Investigations to Determine Rootstock Cultivar Performance for Sustainable Apple and Bunch Grape Production in Alabama

by

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Abstract

Evaluating various scion-rootstock combinations in local environmental conditions is critical to gain further insights and knowledge on vine vigor for sustainable production in the southeast. Very little is known concerning vegetative growth, productivity, fruit quality, and overall performance of grape rootstocks in central Alabama and the potential vine Pierce's Disease (PD) resistance, drought and nematode resistance, and other biotic and abiotic challenges common to the southeastern environment. The main objective of the present study was to determine best suited rootstocks for enhanced sustainability of hybrid bunch grape production in Alabama and the southeast. The experimental vineyard was established in 2014 and data collected during 2017-2018. Experiment consisted of six rootstock-scion combinations: own-rooted 'Chardonel', 'Chardonel' grafted on '1103P' rootstock, own-rooted 'Norton', and 'Norton' grafted on '1103P', '5BB', and '5C' rootstocks. Total yield per vine of 'Chardonel' grafted on '1103P' was higher than the yield of own-rooted control vines. 'Norton' grafted on '1103P' had the highest pruning weight per vine, while 'Norton' grafted on '5BB' had the lowest. Our preliminary results indicate that '1103P' grafted 'Chardonel' produced higher yield and larger cluster size in comparison to own-rooted 'Chardonel' vines. Rootstocks '1103P', '5BB', and '5C' did not affect fruit quality, and yield of 'Norton' grape. 'Norton' grafted on '5BB' did not performed well based on symptoms of vine decline and low survival rate in the Alabama environment during the period of present study.

Fire blight (FB) (*Erwinia amylovora*) disease management costs are estimated at approximately $100 million a year in the USA. Newly released FB resistant apple rootstocks can aid in disease management and improve production sustainability. Semi-dwarf and dwarf size-controlling rootstocks are available and utilized in high density orchards, but their effects on plant vigor, production efficiency and fruit quality have not been established in the Alabama environment. The objective of this study was to determine the best performing apple rootstocks using an innovative cultivation system. In 2014, as part of the NC-140 Regional Research Project, an experiment was established at the Chilton Research and Extension Center (CREC) Clanton, using 'Aztec Fuji' apple grafted on fourteen newly released rootstocks: 'V.1', 'V.5', 'V.6', 'V.7', 'G.11', 'G.30', 'G.41', 'G.202', 'G.214', 'G.935', 'G.969', 'M.9-T337', 'B.10', and 'M.26 EMLA'. Our results suggest 'G.969' and 'G.214' are promising rootstocks for Alabama conditions based on total yield and yield efficiency during the study period. Trees grafted on 'G.202', 'G.214', and 'G.935' produced the sweetest fruit. 'G.202' trees had an advanced fruit maturity in comparison to other rootstocks in this test. The Vineland series of rootstocks 'V.5', 'V.6', and 'V.7' produced relatively high total yield, but were the most vigorously growing rootstocks in the present study, and may not be a good choice of size-controlling rootstocks for a high density apple orchard system in Alabama. Multiple year evaluations will be needed to obtain a more thorough understanding of rootstock effect on apple tree size, production efficiency, and overall performance in Alabama.

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List of Abbreviations

‘1103P’	‘Paulsen 1103P’
‘5BB’	‘Kober 5BB’
‘5C’	‘Teleki 5C’
°B	Degrees Brix
°C	Degrees Celsius
B.10	Budagovsky 10
cm	Centimeter
CREC	Chilton Research and Extention Center
EMLA 26	East Malling/Ashton Long 26
g	gram
G.11	Geneva 11
G.30	Geneva 30
G.41	Geneva 41
G.202	Geneva 202
G.214	Geneva 214
G.935	Geneva 935
G.969	Geneva 969
h	hours

m	meter
M.9-T337	Malling 9-T337
PD	Pierce's Disease
SSC	Soluble Solids Content
USDA	United States Department of Agriculture
V.1	Vineland 1
V.5	Vineland 5
V.6	Vineland 6
V.7	Vineland 7
X.f.	*Xylella fastidiosa*

CHAPTER ONE

Literature Review

Grapes belong to the family Vitaceae that includes approximately 1,000 species in 17 genera (Keller, 2010). *Vitis* and *Muscadinia*, are the two genera of economic importance. *Vitis* is the most important genus in cultivation and production. There are 60 to 70 species in this genus comprised of Eurasian and American species (Keller, 2010; Mullins et al., 1992). There are as many as 40 Eurasian species, but *Vitis vinifera* L., is the most economically important. However, the American *Vitis* species are also valued for fresh consumption, processing into wine, or juice, or for use as rootstocks (Keller, 2010). *Vitis labrusca* L. has numerous excellent cultivars, such as ‘Concord’ and ‘Niagara’, that are commercially grown in the United States for table fruit, juice, and wine production. The distinct foxy or musky flavor characterizing this species is popular in the United States, but unaccustomed to Europeans (Keller, 2010). *Vitis aestivalis* Michaux is a very cold hardy and drought tolerant species which tolerates wet and humid summers as well, and is resistant to phylloxera (*Daktulosphaira vitifoliae* Fitch), powdery mildew (*Uncinula necator* [Schwein.] Burrill), downy mildew (*Plasmopara viticola* [Berk. & Curt.] Berl. & De Toni), and Pierce’s disease (PD) (Davis et al., 1978). ‘Norton’ (also known as ‘Cynthiana’) is considered an economically important cultivar solely derived from *V. aestivalis.* According to Kamas, (2014) some authors believe that the lineage of ‘Black Spanish’ is a complex hybrid that includes *V. aestivalis. Vitis rupestris* Scheele is known for its high vigor, drought tolerance, and strong resistance to phylloxera, which roots easily. *V. rupestris* is a common parent of commercially important rootstocks such as ‘St. George’, which is solely derived from this species (Kamas, 2014). In the Eastern U.S., cultivars of *V. vinifera* and *V. labrusca,* as well as hybridized species are commonly grown for wine production.

U.S. total grape production was 7,363,260 tons in 2017, with 4.3% decrease in comparison to 2016 total production of 7,697,030 tons (USDA-NASS, 2017a). California produced 4,014,000 tons of grapes for wine production in 2017, which accounted for 54.5% of total production (USDA-NASS, 2017b). The grape industry is relatively small in Alabama, but increased from 345 acres in 2007 to 426 acres in 2012 (USDA-NASS, 2012), and the interest in grape production is currently expanding.

Training

Training system is a systematized approach to arranging both permanent and annual parts of the vine to optimally intercept light and produce a crop (Kamas, 2014). There is evidence that training system was performed in the ancient vineyards of the Middle East, Greece, and Rome (Winkler, 1962), and today many training systems are encountered, several of which are indigenous to the viticultural regions in which training systems are found (Reynolds et al., 2009). Training systems are typically classified within four categories consisting of : 1) head/spur; 2) head/cane; 3) cordon/spur; and 4) cordon/cane (Reynolds et al., 2009). Head/spur training systems consist of short trunk and several two node-bearing units. Head/cane training systems consist of short trunk with one or more bearing units. Cordon/spur training systems consist of horizontal extension(s) of the trunk with several two-node spurs. Cordon/cane training systems consist head/spur similar to cordon/spur with longer bearing units. Regardless of training system selected, the primary goal is to optimize production through adoption of one or more combinations. Most *V. vinifera* wine grapes have an erect growth habit and therefore, trained to vertical shoot positioned (VSP) system (Jackson and Lombard, 1993). In cool-climate areas such as Michigan, high-cordon systems provide increased yields while maintaining proper vine size (Howell et al., 1991) and are cost-effective (Howell et al., 1987). Geneva double-curtain (GDC) training system was originally developed as a management tool to address excessive vine vigor (Shaulis et al., 1966). Physiologically, accelerated fruit maturation is achieved with adoption of GDC training system through expansion of leaf area to fruit weight ratio per unit land area (Bates, 2008). In addition, GDC-trained vines on 'Norton' typically are 46% higher yielding when compared to single curtain-trained vines. Juice pH was lower on GDC-trained vines, while other measures of fruit composition were similar between the two training systems in studies by Morris and Main, (2010). Another study compared the effect of three training systems on 'Traminette' and showed that vines trained to a divided-canopy Scott Henry system had the highest yield and largest vine size. Single high-wire (SHW) training system is considered the standard for hybrid and American varieties in the Midwestern and Eastern United States (Bordelon et al., 2008). SHW has two additional advantages over VSP: 1) planting and management costs are 20% to 30% lower due to design simplicity; 2) vines on SHW have canopies with higher photosynthetic efficiency (Poni et al., 2014).

Phenology of grapevines

The first sign of grapevine renewed activity in spring is the "bleeding" of sap from the cut ends of canes or spurs. The primary bud in the dormant bud becomes active in the spring.

The secondary and tertiary buds remain inactive unless the primary bud is destroyed or severely damaged (Jackson, 2008). Flower development in the spring progresses from the outermost ring of flower parts inward to the pistil (Jackson, 2008). Bloom events are strongly correlated with maximum temperatures in the preceding month (Calò et al., 1994). Short-term exposures to high temperature and high light intensity promotes grapevine flowering (Mullins et al., 1992). Self-pollination typically occurs as liberated pollen falls onto the stigma (Jackson, 2008). Embryonic fruit sheds from clusters that are un-fertilized, or the embryos aborted. At least one seed is normally required for berry development to continue (Jackson, 2008). Veraison is the stage of grape development with the onset of berry color change and the beginning of the fruit ripening. Anthocyanin biosynthesis in grape is directly affected by exposure to sunlight (Downey et al., 2006) and sunlight is a fundamental requirement for color formation (Jackson and Lombard, 1993). However at times, high light has resulted in decreased anthocyanin concentration (Bergqvist et al., 2001). Strategically, most deficit irrigation strategies are targeting specific growth stages from budburst to fruit set, fruit set to veraison, and veraison to harvest (Ayars et al., 2017). Maximum yields of 'Thompson Seedless' grapes were achieved with a sustained deficit irrigation (SDI) application equal to 80% of the crop water requirement (Williams et al., 2003). When 'Baco noir' was under three regulated deficit irrigation (RDI) levels (100, 50, or 25% crop evapotranspiration), and a non-irrigated control treatments, Balint and Reynolds (2017) found that the control and the 100% crop evapotranspiration initiated at fruit set treatments did not show differences in yield.

Balanced pruning theory

Spur pruning and cane pruning are two major grapevine-pruning methods. In spur pruning, a spur should be pruned to two to four buds, depending on the desired crop level (Winkler, 1962). Cane pruning was conducted by selecting strong canes and pruning off the weak ones. Large canes of 12.7 mm or greater diameter can be pruned to 15 buds per cane (Kamas, 2014). Advantages to spur pruning are that pruning requires less skill and less time than cane pruning, where mechanical pre-pruning could be applied.

There are many metrics to evaluate vine balance and two commonly used methods to achieve vine balance in terms of grape yield, fruit quality, and vine growth are known as Ravaz index and pruning formula (Goldammer, 2013). The Ravaz index is a ratio used to determine vine balance; it is a ratio of fruit yield to prune weight where the weight of fruit harvested per vine in the previous year is divided by the dormant pruning weight per vine in the current year. Ideal Ravaz index values varied by region and variety, but generally a yield to pruning weight number should be between 5 and 10 to limit vine vigor and encourage productivity. In some wine-growing regions, balanced pruning formulas were also used to guide growers' decisions on the number of buds to retain (Boulton et al., 1996). Bud count was based on an estimate of the weight of extraneous canes removed by pruning. Pruning formula varies by variety, and consists of retaining a certain number of fruiting buds for the first pound of pruning weight followed by retaining an additional number of buds for each additional pound of pruning weight.

Kamas (2014) proposed that the three principles of balanced pruning were bud number, bud quality, and bud distribution. The proper bud number to leave after dormant pruning varied by grape variety, vine age, vine size, training system, and environmental and site influences, and it can be achieved by Ravaz index or balanced pruning formula. High bud quality should meet the standards of internode length of 7.6 cm, retained dormant canes or spurs in bright color instead of dull, and canes and spurs between 6.4 to 12.7 mm in diameter. Buds retained after dormant pruning should be evenly distributed in the space allotted for that vine in the trellis to have greatest chance of receiving full sunlight.

Major hybrid bunch grape production constraints in Alabama and the southeast - Pierce's disease

Pierce's Disease has occurred in California at least since the 1880s, when it devastated the infant viticultural industry of the Los Angeles basin (Gardner and Hewitt, 1974). In addition to being a causal agent of PD, strains of *Xylella fastidiosa* are responsible for similar diseases of the vascular system in almond, citrus, alfalfa, and oleander (Hopkins and Purcell, 2002). The recent outbreak of PD in Temecula, California, was attributed to the introduction of the glassy-winged sharpshooter (*Homalodisca vitripennis*) (Takiya et al., 2006). A zone of high PD severity includes all of Florida and stretches along the coast, moving west to Texas and north to North Carolina (Ruel and Walker, 2006). Disease severity found in the warmer parts of North America is probably due to the combination of high vector populations and longer growing seasons (Hopkins and Purcell, 2002). *Mascadinia rotundifolia* appears to have exceptional resistance and cultivars of these species are planted throughout the Southeastern United States (Ruel and Walker, 2006). Another study examined the response of 18 grape genotypes to *X. fastidiosa* infection (Fritschi et al., 2007). Identified accessions and breeding selections differed dramatically in their ability to support *X. fastidiosa* growth. Given the widespread occurrence of *X. fastidiosa* in native plants across the Southern United Sates (Hopkins, 1989; Hopkins and Purcell, 2002) and the now-endemic status of *H. vitripennis* in California (Blua et al., 2000), breeding resistant grape cultivars continues to be the best long-term strategy against PD (Fritschi et al., 2007). A wealth of PD-resistant germplasm is available to grape breeders, despite the fact that much of it needs genetic characterization before it can be used effectively (Fritschi et al., 2007).

Rootstock breeding program

Rootstocks were first used for grapes to overcome damage from phylloxera, a root-feeding aphid (Cousins, 2005). Since 1870, there were many rootstocks released, particularly from the Couderc breeding program. *V. riparia* × *V. rupestris* rootstocks, such as ‘C. 3306’ and ‘C. 3309’, are currently widely used worldwide (Reynolds, 2015). ‘1103 Paulsen’ (‘1103 P’) (*V. berlandieri* × *V. rupestris*) was selected in Southern Italy for its strong drought tolerance and its ability to grow well on lime-based soils. In 1896, Sigmund Teleki received 10 kg of seeds from a French nursery that were crosses (open pollinations) of *V. berlandieri* (Manty, 2006). He planted around 40,000 seeds and graded the seedlings according to their appearance with letters (‘A’ or ‘B’) and numbers. ‘A’ stands for glabrous shoots and more *V. riparia* appearance whereas ‘B’ describes pubescent shoots and a more *V. berlandieri* look. Valuable selected rootstock cultivars ‘Teleki 5A’ and ‘Teleki 8B’ still exist in various European countries (Manty, 2006). Several years later, Franz Kober took a large sample of valuable *Vitis berlanderi* genotypes from Teleki and started with field experiments in 1910 (Regner, 2015) and later, he proposed two genotypes: ‘5BB’ (*V. berlandieri* × *V.*

riparia) and '125AA' (*V. berlandieri* × *V. riparia*) (Manty, 2006).

In contrast to most other European countries, the spread of phylloxra in Germany was slow due to strict quarantine measures and unfavorable conditions. At Geisenheim, rootstock breeding commenced in 1880 with *V. riparia* seeds that were sent from New England, where the species grow in abundance. However, a problem soon became obvious due to lime-induced iron chlorosis (Schmid et al., 2009). Because *V. vinifera*, the indigenous species of Europe, was lime tolerant, the idea of crossing the domesticated European grape with American species soon followed, resulting in a commercial rootstock 'Schiava Grossa' (Trollinger, Black Hamburg) × 'Riparia 26 Geisenheim' ('26G'), which was still used in some areas until the 1990s despite its rather limited phylloxera tolerance. In 1912, the director of the research station in Oppenheim, Heinrich Fuhr, imported some of Teleki's selections from Hungary. He worked with 'Teleki #4' and in 1919 selected 'SO4' (Selection Oppenheim #4), 'SO5' and 'SO8'. 'SO4' was regarded as the best, and its multiplication commenced after 1922 (Reynolds, 2015). In 1922, Alexander Teleki continued the work with a focus on 'Teleki 5A' and 'Teleki 5C'.

Aside from phylloxera resistance, rootstocks can be used to combat other soil-borne pests, primarily nematodes. Before 1900, Munson selected one of his most outstanding *V. champini* cultivar 'Dog Ridge', which proved to be resistant to Pierce's disease and to parasitic nematodes (Harmon and Snyder, 1956; Lider, 1960). In the fall of 1935, in Fresno, California, E. Snyder and F.N. Harmon collected seeds from open-pollinated blooms of 'Dog Ridge' *(Vitis × champinii*) and '1613 Couderc' (*V. solonis* × Othello), which were known to be resistant to the root-knot nematode (*Meloidogyne incognita*) (Snyder and Harmon, 1952).

Two of the open-pollinated seedlings, selected for their nematode resistance ('1613-59' and 'Dog Ridge 5'), were crossed and a seedling from the '1613-59' × 'Dog Ridge 5' cross was selected as the rootstock 'Freedom' (Brooks and Olmo, 1997). 'Freedom' is a widely used rootstock, particularly in the vineyards of San Joaquin Valley, California, where root-knot nematodes are the key soil-borne pest. In the 40 years since its release, 'Freedom' and its half-sibling rootstock 'Harmony' have largely replaced '1613C' and 'Dog Ridge' in new plantings due to their nematode resistance and improved horticultural characteristics (Garris et al., 2009).

