En York	L37	MM	1.1667	0.2468	119.6	4.73	0.0001
En York	L39	MF	1	0.2468	119.6	4.05	0.0001
En York	L39	MM	1	0.2468	119.6	4.05	0.0001
En York	L40	MF	1.0833	0.2468	119.6	4.39	0.0001
En York	L40	MM	1.0833	0.2468	119.6	4.39	0.0001
En York	MF	RD	-1.0833	0.2468	119.6	-4.39	0.0001
En York	MM	RD	-1.0833	0.2468	119.6	-4.39	0.0001

Appendix B-6 Significant Differences of Multiple Comparisons for Internal Fruit Color Score by Location

The GLIMMIX Procedure for Internal Fruit Color, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G18	MM	0.9167	0.2768	118.9	3.31	0.0012
En Altoona	G26	MM	1.25	0.2768	118.9	4.52	0.0001
En Altoona	G26	RD	0.9167	0.2768	118.9	3.31	0.0012
En Altoona	G4	MM	1.25	0.2768	118.9	4.52	0.0001
En Altoona	G4	RD	0.9167	0.2768	118.9	3.31	0.0012
En Altoona	G49	MF	1.1808	0.3956	122.1	2.98	0.0034
En Altoona	G49	MM	1.5	0.2768	118.9	5.42	0.0001
En Altoona	G49	RD	1.1667	0.2768	118.9	4.22	0.0001
En Altoona	G73	MM	1.3333	0.2768	118.9	4.82	0.0001
En Altoona	G73	RD	1	0.2768	118.9	3.61	0.0004
En Altoona	G74	MM	1.1667	0.2768	118.9	4.22	0.0001
En Altoona	G74	RD	0.8333	0.2768	118.9	3.01	0.0032
En Altoona	G81	MM	1	0.2768	118.9	3.61	0.0004
En Altoona	G83	MM	1.25	0.2768	118.9	4.52	0.0001
En Altoona	G83	RD	0.9167	0.2768	118.9	3.31	0.0012

En Altoona	G9	MM	1.1667	0.2768	118.9	4.22	0.0001
En Altoona	G9	RD	0.8333	0.2768	118.9	3.01	0.0032
En Altoona	L37	MM	1.3352	0.3108	120.3	4.3	0.0001
En Altoona	L37	RD	1.0019	0.3108	120.3	3.22	0.0016
En Altoona	L39	MM	1.3333	0.2768	118.9	4.82	0.0001
En Altoona	L39	RD	1	0.2768	118.9	3.61	0.0004
En Altoona	L40	MM	1.25	0.2768	118.9	4.52	0.0001
En Altoona	L40	RD	0.9167	0.2768	118.9	3.31	0.0012
En Homer	G18	MF	2.125	0.339	118.9	6.27	0.0001
En Homer	G18	MM	1.875	0.339	118.9	5.53	0.0001
En Homer	G26	MF	2.375	0.339	118.9	7.01	0.0001
En Homer	G26	MM	2.125	0.339	118.9	6.27	0.0001
En Homer	G26	RD	1.125	0.339	118.9	3.32	0.0012
En Homer	G4	MF	2.25	0.339	118.9	6.64	0.0001
En Homer	G4	MM	2	0.339	118.9	5.9	0.0001
En Homer	G4	RD	1	0.339	118.9	2.95	0.0038
En Homer	G49	MF	2.5	0.339	118.9	7.38	0.0001
En Homer	G49	MM	2.25	0.339	118.9	6.64	0.0001
En Homer	G49	RD	1.25	0.339	118.9	3.69	0.0003
En Homer	G73	MF	2.5	0.339	118.9	7.38	0.0001
En Homer	G73	MM	2.25	0.339	118.9	6.64	0.0001
En Homer	G73	RD	1.25	0.339	118.9	3.69	0.0003
En Homer	G74	MF	2.5	0.339	118.9	7.38	0.0001
En Homer	G74	MM	2.25	0.339	118.9	6.64	0.0001
En Homer	G74	RD	1.25	0.339	118.9	3.69	0.0003
En Homer	G81	MF	2.25	0.339	118.9	6.64	0.0001
En Homer	G81	MM	2	0.339	118.9	5.9	0.0001
En Homer	G81	RD	1	0.339	118.9	2.95	0.0038
En Homer	G83	MF	2.375	0.339	118.9	7.01	0.0001
En Homer	G83	MM	2.125	0.339	118.9	6.27	0.0001
En Homer	G83	RD	1.125	0.339	118.9	3.32	0.0012
En Homer	G9	MF	2.25	0.339	118.9	6.64	0.0001
En Homer	G9	MM	2	0.339	118.9	5.9	0.0001
En Homer	G9	RD	1	0.339	118.9	2.95	0.0038
En Homer	L37	MF	2.5	0.339	118.9	7.38	0.0001
En Homer	L37	MM	2.25	0.339	118.9	6.64	0.0001
En Homer	L37	RD	1.25	0.339	118.9	3.69	0.0003
En Homer	L39	MF	2.375	0.339	118.9	7.01	0.0001
En Homer	L39	MM	2.125	0.339	118.9	6.27	0.0001

En Homer	L39	RD	1.125	0.339	118.9	3.32	0.0012
En Homer	L40	MF	2.125	0.339	118.9	6.27	0.0001
En Homer	L40	MM	1.875	0.339	118.9	5.53	0.0001
En Homer	MF	RD	-1.25	0.339	118.9	-3.69	0.0003
En Homer	MM	RD	-1	0.339	118.9	-2.95	0.0038
En Rock	G18	G26	-0.75	0.2768	118.9	-2.71	0.0077
En Rock	G18	G49	-1	0.2768	118.9	-3.61	0.0004
En Rock	G18	G73	-0.75	0.2768	118.9	-2.71	0.0077
En Rock	G18	G9	-0.8333	0.2768	118.9	-3.01	0.0032
En Rock	G18	L37	-1	0.2768	118.9	-3.61	0.0004
En Rock	G18	L39	-0.8333	0.2768	118.9	-3.01	0.0032
En Rock	G18	L40	-0.75	0.2768	118.9	-2.71	0.0077
En Rock	G18	MF	0.75	0.2768	118.9	2.71	0.0077
En Rock	G18	MM	0.75	0.2768	118.9	2.71	0.0077
En Rock	G26	MF	1.5	0.2768	118.9	5.42	0.0001
En Rock	G26	MM	1.5	0.2768	118.9	5.42	0.0001
En Rock	G4	MF	1.1667	0.2768	118.9	4.22	0.0001
En Rock	G4	MM	1.1667	0.2768	118.9	4.22	0.0001
En Rock	G49	MF	1.75	0.2768	118.9	6.32	0.0001
En Rock	G49	MM	1.75	0.2768	118.9	6.32	0.0001
En Rock	G49	RD	0.9167	0.2768	118.9	3.31	0.0012
En Rock	G73	MF	1.5	0.2768	118.9	5.42	0.0001
En Rock	G73	MM	1.5	0.2768	118.9	5.42	0.0001
En Rock	G74	MF	1.4167	0.2768	118.9	5.12	0.0001
En Rock	G74	MM	1.4167	0.2768	118.9	5.12	0.0001
En Rock	G81	MF	1.4167	0.2768	118.9	5.12	0.0001
En Rock	G81	MM	1.4167	0.2768	118.9	5.12	0.0001
En Rock	G83	MF	1.3333	0.2768	118.9	4.82	0.0001
En Rock	G83	MM	1.3333	0.2768	118.9	4.82	0.0001
En Rock	G9	MF	1.5833	0.2768	118.9	5.72	0.0001
En Rock	G9	MM	1.5833	0.2768	118.9	5.72	0.0001
En Rock	G9	RD	0.75	0.2768	118.9	2.71	0.0077
En Rock	L37	MF	1.75	0.2768	118.9	6.32	0.0001
En Rock	L37	MM	1.75	0.2768	118.9	6.32	0.0001
En Rock	L37	RD	0.9167	0.2768	118.9	3.31	0.0012
En Rock	L39	MF	1.5833	0.2768	118.9	5.72	0.0001
En Rock	L39	MM	1.5833	0.2768	118.9	5.72	0.0001
En Rock	L39	RD	0.75	0.2768	118.9	2.71	0.0077
En Rock	L40	MF	1.5	0.2768	118.9	5.42	0.0001

