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Effect of Rootstock on Vegetative Growth, Yield, and Fruit Composition of Norton Grapevines

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Master of Science

By

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Dr. Michele Warmund, Thesis Supervisor

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The undersigned, appointed by the dean of the Graduate School,

have examined the Thesis entitled

EFFECT OF ROOTSTOCK ON VEGETATIVE GROWTH, YIELD, AND FRUIT COMPOSITION OF NORTON GRAPEVINES

Presented by Jackie Leigh Harris

A candidate for the degree of

Master of Science

And hereby certify that, in their opinion, it is worthy of acceptance.

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David Trinklein

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ABSTRACT

Norton is an important commercial grape cultivar commonly grown in Missouri and the surrounding region because of its wine quality and disease resistance. However, own-rooted Norton vines typically produce fruit with high pH, malic acid, and potassium, which are known to reduce quality, aging potential, and stability of wine. Additionally, own-rooted Norton vines often produce excessive vegetative growth. Thus, effects of selected rootstocks on Norton fruit composition, yield, and vegetative growth were studied in Phelps County, MO within a commercial vineyard during 2010 and 2011. Rootstocks included 3309C, 101-14, Schwarzmann, 5BB, SO4, 1103P, 110R, 140Ru, 1616C, and 44-53M. Own-rooted Norton vines were also included as a control. Rootstocks did not affect vegetative growth or fruit characteristics (organic acids, glucose, or fructose). However, Norton petiole contents of Ca and P were deficient on some rootstocks in 2010 and 2011. Vines on 101-14, 110R, and 1616C rootstocks produced greater fruit yield than own-rooted vines. Nitrogen, P, K, Ca, Mg, S, and Mn contents in juice were also affected by rootstock, but all were within acceptable ranges. While fruit yields were enhanced by the rootstocks, it may be necessary to alter fertilization and pruning practices to sustain high cropping.

CHAPTER 1: INTRODUCTION

Grapevines are grown on every continent with more than 10 million ha planted worldwide (Howell 1987). Global production of grapes ranked fourth among fruit crops behind bananas, apples, and oranges with over 68 t harvested in 2010 (FAO 2011). Within the United States, grapes were ranked as the highest value fruit crop ($3.8 billion) and sixth among all US crops in 2011 (FAO 2011). Half of all grape production in the US is wine grapes while the remainder are used for raisins, table grapes, and juice grapes (30%, 11%, and 9%, respectively) (MKF 2007).

Grapes belong to the family *Vitaceae* which includes around 1,000 species within 17 genera (Keller 2010). Only two genera, *Vitis* and *Muscadinia*, are of economic importance. *Vitis* is the most important genus in terms of cultivation and production. There are 60 to 70 species within this genus, which can be separated into Eurasian and American species (Keller 2010, Mullins 1992). There are as many as 40 Eurasian species, but *Vitis vinifera* L., is the most economically important. However, the American species of *Vitis*, with 8 to 34 species, are also valued for fresh consumption, wine, or juice or for use as rootstocks. (Keller 2010). Cultivars of *V. vinifera* and *V. labrusca* (American species) are commonly grown in the eastern U.S. for wine production as well as hybridized species, such as Norton.

The American group is typically used as a rootstock for grafted grapevines. For grafted grapevines, the top portion of the plant is referred to as the scion and is the desired cultivar. This is typically a *V. vinifera* or French-American hybrid. The

rootstock portion of the grapevine absorbs water and nutrients and provides anchorage and resistance to various soil conditions and pests.

Although its true parentage is unknown, Norton is believed to be derived from *V. aestivalis*, *V. labrusca* L., and *V. vinifera* cv. Chasselas (Parker et al. 2009). This cultivar, has gained considerable attention in the Midwest and Eastern United States for its potential as a high quality wine grape. Currently, Norton is the most widely planted cultivar in Missouri comprising 19.3% of the total bearing acreage (USDA-NASS 2012). 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. 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, use of a rootstock grafted onto Norton may ameliorate less favorable attributes of the scion. Various studies with other cultivars have shown that rootstocks influence vegetative and reproductive growth, as well as juice chemistry (Reynolds and Wardle 2001, Ruhl et al. 1988, Vanden Heuvel et al. 2004). Because own-rooted Norton grapevines typically grow well, grafted plants on rootstocks have not been tested. Therefore, this study was conducted to evaluate the effect of various rootstocks on vegetative growth of Norton grapevines, as well as on fruit yield and juice composition.