In 1986, Dr. Olmo at U.C. Davis released a rootstock that has been successful at controlling fanleaf virus and dagger nematode (*Xiphinema*). That rootstock is 'O39-16' ('Almeria' × *M. rotundifolia*), and it is able to counteract the effect of fanleaf virus when grafted to an infected scion. The rootstock also carries very strong resistance to *Xiphinema* that prevents the nematode from successful reproduction (Walker et al., 1991).

Five new rootstocks ('UCD-GRN 1-5') with broad and durable resistance to root-knot and dagger nematodes, were patented and released to nurseries for propagation and thence to the grape industry (Walker and Ferris, 2009). During the initial testing of cultivars 'GRN 1-5', their resistance was tested against multiple individual types of nematodes as well as mixtures of nematodes. Of the new resistant rootstocks, 'UCD-GRN 1' had broadest nematode resistance (Ferris et al., 2012).

Rootstock evaluation

The American grapevine group is typically used as rootstocks for grafted grapevines.

Reynolds and Wardle (2001) outlined seven major criteria for choosing rootstocks in the order of their importance as phylloxera resistance, nematode resistance, adaptability to high pH soils, saline soils, low pH soils, wet or poorly drained soils and drought. Additionally, many investigations showed that rootstocks also affect vine growth, yield, and fruit quality through interactions between environmental factors and the physiology of scions and rootstock cultivars employed (Rizk-Alla et al., 2011). Choice of rootstock is one of the most important factors in the establishment of a vineyard, but given the many choices available, identifying the most suitable rootstock for a particular scion is difficult (Loreti and Massai, 2006). There is no such thing as a universal rootstock, making variety-specific research to identify the best rootstock a necessity.

Rootstock can influence the vigor of grapevines. Wunderer et al. (1999) mentioned that 'Gruner Veltliner' grape had a higher wood productivity when grafted on the three rootstocks tested ('SO4', 'K5BB' and '5C') than that of the own-rooted vines. When 'Merzifon Karasi' (*Vitis vinifera* L.) was grafted on nine different rootstocks, the '1103P' genotype had the shortest shoot length (Köse et al., 2014). The rootstock chosen affected mineral nutrition of the grafted variety. Brancadoro and Valenti (1995), grafted 'Croatina' onto 20 different rootstocks and found that K^+ content of leaves was significantly affected by rootstocks. They suggested that K^+ deficiency could be ameliorated by choosing an appropriate rootstock. However, Csikász-Krizsics and Diófási (2008), reported that rootstocks had no effect on leaf nitrogen levels.

Despite the fact that grape growing requires less water than most crops, the predicted climatic change (i.e. reduced rainfall and increased evapotranspiration rates) will intensify water stress on vines, especially in water-limited regions. Ezzahouani and Williams (1995), suggested that hybrids (‘110R’, ‘140Ru’ and ‘1103P’) from rootstocks *V. berlandieri* × *V. rupestris* can be used in drought prone areas where water is a limiting factor for grapevine productivity. Another study revealed that ‘SO4’ was able to sustain leaf water status and physiological mechanisms at similar rates with ‘1103P’ due to its lower leaf area and to possible adjustments of leaf structure (Koundouras et al., 2008).

Rootstocks were shown to affect yield in multiple studies. Hedberg (1980), found that yields of all grafted cultivars were much higher than those of own-rooted vines, especially those grafted on ‘Ramsey’ and ‘Dogridge’ rootstocks. In a study conducted in Australia, ‘101-14’, ‘Ramsey’, ‘Schwarzmann’, ‘Harmony’, and ‘SO4’ rootstocks generally increased fruit berry weight when compared to own-rooted vines (Ruhl et al. 1988). Another study revealed that ‘Chardonel’ grown on ‘Cynthiana’ roots had the lowest berry weight while ‘5BB’ had the highest berry weight (Main et al., 2002). However, several studies found that the scion cultivar or site characteristics had a greater influence on yield than rootstock (Lipe and Perry, 1988; Morris et al., 2007; Reynolds and Wardle, 2001).

Rootstock is one of the factors that influences fruit composition. ‘Red Globe’ grafted onto ‘Freedom’, ‘Harmony’, and ‘1103P’ rootstocks had the highest percentages of total soluble solids (TSS), TSS/acid ratio, and anthocyanin content of berry skin and the lowest percentages of acidity of the berry juice (Rizk-Alla et al., 2011). Cirami et al. (1984) recorded higher juice pH in ‘Shiraz’ grafted onto ‘Ramsey’, ‘Dog Ridge’, ‘Harmony’, ‘Schwarzmann’, and ‘1613C’ than in own-rooted vines. Kubota et al. (1993) grafted ‘Fujimori’ grapes onto seven different rootstocks and found that the highest level of skin anthocyanin was observed in berries from vines grafted onto ‘3306C’. Reynolds and Wardle (2001) found that vines grafted to ‘5BB’ rootstock produced fruit with higher percent soluble solids in all cultivars tested than own-rooted vines. Satisha et al. (2007), found that berries from vines grafted with ‘110R’ and ‘1103P’ rootstocks, had higher phenolics, flavon-3-ols, flavanoids, proline, and total proteins than berries harvested from vines grafted with *V. champinii*, *V. rupestris*, and *V. riparia* × *V. berlandieri*. When ‘Cabernet Sauvignon’ was grafted onto ‘1103P’ and ‘SO4’ rootstocks, fruit phenolic concentrations were similar among rootstocks (Koundouras et al., 2009). In two studies with different rootstock/scion combinations, berry juice from vines grafted with ‘140Ru’, ‘1103P’, or ‘110R’ had lower K^+ concentrations than from vines grafted with ‘Freedom’, ‘Dog Ridge’, ‘St. George’, and ‘101-14’ (Ruhl et al., 1988; Walker and Blackmore, 2012).

Rootstocks are also used in viticulture to manage damage from PD. Grape rootstock trials in Mississippi showed a large effect of rootstock on vine longevity in a region recognized for high PD pressure (Loomis, 1952, 1965; Magoon and Magness, 1937). When Florida hybrid bunch grape ‘Blanc du Bois’ was grafted onto muscadine, symptoms of PD and anthracnose were reduced (Ren and Lu, 2003). ’Chardonnay’ vines grafted on ‘Dog Ridge’ were the largest in vine size and had the least PD symptoms under high PD pressure in the Rio Grande Valley (Cousins and Goolsby, 2011).

‘Chardonel’ and ‘Norton’

‘Chardonel’ is an upright-growing, white wine grape resulting from an interspecific hybrid between ‘Seyval blanc’ (Seibel 5656 × Rayon d’Or) and ‘Chardonnay’ (*Vitis vinifera*

L.) (Reisch et al., 1990). Flowers of ‘Chardonel’ are perfect and self-fertile with medium-late bloom following a late budbreak. Clusters are shouldered and medium-large (200 g), averaging 1.6 clusters per shoot. Very little crop is borne on lateral shoots and cluster. Thinning is required only infrequently. There are an average of 2.8 seeds per berry, weighing 42.3 mg per seed. The seed weight accounts for about 5% of the total berry weight. The seeds are pyriform in shape, with a long, prominent beak. Juice soluble solids concentration and titratable acidity are usually higher than for ‘Cayuga White’. The wine has good body and very little of the flavor characteristics of interspecific hybrid grapes. In Michigan and Arkansas, ‘Chardonel’ is more productive than ‘Cayuga White’ (Reisch et al., 1990). It was suggested that ‘Chardonel’ be evaluated in California as attempts are being made to reduce the use of chemicals in vineyards. Due to the tolerance of ‘Chardonel’ to powdery mildew and Botrytis, this cultivar may be attractive for use in reduced pesticide or organic farming systems in California (Main et al., 2002). As this is a recently patented cultivar, there is little information on performance of grafted ‘Chardonel’ vines.

‘Norton’ is believed to have resulted from a lost *Vitis vinifera* cultivar ‘Bland’ being pollinated by stray pollen, possibly from *Vitis aestivalis* (Ambers and Ambers, 2004). ‘Norton’ and ‘Cynthiana’ were previously considered distinct cultivars or ‘Cynthiana’ possibly being a sport of ‘Norton’. Recent isozyme and genetic analysis has shown they are the same cultivar. ‘Norton’ is the most widely planted cultivar in Missouri accounting for over 15% of the total acreage planted in grapevines (Missouri Grape Growers Assoc., 2001). It has good phylloxera resistance, mildew resistance, Pierce’s disease tolerance, winter and spring low temperature tolerance, and the potential to produce high quality wines. These traits allow growers to use less pesticides (20% - 25% of the current rate of pesticide use in equivalent European varieties) when growing ‘Norton’ grapevines. However, own-rooted ‘Norton’ grapevines are challenging to grow due to excessive vegetative growth and low fruit yield. ‘Norton’ juice also has undesirable characteristics, such as high pH, potassium, malic acid, and titratable acidity. However, the use of a rootstock may improve less favorable attributes of the ‘Norton’ scion.

Evaluating various scion-rootstock combinations in local environmental conditions is critical to gain knowledge on a vine’s potential for sustainable production in the southeast, yet very little is known about the performance of grape rootstocks in central Alabama and how they impact vine PD resistance, drought and nematode resistance, phylloxera resistance, and other biotic and abiotic challenges common to the southeastern environment. The main objective is to determine the best suited rootstocks for enhanced sustainability of hybrid bunch grape production in Alabama and the southeast. The hybrid bunch grape rootstock study was initiated in 2014 in our lab and Svyantek (2016) conducted preliminary research as part of his graduate studies.

Apple production

Apple is the most important temperate fruit crop and has been cultivated in Asia and Europe from ancient times (Janick et al., 1996). The genus *Malus* has, according to most authorities, 25–30 species and several subspecies of so-called crab apples. The cultivated apple is a result of interspecific hybridization. The denomination *Malus* × *domestica* has been generally accepted as the appropriate scientific name (Korban and Skirvin, 1984). The world's most important commercially produced apple cultivars belong to the species *Malus* × *domestica* Borkh. Some other species also have significance in commercial apple production and almost all scab resistant cultivars commercially available have *M.* × *floribunda* Siebold ex Van Houte in their ancestry (Kellerhals, 2009). Throughout its history of cultivation, at least 10,000 apple cultivars were developed, many of which are now lost. Commercially, about 100 cultivars are currently being grown, but only 10 make up over 90 percent of U.S. production (Rieger, 2006).

For many years, the U.S. had dominated worldwide production of apples, and continued to do so until 1990. However, because of agrarian reforms carried out in the 1980s and extending into the 90's, China has become the world leader in apple production (Powell et al., 2000). 'Fuji' is the dominant commercial cultivar produced in China, other important cultivars include 'Starkrimson', 'Jonagold', 'Golden Delicious' and 'Gala' (Wang et al., 2016). U.S. production was 4,649,323 tons in 2016, an increase of 2.5% from the previous year (4,537,693 tons for 2015) (FAOSTAT, 2016).

In Washington State, the largest producer of fresh apples in the United States, the cultivated area of 'Honeycrisp' increased from 300 acres in 2001 to 9,098 acres in 2011, whereas cultivated areas for the traditional 'Red Delicious' fell from 82,000 to 43,379 acres, between 2001 and 2011 (Gallardo et al., 2018). Alabama growers have generally followed U.S. trends as a whole about establishing apple varieties. Sports of 'Red Delicious' have largely dominated apple production in the state for many years, with selections of 'Golden Delicious' being second in importance (Powell et al., 2000). However, historically, Alabama and the entire Southeast U.S. has had problems producing 'Red Delicious' selections that develop acceptable red skin color for the wholesale market. The heat of August and early September is largely responsible for the poor red finish of ‘Red Delicious’ grown in the south (Powell et al., 2000). The shape of eastern grown ‘Red Delicious’, which tend to be rounder than more elongated, have been considered inferior to ‘Red Delicious’ grown in Washington State. In contrast, ‘Fuji’ has adapted well to southeastern conditions and continues to be planted by commercial producers. Since its internal fruit quality is outstanding, growers remain optimistic about its future and have successfully marketed the fruit (Powell et al., 2000).

‘Fuji’ apples

The ‘Fuji’ apple is a hybrid developed by H. Niitsi at the Horticulture Research Station in Morioka, Japan, in 1939, and brought to market in 1962 (Marquina et al., 2004). It originated as a cross between ‘Red Delicious’ and ‘Ralls Janet’. ‘Fuji’ has gained high popularity due to its outstanding flavor, high soluble solids concentration (SSC), low starch degradation pattern (SDP), and long storage life. However, poor fruit color of this cultivar is a major problem worldwide, and researchers and apple growers have been focusing on finding high-coloring strains with high quality in the past decades (Marquina et al., 2004). Iglesias et al. (2012) measured fruit anthocyanin content and visual color of different strains and reported that the most colored strain was ‘Aztec Fuji’. The ‘Aztec Fuji’ apples full name is ‘Zhen Aztec Fuji’, selected by Austin Orchard Ltd. in Nelson, New Zealand (Brown and Maloney, 2013). Since it is an unpatented cultivar, very little is known about the performance of ‘Aztec Fuji’ in North America.

Chilling temperature requirements

Temperate perennial crops that are grown in seasonally restricted temperate regions require chilling temperatures that should be satisfied to initiate growth and flowering in spring (Saure, 1985). They exhibit a cycle of dormancy requirement that inhibits growth until exposure to low winter temperatures (chilling), prior to spring budbreak. Failure to receive sufficient chilling can lead to serious consequences including reduction of flower quality, abscission of flower buds, protraction of the flowering process, and reduced fruit set (Jackson et al., 1983).

Richardson et al. (1975) developed the concept of determining 'chill units', one chill unit was defined as an hour exposure at the optimum temperature required meeting a species or cultivar's chilling requirement. A cultivar's chilling requirement was therefore measured by the number of hours required, at a set temperature, below which chilling is received. Studies of chilling temperatures have resulted in the development of several models designed to better measure the accumulation of chilling and determine when rest is satisfied. These models were developed as improvements over the old method of measuring chilling accumulation by monitoring daily temperatures of 7.2 °C and lower beginning October 1 each year (Powell et al., 2000). After 5 years of study, the Modified 7.2°C model has proven superior to the Utah, the Florida, and the Old 7.2°C methods of measuring chilling under Alabama conditions (Powell et al., 2000). Fishman et al. (1987) developed the Dynamic Model for warm winter conditions, which proposed that chill accumulation is measured in portions, and that once a portion was meet, its effect was fixed and could not be cancelled by subsequent high temperatures. However, the use of the peach dynamic model to predict dormancy completion of vegetative apple buds in Israel resulted in an overestimation of chilling effect (Naor et al., 2003).

Apples are adaptable to various climates, but best adapted to the cool temperate zones from about 35–50◦ latitude (Kellerhals, 2009). Chilling hours of apple range from 200 to 2000 hours. Mild winter in the southeast makes it harder to grow apple trees due to their high chilling requirements. Some apple cultivars were evaluated in Florida. However, relatively few apple cultivars can be grown successfully there. Of 43 tested cultivars, only 'Anna', 'Dorsett Golden' and 'Tropic Sweet' were recommended for Florida (Andersen and Crocker, 2009). These cultivars each have a chilling requirement of 250–300 hours. 'Anoka' apple, often called "The Old Folks Apple" because the tree bears at an early age, often the first year after planting, has shown some promise in Central Florida (Rowland, 1977).

Fire blight

Fire blight (FB), a devastating necrogenic disease caused by the Gram-negative bacterium *Erwinia amylovora*, is the most important bacterial disease affecting pome fruit and several other members of the Rosaceae family (Malnoy et al., 2012). The majority of known strains of *E. amylovora* were isolated from *Maloideae* plants (Vanneste, 2000). Differences in virulence among *E. amylovora* strains were reported by several researchers. Strains with differential virulence in apple are not rare in North America (about 10% of the strains tested by Norelli et al., 1986), but they have never been found in Europe. At moderately warm temperatures in the 18–24^{o} C range, the bacterium has the potential to double every 20–30 minutes. One bacterium gives rise to 1 trillion cells with just 31 divisions, which occur within just 2–3 days (Steiner, 2001). FB infects blossoms, fruits, stems, leaves, woody branches, and rootstocks crowns, thereby causing blossom blight, shoot blight, and rootstock blight (Peil et al., 2009) with affected areas appearing to have been scorched by fire. Once *E. amylovora* enter the rootstock, no cultural control or chemical treatment can prevent disease development (Norelli et al., 2003), and the bacteria initiates the formation of new cankers that can completely girdle and kill the tree in one to a few months.

The earliest known observations of FB were made in the Hudson Valley of New York State in 1780 (Denning, 1794). Since then, FB disease has spread to 39 additional countries. Many efforts were made to reduce the loss caused by FB. Copper compounds were established as effective bactericides and have been used against fire blight on apples and pears since 1900 (Zwet and Keil, 1979). However, the copper ion, which is the main active ingredient in the compounds, is very toxic to the plant tissue. The antibiotic streptomycin (Agrimycin 17) provides better control under higher disease pressure than the copper compounds, and does not cause fruit russeting. However, long-term use can result in the development of resistant strains. Biological control of FB using epiphytic bacteria is now considered a promising alternative to chemical control. *Pseudomonas fluorescens* strain A506, a biological control agent of FB, has been used extensively and effectively in controlling fire blight of pear in California (Wilson and Lindow, 1993). A study demonstrated that when *P. fluorescens* A506 blooms were inoculated 72 h in advance of *E. amylovora* Ea8R and the blossoms were incubated either at high or ambient relative humidities, the biological control agent significantly reduced the pathogen population size on both pistils and nectaries in all experiments. In addition, scientists began to breed FB resistant rootstocks. The apple rootstock breeding program at the New York State Agricultural Experiment Station (Cornell University) has released the Geneva series of apple rootstocks that were bred for tolerance to FB and Phytophthora root rot, and have high yield efficiency and good tree survival (Norelli et al., 2003).