En Rock	L40	MM	1.5	0.2768	118.9	5.42	0.0001
En Rock	MF	RD	-0.8333	0.2768	118.9	-3.01	0.0032
En Rock	MM	RD	-0.8333	0.2768	118.9	-3.01	0.0032
En York	G18	MF	1.8333	0.2768	118.9	6.62	0.0001
En York	G18	MM	1.1667	0.2768	118.9	4.22	0.0001
En York	G26	MF	2.3333	0.2768	118.9	8.43	0.0001
En York	G26	MM	1.6667	0.2768	118.9	6.02	0.0001
En York	G26	RD	1	0.2768	118.9	3.61	0.0004
En York	G4	MF	2.3333	0.2768	118.9	8.43	0.0001
En York	G4	MM	1.6667	0.2768	118.9	6.02	0.0001
En York	G4	RD	1	0.2768	118.9	3.61	0.0004
En York	G49	MF	2.5	0.2768	118.9	9.03	0.0001
En York	G49	MM	1.8333	0.2768	118.9	6.62	0.0001
En York	G49	RD	1.1667	0.2768	118.9	4.22	0.0001
En York	G73	MF	2.4167	0.2768	118.9	8.73	0.0001
En York	G73	MM	1.75	0.2768	118.9	6.32	0.0001
En York	G73	RD	1.0833	0.2768	118.9	3.91	0.0002
En York	G74	MF	2.25	0.2768	118.9	8.13	0.0001
En York	G74	MM	1.5833	0.2768	118.9	5.72	0.0001
En York	G74	RD	0.9167	0.2768	118.9	3.31	0.0012
En York	G81	MF	2.3333	0.2768	118.9	8.43	0.0001
En York	G81	MM	1.6667	0.2768	118.9	6.02	0.0001
En York	G81	RD	1	0.2768	118.9	3.61	0.0004
En York	G83	MF	2.25	0.2768	118.9	8.13	0.0001
En York	G83	MM	1.5833	0.2768	118.9	5.72	0.0001
En York	G83	RD	0.9167	0.2768	118.9	3.31	0.0012
En York	G9	MF	2	0.2768	118.9	7.23	0.0001
En York	G9	MM	1.3333	0.2768	118.9	4.82	0.0001
En York	L37	MF	2.3333	0.2768	118.9	8.43	0.0001
En York	L37	MM	1.6667	0.2768	118.9	6.02	0.0001
En York	L37	RD	1	0.2768	118.9	3.61	0.0004
En York	L39	MF	2.25	0.2768	118.9	8.13	0.0001
En York	L39	MM	1.5833	0.2768	118.9	5.72	0.0001
En York	L39	RD	0.9167	0.2768	118.9	3.31	0.0012
En York	L40	MF	2.1667	0.2768	118.9	7.83	0.0001
En York	L40	MM	1.5	0.2768	118.9	5.42	0.0001
En York	L40	RD	0.8333	0.2768	118.9	3.01	0.0032
En York	MF	RD	-1.3333	0.2768	118.9	-4.82	0.0001

Appendix B-7 Significant Differences of Multiple Comparisons for External Fruit Color Score by Location

The GLIMMIX Procedure for External Fruit Color, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G18	MM	0.8333	0.2355	118.4	3.54	0.0006
En Altoona	G26	MM	1.0833	0.2355	118.4	4.6	0.0001
En Altoona	G4	MM	1.0833	0.2355	118.4	4.6	0.0001
En Altoona	G49	MF	1.1738	0.3345	124.1	3.51	0.0006
En Altoona	G49	MM	1.4167	0.2355	118.4	6.02	0.0001
En Altoona	G49	RD	0.6667	0.2355	118.4	2.83	0.0055
En Altoona	G73	MM	1	0.2355	118.4	4.25	0.0001
En Altoona	G74	MM	1.0833	0.2355	118.4	4.6	0.0001
En Altoona	G81	MM	1.0833	0.2355	118.4	4.6	0.0001
En Altoona	G83	MF	0.9238	0.3345	124.1	2.76	0.0066
En Altoona	G83	MM	1.1667	0.2355	118.4	4.95	0.0001
En Altoona	G9	MF	0.9238	0.3345	124.1	2.76	0.0066
En Altoona	G9	MM	1.1667	0.2355	118.4	4.95	0.0001
En Altoona	L37	MF	1.0064	0.3543	122.4	2.84	0.0053
En Altoona	L37	MM	1.2493	0.2638	121	4.74	0.0001
En Altoona	L39	MF	1.0071	0.3345	124.1	3.01	0.0032
En Altoona	L39	MM	1.25	0.2355	118.4	5.31	0.0001
En Altoona	L40	MF	0.9238	0.3345	124.1	2.76	0.0066
En Altoona	L40	MM	1.1667	0.2355	118.4	4.95	0.0001
En Altoona	MM	RD	-0.75	0.2355	118.4	-3.18	0.0019
En Homer	G18	MF	1.125	0.2884	118.4	3.9	0.0002
En Homer	G26	MF	1	0.2884	118.4	3.47	0.0007
En Homer	G4	MF	1.125	0.2884	118.4	3.9	0.0002
En Homer	G49	L40	1	0.2884	118.4	3.47	0.0007
En Homer	G49	MF	1.5	0.2884	118.4	5.2	0.0001
En Homer	G49	MM	1	0.2884	118.4	3.47	0.0007
En Homer	G73	MF	1.125	0.2884	118.4	3.9	0.0002
En Homer	G74	MF	1.125	0.2884	118.4	3.9	0.0002
En Homer	G81	MF	0.875	0.2884	118.4	3.03	0.003
En Homer	G83	MF	1.125	0.2884	118.4	3.9	0.0002
En Homer	G9	MF	1.125	0.2884	118.4	3.9	0.0002
En Homer	L37	L40	1	0.2884	118.4	3.47	0.0007
En Homer	L37	MF	1.5	0.2884	118.4	5.2	0.0001