Apple rootstocks

The current trend worldwide is to use smaller tree size and higher-density orchards to reduce labor inputs and overall cost. One of the primary ways to maintain small, compact tree size in commercial as well as home plantings is to grow spur-type varietal strains. However, spur-type trees grow slowly, are compact, and begin fruiting at only 2 to 3 years of age. Among the common temperate tree fruits, the apple is the only one that has truly effective dwarfing rootstocks (Powell et al., 2000). This is important because many popular varieties do not have superior spur types, so the use of dwarfing rootstocks is the method of choice for maintaining small tree size, particularly in high-density systems where the economic risks and potential returns are the highest (Powell et al., 2000).

Over the last 60 years, as growers worldwide have used the Malling (M), Merton Immune (MI), and Malling-Merton (MM) series of rootstocks from England, their limitations have become apparent (Robinson et al., 2006b). These included lack of winter hardiness, lack of resistance to *Phytophthora* root rot, susceptibility to FB bacterial disease, burrknots, poor anchorage, root suckers, and brittle graft unions. New apple rootstocks are made available regularly from a number of sources with the potential of providing greater growth control, enhanced precocity, higher yield, improved adaptability to environmental conditions, and enhanced pest resistance (Autio et al., 2013). Numerous new rootstocks are available for evaluation from the Budagovsky, Cornell-Geneva, and Vineland breeding programs.

Budagovsky rootstocks are from the Michurinsk State Agrarian University in Michurinsk, Russia. The breeding program began with crosses in 1938, with the principle goal of developing rootstocks with enhanced winter hardiness (Cummins and Aldwinckle, 1983). They released one of the best known Budagovsky Rootstocks, ‘B.9’, in 1962. Rootstock evaluation revealed ‘B.9’ is highly susceptible to *E. amylovora* when leaves were inoculated, but highly resistant when woody tissue was directly challenged by the bacterium (Russo, 2007). NC-140, a north central regional project founded by United States Department of Agriculture (USDA), first tested Budagovsky rootstocks (‘B.9’ and ‘B.490’) in the 1984 NC-140 Apple Rootstock Trial (NC-140, 1996) and has included Budagovsky rootstocks in numerous trials in the subsequent years (Autio et al., 2001, 2013; Marini et al., 2014).

The Cornell-Geneva Apple Rootstock Breeding Program is managed jointly by Cornell University and the United States Department of Agriculture (USDA). Several rootstocks were released from this program, most with a high degree of disease resistance, particularly to the FB bacterium (*E. amylovora*). Four apple rootstocks, ‘Geneva (G.) 65’, ‘G.11’, ‘G.30’, and ‘G.16’, were the first released for commercial sales. In 2010, the Cornell-USDA apple rootstock breeding program released another four new apple rootstocks (‘Geneva® 210’, ‘Geneva® 214’, ‘Geneva® 890’, and ‘Geneva® 969’) (Robinson et al., 2014). Some Geneva® rootstocks are resistant to Ea273 and E2017a, but more susceptible to strains E2002a and E4001a (Fazio et al., 2006). Interestingly the rootstocks ‘Geneva® 3041’ (‘M.27’ × ‘R.5’) and Geneva® 5179 (‘O.3’ × ‘R.5’) show virtually full resistance to all strains tested. The Geneva rootstocks evaluated had significantly lower probability of developing rootstock blight than the standard Malling rootstocks. Even ‘G.11’, previously described as fire blight-tolerant (Norelli et al., 2003), had significantly less overall rootstock blight, even with the highly susceptible cultivars ‘Gala’ and ‘Honeycrisp’. The Geneva rootstock program has developed several promising new genotypes, and the current focus of the conventional portion of the breeding program is to produce new rootstock genotypes that retain the disease resistance of the first generation of Geneva rootstocks, but with improved horticultural properties.

The Vineland (V.) rootstocks originated at the Horticultural Research Institute of Ontario, Vineland Station, as open-pollinated seedlings of ‘Kerr’ crab apple (Elvfing et al., 1993). The primary objectives were to develop fully-dwarfing rootstocks adapted to the Ontario climate of colder winters and warmer summers. Among hundreds of seedlings selected from the numerous seed collections over the years, seven open-pollinated ‘Kerr’ seedlings originating from the ‘V605’ collection displayed desirable selection criteria and were initially designated as ‘V605-1’ to ‘V605-7’ (now ‘V. 1’ to ‘V. 7’) (Elvfing et al., 1993). ‘V. 1’ and ‘V. 3’ look especially promising in comparison to ‘M. 9 EMLA’, displaying excellent size control and yield efficiency. ‘V. 7’ produced trees in the ‘M.26’ to ‘M. 7’ size and productivity range, while ‘V. 4’ produced larger trees. No data are available on the performance of ‘V.5’ or ‘V.6’ as rootstocks. Consistent with other Vineland rootstocks, ‘V.2’ was highly resistant to rootstock blight, but resistance evaluation was only done with the cultivar ‘Golden Delicious’ (Russo, 2007).

Development of Tall Spindle System

The move to high planting densities has been driven primarily by the need for early production to pay back the initial investment cost and improve profitability. With higher tree planting densities, cumulative fruit production over the first 10 years of an orchard's life has improved dramatically. With most modern high-density planting systems, a small but significant yield is expected during the second growing season of the orchard. Substantial yields are expected in the third year and mature yields are expected by years 5 or 6. In contrast, traditional low-density systems on vigorous rootstocks began production around years 6 or 7 and did not reach mature yields until years 10–15 (Robinson, 2006a).

The Tall Spindle is a combination of the Slender Spindle (Wertheim, 1968), the Vertical Axis (Lespinasse, 1980), the Super Spindle (Nüberlin, 1993) and the Solaxe (Lespinasse, 1996) systems. It is based on the Slender Spindle tree, which was designed to improve early yields and management efficiency by planting higher tree densities and reducing tree height to allow all management to be done from the ground. However, the short stature of the Slender Spindle tree and moderate density often resulted in moderate yield and dense canopies. A significant trend in the late 1980's and 1990's was to increase tree-planting density in Slender Spindle orchards to improve yields (Oberhofer, 1990). However, the dense canopies were difficult to manage, and vigor usually became a problem as the orchard matured. During the early 1990's, much higher tree densities, between 2,000 and 5,500 trees/acre, were tested in single rows and a narrower and taller tree form was developed: The Super Spindle system. These trees had a tree canopy diameter of 45–60 cm and a height of 2.5 m. Through managing this system, growers and researchers learned that by never allowing permanent scaffold branches to develop, the tree could be kept very compact for many years. However, the cost of the Super Spindle system was prohibitive for all except those who grew their own trees (Robinson et al., 2006a).

For very high-density systems that depend on significant 2nd and 3rd year yields, feathered trees have become an essential part of the success of these systems. However, many of the trees used in the 1980's and 1990's had feathers that started at 50 cm above the soil. The low height of the feathers required significant labor to tie the branches up when they began to fruit to prevent fruit from touching the ground. In the late 1990's, the minimum height of feathers was raised to 76–88 cm (Balkhoven-Baart et al., 1998). This allowed branches to hang in a pendant position when cropping and still not touch the ground, thus eliminating the need to tie up branches.

Researchers started to increase tree height from 1.8–2.4 m to 2.7–3.0 m to obtain higher mature tree yield (Robinson and Lakso, 1991). This resulted in greater light interception, which is directly related to yield, and a greater distance between fruiting branches spread along the trunk. In the 1990's, many growers began to avoid pruning Slender Spindle trees after planting or during the first few years. If the central leader was cut, as was typical with slender spindle trees, a vigorous frame developed, which needed a lot of summer pruning labor to maintain light distribution in the tree for good fruit quality. Without pruning of the leader and with feathers starting at 75 cm above the soil, the tree could be allowed to crop in the second year, which resulted in the natural bending of lateral branches to keep the canopy narrow. In the 1990's, as growers allowed Slender Spindle trees to grow taller, yields increased, and fruit quality often increased as well since there was more space between the branches along the axis. These trends led to the development of the Tall Spindle Tree with a tree diameter of 0.9–1.2 m, tree height of 3 m, and a density between 1,000 and 1,500 trees per acre (Robinson et al., 2006a).

The Tall Spindle growing system is rapidly gaining popularity around the world. It incorporates the optimum economic planting density, high early productivity due to the use of feathered trees, minimal pruning and branch bending, high mature yield due to its high light interception, high fruit quality due to its narrow canopy shape, and reduced labor costs with its simple pruning recipe (Robinson et al., 2012). The use of motorized platforms for increased labor productivity and the use of mechanical side-wall shearing to create a fruiting wall are further benefits.

Limb angle

Lespinasse (1977) studied branch angle and its effect on flowering, cropping, and fruit size. Branch angles above 45° produced vigorous growth and little flowering. Angles from 45° to horizontal produced less growth, heavy flowering, and high fruit size and quality. Angles below horizontal produced almost no terminal growth, but often had small spurs and small fruit size. Thus, branch angle manipulation became an important tool in managing high-density orchards. With moderate tree planting densities, lower tier branches were trained to an angle slightly above horizontal to allow continued extension growth of the branch. However, with the very high planting densities of the Tall spindle or the Solaxe, branches are tied below the horizontal to induce early cropping and prevent further extension of lateral branches. By manipulating branch angle, fruit growers have been able to manage tree growth at a wide variety of planting densities (Robinson, 2006a)

Fruit thinning

Initially, flower clusters were thinned by hand to a single king flower per cluster, but this is no longer practical. Present labor costs make this approach prohibitively expensive. In addition, due to time limitations and the difficulty of thinning early in the season when the fruits are small and inconspicuous, it is difficult to complete thinning early enough for maximum effect. Mechanical methods of thinning fruit trees such as high-pressure spray guns, tree shakers, club thinning, rope thinners, drum shakers, and string thinners can produce a thinning response in stone fruits and some nut crops (Dennis, 2000). However, there are two primary factors limiting adoption of mechanical thinning practices in apple: 1) the damage and removal of spurs, and 2) the potential to spread the fireblight pathogen *Erwina amylovora*. Compared with these two thinning methods, chemical thinning is much more practical.

Chemical fruit thinning is an established practice in all apple-producing areas of the world (Forshey, 1986). Fruit thinning can be applied with two hormone-type thinners: auxin such as naphthylacetic acid (NAA) and cytokinin such as benzyladenine (BA). A carbamate insecticide (carbaryl, 1-naphthalenyl methylcarbamate) also is used for fruit thinning. Greene and Autio (1989) reported that BA effectively thinned 'McIntosh' apples, and BA and NAA thinned more effectively when each was combined with carbaryl. Other than that, the ethephon (2-chloroethylphosphonic acid) plus carbaryl combination has given good thinning in most tests in Virginia (Byers et al., 1990a). Two days of artificial shade decreased photosynthesis, reduced the carbohydrates available to the fruitlets, and induced more fruit abscission than NAA, ethephon, or carbaryl plus oil spray (Yuan and Greene , 2000). Terbacil, a photosynthetic inhibitor, applied to the foliage at very low rates, or artificially shading the tree for 2 days, caused thinning (Byers et al., 1990a, 1990b). The standard technique of carbaryl is to make the first application at 8–9 mm fruit diameter followed by a second application at 11–12 mm in a tank-mix with BA resulting in adequate thinning and excellent fruit quality in terms of size and color for ‘Fuji’ (Dorigoni and Lezzer, 2007). New chemistries have emerged that show real promise as new chemical thinners. These include the photosynthesis inhibitor metamitron (Brevis) and two naturally occurring compounds, abscisic acid (ABA), and 1-aminocyclopropane-1-carboxylic acid (ACC) (Greene and Costa, 2012). Manual, chemical and mechanical methods are used for fruit thinning, alone or in combination, but the method chosen depends upon species, climatic conditions and the historic reliability of the proposed method.

FB is the most important bacterial disease affecting apple production (Aćimović et al., 2015). With the newly released FB resistant rootstocks from Cornell-USDA apple rootstock breeding program, along with other rootstocks, the objective of this study is to determine the best performing rootstock within innovative cultivation system for enhanced sustainability of apple production in Alabama.

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CHAPTER TWO

Viticultural Performance of ‘Chardonel’ and ‘Norton’ Hybrid Bunch Grape Cultivars on Selected Rootstocks in Alabama

Abstract

Evaluating scion-rootstock combinations in local environmental conditions is critical to elucidating a vine’s potential for sustainable production in the southeast, yet very little is known about the grape rootstock performance in central Alabama, and how they impact vine Pierce’s disease (PD) resistance, drought and nematode resistance, phylloxera resistance, and other biotic and abiotic challenges common to the southeastern environment. The main objective of the present study was to determine the best-suited rootstocks for enhanced sustainability of hybrid bunch grape production in Alabama and the southeast. The experimental vineyard was established in 2014 and consisted of six rootstock-scion combinations: own-rooted ‘Chardonel’, ‘Chardonel’ grafted on ‘1103P’ rootstock, own-rooted ‘Norton’, and ‘Norton’ grafted on ‘1103P’, ‘5BB’, and ‘5C’ rootstocks. Total yield per vine of ‘Chardonel’ grafted on ‘1103P’ was higher than yield of own-rooted vines. No differences were found in titratable acidity (TA) and soluble solids content (SSC) among rootstocks. ‘Norton’ grafted on ‘1103P’ had the highest pruning weight per vine, while ‘Norton’ grafted on ‘5BB’ had the lowest. Our preliminary results indicate that ‘Chardonel’ grafted on ‘1103P’ increased yield as compared to own-rooted ‘Chardonel’. ‘Norton’ grafted on ‘5BB’ did not adapt well based on low survival rate in the environment of Alabama.

Introduction

Grapes belong to the family Vitaceae that includes approximately 1,000 species 17 genera (Keller, 2010). *Vitis* and *Muscadinia*, are the only genera two of economic importance. *Vitis* is the most important genus in cultivation and production. There are 60 to 70 known species in this genus comprised of Eurasian and American species (Keller, 2010; Mullins et al., 1992). There are as many as 40 Eurasian species, but *Vitis vinifera* L., is the most economically important. However, the American *Vitis* species are also valued for fresh consumption, processing into wine or juice, or for use as rootstocks (Keller, 2010). *Vitis labrusca* L. has numerous excellent cultivars, such as 'Concord' and 'Niagara', that are commercially grown in the United States for table fruit, juice, and wine production. *Vitis aestivalis* Michaux is cold hardy and drought tolerant species which tolerates wet and humid summers and is resistant to phylloxera (*Daktulosphaira vitifoliae* Fitch), powdery mildew (*Uncinula necator* [Schwein.] Burrill), downy mildew (*Plasmopara viticola* [Berk. & Curt.] Berl. & De Toni), and Pierce's disease (*Xylella fastidiosa*) (Davis, et al., 1978). One economically important cultivar, 'Norton' ('Cynthiana'), is thought to be solely derived from *V. aestivalis*, and some believe the lineage 'Black Spanish' is a complex hybrid that includes *V. aestivalis* (Kamas, 2014). *Vitis rupestris* Scheele is known for high vigor, drought tolerance, and strong resistance to phylloxera. *V. aestivalis* roots easily and is a common parent of commercially important rootstocks, such as 'St. George', which is solely derived from this species (Kamas, 2014).

The U.S. total grape production was 7,363,260 tons in 2017, a 4.3% decrease in comparison to 2016 of 7,697,030 tons (USDA-NASS, 2017a). California produced 4,014,000 tons of grapes for wine production in 2017, which accounted for 54.5% of total U.S. production (USDA-NASS, 2017b). The grape industry was relatively small in Alabama, but increased from 345 acres in 2007 to 426 acres in 2012 (USDA-NASS, 2012).

The first sign of grapevine renewed activity in spring is the “bleeding” of sap from the cut ends of canes or spurs. The primary bud in the dormant bud becomes active in the spring. The secondary and tertiary buds remain inactive unless the primary bud is destroyed or severely damaged (Jackson, 2008). Bloom events are strongly correlated with maximum temperature levels in the preceding month (Calò et al., 1994). Short-term exposures to high temperature and high light intensity promoted grapevine flowering (Mullins et al., 1992). Self-pollination typically occurs as liberated pollen falls onto the stigma (Jackson, 2008). Embryonic fruit sheds from clusters that are un-fertilized, or the embryos aborted. At least one seed is normally required for berry development to continue (Jackson, 2008). Veraison is the stage of grape development with the onset of berry color change and the beginning of the fruit ripening. Reports have shown that anthocyanin biosynthesis in grape is directly affected by exposure to sunlight (Downey et al., 2006). However at times, high light has resulted in decreased anthocyanin levels (Bergqvist et al., 2001). The goal of deficit irrigation strategies is targeting specific growth stages from budburst to fruit set, fruit set to veraison, and veraison to harvest (Ayars et al., 2017). Maximum yields of Thompson Seedless grapes were achieved with a sustained deficit irrigation (SDI) application equal to 80% of the crop water requirement (Williams et al., 2003). When ‘Baco noir’ was under three regulated deficit irrigation (RDI) levels (100, 50, or 25% crop evapotranspiration) and a non-irrigated control treatments, Balint and Reynolds (2017) found that the control and 100% crop evapotranspiration initiated at fruit set treatments did not show differences in yield.

Pruning is required to manage an optimal crop load in grapevine (Kamas, 2014). There are many metrics to evaluate vine balance and two commonly used methods to achieve vine balance in terms of grape yield, fruit quality, and vine growth are known as Ravaz index and pruning formula (Goldammer, 2013). The Ravaz index is a ratio of fruit yield to prune weight where the weight of fruit harvested per vine in the previous year is divided by the dormant pruning weight per vine in the current year. Ideal Ravaz index values varied by region and variety, but generally a yield to pruning weight number should be between 5 and 10 to limit vine vigor and encourage productivity. In some wine-growing regions, balanced pruning formulas were also used to guide growers' decisions on the number of buds to retain (Boulton et al., 1996). Bud count was based on an estimate of the weight of extraneous canes removed by pruning. Pruning formula varies by variety, and consists of retaining a certain number of fruiting buds for the first pound of pruning weight followed by retaining an additional number of buds for each additional pound of pruning weight.

Pierce's Disease has occurred in California at least since the 1880s, when it devastated the infant viticultural industry of the Los Angeles basin (Gardner and Hewitt, 1974). The recent outbreak of PD in Temecula, California was attributed to the introduction of the glassy-winged sharpshooter (*Homalodisca vitripennis*) (Takiya et al., 2006). A zone of high disease severity includes all of Florida and stretches along the coast, moving west to Texas and north to North Carolina (Ruel and Walker, 2006). The disease severity found in the warmer parts of North America is probably due to the combination of high vector populations and longer growing seasons (Hopkins and Purcell, 2002). *Mascadinia rotundifolia* appears to have exceptional resistance and cultivars of these species are planted throughout the Southeastern United States (Ruel and Walker, 2006). Another study examined the response of 18 grape genotypes to *X. fastidiosa* infection (Fritschi et al., 2007). Identified accessions and breeding selections differed dramatically in their ability to support *X. fastidiosa* growth. Given the widespread occurrence of *X. fastidiosa* in native plants across the Southern United States (Hopkins, 1989; Hopkins and Purcell, 2002) and the now-endemic status of *H. vitripennis* in California (Blua et al., 2000), breeding resistant grape cultivars continues to be the best long-term strategy for PD (Fritschi et al., 2007). A wealth of PD-resistant germplasm is available to grape breeders, despite the fact that much of it needs genetic characterization before it can be used effectively.

Rootstocks were first used for grapes to overcome damage from phylloxera, a root-feeding aphid (Cousins, 2005). Since 1870, there were many rootstocks developed, particularly those from the Couderc breeding program. *V. riparia* × *V. rupestris* rootstocks, such as ‘C. 3306’ and ‘C. 3309’, are currently widely used worldwide (Reynolds, 2015). ‘1103 Paulsen’ (1103 P) (*V. berlandieri* × *V. rupestris*) was selected in Southern Italy for its strong drought tolerance and ability to grow well on lime-based soils. In 1896, Sigmund Teleki selected ‘Teleki 5A’ and ‘Teleki 8B’ from *V. berlandieri* (Manty, 2006). Franz Kober crossed *V. berlandier* with *V. riparia* and introduced two new genotypes, namely ‘5BB’ and ‘125AA’ due to their good performance under calcareous soil.

Heinrich Fuhr worked with ‘Teleki #4’ and selected ‘SO4’, ‘SO5’, and ‘SO8’. In 1922, Alexander Teleki continued the work with focus on ‘Teleki 5A’ and ‘Teleki 5C’. Further breeding work resulted in cultivar ‘5C Geisenheim’, released in 1936 (Reynolds, 2015).

Aside from phylloxera resistance, rootstocks were used to combat other soil-borne pests, primarily nematodes. Before 1900, Munson selected one of his most outstanding *V. champinii* cultivars 'Dog Ridge', which proved to be resistant to Pierce's disease and to parasitic nematodes (Harmon and Snyder, 1956; Lider, 1960). Open-pollinated seeds of 'Dog Ridge' *(Vitis* × *champinii*) and '1613 Couderc' (*V. solonis* × Othello), which were known to be resistant to the root-knot nematode (*Meloidogyne incognita*), were collected (Snyder and Harmon, 1952). Two of the open-pollinated seedlings, selected for their nematode resistance ('1613-59' and 'Dog Ridge 5'), were crossed and a seedling from the '1613-59' × 'Dog Ridge 5' cross was selected as the rootstock 'Freedom' (Brooks and Olmo, 1997). 'Freedom' is a widely used rootstock, particularly in the vineyards of San Joaquin Valley, California, where root-knot nematodes are the key soil-borne pest. In the 40 years since its release, 'Freedom' and its half-sibling rootstock 'Harmony' have largely replaced '1613C' and 'Dog Ridge' in new plantings due to their nematode resistance and improved horticultural characteristics (Garris et al., 2009).

In 1986, Dr. Olmo at U.C. Davis released 'O39-16' ('Almeria' × *M. rotundifolia*) that has been successful at controlling fanleaf virus and dagger nematode (*Xiphinema*). The rootstock also carries very strong resistance to *Xiphinema* that prevents the nematode from successful reproduction (Walker et al., 1991).

Five new rootstocks ('UCD-GRN 1-5') with diverse and durable resistance to root-knot and dagger nematodes, were patented and released to nurseries for propagation and thence to the grape industry (Walker and Ferris, 2009). During the initial testing of cultivars 'GRN 1-5', resistance against multiple individual types of nematodes as well as mixtures of nematodes was evaluated. Of the new resistant rootstocks, ‘UCD-GRN 1’ had broadest nematode resistance (Ferris et al., 2012).

Reynolds and Wardle (2001) outlined seven major criteria for choosing rootstocks in the order of their importance as phylloxera resistance, nematode resistance, adaptability to high pH soils, saline soils, low pH soils, wet or poorly drained soils, and drought. Additionally, investigations showed that rootstocks also affect vine growth, yield, and fruit quality through the interactions between environmental factors and the physiology of scions and rootstock cultivars employed (Rizk-Alla et al., 2011). Choice of rootstock is one of the most important factors in the establishment of a vineyard, but given the many choices available, identifying the most suitable rootstock for a particular scion is difficult (Loreti and Massai, 2006). There is no commercial universal rootstock, making variety-specific research to identify the best rootstock a necessity.

Rootstock choice can influence vigor of grapevines. Wunderer et al., (1999) mentioned that ‘Gruner Veltliner’ grape had a higher wood productivity when grafted on the three rootstocks tested (‘SO4’, ‘K5BB’, and ‘5C’) than that of the own-rooted vines. When ‘Merzifon Karasi’ (*Vitis vinifera* L.) was grafted on nine different rootstocks, the ‘1103P’ genotype had the shortest shoot length (Köse et al., 2014). The rootstock chosen affected mineral nutrition of the grafted variety. Brancadoro and Valenti (1995) grafted ‘Croatina’ onto 20 different rootstocks and found that K^+ content of leaves was significantly affected by rootstocks. The authors suggested that K^+ deficiency could be ameliorated by choosing an appropriate rootstock. However, Csikász-Krizsics and Diófási (2008) reported that rootstocks had no effect on leaf nitrogen levels, while the scion varieties increased nitrogen content of the leaves.

Despite the fact that grape growing requires less water than most crops, the predicted climatic change (i.e. reduced rainfall and increased evapotraspiration rates) will intensify water stress on vines, especially in water-limited regions. Ezzahouani and Williams (1995) suggested that hybrids (‘110R’, ‘140Ru’, and ‘1103P’) from rootstocks *V. berlandieri* × *V. rupestris* could be used in drought prone areas where water is a limiting factor for grapevine productivity. Another study revealed that ‘SO4’ was able to sustain leaf water status and physiological mechanisms at similar rates with ‘1103P’ due to its lower leaf area and to possible adjustments of leaf structure (Koundouras et al., 2008).

Rootstocks were shown to affect yield in multiple studies. In a study conducted in Australia, ‘101-14’, ‘Ramsey’, ‘Schwarzmann’, ‘Harmony’, and ‘SO4’ rootstocks generally increased fruit berry weight when compared to own-rooted vines (Ruhl et al., 1988). Another study revealed that ‘Chardonel’ grown on ‘Cynthiana’ roots had the lowest berry weight while ‘5BB’ had the highest berry weight (Main et al., 2002). In addition, yields of ‘Chardonel’ were highest on ‘5BB’ and lowest on Cynthiana. However, several studies found that the scion cultivar or site characteristics had a greater influence on yield than rootstock (Lipe and Perry, 1988; Morris et al., 2007; Reynolds and Wardle, 2001).

Rootstock is one of the factors that influence fruit quality and nutritional composition. ‘Red Globe’ grafted onto ‘Freedom’, ‘Harmony’, or ‘1103P’ rootstocks had the highest percentages of total soluble solids (TSS), TSS/acid ratio, and anthocyanin content of berry skin and the lowest percentages of berry juice acidity (Rizk-Alla et al., 2011). Reynolds and

Wardle (2001) found that vines grafted to '5BB' rootstock produced fruit with higher percent soluble solids in all cultivars tested than own-rooted vines. Satisha et al. (2007), found that berries from vines grafted on '110R' and '1103P' rootstocks, had higher berry phenolic content, flavon-3-ols, flavanoids, proline, and total proteins than that of berries harvested from vines grafted on *V. champinii*, *V. rupestris*, or *V. riparia* × *V. berlandieri*. In two studies with different rootstock/scion combinations, berry juice from vines grafted on '140Ru', '1103P', or '110R' had lower juice K^+ concentrations than that from vines grafted on 'Freedom', 'Dog Ridge', 'St. George', or '101-14' (Ruhl et al., 1988; Walker and Blackmore, 2012).

Rootstocks are also used in viticulture to manage damage from PD. When Florida hybrid bunch grape 'Blanc du Bois' was grafted onto muscadine, symptoms of PD and anthracnose were reduced (Ren and Lu, 2003). 'Chardonnay' vines grafted on 'Dog Ridge' had the largest in vine size and had the least PD symptoms under high PD pressure in the Rio Grande Valley, Texas (Cousins and Goolsby, 2011).

'Chardonel' is an upright-growing, white wine grape resulting from an interspecific hybrid between 'Seyval blanc' (Seibel 5656 × Rayon d'Or) and 'Chardonnay' (*Vitis vinifera L.*) (Reisch et al., 1990). Flowers of 'Chardonel' are perfect and self-fertile with medium-late bloom following a late budbreak. Clusters are shouldered and medium-large (200 g), averaging 1.6 clusters per shoot. Thinning is required only infrequently. There are an average of 2.8 seeds per berry, weighing 42.3 mg per seed. Seeds are pyriform in shape, with a long, prominent beak. Juice soluble solids concentration and titratable acidity are usually higher than for 'Cayuga White'. Wine has good body and very little of the flavor characteristics of interspecific hybrid grapes. In Michigan and Arkansas, ‘Chardonel’ is more productive than ‘Cayuga White’. It was suggested that ‘Chardonel’ be evaluated in California as attempts are being made to reduce the use of chemicals in vineyards. Due to the ‘Chardonel’ tolerance to powdery mildew and Botrytis, this cultivar may be attractive for use in reduced pesticide or organic farming systems in California (Main et al., 2002). As this is a recently patented cultivar, there little history of performance of grafted ‘Chardonel’ vines.

‘Norton’ is believed to have resulted from a lost *Vitis vinifera* cultivar ‘Bland’ being pollinated by stray pollen, possibly from *Vitis aestivalis* (Ambers and Ambers, 2004). ‘Norton’ and ‘Cynthiana’ were previously considered distinct cultivars or ‘Cynthiana’ possibly a sport of ‘Norton’. Recent isozyme and genetic analysis has shown they are the same cultivar. ‘Norton’ is the most widely planted cultivar in Missouri accounting for over 15% of the total acreage planted in grapevines (Missouri Grape Growers Assoc., 2001). It has good phylloxera resistance, mildew resistance, Pierce’s disease tolerance, winter and spring low temperature tolerance, and the potential to produce high quality wines. These traits allow growers to use less pesticides (20%–25% of the current rate of pesticide use in equivalent European varieties) when growing ‘Norton’ grapevines. However, own-rooted ‘Norton’ grapevines are challenging to grow due to excessive vegetative growth and low fruit yield. ‘Norton’ juice has undesirable characteristics, such as high pH, potassium, malic acid, and titratable acidity. However, the use of rootstock may improve favorable quality attributes of the ‘Norton’ scion.

Evaluating various scion-rootstock combinations in local environmental conditions is critical to gain knowledge on vine’s potential for sustainable production in the southeast. Yet very little is known concerning the performance of grape rootstocks in central Alabama, and how rootstocks impact vine PD resistance, drought and nematode resistance, phylloxera resistance, and other biotic and abiotic challenges common to the southeastern environment. The main objective of present study is to determine the best suited rootstocks for enhanced sustainability of hybrid bunch grape production in Alabama and the southeast. The experiment was initiated in 2014 at Auburn University, and Svyantek (2016) conducted preliminary research as part of his graduate studies.

Materials and Methods

Experimental design

A field experiment with hybrid bunch grape cultivars 'Norton' and 'Chardonel' either grown on their own roots or grafted to 'Paulsen 1103' ('1103P'), 'Kober 5BB' ('5BB'), or 'Teleki 5C' ('5C') was established at Chilton Research and Extension Center (CREC) (32°55'11.6" N, 86°40'25.4" W), USDA Plant Hardiness Zone 8A in 2014. Vines were planted in a generalized randomized complete block design comprised of seven replications, with two experimental vines per rootstock-scion combination per replication.

Data to determine vine phenology, vegetative characteristics, and fruit characteristics was collected from each cultivar and rootstock combination during 2017–2018.

Dormant pruning weight

Data on dormant pruning weight was collected to determine vine vigor of each rootstock-scion combination. Annual dormant pruning was conducted in February. Pruning weights were determined for each individual vine using an Adam CPW plus-35 scale (Adam

Equipment Inc., Danbury, CT). Vines were pruned to retain seven spurs per cordon with two buds per spur for fifteen spurs per vine and 30 buds per vine according to the balanced pruning theory (Smart and Robinson, 1991).

Phenology

Vine shoot growth and fruit maturation were evaluated phenologically using the modified E-L system for identifying major and intermediate grapevine growth stages (Coombe, 1972). On each vine, two spurs per arm were designated for monitoring and data was recorded at the basal and distal regions of each cordon arm for four spurs per vine.

Bud scales opening (stage 2) is the first stage of grapevine development in the spring. Early shoot development data was recorded by counting unfolded leaf number and measuring early shoot length. Data was collected at six fully unfolded leaves (stage 13) was modified to utilize the E-L scale (Coombe, 1972). Thus, data of grapevine phenological development is reported starting from the stage of six fully unfolded leaves (stage 13). Phenological development was evaluated on a weekly basis from 9 Mar. to 17 Apr. 2018. Flowering was monitored twice a week in spring to determine the flowering progression from 2 May to 22 May 2018. Full bloom was estimated to have occurred when the mean value of vines' inflorescences exceeded 50% flowers open.

Fruit development was monitored as berries progressed from fruit set to berry touch stages from 22 May to 31 July 2018. Veraison and berry ripening were assessed throughout changes in berry color and fruit softening.

To determine ripening and harvest time, berry fruit sugar accumulation was monitored periodically using a small sample size of 5–10 berries per block.

Fruit characteristics

Total yield per vine was measured at harvest for each vine. Vines were harvested by hand. Total number of clusters per vine was counted at harvest. For each individual vine, five representative clusters were collected to determine cluster weight, and berry weight was determined based on a 50-berry subsample per vine using a digital scale (Adventurer Pro AV4101, Ohaus Corp., Pine Brook, NJ). Following harvest evaluations, grape berries were stored at 4 ℃ until fruit quality analysis was conducted.

Fruit quality analysis was conducted to evaluate pH, titratable acidity (TA), and soluble solids content (SSC) using a 50-berry subsample per vine. Grapes were crushed with mortar and pestle, filtered through cheesecloth, and juice was stored in nonreactive 50 mL Falcon® tube (Cat# 21008-940 VWR, Wayne, PA) at 4 ℃ until further analysis. Berry pH and TA were measured using a DL 15 Titrator (Mettler-Toledo LLC., Columbus, OH). To measure TA, a 1 mL sample of grape juice was diluted to 40 mL of solution using distilled deionized water having an electrical conductivity of 18.2 MΩ cm^2 obtained through a Millipore Direct -QTM. 5 filter system (Millipore Corp., Bedford, MA). Titration was conducted to an endpoint of pH 8.2 using a 0.1 N NaOH titrant solution in the titrator. Results were recorded as grams of tartaric acid equivalent per liter of juice. SSC was measured at room temperature using extracted juice analyzed via a digital refractometer (Pal-1; Atago Co., Tokyo, Japan) and expressed as Brix (°B).

Foliar characteristics

Data was collected to determine the vine foliar characteristics of each rootstock-scion combination. Leaf area was measured by collecting 15 fully expanded leaves per vine for a total composite sample of 30 leaves per replication. Recently matured leaves were collected at random from the interior and exterior portions of the canopy during late summer, at a minimum distance of five nodes below the terminal bud. Leaf area was measured from a composite sample of 30 leaves per replication using a Licor LI-3100 (Licor Inc., Lincoln, NB, USA) meter.

Leaf chlorophyll content was measured on 10 fully expanded leaves per vine. Leaf chlorophyll content was measured using a nondestructive SPAD-502 Plus (Konica Minolta Sensing, Inc., Osaka, Japan) meter.