En Homer	L37	MM	1	0.2884	118.4	3.47	0.0007
En Homer	L39	L40	0.875	0.2884	118.4	3.03	0.003
En Homer	L39	MF	1.375	0.2884	118.4	4.77	0.0001
En Homer	L39	MM	0.875	0.2884	118.4	3.03	0.003
En Rock	G26	MM	0.75	0.2355	118.4	3.18	0.0019
En Rock	G49	MF	0.6667	0.2355	118.4	2.83	0.0055
En Rock	G49	MM	0.8333	0.2355	118.4	3.54	0.0006
En Rock	G73	MF	0.6667	0.2355	118.4	2.83	0.0055
En Rock	G73	MM	0.8333	0.2355	118.4	3.54	0.0006
En Rock	G74	MM	0.75	0.2355	118.4	3.18	0.0019
En Rock	G81	MM	0.75	0.2355	118.4	3.18	0.0019
En Rock	G9	MM	0.75	0.2355	118.4	3.18	0.0019
En Rock	L37	MF	0.75	0.2355	118.4	3.18	0.0019
En Rock	L37	MM	0.9167	0.2355	118.4	3.89	0.0002
En Rock	L39	MF	0.8333	0.2355	118.4	3.54	0.0006
En Rock	L39	MM	1	0.2355	118.4	4.25	0.0001
En Rock	L40	MF	0.6667	0.2355	118.4	2.83	0.0055
En Rock	L40	MM	0.8333	0.2355	118.4	3.54	0.0006
En Rock	MM	RD	-0.6667	0.2355	118.4	-2.83	0.0055
En York	G18	MF	0.8333	0.2355	118.4	3.54	0.0006
En York	G26	MF	0.9167	0.2355	118.4	3.89	0.0002
En York	G26	MM	0.6667	0.2355	118.4	2.83	0.0055
En York	G4	MF	0.8333	0.2355	118.4	3.54	0.0006
En York	G49	G9	0.75	0.2355	118.4	3.18	0.0019
En York	G49	MF	1.25	0.2355	118.4	5.31	0.0001
En York	G49	MM	1	0.2355	118.4	4.25	0.0001
En York	G49	RD	0.9167	0.2355	118.4	3.89	0.0002
En York	G73	MF	1	0.2355	118.4	4.25	0.0001
En York	G73	MM	0.75	0.2355	118.4	3.18	0.0019
En York	G73	RD	0.6667	0.2355	118.4	2.83	0.0055
En York	G74	MF	0.9167	0.2355	118.4	3.89	0.0002
En York	G74	MM	0.6667	0.2355	118.4	2.83	0.0055
En York	G81	MF	0.8333	0.2355	118.4	3.54	0.0006
En York	G83	MF	0.8333	0.2355	118.4	3.54	0.0006
En York	L37	MF	0.9167	0.2355	118.4	3.89	0.0002
En York	L37	MM	0.6667	0.2355	118.4	2.83	0.0055
En York	L39	MF	1	0.2355	118.4	4.25	0.0001
En York	L39	MM	0.75	0.2355	118.4	3.18	0.0019
En York	L39	RD	0.6667	0.2355	118.4	2.83	0.0055

En York	L40	MF	1	0.2355	118.4	4.25	0.0001
En York	L40	MM	0.75	0.2355	118.4	3.18	0.0019
En York	L40	RD	0.6667	0.2355	118.4	2.83	0.0055

Appendix B-8 Significant Differences of Multiple Comparisons for Locule Distribution Score by Location

The GLIMMIX Procedure for Locule Distribution, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G18	MM	0.75	0.2603	120.2	2.88	0.0047
En Altoona	G18	RD	0.75	0.2603	120.2	2.88	0.0047
En Altoona	G4	MM	0.8333	0.2603	120.2	3.2	0.0017
En Altoona	G4	RD	0.8333	0.2603	120.2	3.2	0.0017
En Altoona	G49	MM	0.8333	0.2603	120.2	3.2	0.0017
En Altoona	G49	RD	0.8333	0.2603	120.2	3.2	0.0017
En Altoona	G73	MM	0.75	0.2603	120.2	2.88	0.0047
En Altoona	G73	RD	0.75	0.2603	120.2	2.88	0.0047
En Altoona	G83	MM	0.9167	0.2603	120.2	3.52	0.0006
En Altoona	G83	RD	0.9167	0.2603	120.2	3.52	0.0006
En Altoona	G9	L40	-0.8333	0.2603	120.2	-3.2	0.0017
En Altoona	L37	MM	1.0147	0.2921	121.8	3.47	0.0007
En Altoona	L37	RD	1.0147	0.2921	121.8	3.47	0.0007
En Altoona	L39	MM	0.9167	0.2603	120.2	3.52	0.0006
En Altoona	L39	RD	0.9167	0.2603	120.2	3.52	0.0006
En Altoona	L40	MF	0.9542	0.2921	121.8	3.27	0.0014
En Altoona	L40	MM	1.1667	0.2603	120.2	4.48	0.0001
En Altoona	L40	RD	1.1667	0.2603	120.2	4.48	0.0001
En Berwick	G81	MF	0.8333	0.2603	120.2	3.2	0.0017
En Berwick	L39	MF	0.8333	0.2603	120.2	3.2	0.0017
En Homer	G18	MF	1.25	0.3188	120.2	3.92	0.0001
En Homer	G18	MM	2	0.3188	120.2	6.27	0.0001
En Homer	G26	MF	1.125	0.3188	120.2	3.53	0.0006
En Homer	G26	MM	1.875	0.3188	120.2	5.88	0.0001
En Homer	G4	MF	1	0.3188	120.2	3.14	0.0021
En Homer	G4	MM	1.75	0.3188	120.2	5.49	0.0001
En Homer	G49	MF	1.125	0.3188	120.2	3.53	0.0006