Vine decline assessment

Each vine in the experiment was visually inspected for symptoms of leaf chlorotic and shoot decline twice throughout the season in 2018. Symptoms severity ratings were recorded a subjective scale: 0 = no decline; 1 = slight decline; 2 = slight to moderate decline; 3 = moderate decline; and 4 = severe decline.

Leaf tissue nutrient analysis, composite sample consisting of 2 leaves per vine and 28 leaves per treatment was sent to Auburn University Soil Testing Laboratory on 22 July 2018. Soil sample was collected at the middle of two vines from the same replication from the at a depth of 15.24 cm using soil probe on 23 July 2018. A composite soil sample per treatment was collected from all seven replications, and samples were sent to Auburn University Soil Testing Laboratory for nutrient analysis.

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The experimental design was a gereralized randomized complete blocks design. Each year was analyzed separately, and block was in the model as a random variable. 'Norton' and 'Chardonel' were analyzed separately. Pruning weight, chlorophyll content, leaf area, total yield per vine, number of clusters per vine, mean cluster weight, and mean berry weight were in 1-way treatment designs of rootstock. Berry juice SSC, TA, and pH in 2017 and 2018 were in 1-way treatment designs of rootstock with sub-sampling. The experimental design for phenological growth stage was a split-split plot with rootstock in the main plot, shoot position in the sub-plot, and date in the sub-sub-plot. The treatment design was a 3-way factorial of rootstock, shoot, and date. Linear and quadratic trends over date were examined using qualitative/quantitative model regressions. Differences among scion-rootstock combinations were determined using the simulated method. All significances were at $\alpha = 0.05$.

Results

Dormant pruning weight

Own-rooted and grafted 'Chardonel' and 'Norton' vines had similar dormant pruning weight per vine in 2017 (Table 1.1). No differences in dormant pruning weight were found between own-rooted 'Chardonel' and 'Chardonel'/'1103P' grapevines in 2018 as well. 'Norton' grafted on '1103P' had the highest dormant pruning weight of 0.3 kg/vine in 2018, which was similar to '5C' and own-rooted 'Norton', but was higher than the pruning weight of '5BB' 'Norton'.

Phenological development from sixth unfolded leaves (stage 13) to berry harvest-ripe (stage 38)

Data on stages of early leaf development suggest 'Chardonel' grafted on '1103P' vines had an advanced growth early in the season when compared to own-rooted 'Chardonel' (Table 1.2). Eight unfolded leaves (stage 15) were observed on 'Chardonel'/'1103P' vines, while own-rooted 'Chardonel' had seven unfolded leaves (stage 14) on 24 Apr. 2018. On 7 May, 'Chardonel'/'1103P' vines had 30% of flower caps fallen (stage 21), and own-rooted 'Chardonel' had 10% of flower caps fallen (stage 20). No difference was found between 'Chardonel' grafted on '1103P' and own-rooted 'Chardonel' from fruit setting (stage 27) to ripening (stage 38). 'Norton' vines grafted on '5C' reached the full bloom stage (50% of flower caps fallen stage 23) on 17 May which was 5 days earlier than 'Norton'/'5BB', 'Norton'/'1103P', and own-rooted 'Norton'. Rootstocks did not have an effect on 'Norton' vines season of ripening (stage 32 to 36). Phenological development (stages 13 to 38) of own-rooted and grafted 'Chardonel' and 'Norton' vines showed a quadratic trend over time in 2018.

Fruit characteristics

'Chardonel' grapevines were harvested by hand on 14 Aug. 2017 and on 3 Aug. 2018, whereas 'Norton' grapevines were harvested on 1 Sept. 2017 and 17 Aug. 2018. No difference was found for total yield per vine between own-rooted 'Chardonel' and 'Chardonel' grafted on '1103P' rootstock in 2017 (Table 1.3), but grafted vines produced slightly higher yield. However, total yield per vine of 'Chardonel'/'1103P' was higher than the yield of own-rooted 'Chardonel' in 2018. Total yield per vine for 'Norton'/'5BB' was higher as compared to own-rooted ‘Norton’ in 2017. No rootstock effect was found for total yield per vine for ‘Norton’ grapes in 2018.

Although the total number of clusters per vine was similar for own-rooted and ‘1103P’ grafted ‘Chardonel’ vines, 33% greater clusters were produced on ‘1103P’ grafted ‘Chardonel’ grapes in 2018 (Table 1.3). ‘Norton’/’5BB’ had the highest number of clusters per vine in 2017, while the own-rooted, ‘1103P’, and ‘5C’ grafted ‘Norton’ vines responded with a similar number of clusters/vine. No rootstock effect was found for the number of clusters per vine for ‘Chardonel’ and ‘Norton’ grapevines in 2018.

Mean cluster weight differences between own-rooted ‘Chardonel’ and ‘1103P’ grafted ‘Chardonel’ vines were not consistent across the two years (Table 1.3). Mean cluster size of ‘Chardonel’/’1103P’ was similar to own-rooted ‘Chardonel’ in 2017, but was 29% higher than own-rooted ‘Chardonel’ in 2018. Tested rootstocks did not have an effect on mean cluster weight of ‘Norton’ vines in both years of our study. Mean cluster weight for ‘Norton’ ranged from 79.0 to 87.0 g in 2017, and between 49.2 to 77.8 g in 2018 with ‘Norton’/’5BB’ producing the largest cluster size in 2017 and the smallest in 2018.

No rootstock effect was found for mean berry weight of ‘Chardonel’ and ‘Norton’ grapevines (Table 1.3).

No rootstock effects were found on SSC values among own-rooted and grafted ‘Norton’ vines (Table 1.4). The majority of scion-rootstock combinations produced fruit with lower SSC in 2018 than 2017. Berry pH was similar among own-rooted and grafted ‘Norton’ vines in 2017. However, juice pH of own-rooted ‘Norton’ was lower than the pH of all grafted

‘Norton’ vines in 2018. No rootstock effects were found on TA values among own-rooted and grafted ‘Norton’ vines. The majority of scion-rootstock combinations produced fruit with higher TA in 2018 as compared to 2017.

Foliar characteristics

Leaf chlorophyll content for ‘Chardonel’/’1103P’ was higher than own-rooted ‘Chardonel’ in both years (Table 1.5). No difference in leaf chlorophyll content was found on ‘Norton’ vines in 2017. Leaf chlorophyll content for ‘Norton’/5BB (27.7) was lower than the remaining ‘Norton’ vines. Mean leaf area increased for all vines from 2017 to 2018. Leaves from ‘Chardonel’/’1103P’ were only numerically larger than own-rooted ‘Chardonel’ in 2017 and 2018. No difference was found in mean leaf area for ‘Norton’ rootstocks in 2017. ‘Norton’/’5BB’ mean leaf area was lower than ‘Norton’/’1103P’, ‘Norton’/’5C’, and own-rooted ‘Norton’ in 2018.

Vine decline assessment

Late in the growing season, symptoms of chlorotic leaves and shoot decline were observed on some ‘Norton’ vines. Own-rooted ‘Norton’ and ‘Norton’/’5C’ vines had less chlorotic leaves and shoot decline as compared to ‘Norton’/’1103P’ and ‘Norton’/’5BB’ grafted vines.

The results of soil nutrient analysis showed concentrations of potassium (K), magnesium (Mg), boron (B), iron (Fe), and manganese (Mn) were lower than the recommended ranges, whereas phosphorus (P) and copper (Cu) were higher than the recommended ranges. Specifically, concentration of K from all six samples was between 34 to 60 ppm, whereas the recommended range was from 100 to 220 ppm. Conversely, concentration of P from all treatments was over the upper limit of 8 ppm except for soil sample from 'Chardonel'/'1103P' where concentration of P was 7 ppm, whereas own-rooted 'Norton' had highest P rate of 38 ppm. Soil pH for all treatments except for own-rooted 'Chardonel' (6.31) was over 6.5 with the highest pH recorded on Norton/'5C' of 6.8. The results of leaf tissue sample nutrient analysis suggested that among all the treatments, K and B were deficient in grape leaf tissue, while Cu was excessive.

Discussion

Despite the fact that 'Chardonel' was reported a late blooming cultivar in New York environmental conditions (Reisch et al., 1990), 'Chardonel' blossomed and matured earlier than 'Norton' under central Alabama conditions. In addition, rootstock was found to affect grapevine phenological development. A previous study showed that shoot growth of 'Gruner veltline' was slower on '5C', but more rapid on '1103P' and ripening of grapes occurred earlier on 1103P (Fardossi et al., 1995). In the present study, rootstock '1103P' advanced the blooming of 'Chardonel' as compared to own-rooted vines. '5C' advanced the phenological development of 'Norton' as compared to own-rooted 'Norton'.

Many studies have shown that the rootstocks induced differences in yield (Hedberg, 1980; Ruhl et al. 1988; Main et al., 2002; Lipe and Perry, 1988; Morris et al., 2007; Reynolds and Wardle, 2001) and '1103P', '5BB', and '5C' tended to increase yields (Main et al., 2002, Benz et al., 2007). In present study, 'Chardonel' grafted on '1103P' increased yield as compared to own-rooted 'Chardonel'. '1103P', '5C', and '5BB' rootstocks did not have an effect on yield of‘Norton’. Feld evaluations on vegetative growth of ‘1103P’ grafted vines have been controversial. Keller et al., (2012) found that ‘1103P’ tended to reduce scion vigor, but the rootstocks generally did not impact vine phenology and fruit set. However, Stockert et al. (2013) showed that the ‘1103P’ rootstock has a root system that tends to produce large canopies and high shoot growth. In the present study, the results for vine pruning weight suggested ‘1103P’ tended to increase scion’s vigor. Despite the fact that rootstocks may lead to considerable differences in scion yield, seasonal effects and scion cultivars have long been considered to strongly outweigh their influence on fruit composition (Benz et al., 2007, Keller et al., 2012). The outcome from the present study are in agreement with this finding. The only exception was observed for juice pH of own-rooted ‘Norton’ vines in 2018, when all of the grafted ‘Norton’ plants had higher pH than own-rooted ‘Norton’. Juice pH for ‘Chardonel’/’1103P’ and own-rooted ‘Chardonel’ were similar, and below 2.7 in 2018. Winemaking practice generally involves pH adjustment with tartaric acid to bring grape juice pH to within the range 3.0–3.3 for white wines and 3.3–3.5 for red wines (Iland et al. 2000), which demonstrates the need of juice pH adjustments for winemaking for all scion-rootstock combinations in the present study.

‘Norton’ is a popular cultivar in the southeast because of its tolerance to PD. In a study to compare *X. fastidiosa* infection among ‘Blanc du Bois’, ‘Norton’ be consistent with the use of cultivar name, and ‘Black Spanish’ in a region with high PD pressure in Texas, crop yield suggested that ‘Blanc du Bios’ and ‘Black Spanish’ may be more productive than ‘Norton’ along the Gulf Coast (Buzombo et al., 2006). ‘Norton’ tested for *X. fastidiosa* showed a dramatic increase in bacterial levels over ten growing seasons. Ferris et al., (2012) showed that ‘5BB’ was susceptible to two types of nematodes: *Xiphinema* (dagger nematode) and *Mesocriconema xenoplax* (ring nematode). In addition, the survival rate of ‘5BB’ on own roots was 10% at the sixth growing season under high PD pressure in Florida (Lu et al., 2008). In the present study, we consider the high levels of dagger nematodes, and ring nematodes found in the soil samples, combined with *Xylella fastidiosa* infection were accountable for the symptoms observed and the overall vine decline of ‘Norton’/5BB grapevines.

This research demonstrates preliminary results on the effect of selected commercially available grape rootstock cultivars on yield potential, vegetative growth, and fruit quality of two commercially available hybrid bunch grape cultivars, ‘Chardonel’ and Norton’. Our results indicate ‘1103P’ was the best performing rootstock for ‘Norton’ and ‘Chardonel’ hybrid bunch grape cultivars in Alabama.

Further evaluation will characterize the long-term sustainability of these rootstock cultivars for future bunch grape production in Alabama and the Southeastern U.S. where the risk of PD is high. Further understanding of vineyard longevity of these rootstock scion combinations in Central Alabama will significantly enhance the environmental, social, and economical sustainability of the viticulture industry in the region by conserving natural resources, optimizing vineyard productivity, reducing chemical use and production cost , and increasing the market competitiveness for locally grown bunch grapes.

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Table 1.1. Rootstock effects on pruning weight per vine of ‘Chardonel’ and ‘Norton’ grapevines grown at the Chilton Research and Extension Center, Clanton, Alabama, 2017–2018.

		Pruning weight (kg/vine)	
Cultivar	Rootstock	2017	2018
Chardonel	1103P	0.5 ns[z]	0.3 ns
Chardonel	Own	0.6	0.2
Norton	1103P	0.7 ns[y]	0.3 a
Norton	5BB	0.6	0.2 b
Norton	5C	0.6	0.3 ab
Norton	Own	0.8	0.3 ab
‘Chardonel’ vs. ‘Norton’[x]		0.0788	0.7261

[z]Least square means between ‘Chardonel’/1103P and own-rooted ‘Chardonel’ using the simulated method at $P < 0.05$. ns = not significant.

[y]Least squares means among ‘Norton’ rootstocks using the simulated method at $P < 0.05$. ns = not significant.

[x]Paired group comparison between all ‘Chardonel’ and all ‘Norton’ using the simulated method at $P < 0.05$.

Table 1.2. Rootstock effect on phenological growth stages (stage 13 to 38) of 'Chardonel' and 'Norton' grapevines grown at the Chilton Research and Extension Center, Clanton, Alabama, 2018.[z]

	Modified E-L scale[y]					
Date	Chardonel 1103P	Chardonel Own	Norton 1103P	Norton 5BB	Norton 5C	Norton Own
24 Apr.	15.2 a[x]	14.1 b	13.6 bc	13.2 c	14.1 b	13.5 bc
2 May	17.9 a	16.9 b	15.3 cd	14.5 d	15.7 c	14.9 cd
4 May	18.9 a	17.8 b	16.0 c	15.4 c	16.3 c	15.5 c
7 May	21.2 a	20.1 b	16.9 cd	16.5 cd	17.2 c	16.3 d
10 May	24.6 a	23.2 b	17.8 c	17.1 c	17.8 c	17.4 c
14 May	26.7 a	25.8 b	20.4 c	20.2 cd	20.8 c	19.5 d
17 May	28.3 a	27.5 a	24.2 c	23.7 cd	25.1 b	23.1 d
22 May	30.2 a	29.5 a	26.4 b	26.2 b	26.6 b	26.0 b
2 June	31.4 a	31.3 a	29.1 bc	28.3 c	29.5 b	28.7 c
7 June	32.4 a	31.9 a	30.5 b	29.3 c	30.7 b	29.8 bc
12 June	32.7 a	32.4 a	31.1 b	29.9 c	31.2 b	30.6 bc
19 June	32.9 a	32.7 a	31.4 bc	30.5 c	31.7 b	31.2 bc
26 June	33.0 a	33.0 a	32.2 ab	31.0 c	32.3 ab	31.9 bc
9 July	35.0 a	34.8 a	33.0 b	32.4 b	33.0 b	33.0 b
17 July	37.0 a	36.9 a	34.3 b	34.2 b	34.4 b	34.3 b
24 July	37.0 a	36.9 a	35.0 b	34.8 b	35.0 b	35.0 b
31 July	38.0 a	37.9 a	36.0 b	35.8 b	36.0 b	36.0 b
Sign.[w]	Q***	Q***	Q***	Q***	Q***	Q***

[z]Only the rootstock by date interaction was significant at $P < 0.05$.

[y]Modified E-L system (Coombe, 1972) for identifying major and intermediate grapevine growth stages: scale 13-38.

[x]Least squares means comparisons using the simulated method at $P < 0.05$. ns = not significant.

[w]Significant (Sign.) quadratic (Q) trends using orthogonal polynomials at $P < 0.001$ (***).

Table 1.3. Rootstock effect on total yield, cluster weight, and berry weight of ‘Chardonel’ and ‘Norton’ grapevines grown at the Chilton Research and Extension Center, Clanton, Alabama, 2017–2018.

		Total yield (kg/ vine)		Number of clusters/ vine (No.)		Mean cluster weight (g)		Mean berry weight (g)	
Cultivar	Rootstock	2017	2018	2017	2018	2017	2018	2017	2018
Chardonel	1103P	9.1 ns[z]	12.7 a	44.6 ns	62.1 ns	217.9 ns	259.2 a	2.3 ns	2.1 ns
Chardonel	Own	7.7	7.0 b	40.1	41.8	230.7	201.4b	2.3	2.0
Norton	1103P	3.8 ab[y]	4.3 ns	52.3 b	79.9 ns	85.2 ns	71.3 ns	1.3 ns	1.2 ns
Norton	5BB	4.5 a	2.5	72.8 a	45.0	87.0	49.2	1.3	1.0
Norton	5C	3.6 ab	3.6	52.0 b	66.4	79.5	77.8	1.3	1.2
Norton	Own	2.7 b	2.5	43.9 b	59.8	79.0	54.3	1.3	1.1
‘Chardonel’ vs. ‘Norton’[x]		<.0001	<.0001	0.0029	0.0563	<.0001	<.0001	<.0001	<.0001

[z]Least square means comparisons between ‘Chardonel’/’1103P’ and own-rooted ‘Chardonel’ using the simulated method at $P < 0.05$. ns = not significant.

[y]Least squares means comparisons among ’Norton’ rootstocks using the simulated method at $P < 0.05$. ns = not significant.

[x]Paired group comparison between all ‘Chardonel’ and all ‘Norton’ using the simulated method at $P < 0.05$.

Table 1.4. Rootstock effect on fruit quality of ‘Chardonel’ and ‘Norton’ grapevines grown at the Chilton Research and Extension Center, Clanton, Alabama, 2017–2018.

		Soluble solids content (°Brix)		pH		Titratable acidity (g/L)	
Cultivar	Rootstock	2017	2018	2017	2018	2017	2018
Chardonel	1103P	18.5 ns[z]	17.3 ns	2.75 ns	2.64 ns	7.4 ns	10.7 ns
Chardonel	Own	17.3	17.5	2.79	2.69	7.8	10.2
Norton	1103P	20.4 ns[y]	19.2 ns	3.06 ns	2.97 a	5.8 ns	8.8 ns
Norton	5BB	20.3	18.6	3.1	2.94 a	5.7	9.2
Norton	5C	20.2	18.9	3.07	2.93 a	5.9	8.1
Norton	Own	20.90	19.5	3.00	2.86 b	5.8	8.6
Chardonel vs. Norton[x]		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

[z]Least square means comparisons between ‘Chardonel’/’1103P’ and own-rooted ‘Chardonel’ using the simulated method at P < 0.05. ns = not significant.

[y]Least squares means comparisons among ‘Norton’ rootstocks using the simulated method at P < 0.05. ns = not significant.

[x]Paired group comparison between all ‘Chardonel’ and all ‘Norton’ using the simulated method at P < 0.05.

Table 1.5. Rootstock effect on chlorophyll content and leaf area of ‘Chardonel’ and ‘Norton’ grapevines grown at the Chilton Research and Extension Center, Clanton, Alabama, 2017-2018.

		Chlorophyll content[z]		Leaf area (cm^2)	
Cultivar	Rootstock	2017	2018	2017	2018
Chardonel	1103P	44.9 a[y]	42.3 a	68.6 ns	105.8 ns
Chardonel	Own	39.9 b	39.5 b	62.8	90.1
Norton	1103P	36.4 ns[x]	32.4 a	106.2 ns	149.4 a
Norton	5BB	34.2	27.7 b	89.5	101.6 b
Norton	5C	36.4	32.1 a	95.4	144.3 a
Norton	Own	35.6	31.9 a	87.1	137 a
Chardonel vs. Norton[x]		<.0001	<.0001	0.0004	<.0001

[z]SPAD-502 meter value.

[y]Least square means comparisons between ‘Chardonel’/’1103P’ and own-rooted ‘Chardonel’ using the simulated method at $P < 0.05$. ns = not significant.

[x]Least squares means comparisons among ’Norton’ rootstocks using the simulated method at $P < 0.05$. ns = not significant.

[x]Paired group comparison between all ‘Chardonel’ and all ‘Norton’ using the simulated method at $P < 0.05$.

CHAPTER THREE

Size Controlling Rootstocks for Enhanced Sustainability of Apple Production in Alabama

Abstract

Fire blight (FB) (*Erwinia amylovora*) is a disease of serious concern in apple and pear production. Warm, humid weather conditions in May in the southeast favor the development of Fire blight. Disease control costs are estimated at approximately $100 million a year in the U.S.A. With the newly released FB resistant rootstocks from the Cornell-USDA apple rootstock breeding program, along with other FB resistant releases, the objective of this study was to determine the best performing rootstocks using an innovative cultivation system for enhanced sustainability of apple production in Alabama. In 2014, a field experiment was established using 'Aztec Fuji' apple grafted on 'V.1', 'V.5', 'V.6', 'V.7', 'G.11', 'G.30', 'G.41', 'G.202', 'G.214', 'G.935', 'G.969', 'M.9-T337', 'B.10', and 'M.26 EMLA ' rootstocks at the Chilton Research and Extension Center located in Chilton County, AL. The results suggest that trees grafted on 'G.969' had the highest yield in 2017, while trees on 'M.26 EMLA' produced the lowest yield during the same season. Trees grafted on 'V.5' produced the highest yield and those on 'V.7', 'G.969', 'V.6', and 'G.30' yielded over 25 kg/tree in 2018, whereas trees grafted on 'G.41' had the lowest yield. Yield efficiency of 'Aztec Fuji' was highest for trees grafted on 'G.935' in 2017, whereas it was highest for trees grafted on 'G.214' in 2018. Mean 'Aztec Fuji' fruit weight was highest for trees grafted on 'G.11', and lowest for trees grafted on 'G.30' in 2017. In 2018, 'V.6' grafted trees produced the largest fruit size of 210.7 g, while the trees on 'B.10' produced the smallest fruit of 171.2

g. Soluble solids content (SSC) of ‘Aztec Fuji’ was highest for trees grafted on ‘G.202’ and ‘G.214’ in 2017, whereas ‘Aztec Fuji’/’G.935’ trees produced the sweetest fruit in 2018. Un-bagging fruit ten days before harvest showed higher skin blush percentage as compared to fruit un-bagged at harvest regardless of rootstock selection in 2018. Longer trial evaluation will be required to obtain a more thorough understanding of rootstock effect on tree size and overall performance in Alabama.

Introduction

Apple is the most important temperate fruit crop and has been cultivated in Asia and Europe since ancient times (Janick et al., 1996). Kellerhals (2009) reported that the genus *Malus* is comprised of 25–30 species and several subspecies of so-called crab apples. The cultivated apple is a result of interspecific hybridization. *Malus* × *domestica* has been generally accepted as the appropriate scientific name (Korban and Skirvin, 1984). The world's most important commercially produced apple cultivars belong to *Malus* × *domestica* Borkh. Throughout its history of cultivation, at least 10, 000 apple cultivars were developed, many of which are now lost. Approximately 100 cultivars are commercially cultivated, however, only ten constitute 90 percent of U.S. production (Rieger, 2006).

Being the first ranking country in total growing area and export of fresh apple fruit, China has assumed the predominant position in world apple production (Wang et al., 2016). 'Fuji' is the dominant commercial cultivar produced in China. Other important cultivars include 'Starkrimson', 'Jonagold', 'Golden Delicious' and 'Gala' (Wang et al., 2016). U.S. production was 4,649,323 tons in 2016, which is a 2.5% increase from the previous year (4,537,693 tons for 2015) (FAOSTAT, 2016).

In Washington State, the largest producer of fresh apples in the United States, the cultivated area for 'Honeycrisp' increased from 300 acres in 2001 to 9,098 acres in 2011, whereas cultivated areas for the traditional 'Red Delicious' declined from 82,000 to 43,379 acres, between 2001 and 2011 (Gallardo et al., 2018). Alabama growers have generally followed the trends of the U.S. as a whole about establishing apple varieties. Sports of 'Red

Delicious' have largely dominated apple production in the state for many years, with selections of 'Golden Delicious' being second in importance (Powell et al., 2000). However, historically, Alabama as well as the entire Southeast U.S. has experienced problems producing 'Red Delicious' selections due to failure to develop acceptable red skin color for the wholesale market. Seasonal climatic heat in August and early September is largely responsible for inadequate or insufficient red finish of 'Red Delicious' grown in the South (Powell et al., 2000). Also, the shape of eastern grown 'Red Delicious', which tend to be round than more elongated, have been considered inferior to Washington state-grown 'Red Delicious' . On the other hand, 'Fuji' has adapted well to southeastern conditions and continues to be cultivated by commercial producers. 'Fuji' internal quality is outstanding and growers remain optimistic concerning future market potential (Powell et al., 2000).

'Fuji' has gained high popularity due to its outstanding flavor, high soluble solids concentration (SSC), low starch degradation pattern (SDP), and long storage life. However, poor fruit color of this cultivar remains problematic globally. During the past decades researchers and apple producers have focused efforts on high-coloring strains with high fruit quality (Marquina et al., 2004). Iglesias et al., (2012) measured fruit anthocyanin content and visual color of different strains and reported that the most pigmented strain was 'Aztec Fuji'. 'Zhen Aztec Fuji' (the full name of 'Aztec Fuji'), was selected by Austin Orchard Ltd. in Nelson, New Zealand (Brown and Maloney, 2013). 'Aztec Fuji' is an unpatented cultivar in North America and very little is known concerning performance in this continental area.

Temperate perennial crops require cumulative chilling temperatures to initiate growth and flowering in spring (Saure, 1985). Temperate perennial crops undergo cyclic dormancy requirement that inhibits growth until exposure to low winter temperatures (chilling), prior to spring budbreak. Failure to receive sufficient chilling can lead to serious consequences including reduction of flower quality, abscission of flower buds, protraction of the flowering process, and reduced fruit set (Jackson et al., 1983). In addition, lack of effective chilling during winter in tropical and sub-tropical areas prolongs dormancy leading to poor blooming, strong apical dominance, unsynchronized growth patterns, and consequently, low yields (Cook and Jacobs, 1999).

Apples are adaptable to various climates, but best adapted to the cool temperate zone from about 35–50° latitude (Kellerhals, 2009). Chilling hours of apple range from 200 to 2000 h. Insufficient chilling hours during winter months in the southeast often times results in less than desirable production performance for apple trees. Limited number of apple cultivars have been evaluated in orchards in Florida under varying environmental conditions. Among 43 tested cultivars, only ‘Anna’, ‘Dorsett Golden’ and ‘Tropic Sweet’ were recommended for Florida environmental conditions (Andersen and Crocker, 2009). These cultivars each have a chilling requirement of 250–300 hours. ‘Anoka’ apple, often designated as “The Old Folks Apple” due to premature fruit bearing during the first year following planting and has responded favorably to Central Florida climate (Rowland, 1977).

Fire blight (FB), a devastating necrogenic disease caused by the Gram-negative bacterium *Erwinia amylovora*, is the most important bacterial disease affecting pome fruit and several other members of the Rosaceae family (Malnoy et al., 2012). FB infects blossoms, fruits, stems, leaves, woody branches, and rootstocks crowns, thereby causing blossom blight, shoot blight, and rootstock blight (Peil et al., 2009) with affected areas appearing scorched by fire. Once *E. amylovora* enters rootstock, no cultural control or chemical treatment can prevent disease development (Norelli et al., 2003), and the bacteria initiates formation of new cankers that can completely girdle and kill the tree in one to a few months.

Many methods have been attempted to reduce the loss caused by FB. Copper compounds are effective bactericides and have been used against fire blight on apples and pears (Zwet and Keil, 1979). However, the copper ion, which is the main active ingredient of the compounds, is very toxic to plant tissues. The antibiotic streptomycin (Agrimycin 17) provided better control under higher disease pressure than copper compounds, and does not cause fruit russeting (Hagan et al., 2004). Long-term use can result in development of resistant FB strains. Biological control of FB using epiphytic bacteria was considered a promising alternative to chemical control (Wilson and Lindow, 1993). *Pseudomonas fluorescens* strain A506, a biological control agent of FB, was used extensively and effectively in controlling fire blight of pear in California (Wilson and Lindow, 1993). A study demonstrated that when blossoms were inoculated with *P. fluorescens* A506 under either high or ambient relative humidities 72 h in advance of *E. amylovora* Ea8R exposure, the biological control agent reduced pathogen population size on both pistils and nectaries in all experiments (Wilson and Lindow, 1993). Breeding for FB resistant rootstocks is considered a reliable disease management tool. The apple rootstock breeding program at the New York State Agricultural Experiment Station (Cornell University) has released the Geneva series of apple rootstocks that were bred for tolerance to FB and Phytophthora root rot, high yield efficiency and good tree survival (Norelli et al., 2003).

The current trend globally is to move toward smaller tree size and higher-density orchards to reduce labor inputs and improve efficiency. One of the primary ways to maintain small, compact tree size in commercial as well as home plantings is to grow spur-type cultivars (Powell et al., 2000). However, spur-type trees grow slowly, are compact, and begin fruiting at only 2 to 3 years of age. Among the common temperate tree fruits, the apple is the only one that has truly effective dwarfing rootstocks. This is important because many popular cultivars do not have superior spur types, therefore, the use of dwarfing rootstocks is the method of choice for maintaining small tree size, particularly in high-density systems where the economic risks and potential returns are the highest.

New apple rootstocks become available regularly from a number of sources with the potential of providing greater growth control, enhanced precocity, higher yield, improved adaptability to environmental conditions, and enhanced pest resistance (Autio et al., 2017a). Numerous new rootstocks are available for evaluation from the Budagovsky, Cornell-Geneva, and Vineland breeding programs.

‘Budagovsky 9’ (‘B.9’) rootstock was developed at the Michurinsk State Agrarian University in Michurinsk, Russia. ‘B.9’ has the potential to surpass ‘M.9’ in modern production systems (Russo, 2007). The north central (NC) regional project NC-140, founded by the United States Department of Agriculture (USDA), tested Budagovsky rootstocks with different scion cultivars in numerous trials for the interaction on yield and tree vigor (Autio et al., 2001; 2013; Marini et al., 2014).

Cornell University and the United States Department of Agriculture (USDA) managed the Cornell-Geneva Apple Rootstock Breeding Program jointly. Several rootstocks are available from this program, most with a high degree of disease resistance, particularly to the FB bacterium. Four apple rootstocks, 'Geneva® (G.) 65', 'G.11', 'G.30', and 'G.16', were initially released for commercial use, followed by 'G. 210', 'G.214', 'G.890', and 'G. 969' (Robinson et al., 2014). Various Geneva rootstocks are resistant to FB strains Ea273 and E2017a, but more susceptible to strains E2002a and E4001a (Fazio et al., 2006). Interestingly, the rootstocks 'G.3041' and 'G.5179' show virtually full resistance to all strains tested (Fazio et al., 2006). The Geneva rootstocks had significantly lower probability of developing rootstock blight than the standard Malling rootstocks. Moreover, 'G.11', previously described as fire blight-tolerant (Norelli et al., 2003), had significantly less overall rootstock blight, even with the highly susceptible cultivars 'Gala' and 'Honeycrisp'. The Geneva rootstock program has developed several promising new genotypes, and the current focus of the conventional portion of the breeding program is to produce new rootstock genotypes that retain the disease resistance of the first generation of Geneva rootstocks, but with improved horticultural properties.

The Vineland (V.) rootstocks originated at the Horticultural Research Institute of Ontario, Vineland Station, as open-pollinated seedlings of 'Kerr' crab apple (Elvfing et al., 1993). The primary objectives were to develop fully-dwarfing rootstocks adapted to the Ontario climate of colder winters and warmer summers. 'V. 1' and 'V. 3' look especially promising in comparison to 'M.9-EMLA', displaying excellent size control and yield efficiency. 'V. 7' produced trees in the 'M.26' to 'M.7' size and productivity range, while 'V. 4' produced larger trees. No data were available on the performance of 'V.5' or 'V.6' as rootstocks (Elvfing et al., 1993). Consistent with other Vineland rootstocks, 'V.2' was highly resistant to rootstock blight, but resistance evaluation was only done with the cultivar ‘Golden Delicious’ (Russo, 2007).

Commercial efforts to adopt high densities orchards is motivated primarily by the need for early production to pay back the initial investment cost and improve profitability. With higher tree planting densities, cumulative fruit production during the first 10 years of an orchard’s life has improved dramatically. With most modern high-density planting systems, a small yield is expected during the second growing season of the orchard. Substantial yields are expected in the third year and mature yields are expected by year 5 or 6. In contrast, traditional low-density systems on vigorous rootstocks began commercial production around year 6 or 7 and did not reach mature yields until year 10 to 15 (Robinson, 2006).

The Tall Spindle is a combination of the Slender Spindle (Wertheim, 1968), the Vertical Axis (Lespinasse, 1980), the Super Spindle (Nüberlin, 1993) and the Solaxe (Lespinasse, 1996) systems. Tall Spindle system was based on the Slender Spindle tree, and designed to improve early yields and management efficiency by planting higher tree densities and reducing tree height to permit entire fruit tree management to be performed at ground level. Tall Spindle growing system is rapidly gaining popularity globally. Tall spindle system incorporates optimal planting density, use of feathered trees, minimal pruning and branch bending and increased light interception that results in superior fruit quality and reduced labor cost (Robinson et al., 2012a). Adoption of this system facilitates the use of mechanical side-wall shearing to create a fruiting wall.

Chemical fruit thinning is an established practice in all apple-producing areas of the world (Forshey, 1986). Fruit thinning was commonly applied with two hormone-type thinners: synthetic auxin such as naphthylacetic acid (NAA) and synthetic cytokinin such as benzyladenine (BA). A carbamate insecticide (carbaryl, 1-naphthalenyl methylcarbamate) also is used for fruit thinning. Greene and Autio (1989) reported that BA effectively thinned 'McIntosh' apples, and BA and NAA thinned more effectively when each was combined with carbaryl. Ethephon (2-chloroethylphosphonic acid) + carbaryl combination has provided good thinning in most tests in Virginia (Byers et al., 1990a). In other studies, two days of artificial shade decreased photosynthesis, reduced the carbohydrates available to the fruitlets, and induced more apple abscission than NAA, ethephon, or carbaryl + oil spray (Yuan and Greene, 2000). Terbacil, a photosynthetic inhibitor, applied to the foliage at very low rates, or artificial shading of the tree for 2 days, also caused thinning (Byers et al., 1990a, 1990b). The standard technique of carbaryl application at 8-9 mm fruit diameter followed by a second application at 11-12 mm in tank-mix with BA resulted in adequate thinning and excellent quality in terms of fruit size and color for 'Fuji' (Dorigoni and Lezzer, 2007). New molecules have emerged and are under evaluation that show real promise as new chemical thinners. These include the photosynthesis inhibitor metamitron (Brevis) and two naturally occurring compounds, abscisic acid (ABA) and 1-aminocyclopropane-1-carboxylic acid (ACC) (Greene and Costa, 2012). Manual, chemical and mechanical methods are used for fruit thinning, alone or in combination, but the method chosen depends upon species, climatic conditions and the historic reliability of the proposed method.