En Homer	G49	MM	1.875	0.3188	120.2	5.88	0.0001
En Homer	G73	MF	1	0.3188	120.2	3.14	0.0021
En Homer	G73	MM	1.75	0.3188	120.2	5.49	0.0001
En Homer	G74	MF	1.125	0.3188	120.2	3.53	0.0006
En Homer	G74	MM	1.875	0.3188	120.2	5.88	0.0001
En Homer	G81	MF	0.875	0.3188	120.2	2.74	0.007
En Homer	G81	MM	1.625	0.3188	120.2	5.1	0.0001
En Homer	G83	MM	1.5	0.3188	120.2	4.71	0.0001
En Homer	G9	MF	1.125	0.3188	120.2	3.53	0.0006
En Homer	G9	MM	1.875	0.3188	120.2	5.88	0.0001
En Homer	L37	MF	1.25	0.3188	120.2	3.92	0.0001
En Homer	L37	MM	2	0.3188	120.2	6.27	0.0001
En Homer	L39	MF	1.375	0.3188	120.2	4.31	0.0001
En Homer	L39	MM	2.125	0.3188	120.2	6.67	0.0001
En Homer	L40	MF	1.375	0.3188	120.2	4.31	0.0001
En Homer	L40	MM	2.125	0.3188	120.2	6.67	0.0001
En Homer	MM	RD	-1.375	0.3188	120.2	-4.31	0.0001
En Rock	G26	L40	-0.75	0.2603	120.2	-2.88	0.0047
En Rock	G4	MF	0.8333	0.2603	120.2	3.2	0.0017
En Rock	G4	MM	0.8333	0.2603	120.2	3.2	0.0017
En Rock	G49	G74	0.75	0.2603	120.2	2.88	0.0047
En Rock	G49	G83	0.75	0.2603	120.2	2.88	0.0047
En Rock	G49	MF	1.1667	0.2603	120.2	4.48	0.0001
En Rock	G49	MM	1.1667	0.2603	120.2	4.48	0.0001
En Rock	G49	RD	0.75	0.2603	120.2	2.88	0.0047
En Rock	G73	MF	0.8333	0.2603	120.2	3.2	0.0017
En Rock	G73	MM	0.8333	0.2603	120.2	3.2	0.0017
En Rock	G74	L37	-0.75	0.2603	120.2	-2.88	0.0047
En Rock	G74	L40	-0.8333	0.2603	120.2	-3.2	0.0017
En Rock	G81	MF	0.8333	0.2603	120.2	3.2	0.0017
En Rock	G81	MM	0.8333	0.2603	120.2	3.2	0.0017
En Rock	G83	L37	-0.75	0.2603	120.2	-2.88	0.0047
En Rock	G83	L40	-0.8333	0.2603	120.2	-3.2	0.0017
En Rock	G9	MF	0.9167	0.2603	120.2	3.52	0.0006
En Rock	G9	MM	0.9167	0.2603	120.2	3.52	0.0006
En Rock	L37	MF	1.1667	0.2603	120.2	4.48	0.0001
En Rock	L37	MM	1.1667	0.2603	120.2	4.48	0.0001
En Rock	L37	RD	0.75	0.2603	120.2	2.88	0.0047
En Rock	L39	MF	1.0833	0.2603	120.2	4.16	0.0001

En Rock	L39	MM	1.0833	0.2603	120.2	4.16	0.0001
En Rock	L40	MF	1.25	0.2603	120.2	4.8	0.0001
En Rock	L40	MM	1.25	0.2603	120.2	4.8	0.0001
En Rock	L40	RD	0.8333	0.2603	120.2	3.2	0.0017
En York	G18	MF	0.9167	0.2603	120.2	3.52	0.0006
En York	G18	MM	0.75	0.2603	120.2	2.88	0.0047
En York	G26	MF	1.0833	0.2603	120.2	4.16	0.0001
En York	G26	MM	0.9167	0.2603	120.2	3.52	0.0006
En York	G4	MF	1.3333	0.2603	120.2	5.12	0.0001
En York	G4	MM	1.1667	0.2603	120.2	4.48	0.0001
En York	G4	RD	0.75	0.2603	120.2	2.88	0.0047
En York	G49	MF	1.4167	0.2603	120.2	5.44	0.0001
En York	G49	MM	1.25	0.2603	120.2	4.8	0.0001
En York	G49	RD	0.8333	0.2603	120.2	3.2	0.0017
En York	G73	MF	1.3333	0.2603	120.2	5.12	0.0001
En York	G73	MM	1.1667	0.2603	120.2	4.48	0.0001
En York	G73	RD	0.75	0.2603	120.2	2.88	0.0047
En York	G74	MF	1.1667	0.2603	120.2	4.48	0.0001
En York	G74	MM	1	0.2603	120.2	3.84	0.0002
En York	G81	MF	1	0.2603	120.2	3.84	0.0002
En York	G81	MM	0.8333	0.2603	120.2	3.2	0.0017
En York	G83	MF	0.9167	0.2603	120.2	3.52	0.0006
En York	G83	MM	0.75	0.2603	120.2	2.88	0.0047
En York	G9	MF	1.0833	0.2603	120.2	4.16	0.0001
En York	G9	MM	0.9167	0.2603	120.2	3.52	0.0006
En York	L37	MF	1.5	0.2603	120.2	5.76	0.0001
En York	L37	MM	1.3333	0.2603	120.2	5.12	0.0001
En York	L37	RD	0.9167	0.2603	120.2	3.52	0.0006
En York	L39	MF	1.3333	0.2603	120.2	5.12	0.0001
En York	L39	MM	1.1667	0.2603	120.2	4.48	0.0001
En York	L39	RD	0.75	0.2603	120.2	2.88	0.0047
En York	L40	MF	1.3333	0.2603	120.2	5.12	0.0001
En York	L40	MM	1.1667	0.2603	120.2	4.48	0.0001
En York	L40	RD	0.75	0.2603	120.2	2.88	0.0047

Appendix B-9 Significant Differences of Multiple Comparisons for Taste Score by Location

The GLIMMIX Procedure for Taste, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G18	MM	1.1667	0.3068	119.1	3.8	0.0002
En Altoona	G26	MM	1.1667	0.3068	119.1	3.8	0.0002
En Altoona	G4	MF	1.2944	0.4394	121.5	2.95	0.0039
En Altoona	G4	MM	1.4167	0.3068	119.1	4.62	0.0001
En Altoona	G49	MF	1.2944	0.4394	121.5	2.95	0.0039
En Altoona	G49	MM	1.4167	0.3068	119.1	4.62	0.0001
En Altoona	G73	MM	1.25	0.3068	119.1	4.07	0.0001
En Altoona	G74	MM	1.0833	0.3068	119.1	3.53	0.0006
En Altoona	G81	MM	1.25	0.3068	119.1	4.07	0.0001
En Altoona	G83	MF	1.3777	0.4394	121.5	3.14	0.0022
En Altoona	G83	MM	1.5	0.3068	119.1	4.89	0.0001
En Altoona	G9	MM	1.1667	0.3068	119.1	3.8	0.0002
En Altoona	L37	MF	1.5684	0.4641	120.7	3.38	0.001
En Altoona	L37	MM	1.6907	0.3449	120.2	4.9	0.0001
En Altoona	L39	MF	1.2111	0.4394	121.5	2.76	0.0067
En Altoona	L39	MM	1.3333	0.3068	119.1	4.35	0.0001
En Altoona	L40	MF	1.2944	0.4394	121.5	2.95	0.0039
En Altoona	L40	MM	1.4167	0.3068	119.1	4.62	0.0001
En Altoona	MM	RD	-0.8333	0.3068	119.1	-2.72	0.0076
En Berwick	G26	RD	0.8333	0.3068	119.1	2.72	0.0076
En Berwick	G73	RD	0.9754	0.3449	120.3	2.83	0.0055
En Berwick	L39	RD	0.8333	0.3068	119.1	2.72	0.0076
En Homer	G18	MF	2	0.3758	119.1	5.32	0.0001
En Homer	G18	MM	1.5	0.3758	119.1	3.99	0.0001
En Homer	G26	MF	1.75	0.3758	119.1	4.66	0.0001
En Homer	G26	MM	1.25	0.3758	119.1	3.33	0.0012
En Homer	G4	MF	2	0.3758	119.1	5.32	0.0001
En Homer	G4	MM	1.5	0.3758	119.1	3.99	0.0001
En Homer	G49	MF	1.75	0.3758	119.1	4.66	0.0001
En Homer	G49	MM	1.25	0.3758	119.1	3.33	0.0012
En Homer	G73	MF	1.875	0.3758	119.1	4.99	0.0001
En Homer	G73	MM	1.375	0.3758	119.1	3.66	0.0004
En Homer	G74	MF	1.25	0.3758	119.1	3.33	0.0012

En Homer	G81	L37	-1	0.3758	119.1	-2.66	0.0089
En Homer	G81	MF	1.125	0.3758	119.1	2.99	0.0034
En Homer	G83	MF	1.25	0.3758	119.1	3.33	0.0012
En Homer	G9	MF	1.625	0.3758	119.1	4.32	0.0001
En Homer	G9	MM	1.125	0.3758	119.1	2.99	0.0034
En Homer	L37	MF	2.125	0.3758	119.1	5.65	0.0001
En Homer	L37	MM	1.625	0.3758	119.1	4.32	0.0001
En Homer	L39	MF	1.875	0.3758	119.1	4.99	0.0001
En Homer	L39	MM	1.375	0.3758	119.1	3.66	0.0004
En Homer	L40	MF	1.5	0.3758	119.1	3.99	0.0001
En Homer	L40	MM	1	0.3758	119.1	2.66	0.0089
En Homer	MF	RD	-1.875	0.3758	119.1	-4.99	0.0001
En Homer	MM	RD	-1.375	0.3758	119.1	-3.66	0.0004
En Rock	G18	MF	0.8333	0.3068	119.1	2.72	0.0076
En Rock	G18	MM	1.25	0.3068	119.1	4.07	0.0001
En Rock	G26	L40	-0.8333	0.3068	119.1	-2.72	0.0076
En Rock	G26	MM	1.1667	0.3068	119.1	3.8	0.0002
En Rock	G4	MF	0.8333	0.3068	119.1	2.72	0.0076
En Rock	G4	MM	1.25	0.3068	119.1	4.07	0.0001
En Rock	G49	G83	0.9167	0.3068	119.1	2.99	0.0034
En Rock	G49	MF	1.3333	0.3068	119.1	4.35	0.0001
En Rock	G49	MM	1.75	0.3068	119.1	5.7	0.0001
En Rock	G73	MF	1	0.3068	119.1	3.26	0.0015
En Rock	G73	MM	1.4167	0.3068	119.1	4.62	0.0001
En Rock	G74	MF	0.8333	0.3068	119.1	2.72	0.0076
En Rock	G74	MM	1.25	0.3068	119.1	4.07	0.0001
En Rock	G81	MF	0.9167	0.3068	119.1	2.99	0.0034
En Rock	G81	MM	1.3333	0.3068	119.1	4.35	0.0001
En Rock	G83	L39	-0.8333	0.3068	119.1	-2.72	0.0076
En Rock	G83	L40	-1.1667	0.3068	119.1	-3.8	0.0002
En Rock	G83	MM	0.8333	0.3068	119.1	2.72	0.0076
En Rock	G9	MF	0.8333	0.3068	119.1	2.72	0.0076
En Rock	G9	MM	1.25	0.3068	119.1	4.07	0.0001
En Rock	L37	MF	1.1667	0.3068	119.1	3.8	0.0002
En Rock	L37	MM	1.5833	0.3068	119.1	5.16	0.0001
En Rock	L39	MF	1.25	0.3068	119.1	4.07	0.0001
En Rock	L39	MM	1.6667	0.3068	119.1	5.43	0.0001
En Rock	L40	MF	1.5833	0.3068	119.1	5.16	0.0001
En Rock	L40	MM	2	0.3068	119.1	6.52	0.0001

En Rock	L40	RD	0.8333	0.3068	119.1	2.72	0.0076
En Rock	MM	RD	-1.1667	0.3068	119.1	-3.8	0.0002
En York	G18	MM	1.4167	0.3068	119.1	4.62	0.0001
En York	G26	MM	1.0833	0.3068	119.1	3.53	0.0006
En York	G4	MM	1.5	0.3068	119.1	4.89	0.0001
En York	G49	MM	1.5833	0.3068	119.1	5.16	0.0001
En York	G73	MM	1.4167	0.3068	119.1	4.62	0.0001
En York	G74	MM	1.5833	0.3068	119.1	5.16	0.0001
En York	G81	MM	1.3333	0.3068	119.1	4.35	0.0001
En York	G83	MM	1.25	0.3068	119.1	4.07	0.0001
En York	G9	MM	1.1667	0.3068	119.1	3.8	0.0002
En York	L37	MM	1.5	0.3068	119.1	4.89	0.0001
En York	L39	MM	1.3333	0.3068	119.1	4.35	0.0001
En York	L40	MM	1.75	0.3068	119.1	5.7	0.0001
En York	L40	RD	0.9167	0.3068	119.1	2.99	0.0034
En York	MF	MM	1.25	0.3068	119.1	4.07	0.0001
En York	MM	RD	-0.8333	0.3068	119.1	-2.72	0.0076

Appendix B-10 Significant Differences of Multiple Comparisons for Uniformity Fruit Size Score by Location

The GLIMMIX Procedure for Uniformity Fruit Size, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By En							
Simple Effect Level	G	_G	Estimate	Standard Error	DF	t Value	Pr > |t|
En Altoona	G83	RD	0.8333	0.3115	104.9	2.67	0.0087
En Altoona	G9	MF	0.8333	0.3115	104.9	2.67	0.0087
En Altoona	G9	RD	1	0.3115	104.9	3.21	0.0018
En Altoona	L37	RD	0.8333	0.3115	104.9	2.67	0.0087
En Berwick	G18	G73	1.202	0.3488	107.2	3.45	0.0008
En Berwick	G18	L37	1.077	0.3488	107.2	3.09	0.0026
En Berwick	G18	MF	1.75	0.3115	104.9	5.62	0.0001
En Berwick	G18	RD	0.8333	0.3115	104.9	2.67	0.0087
En Berwick	G26	MF	1.25	0.3115	104.9	4.01	0.0001
En Berwick	G4	G73	1.1346	0.383	110.1	2.96	0.0037
En Berwick	G4	L37	1.0096	0.383	110.1	2.64	0.0096
En Berwick	G4	MF	1.6827	0.3488	107.2	4.82	0.0001
En Berwick	G49	G73	1.2853	0.3488	107.2	3.68	0.0004