FB is the most important bacterial disease affecting apple production (Aćimović et al., 2015). Newly released FB resistant rootstocks can aid in disease management and improve production sustainability. Semi-dwarf and dwarf size-controlling rootstocks are available and utilized in high density orchards, but their effects on plant vigor, production efficiency and fruit quality have not been established in Alabama environments. The objective of this study is to determine the best performing FB resistant size-controlling rootstocks incorporated in an innovative cultivation system for enhanced sustainability of apple production in Alabama.

Materials and Methods

Experimental layout

The experimental apple orchard was planted at the Chilton Research and Extension Center (CREC) located in Chilton County, AL, (32°55’11.6” N, 86°40’25.4” W), USDA Plant Hardiness Zone 8A, in 2014. The experimental layout was a randomized complete block design with ten blocks comprised of fourteen plants per block and planted at a distance of 3.96 m between rows and 1.52 m between trees at a density of 672 trees per acre. The treatments consisted of ‘Aztec Fuji’ apple grafted on fourteen FB resistant, size controlling rootstocks: ‘V.1’, ‘V.5’, ‘V.6’, ‘V.7’, ‘G.11’, ‘G.30’, ‘G.41’, ‘G.202’, ‘G.214’, ‘G.935’, ‘G.969’, ‘M.9-T337’, ‘B.10’, and ‘M.26 EMLA’. Trees were trained to a Tall Spindle (Robinson, 2006) system with a 3-row wire supporting to a height of 3.0 m. Drip irrigation system was installed prior to planting and trees were irrigated as needed. Experiment management practices were applied according to the S.E. Apple Production Guide (Tarpy, 2018). Minimal dormant pruning was conducted in late spring. One limb larger than one-third of the trunk diameter at the point of interception was removed using a bevel cut for each tree.

Flowering season development

Data on percent open flower was not collected in the spring of 2017. To determine the flowering season, data on the percent open flowers per tree was collected from the beginning of bloom (~10% open flowers starting on 15 Mar.) until the full bloom stage (~80% of flowers open, on 30 Mar.) in 2018.

Fruit thinning

Fruit was thinned by hand on 26 May 2017 and 27 Apr. 2018. Thinning amount was calculated based on retaining five king fruit per squared centimeter trunk cross sectional area (TCSA) for a four yr-old apple orchard trained to a Tall Spindle training system (Robinson, 2006).Trunk diameter was measured at 30 cm above graft union on 1 Nov. 2017 and 20 Sept. 2018, from which the TCSA was calculated. Subsequent thinning was conducted as needed to remove the excess king flowers on each tree and bring the total fruit number to five fruit per squared centimeter of TSCA.

Fruit bagging and un-bagging

To evaluate the effect of fruit bagging on pest exclusion and skin color, fruit were bagged on 21 June 2017 and 31 May 2018. Twelve randomly selected fruit per tree were bagged in 2017, while 10 randomly selected fruit per tree were bagged in 2018 using Clemson Fruit Bags (Clemson fruit bags, 2018).

All bagged apples were un-bagged on 5 Sept. 2017. In 2018, half of the bagged apples were un-bagged 10 days before estimated harvest, on 27Aug. Apple fruit maturation was assessed by monitoring sugar accumulation and change in percent skin blush. Visual observations concerning skin blush color development were conducted in 2017. A five-bagged and five-unbagged fruit sample were collected on 6 Sept. 2018 to determine the percent skin blush, fruit length and width, individual fruit weight, fruit firmness, and SSC.

Fruit harvest

On 5 Sept. 2017, a 10 large-size fruit sample was collected from each tree prior to the general harvest on 18 Sept. Fruit skin blush color development was assessed by visual rating and expressed as percentage of skin covered with red blush. Fruit length and width were measured using a Vernier caliper. Single fruit weight was measured using a digital scale. Fruit firmness was measured on the two sides of each individual fruit using a penetrometer with a 7.5 mm-diameter probe (Facchini, Alfonsine, Italy). Soluble solids concentration (SSC) was measured by temperature-compensated refractometer (Atago Nl, Tokyo, Japan) and expressed as Brix (°B).

General harvest was on 18 Sept. 2017. Total yield per tree was collected at harvest using a digital scale (Adventurer Pro AV4101, Ohaus Corp., Pine Brook, NJ). Total fruit number per tree was counted. Mean fruit weight for each tree was calculated as a ratio of total yield per tree divided by the total number of apples per tree. Yield efficiency was calculated as a ratio of total yield per tree divided by the TCSA. Fruit quality characteristics including percent of skin blush, fruit length and width, individual fruit weight, fruit firmness, and SSC were measured on a 10-apple sample from each individual tree.

Two apple harvests were conducted in 2018 due to higher crop load as compared to 2017 and variations in fruit maturity based on visual observations. The first harvest was on 6 Sept., and the second was on 18 Sept. Data was collected to compare fruit quality in both harvest dates and determine the rootstock effect on fruit maturity.

On 6 Sept. 2018, all of the bagged and un-bagged fruit were harvested and data collected on percent skin blush, fruit length and width, individual fruit weight, fruit firmness, and SSC. Mature fruit with larger size and better blush color development was also harvested on 6 Sept. Total yield per tree and total fruit number per tree were recorded at harvest. Mean fruit weight for the first harvest was calculated as a ratio of total yield per tree to total number of fruit per tree. Fruit quality characteristics including percent skin blush, fruit length and width, individual fruit weight, fruit firmness, and SSC were determined on a 10-apple sample from each individual tree. To measure fruit TA, a composite sample consisting of one apple per tree and 10 fruit per treatment was utilized. Prior to juicing, two opposing longitudinal slices were used from each apple, then the slices were peeled and crushed into juice using a hand press, and the juice was filtered through cheesecloth. A 4 g sample of apple juice from the 10-apple sample was diluted to 40 mL of solution using deionized water. Titration was to an endpoint of pH 8.2 using a 0.1 N NaOH titrant solution in a DL 15 Titrator (Mettler-Toledo LLC, Columbus, OH). Results were expressed as grams of malic acid equivalent per liter of juice.

The second harvest occurred on 18 Sept. Total yield per tree and total number of fruit per tree were recorded at harvest. Mean fruit weight for the second harvest was calculated. To compare differences in fruit starch content among treatments, a five-fruit composite sample was collected from five replications per treatment in 2018. Each apple was cut equatorially, the stem-end half of the fruit was dipped in iodine solution for one minute. The starch degradation pattern (SDP) for each fruit was determined by following the Cornell University starch-iodine index chart (Blanpied and Silsby, 1992). Index one indicated maximum starch content (maximal dark stain) and index 8 represented maximum starch hydrolysis (clear stain).

Vegetative growth characteristics

Trunk diameter was measured 30 cm above graft union in late fall of each season using a digital caliper and used to calculate TCSA. Tree survival rate for each rootstock and the total number of root suckers per tree were counted at the end of each season. Tree height and in-row and between-rows canopy diameters were measured in late fall, to calculate canopy volume.

To evaluate the leaf area and leaf chlorophyll content, samples were collected from mature leaves in the mid portion of the current year's extension shoot in late summer. Leaf area was measured by collecting 10 leaves per tree using a Licor LI-3100 (Licor Inc., Lincoln, NB, USA) area meter. Leaf chlorophyll content was measured on 10 recently matured leaves per tree using a SPAD-502 Plus (Konica Minolta Sensing, Inc., Osaka, Japan) chlorophyll meter. SPAD readings were measured on the midrib of each leaf at the widest part.

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The experimental design was a randomized complete block design. Each year was analyzed separately, and block was in the model as a random variable. Percent open flowers was analyzed as a 2-way design of rootstock and date with repeated measures on date and using a Toeplitz covariance structure. Differences in rootstocks least squares means at each date were determined using the simulated method. Linear and quadratic trends over dates were examined using qualitative/quantitative regression models. Targeted number of fruit per tree, number of fruit per tree retained after thinning, number of thinned fruit per tree, total yield per tree, total yield per tree at each harvest, total fruit number per tree, total number of fruit per tree in each harvest, mean fruit weight, mean fruit weight at the first harvest, mean fruit weight at the second harvest, leaf chlorophyll content, mean leaf area, trunk cross sectional area, and yield efficiency were in 1-way treatment designs of rootstock. Fruit SSC, visual blush percent, and firmness in 2017 and 2018 were in 1-way treatment designs of rootstock with sub-sampling. Visual blush of bagged or un-bagged fruit were in a 2-way treatment design of rootstock and bagged or un-bagged with sub-sampling. Fruit numbers were analyzed using the Poisson probability distribution. Where residual plots and a significant covariance test indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity. Differences among rootstocks were determined using the simulated method. All significances were at $\alpha = 0.05$.

Results

Bloom development

Percent open flowers of ‘Aztec Fuji’ grafted on ‘G.202’ and ‘M.9-T337’ followed increasing quadratic trends, whereas all the other trees followed increasing linear trends over date in 2018 (Table 2.1). Trees grafted on ‘V.6’ and ‘V.7’ were the earliest to initiate bloom and started flowering on 15 Mar. Percent open flowers did not differ among rootstocks on 15 Mar., 19 Mar., 22 Mar., or 30 Mar. On 22 Mar., trees on ‘B.10’, ‘G.11’, ‘G.969’, and ‘V.6’ had over 40% open flowers, whereas trees on ‘G.202’ and ‘M.9-T337’ had the lowest percent open flowers of 19.4% and 20%, respectively. Differences in rootstocks were found for percent open flowers on 26 Mar., when trees grafted on ‘B.10’ and ‘V.7’ had the highest percent of open flowers and G.202’ had the fewest open flowers. Although no treatment difference was found in percent open flowers on 30 Mar., trees on ‘B.10’, ‘G.11’, ‘G.214’, ‘G.41’, ‘G.969’, and ‘V.1’ had over 80% open flowers, whereas trees on ‘G.202’ and ‘M.26 EMLA’ had the least percent open flowers.

Fruit thinning

Rootstock cultivar was accountable for differences in number of fruit per tree retained after hand thinning (Table 2.2). Highest number of fruit per tree was recorded on ’V.6’. All Vineland series rootstocks along with ‘G.30’ and ‘G.969’ produced over 110 fruit per tree, whereas ’G.202’ had the least number of fruit per tree.

No difference was found in the number of fruit thinned per tree (Table 2.2), which was highest on ’G.969’, while lowest was on ’G.41’.

Yield characteristics

Our results demonstrate rootstock effects on total yield per tree and total fruit number per tree in both years (Table 2.3). In 2017, ‘G.969’ had the highest yield, while ‘M.26 EMLA’ had the lowest. Total yield of ‘V.5’, ‘V.6’, and ‘V.7’ was over 10 kg per tree in 2017. ‘V.5’ had the highest total yield in 2018, while trees on ‘G.41’ had the lowest total yield. All other rootstocks produced intermediate total yields with trees on ‘V.7’, ‘G.969’, ‘V.6’, and ‘G.30’ yielding over 25 kg per tree.

Total number of fruit per tree was the highest for ‘V.7’, while trees on ‘M.26 EMLA’ produced the fewest fruits in 2017 (Table 2.3). Trees grafted on ‘G.935’, ‘V.6’, ‘G.969’, ‘V.5’, ‘V.1’, ‘G.202’, and ‘G.30’ had over 60 fruit per tree. ’G.30’ trees produced the highest number of fruit per tree in 2018, while trees on ‘G.41’ had the fewest fruit per tree. Trees on ‘V.5’ and ‘G. 969’ had a total fruit number per tree similar to the highest fruit number produced by ’G.30’.

Mean fruit weight differ depending on rootstock selection (Table 2.3) and was highest for trees on ‘G.11’, and lowest for trees grafted on ‘G.30’ in 2017. ‘V.6’ grafted trees produced the largest fruit size, while the trees on ‘B.10’ produced the smallest fruit in 2018. Trees on ‘G.11’, ‘V.7’, and ‘V.5’ also had mean fruit weight of over 200 g in 2018.

TCSA and yield efficiency

The largest vegetative growth based on TCSA was recorded for ’V.6’ trees, while trees on ‘G.41’ had the lowest growth in 2017 (Table 2.4). This trend was similar in 2018, when ‘V.6’ had the largest TCSA, while ’G.41’ and ‘G.214’ had the smallest. Trees grafted on Vineland series of rootstocks (‘V.1’, ‘V.5’, ‘V.6’, ‘V.7’) grew more vigorously during the study period. Among the Geneva series of rootstocks tested, ‘G.30’ produced the largest tree trunk, while ‘G.41’ and ‘G.214’ had the smallest vigor as indicated by the TCSA responses.

Yield efficiency of ‘Aztec Fuji’ was the highest for trees grafted on ‘G.935’ and the lowest on ‘M.26 EMLA’ in 2017, when trees grafted on all other rootstocks had an intermediate yield efficiencies (Table 2.4). In 2018, ’G.214’ had the highest yield efficiency, while ‘V.6’ and ‘V.7’ had the lowest.

First and second harvests in 2018

Rootstocks did not affect total yield inthe first harvest of ‘Aztec Fuji’ trees (Table 2.5).

Total yield per tree was numerically higher for ’G.214’ trees. However, differences were found in total yield per tree for the second harvest, when ’G.30’ trees produced the highest yield, whereas trees on ‘G.202’ and ‘G.41’ produced the lowest. Differences were found for the total number of fruit per tree in both harvests during 2018. ’G.214’ had the highest number of fruit per tree harvested on 6 Sept., whereas the number of fruit per tree was lowest for ’G.11’ trees. Trees on ‘G.202’ and ‘G.969’ also produced over 40 fruit per tree in the first harvest. For the second harvest on 18 Sept., ’G.30’ had the highest number of fruit per tree, while trees on ‘G.202’ had the fewest number fruit. Differences in rootstocks were found for mean fruit weight of the first and second harvests in 2018 (Table 2.5). ’V.6’ had the largest fruit weight, and fruit weight of trees on ‘B.10’, ‘G.214’. ’V.7’ produced the largest fruit weight in the second harvest, while the smallest fruit weight was found on ‘B.10’.

Fruit quality

Differences in rootstocks were found for percent skin blush in 2017, with trees on ‘G.202’ having the highest percent blush, and trees on G.11 having the least skin blush (Table 2.6). No differences were found in skin blush percent in 2018, when blush development ranged from 17.2 to 22.0%.

Differences in rootstocks were found for fruit firmness in both years (Table 2.6). ‘G.202’ trees produced the firmest fruit, whereas trees on ‘V.7’ produced the softest fruit in 2017. In 2018, ’G.935’ had the firmest fruit, whereas ‘V.1’ produced the softest fruit.

Rootstocks were found to also affect fruit SSC (Table 2.6), where trees on ‘G.202’ and ‘G.214’ had the highest SSC and fruit of ‘V.7’ trees had the lowest SSC in 2017. ’G.935’ trees had the highest SSC in 2018, while ’M.26 EMLA’ had the lowest SSC.

Bagging fruit

Apples bagged on 31 May 2018 and un-bagged 10 days before harvest on 27 Aug. 2018 showed higher percent skin blush at harvest as compared to bagged fruits harvested on 6 Sept. regardless of rootstock selection (Table 2.7).

Foliar characteristics

Leaf chlorophyll content of ‘Aztec Fuji’ did not differ among rootstocks in 2017 (Table 2.8), whereas trees on ‘G.969’ produced leaves with higher chlorophyll content in comparison with trees on ‘G.214’ and ‘M.9-T337’ in 2018. Rootstock treatments did not affect leaf area in 2017. However, trees on ‘V.7’ had larger leaves than trees on ‘B.10’ in 2018.

Discussion

All rootstocks from the Vineland series except ‘V.1’ produced high total yield per tree. Conversely, ‘Golden Delicious’ grafted on Vineland rootstock yielded lower than expected in a study by Russo (2007). Based on our results for tree vigor expressed as TCSA, Vineland series ‘V.1’, ‘V.5’, ‘V.6’, and ‘V.7’ were the most vigorous trees in the present study, and may not be the best choice of size-controlling rootstocks for a high density apple orchard system.

‘G.969’ and ‘G.30’ were the best performing rootstocks from the Geneva series in total yield. ‘G.214’ was the rootstock with the highest yield efficiency for ‘Aztec Fuji’ trees among all of the rootstocks tested. It was reported that cumulative yield efficiency of ‘Fuji’ was greatest on ‘G.969’ followed by ‘CG.5087’, ‘G.935’, ‘G.214’, ‘G.222’, ‘G.11’, ‘M.9’, ‘G.890’, ‘M.27’, ‘M.26’, ‘G.210’, ‘MM.106’, ‘B.118’ and ‘M.7’ (Robinson et al., 2012b).

‘Aztec Fuji’ on ‘G.935’ had less yield and lower yield efficiency as compared to ‘G.214’, but it produced the sweetest fruit. Several studies have reported that ‘G.935’ performed well with various scion cultivars. ‘Brookfield Gala’ on ‘G.935’ had the highest cumulative yield and yield efficiency as compared to that on ‘G.202’, ‘G.202TC’ (TC=liners from tissue culture), and ‘G.41’ (Wallis et al., 2017). ‘Honeycrisp’ on ‘G.935N’ (N=liners from stool beds), ‘CG.4214’, ‘G.935TC’, ‘G.202TC’, and ‘Aztec Fuji’ on ‘G.935N’ performed the best in yield efficiency in the large dwarf category (Autio et al., 2017a;. Autio et al., 2017b).