En Berwick	G49	L37	1.1603	0.3488	107.2	3.33	0.0012
En Berwick	G49	MF	1.8333	0.3115	104.9	5.88	0.0001
En Berwick	G49	RD	0.9167	0.3115	104.9	2.94	0.004
En Berwick	G73	G83	-1.1186	0.3488	107.2	-3.21	0.0018
En Berwick	G73	G9	-1.0096	0.383	110.1	-2.64	0.0096
En Berwick	G73	L39	-1.0353	0.3488	107.2	-2.97	0.0037
En Berwick	G73	L40	-0.952	0.3488	107.2	-2.73	0.0074
En Berwick	G73	MM	-0.952	0.3488	107.2	-2.73	0.0074
En Berwick	G74	MF	1.25	0.3115	104.9	4.01	0.0001
En Berwick	G81	MF	1.3333	0.3115	104.9	4.28	0.0001
En Berwick	G83	L37	0.9936	0.3488	107.2	2.85	0.0053
En Berwick	G83	MF	1.6667	0.3115	104.9	5.35	0.0001
En Berwick	G9	MF	1.5577	0.3488	107.2	4.47	0.0001
En Berwick	L39	MF	1.5833	0.3115	104.9	5.08	0.0001
En Berwick	L40	MF	1.5	0.3115	104.9	4.81	0.0001
En Berwick	MF	MM	-1.5	0.3115	104.9	-4.81	0.0001
En Berwick	MF	RD	-0.9167	0.3115	104.9	-2.94	0.004
En Rock	G26	MF	0.8333	0.3115	104.9	2.67	0.0087
En Rock	G4	MF	0.9167	0.3115	104.9	2.94	0.004
En Rock	G49	MF	0.8333	0.3115	104.9	2.67	0.0087
En Rock	L40	MF	0.9167	0.3115	104.9	2.94	0.004

C. Significant differences of multiple comparisons for trait Score by variety

Appendix C-1 Significant Differences of Multiple Comparisons for Plant Disease Resistance Score by Variety

The GLIMMIX Procedure for Plant Disease Resistance, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G G18	Altoona	Berwick	2.0833	0.3541	121.3	5.88	0.0001
G G18	Altoona	Homer	1.8333	0.3959	121.3	4.63	0.0001
G G18	Altoona	York	1.25	0.3541	121.3	3.53	0.0006
G G18	Berwick	Rock	-1.6667	0.3541	121.3	-4.71	0.0001
G G18	Homer	Rock	-1.4167	0.3959	121.3	-3.58	0.0005
G G26	Altoona	Berwick	2.0833	0.3541	121.3	5.88	0.0001
G G26	Altoona	York	1	0.3541	121.3	2.82	0.0056
G G26	Berwick	Homer	-1.3333	0.3959	121.3	-3.37	0.001
G G26	Berwick	Rock	-1.5833	0.3541	121.3	-4.47	0.0001
G G26	Berwick	York	-1.0833	0.3541	121.3	-3.06	0.0027
G G4	Altoona	Berwick	2.4067	0.3944	125.8	6.1	0.0001
G G4	Altoona	Homer	1.125	0.3959	121.3	2.84	0.0053
G G4	Altoona	York	1.3333	0.3541	121.3	3.77	0.0003
G G4	Berwick	Homer	-1.2817	0.4323	125.2	-2.96	0.0036
G G4	Berwick	Rock	-1.6567	0.3944	125.8	-4.2	0.0001
G G4	Berwick	York	-1.0734	0.3944	125.8	-2.72	0.0074
G G49	Altoona	Berwick	2.25	0.3541	121.3	6.35	0.0001
G G49	Altoona	Homer	1.625	0.3959	121.3	4.1	0.0001
G G49	Berwick	Rock	-2.0833	0.3541	121.3	-5.88	0.0001
G G49	Berwick	York	-1.4167	0.3541	121.3	-4	0.0001
G G49	Homer	Rock	-1.4583	0.3959	121.3	-3.68	0.0003
G G73	Altoona	Berwick	2.7039	0.3944	125.8	6.86	0.0001
G G73	Altoona	Homer	2	0.3959	121.3	5.05	0.0001
G G73	Berwick	Rock	-2.1206	0.3944	125.8	-5.38	0.0001
G G73	Berwick	York	-2.0372	0.3944	125.8	-5.17	0.0001
G G73	Homer	Rock	-1.4167	0.3959	121.3	-3.58	0.0005
G G73	Homer	York	-1.3333	0.3959	121.3	-3.37	0.001

G G74	Altoona	Berwick	2.8333	0.3541	121.3	8	0.0001
G G74	Altoona	Homer	1.0833	0.3959	121.3	2.74	0.0072
G G74	Berwick	Homer	-1.75	0.3959	121.3	-4.42	0.0001
G G74	Berwick	Rock	-2.5	0.3541	121.3	-7.06	0.0001
G G74	Berwick	York	-2.3333	0.3541	121.3	-6.59	0.0001
G G81	Altoona	Berwick	2.4167	0.3541	121.3	6.82	0.0001
G G81	Altoona	Homer	2.75	0.3959	121.3	6.95	0.0001
G G81	Altoona	York	1.4167	0.3541	121.3	4	0.0001
G G81	Berwick	Rock	-1.5833	0.3541	121.3	-4.47	0.0001
G G81	Berwick	York	-1	0.3541	121.3	-2.82	0.0056
G G81	Homer	Rock	-1.9167	0.3959	121.3	-4.84	0.0001
G G81	Homer	York	-1.3333	0.3959	121.3	-3.37	0.001
G G83	Altoona	Berwick	2.5	0.3541	121.3	7.06	0.0001
G G83	Berwick	Homer	-1.7083	0.3959	121.3	-4.31	0.0001
G G83	Berwick	Rock	-2.0833	0.3541	121.3	-5.88	0.0001
G G83	Berwick	York	-2	0.3541	121.3	-5.65	0.0001
G G9	Altoona	Berwick	2.3234	0.3944	125.8	5.89	0.0001
G G9	Altoona	Homer	1.7917	0.3959	121.3	4.53	0.0001
G G9	Altoona	Rock	1.0833	0.3541	121.3	3.06	0.0027
G G9	Altoona	York	1.0833	0.3541	121.3	3.06	0.0027
G G9	Berwick	Rock	-1.2401	0.3944	125.8	-3.14	0.0021
G G9	Berwick	York	-1.2401	0.3944	125.8	-3.14	0.0021
G L37	Altoona	Berwick	2.5372	0.3944	125.8	6.43	0.0001
G L37	Altoona	York	1	0.3541	121.3	2.82	0.0056
G L37	Berwick	Homer	-2.0789	0.4323	125.2	-4.81	0.0001
G L37	Berwick	Rock	-2.6206	0.3944	125.8	-6.64	0.0001
G L37	Berwick	York	-1.5372	0.3944	125.8	-3.9	0.0002
G L37	Rock	York	1.0833	0.3541	121.3	3.06	0.0027
G L39	Altoona	Berwick	2.3333	0.3541	121.3	6.59	0.0001
G L39	Altoona	York	2.5833	0.3541	121.3	7.29	0.0001
G L39	Berwick	Homer	-1.8333	0.3959	121.3	-4.63	0.0001
G L39	Berwick	Rock	-2.25	0.3541	121.3	-6.35	0.0001
G L39	Homer	York	2.0833	0.3959	121.3	5.26	0.0001
G L39	Rock	York	2.5	0.3541	121.3	7.06	0.0001
G L40	Altoona	Berwick	2.4167	0.3541	121.3	6.82	0.0001
G L40	Berwick	Homer	-1.6667	0.3959	121.3	-4.21	0.0001
G L40	Berwick	Rock	-2.3333	0.3541	121.3	-6.59	0.0001
G L40	Berwick	York	-1.5833	0.3541	121.3	-4.47	0.0001
G MF	Altoona	Berwick	2.5	0.3541	121.3	7.06	0.0001

G MF	Altoona	Homer	2	0.3959	121.3	5.05	0.0001
G MF	Altoona	York	1.1667	0.3541	121.3	3.29	0.0013
G MF	Berwick	Rock	-1.5833	0.3541	121.3	-4.47	0.0001
G MF	Berwick	York	-1.3333	0.3541	121.3	-3.77	0.0003
G MF	Homer	Rock	-1.0833	0.3959	121.3	-2.74	0.0072
G MM	Altoona	Berwick	2.3333	0.3541	121.3	6.59	0.0001
G MM	Altoona	Homer	3	0.3959	121.3	7.58	0.0001
G MM	Altoona	York	1.25	0.3541	121.3	3.53	0.0006
G MM	Berwick	Rock	-1.9167	0.3541	121.3	-5.41	0.0001
G MM	Berwick	York	-1.0833	0.3541	121.3	-3.06	0.0027
G MM	Homer	Rock	-2.5833	0.3959	121.3	-6.52	0.0001
G MM	Homer	York	-1.75	0.3959	121.3	-4.42	0.0001
G RD	Altoona	Berwick	2.9167	0.3541	121.3	8.24	0.0001
G RD	Altoona	Homer	1.5833	0.3959	121.3	4	0.0001
G RD	Berwick	Homer	-1.3333	0.3959	121.3	-3.37	0.001
G RD	Berwick	Rock	-2.75	0.3541	121.3	-7.77	0.0001
G RD	Berwick	York	-3	0.3541	121.3	-8.47	0.0001
G RD	Homer	Rock	-1.4167	0.3959	121.3	-3.58	0.0005
G RD	Homer	York	-1.6667	0.3959	121.3	-4.21	0.0001

Appendix C-2 Significant Differences of Multiple Comparisons for Fruit Disease Resistance Score by Variety

The GLIMMIX Procedure for Fruit Disease Resistance, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard	DF	t Value	Pr > |t|
G G73	Altoona	Berwick	1.331	0.1888	56.62	7.05	0.0001
G G73	Berwick	Homer	-1.331	0.208	54.37	-6.4	0.0001
G G73	Berwick	Rock	-1.331	0.1888	56.62	-7.05	0.0001
G G73	Berwick	York	-1.331	0.1888	56.62	-7.05	0.0001
G G74	Altoona	Berwick	0.6667	0.1747	45.16	3.82	0.0004
G G74	Berwick	Homer	-0.6667	0.1953	45.16	-3.41	0.0014
G G74	Berwick	Rock	-0.6667	0.1747	45.16	-3.82	0.0004
G G74	Berwick	York	-0.6667	0.1747	45.16	-3.82	0.0004
G G83	Altoona	Berwick	0.6667	0.1747	45.16	3.82	0.0004
G G83	Berwick	Homer	-0.6667	0.1953	45.16	-3.41	0.0014
G G83	Berwick	Rock	-0.6667	0.1747	45.16	-3.82	0.0004

G G83	Berwick	York	-0.6667	0.1747	45.16	-3.82	0.0004
G L40	Altoona	Berwick	0.5833	0.1747	45.16	3.34	0.0017
G L40	Berwick	Homer	-0.5833	0.1953	45.16	-2.99	0.0045
G L40	Berwick	Rock	-0.5833	0.1747	45.16	-3.34	0.0017
G L40	Berwick	York	-0.5833	0.1747	45.16	-3.34	0.0017
G MF	Altoona	Berwick	0.5	0.1747	45.16	2.86	0.0064
G MF	Berwick	Rock	-0.5	0.1747	45.16	-2.86	0.0064
G MF	Berwick	York	-0.5	0.1747	45.16	-2.86	0.0064
G MM	Altoona	Berwick	0.5833	0.1747	45.16	3.34	0.0017
G MM	Berwick	Homer	-0.5833	0.1953	45.16	-2.99	0.0045
G MM	Berwick	Rock	-0.5833	0.1747	45.16	-3.34	0.0017
G MM	Berwick	York	-0.5833	0.1747	45.16	-3.34	0.0017
G RD	Altoona	Berwick	0.5833	0.1747	45.16	3.34	0.0017
G RD	Berwick	Homer	-0.5833	0.1953	45.16	-2.99	0.0045
G RD	Berwick	Rock	-0.5833	0.1747	45.16	-3.34	0.0017
G RD	Berwick	York	-0.5833	0.1747	45.16	-3.34	0.0017

Appendix C-3 Significant Differences of Multiple Comparisons for Stem End Score by Variety

The GLIMMIX Procedure for Stem End, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G G73	Altoona	Homer	0.9167	0.3485	123.8	2.63	0.0096
G G73	Homer	Rock	-0.9167	0.3485	123.8	-2.63	0.0096
G L37	Altoona	Homer	1	0.3485	123.8	2.87	0.0048
G L37	Homer	York	-0.9167	0.3485	123.8	-2.63	0.0096
G MF	Altoona	Homer	1.5833	0.3485	123.8	4.54	0.0001
G MF	Altoona	York	0.8333	0.3117	123.8	2.67	0.0085
G MF	Berwick	Homer	1.4167	0.3485	123.8	4.07	0.0001
G MF	Homer	Rock	-1	0.3485	123.8	-2.87	0.0048

Appendix C-4 Significant Differences of Multiple Comparisons for Blossom End Score by Variety

The GLIMMIX Procedure for Blossom End, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G L37	Altoona	Rock	-0.8333	0.2413	125.4	-3.45	0.0008
G L40	Homer	Rock	-0.8333	0.2697	125.4	-3.09	0.0025
G MF	Altoona	Berwick	-0.6667	0.2413	125.4	-2.76	0.0066
G MF	Altoona	Rock	-0.6667	0.2413	125.4	-2.76	0.0066