In present study, ‘G.11’ was similar to ‘G.935’ in total yield and yield efficiency. However, in a study by Autio et al., (2017b) ‘Aztec Fuji’ on ‘G.11’ along with two other rootstocks was the most yield efficient in the moderate dwarf category.

Our results suggest that trees grafted on ‘G.202’ and ‘G.41’ were not impressive either in yield efficiency or fruit quality as compared to other rootstocks from the Geneva series. Specifically, ‘Aztec Fuji’ on ‘G.41’ had the lowest yield among all the rootstocks. In two recent studies, ‘G.202’ resulted in different relative tree sizes with ‘Honeycrisp’ and ‘Fuji’. ‘Honeycrisp’ trees on ‘G.202N’ were moderate semi-dwarfs, 61% larger than comparable trees on ‘M.26 EMLA’ (Autio et al., 2017a), whereas, ‘Fuji’ trees on ‘G.202N’ were large dwarfs that were 16% smaller than comparable trees on ‘M.26’ (Autio et al., 2017b).

‘Aztec Fuji’ trees on ‘B.10’, ‘M.26 EMLA’, and ‘M.9-T337’ produced moderate total yields and average fruit quality in the present study.

Skin blush color is an important quality attribute in determining consumer acceptance of apples (Telias et al., 2011). Poor fruit color of ‘Aztec Fuji’ in this study was probably due to high temperatures during the preharvest period. It was reported that a decrease in orchard temperature improved the color of apple fruit (Iglesias et al., 2005), indicating the effect of temperature on accumulation of anthocyanin, which influences red coloration in apple fruit skin as a result. Honda et al. (2014) reported that the anthocyanin concentration in ‘Misuzu Tsugaru’ apple fruit under the hotter climatic condition was lower than that under the control condition at harvest. The application of overhead irrigation (Iglesias et al., 2005) or the use of ethephon (Li et al., 2002) was studied to improve fruit skin color. We speculate that these practices might be solutions for better coloration of apple skin in Alabama.

Fruit bagging is a common practice used in the production of apples to protect fruit against damage from insect pests, birds, and diseases (Ju, 1998; Fallahi et al., 2001). In this study, un-bagging treatment 10 days prior to harvest showed higher percent skin blush at harvest as compared to fruit kept in bags until harvest. The result was in line with the findings of Feng et al. (2014) who found that when ‘Jonagold’ apple fruits were non-bagged, always bagged, or un-bagged, bagged fruit were always yellowish and had the lowest anthocyanin concentrations. In addition, early bag removal led to up-regulation of gene expression involved in anthocyanin biosynthesis, and subsequent anthocyanin accumulation (Feng et al., 2014). In another study, the transcript levels of anthocyanin biosynthetic and regulatory genes were very low or barely detectable in bagged apples of ‘Ralls’ and its blushed sport, but they were induced dramatically within the first 5 days after bag removal, reaching maximum levels within 10 days (Xu et al., 2012). Based on the evidence given above, we conclude that un-bagging ‘Aztec Fuji’ fruit 10 days prior to harvest could aid in skin color development.

We expected that the rootstock cultivar might have an effect on fruit maturity. Yield of'G.202' from the first harvest accounted for 49% of total yield in 2018, which was the highest yield among all rootstocks. In addition, 'G.202' produced sweetest fruit with higher percent skin blush in 2017. We suggest G.202 had advanced fruit maturity of 'Aztec Fuji' in comparison to other rootstocks. Second harvest yield of trees on 'G.30' accounted for 77% of their total yield in 2018, which was the highest proportion of second harvest yield. The high percent of second harvest yield was combined with a low mean fruit weight in the first harvest, and both results suggest a slight delay in fruit maturity for 'G.30' grafted trees.

Actual number of fruit per tree retained after thinning was slightly lower than the targeted number of 5 fruit per square centimeter TCSA . That was due to the botryosphaeria damage in winter and spring of 2015/2016 that required infected branches or leaders to be cut back to healthy tissue in order to manage the infection. In some cases, a new leader needed to be trained to maintain the training system, but the process lead to a temporary loss of productivity, which has reflected in a poorer return bloom as demonstrated by the total number of fruit clusters per tree.

After five years, rootstocks start separating based on size and tree performance (Autio et al., 2017b). The third and fourth season results represent an early assessment of the rootstocks tested in present study. Multiple years trail evaluation will be required to obtain a thorough understanding of rootstock effect on tree size and performance in Alabama.

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Table 2.1. Rootstock effect on percent open flowers of ‘Aztec Fuji’ apple trees grown at the Chilton Research and Extension Center, Clanton, Alabama, 2018.[z]

	Open flowers (%)					
	Date					
Rootstock	15 Mar.	19 Mar.	22 Mar.	26 Mar.	30 Mar.	Sign.[y]
B.10	0 ns[x]	30.0 ns	40.0 ns	65.0 a	84.4 ns	L***
G.11	0	29.5	42.0	54.0 ab	80.5	L***
G.202	0	15.0	19.4	38.9 b	68.3	Q*
G.214	0	19.4	27.8	52.8 ab	83.3	L***
G.30	0	19.0	28.0	51.0 ab	77.5	L***
G.41	0	29.4	38.9	62.8 ab	81.7	L***
G.935	0	23.9	30.6	53.9 ab	78.3	L***
G.969	0	35.5	42.0	59.5 ab	85.0	L***
M.26 EMLA	0	15.6	26.9	45.0 ab	69.4	L***
M.9-T337	0	11.1	20.0	40.6 ab	70.6	Q**
V.1	0	25.5	34.5	55.0 ab	83.5	L***
V.5	0	29.5	34.5	58.5 ab	76.0	L***
V.6	2.2	35.6	43.3	61.7 ab	78.9	L***
V.7	0.5	31.5	39.0	63.5 a	78.0	L***

[z]The rootstock treatment by date interaction was significant at $P < 0.05$.

[y]Significant (Sign.) linear (L) or quadratic (Q) trends using qualitative/quantitative regression models at $P < 0.05$ (*), 0.01 (**) or 0.001 (***).

[x]Least squares means comparisons among cultivars (lower case in columns) using the simulated method at $P < 0.05$. ns = not significant.

Table 2.2. Rootstock effect on fruit thinning characteristics of 'Aztec Fuji' apple trees grown at the Chilton Research and Extension Center, Clanton, Alabama, 2018.

Rootstock	Targeted number of fruit/tree (No.)	Number of fruit per tree retained after thinning (No.)	Number of thinned fruit per tree (No.)
B.10	87.0 cd[z]	85.0 b	145.1 ns
G.11	92.8 cd	80.1 b	169.2
G.202	86.2 cd	68.7 b	170.6
G.214	77.5 cd	73.9 b	240
G.30	149.8 abc	126.4 ab	236.9
G.41	77.1 d	71.6 b	152.7
G.935	100.4 cd	93.1 ab	230.9
G.969	120.1 abc	113.1 ab	270.6
M.26 EMLA	119.9 abcd	90.1 ab	169.8
M.9-T337	102.2 bcd	92.3 ab	197.7
V.1	144.7 abc	113.2 ab	175.5
V.5	162.1 abc	138.9 ab	190
V.6	187.9 a	141.9 a	219.8
V.7	163.2 ab	135.7 ab	216.8

[z]Least squares means comparisons among cultivars using the simulated method at $P < 0.05$. ns = not significant.

Table 2.3. Rootstock effect on total yield, number of fruit per tree, and fruit weight of 'Aztec Fuji' apple trees grown at the Chilton Research and Extension Center, Clanton, Alabama 2017–2018.

	Total yield (kg/tree)		Total number of fruit/ tree (No.)		Mean fruit weight[z] (g)	
Rootstock	2017	2018	2017	2018	2017	2018
B.10	5.8 ab[y]	17.6 ab	32.0 ef	103.0 fgh	189.7 ab	171.2 c
G.11	9.1 ab	21.0 ab	47.0 cd	106.6 fg	197.6 a	209.2 ab
G.202	9.0 ab	17.3 ab	60.4 b	99.0 gh	170.5 ab	186.3 abc
G.214	8.6 ab	20.4 ab	58.5 bc	120.6 def	168.9 ab	175.2 c
G.30	9.0 ab	25.7 ab	60.2 b	167.1 a	166.8 b	184.5 abc
G.41	7.2 ab	15.7 b	39.4 de	88.9 h	193.4 ab	183.8 bc
G.935	12.6 ab	19.2 ab	71.8 ab	109.0 efg	190.6 ab	199.8 abc
G.969	13.1 a	27.5 ab	67.3 ab	150.7 ab	180.0 ab	186.5 abc
M.26 EMLA	4.3 b	18.1 ab	26.4 f	95.4 gh	175.2 ab	194.3 abc
M.9-T337	4.9 ab	22.1 ab	30.6 ef	119.3 ef	170.4 ab	194.5 abc
V.1	9.8 ab	23.8 ab	63.5 ab	125.6 cde	182.3 ab	194.6 abc
V.5	10.4 ab	30.0 a	64.0 ab	154.3 ab	189.9 ab	204.0 abc
V.6	10.5 ab	26.6 ab	68.6 ab	138.6 bcd	177.7 ab	210.7 a
V.7	12.9 ab	28.2 ab	75.7 a	141.5 bc	194.7 ab	208.0 ab

[z]Mean fruit weight was calculated as a ratio of total yield per tree and total number of fruit per tree.
[y]Least squares means comparisons among rootstocks using the simulated method at $P < 0.05$.

Table 2.4. Rootstock effect on trunk cross sectional area and yield efficiency of ‘Aztec Fuji’ apple trees grown at the Chilton Research and Extension Center, Clanton, Alabama, 2017–2018.

	Trunk cross sectional area[z] (cm^2)		Yield efficiency[y] ($kg•cm^2$)	
Rootstock	2017	2018	2017	2018
B.10	17.4 de[x]	19.9 c	0.36 ab	0.93 ab
G.11	18.6 de	23.8 bc	0.50 ab	0.89 ab
G.202	17.3 de	21.6 bc	0.51 ab	0.62 ab
G.214	15.5 e	16.3 c	0.61 ab	1.18 a
G.30	30.0 abc	36.9 ab	0.35 ab	0.82 ab
G.41	15.4 e	18.1 c	0.50 ab	0.93 ab
G.935	20.1 cde	23.6 bc	0.64 a	0.96 ab
G.969	24.0 bcd	30.8 abc	0.58 ab	0.90 ab
M.26 EMLA	24.0 bcde	32.7 abc	0.20 b	0.67 ab
M.9-T337	20.4 bcde	29.4 abc	0.25 ab	0.74 ab
V.1	29.8 abc	40.0 ab	0.36 ab	0.65 ab
V.5	32.1 abc	40.9 ab	0.33 ab	0.65 ab
V.6	37.8 a	50.9 a	0.28 ab	0.54 b
V.7	32.7 ab	47.5 a	0.40 ab	0.60 b

[z]Trunk diameter was measured for each vine at 30 cm above the graft union using a digital caliper, and then the trunk cross sectional area was calculated as $\pi \times (d/2)^2$.
[y]Yield efficiency was calculated as a ratio of total yield and trunk cross sectional area.
[x]Least squares means comparisons among rootstocks using the simulated method at $P < 0.05$.

Table 2.5. Rootstock and harvest timing effect on total yield, number of fruit per tree, and weight of 'Aztec Fuji' apple trees grown at the Chilton Research and Extension Center, Clanton, Alabama, 2018.

	Total yield in each harvest (kg/tree)		Total number of fruit per tree in each harvest (No.)		Mean fruit weight in each harvest[z] (g)	
Rootstock	6 Sep	18 Sep	6 Sep	18 Sep	6 Sep	18 Sep
B.10	7.2 ns[y]	10.5 de	39.9 abc	63.1 gh	182.1 b	160.9 b
G.11	6.2	14.8 abcde	28.0 e	78.5 ef	226.8 ab	191.6 ab
G.202	8.6	9.0 e	43.9 ab	55.1 h	198.6 ab	173.0 ab
G.214	9.1	11.7 bcde	47.2 a	73.3 fg	187.8 b	162.6 ab
G.30	7.1	23.3 a	36.2 bcde	130.9 a	191.0 b	178.0 ab
G.41	6.8	9.4 e	35.2 bcde	53.7 h	194.7 ab	172.8 ab
G.935	6.3	13.4 bcde	29.2 de	79.8 ef	217.7 ab	181.1 ab
G.969	8.4	19.1 abcd	40.3 abc	110.4 bc	203.4 ab	169.7 ab
M.26 EMLA	6.8	11.5 cde	32.4 cde	63.0 gh	212.6 ab	176.2 ab
M.9-T337	7.5	15.0 abcde	35.5 bcde	83.8 ef	213.3 ab	176.2 ab
V.1	7.6	16.2 abcde	34.5 bcde	91.1 de	215.1 ab	174.1 ab
V.5	8	21.8 ab	36.3 bcde	118.0 ab	225.5 ab	182.2 ab
V.6	8.5	18.6 abcde	38.1 abcd	100.5 cd	229.7 a	191.9 ab
V.7	7.6	20.6 abc	33.6 cde	107.9 bc	222.4 ab	193.5 a

[z]Mean Fruit weight was calculated as a ratio of total yield in each harvest and total number of fruit per tree in each harvest

[y]Least squares means comparison among rootstocks using the simulated method at $P < 0.05$. ns = not significant.

Table 2.6. Rootstock effect on percent skin blush, fruit firmness, and SSC of ‘Aztec Fuji’ apple trees grown at the Chilton Research and Extension Center, Clanton, Alabama, 2017–2018.

	Skin Blush (%)		Fruit firmness (kg•cm^2)		SSC (°Brix)	
Rootstock	2017	2018	2017	2018	2017	2018
B.10	38.2 ab	20.7 ns	4.3 bcd	3.8 abc	14.5 ab[z]	15.3 ab
G.11	27.3 b	17.2	4.6 abcd	3.7 abcd	14.0 abcd	15.2 ab
G.202	46.3 a	21.9	5.0 a	3.6 bcd	14.9 a	15.2 ab
G.214	40.0 ab	18.1	4.8 abc	3.5 cd	14.7 a	15.0 abc
G.30	32.1 ab	18.8	4.5 abcd	3.7 abcd	13.7 bcde	15.0 abc
G.41	37.1 ab	22.0	4.4 abcd	3.9 ab	14.2 abc	15.5 ab
G.935	30.5 ab	18.9	4.8 ab	4.0 a	14.1 abcd	15.8 a
G.969	37.0 ab	18.8	4.6 abcd	3.5 cd	14.0 abcd	14.8 bc
M.26 EMLA	35.8 ab	18.1	4.7 abcd	3.5 cd	13.4 cde	14.2 c
M.9-T337	44.9 ab	19.9	4.5 abcd	3.5 cd	14.4 ab	14.8 bc
V.1	31.4 ab	21.3	4.3 bcd	3.4 d	13.3 de	14.9 bc
V.5	35.4 ab	21.9	4.3 cd	3.5 cd	13.3 de	15.1 abc
V.6	35.4 ab	21.7	4.3 bcd	3.5 cd	13.4 de	14.8 bc
V.7	30.7 ab	19.9	4.2 d	3.5 cd	13.2 e	14.7 bc
Pr > F	0.0177	0.6832	0.0002	0.0002	<.0001	<.0001

[z]Least squares means comparisons among rootstocks using the simulated method at $P < 0.05$. ns = not significant.

Table 2.7. Bagging effect on percent skin blush of ‘Aztec Fuji’ apple trees grown at the Chilton Research and Extension Center, Clanton, Alabama, 2018..[z]

Bagged	Blush, (%)
B	4.2 b[y]
UB	14.7 a

[z]Only the bagged or un-bagged fruit main effect was significant at $P < 0.05$.
[y]Least squares means comparisons between bagged or un-bagged fruit using the simulated method at $P < 0.05$.

Table 2.8. Rootstock effect on leaf chlorophyll and leaf area of 'Aztec Fuji' apple trees grown at the Chilton Research and Extension Center, Clanton, Alabama, 2017–2018.

	Mean leaf chlorophyll content[z]		Mean leaf area[y] (cm^2)	
Rootstock	2017	2018	2017	2018
B.10	50.2 ns[x]	49.8 ab	26.0 ns	29.7 b
G.11	49.5	48.7 ab	27.0	34.9 ab
G.202	48.8	47.6 ab	24.4	35.2 ab
G.214	48.8	46.2 b	22.6	30.8 ab
G.30	48.6	49.3 ab	27.8	35.3 ab
G.41	48.9	49.5 ab	25.6	32.8 ab
G.935	47.8	47.0 ab	26.9	35.9 ab
G.969	50.7	50.7 a	24.1	34.2 ab
M.26 EMLA	49.7	48.5 ab	25.0	37.7 ab
M.9-T337	51.1	46.7 b	27.5	34.6 ab
V.1	49.7	47.7 ab	27.9	34.3 ab
V.5	48.9	49.0 ab	26.8	35.9 ab
V.6	48.9	49.1 ab	25.3	35.8 ab
V.7	49.5	49.2 ab	27.4	38.4 a

[z]SPAD-502 meter value. Ten leaves per tree were sampled for mean leaf chlorophyll content.
[y]10 leaves per tree were sampled for mean leaf area.
[x]Least squares means comparisons among rootstocks using the simulated method at $P < 0.05$. ns = not significant.