Appendix C-5 Significant Differences of Multiple Comparisons for Fruit Firmness Score by Variety

The GLIMMIX Procedure for Fruit Firmness, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G G4	Altoona	Homer	0.75	0.2797	126.8	2.68	0.0083
G G4	Homer	Rock	-1	0.2797	126.8	-3.58	0.0005
G G4	Homer	York	-0.75	0.2797	126.8	-2.68	0.0083
G G49	Berwick	Homer	0.9167	0.2797	126.8	3.28	0.0014
G G49	Homer	York	-0.75	0.2797	126.8	-2.68	0.0083
G G73	Berwick	Homer	0.878	0.3062	127.4	2.87	0.0048
G G83	Berwick	Homer	0.8333	0.2797	126.8	2.98	0.0035
G G83	Homer	York	-1	0.2797	126.8	-3.58	0.0005
G L40	Homer	Rock	-0.9167	0.2797	126.8	-3.28	0.0014
G MF	Altoona	Berwick	-1.8416	0.3531	128	-5.22	0.0001
G MF	Berwick	Homer	2.5833	0.2797	126.8	9.24	0.0001
G MF	Berwick	Rock	1.25	0.2502	126.8	5	0.0001
G MF	Berwick	York	1.5	0.2502	126.8	6	0.0001
G MF	Homer	Rock	-1.3333	0.2797	126.8	-4.77	0.0001
G MF	Homer	York	-1.0833	0.2797	126.8	-3.87	0.0002
G MM	Altoona	Berwick	-1	0.2502	126.8	-4	0.0001
G MM	Altoona	Homer	0.8333	0.2797	126.8	2.98	0.0035
G MM	Berwick	Homer	1.8333	0.2797	126.8	6.55	0.0001
G MM	Berwick	Rock	1.3333	0.2502	126.8	5.33	0.0001
G MM	Berwick	York	1	0.2502	126.8	4	0.0001

G MM	Homer	York	-0.8333	0.2797	126.8	-2.98	0.0035

Appendix C-6 Significant Differences of Multiple Comparisons for Internal Fruit Color Score by Variety

The GLIMMIX Procedure for Internal Fruit Color, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G MF	Altoona	Homer	1.2359	0.431	125.9	2.87	0.0049
G MF	Altoona	York	1.1525	0.4057	126.7	2.84	0.0052
G MF	Berwick	Homer	1.75	0.3254	113.9	5.38	0.0001
G MF	Berwick	Rock	1	0.2911	113.9	3.44	0.0008
G MF	Berwick	York	1.6667	0.2911	113.9	5.73	0.0001
G MM	Altoona	Berwick	-0.9167	0.2911	113.9	-3.15	0.0021
G MM	Berwick	Homer	1.5833	0.3254	113.9	4.87	0.0001
G MM	Berwick	Rock	1.0833	0.2911	113.9	3.72	0.0003
G MM	Berwick	York	1.0833	0.2911	113.9	3.72	0.0003

Appendix C-7 Significant Differences of Multiple Comparisons for External Fruit Color Score by Variety

The GLIMMIX Procedure for External Fruit Color, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G G26	Berwick	Homer	0.75	0.2662	127.1	2.82	0.0056
G G81	Berwick	Homer	0.7083	0.2662	127.1	2.66	0.0088
G L40	Altoona	Homer	0.9167	0.2662	127.1	3.44	0.0008
G L40	Berwick	Homer	0.8333	0.2662	127.1	3.13	0.0022
G L40	Homer	Rock	-1	0.2662	127.1	-3.76	0.0003
G L40	Homer	York	-1	0.2662	127.1	-3.76	0.0003
G MF	Altoona	Berwick	-1.0071	0.3363	128	-2.99	0.0033
G MF	Berwick	Homer	1.5	0.2662	127.1	5.63	0.0001
G MF	Berwick	Rock	0.6667	0.2381	127.1	2.8	0.0059
G MF	Berwick	York	1	0.2381	127.1	4.2	0.0001
G MF	Homer	Rock	-0.8333	0.2662	127.1	-3.13	0.0022

G MM	Altoona	Berwick	-1	0.2381	127.1	-4.2	0.0001
G MM	Berwick	Homer	0.75	0.2662	127.1	2.82	0.0056

Appendix C-8 Significant Differences of Multiple Comparisons for Locule Distribution Score by Variety

The GLIMMIX Procedure for Locule Distribution, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G G9	Altoona	Homer	-0.7917	0.3021	120.8	-2.62	0.0099
G G9	Altoona	Rock	-0.75	0.2702	120.8	-2.78	0.0064
G MM	Altoona	Berwick	-0.8333	0.2702	120.8	-3.08	0.0025
G MM	Berwick	Homer	1.5833	0.3021	120.8	5.24	0.0001
G MM	Berwick	York	0.8333	0.2702	120.8	3.08	0.0025
G MM	Homer	Rock	-0.9167	0.3021	120.8	-3.03	0.003
G RD	Altoona	Berwick	-0.75	0.2702	120.8	-2.78	0.0064

Appendix C-9 Significant Differences of Multiple Comparisons for Taste Score by Variety

The GLIMMIX Procedure for Taste, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G MF	Altoona	York	-1.2111	0.4566	124.1	-2.65	0.009
G MF	Berwick	Homer	1.4167	0.3701	101.7	3.83	0.0002
G MF	Homer	York	-1.6667	0.3701	101.7	-4.5	0.0001
G MF	Rock	York	-0.9167	0.331	101.7	-2.77	0.0067
G MM	Altoona	Berwick	-1	0.331	101.7	-3.02	0.0032
G MM	Berwick	Rock	1	0.331	101.7	3.02	0.0032
G MM	Berwick	York	0.9167	0.331	101.7	2.77	0.0067

Appendix C-10 Significant Differences of Multiple Comparisons for Uniformity Fruit Size Score by Variety

The GLIMMIX Procedure for Uniformity Fruit Size, p < 0.01							
Simple Effect Comparisons of G*En Least Squares Means By G							
Simple Effect Level	En	_En	Estimate	Standard Error	DF	t Value	Pr > |t|
G G73	Altoona	Berwick	1.0353	0.3515	112.8	2.95	0.0039
G G73	Berwick	Rock	-1.1186	0.3515	112.8	-3.18	0.0019
G G73	Berwick	York	-1.202	0.3515	112.8	-3.42	0.0009
G L37	Altoona	Berwick	0.9936	0.3515	112.8	2.83	0.0056
G L37	Berwick	Rock	-1.077	0.3515	112.8	-3.06	0.0027
G MF	Altoona	Berwick	1	0.3145	112.5	3.18	0.0019
G MF	Berwick	Rock	-1	0.3145	112.5	-3.18	0.0019
G MF	Berwick	York	-1	0.3145	112.5	-3.18	0.0019
G RD	Altoona	Rock	-0.8333	0.3145	112.5	-2.65	0.0092