CHAPTER 2: LITERATURE REVIEW

2.1: Development and use of rootstocks in viticulture

Grapevines have been cultivated for thousands of years (Thomas and Heeswijck 2004). *Vitis vinifera* L., the most widely planted species presumably has been cultivated as early as the Bronze Age (Zohary 1996). This grape species thrived until the mid 1800's when the grape phylloxera *(Daktulosphaira vitifoliae* Fitch), a root feeding insect, threatened to destroy the European wine industry. This pest was likely introduced into Europe on the roots of grapevines shipped from the eastern United States (Campbell 2004).

Various control methods for *D. vitifoliae* were tested in Europe, including carbon bisulfide applications, flooding, planting on sandy soils, and growing American or French-American grape hybrids. However, none of these methods proved adequate or provided sufficient insect control (Campbell 2004, Gale 2011, Ordish 1972). In the late 1800's, a solution was identified in which the European cultivars were grafted onto resistant native American rootstocks (Campbell 2004, Gale 2011, Ordish 1972). Research during this period revealed that three *Vitis* species (*V. riparia* Michx., *V. rupestris* Scheele, and *V. berlandieri* Planch.) were phylloxera resistant and were adapted to varying soil conditions. These *Vitis* species remain the most widely used rootstocks selections to date.

In the United States, *D. vitifoliae* was found on grapevines in California as early as 1858 (Gale 2011, Ordish 1972). Eventually this led to massive replanting of

V. vinifera cultivars onto resistant rootstocks in California (and worldwide) as the pest continued to spread. Currently, rootstocks may also be used for *V. vinifera* cultivars to reduce vegetative growth, increase yield, and to a lesser extent, alter fruit composition (Reynolds and Wardle 2001, Ruhl et al. 1988, Vanden Heuvel et al. 2004). However, the adoption of rootstocks has been slow in the eastern United States where French-American hybrid cultivars are grown. For most of these cultivars, own-rooted vines are sufficiently resistant or tolerant to phylloxera with the exception of newer hybrids derived from ≥ 50% *V. vinifera* (Wolf 1998).

Today, the primary reason for planting grafted grapevines with a rootstock is for *D. vitifoliae* resistance. However, rootstocks can also provide resistance to other pests and diseases such as nematodes, crown gall and *Phytophthora*, as well as tolerance to some environmental stresses (Cousins 2010, Walter and Wicks 2003). Additionally, grape rootstocks can also influence vegetative growth, fruit maturity, yield, and berry composition when grown under various climatic and edaphic conditions (Walker and Clingeleffer 2009).

Similar to all plants, grapevine species developed characteristics to survive in their natural habitats. Since soil conditions, pest pressure, and environmental conditions are variable, rootstocks have been developed from native grapevine species that are adapted to diverse situations (Cousins 2005).

2.2: Biotic factors influencing grapevine growth

2.2.1: Phylloxera

Grape phylloxera (*D. vitifoliae*) is an aphid-like insect with two forms, one that attacks the roots and one that feeds on leaves (Granett et al. 2001, Johnson et al. 2010). In warm and humid climates grape phylloxera can overwinter as the immature form or as eggs (Johnson et al. 2010). During spring and summer, the root feeding form asexually produces multiple generations that cause nodosities on root tips (Johnson et al. 2010). Then in late summer, the winged form emerges from the soil and matures. After mating, each winged female produces one egg in the fall that overwinters on the trunk. In early spring, crawlers emerge from the eggs, move towards shoot tips and feed on the young leaves, which produce galls enclosing the crawler (Johnson et al. 2010). These crawlers mature into stem mothers which can produce up to 300 eggs. After hatching, crawlers move to expanding leaves, and induce more galls with each generation (Johnson et al. 2010). Some crawlers drop from the leaves or crawl back down to the soil to feed on the roots (Johnson et al. 2010). This is the most serious type of injury because it leads to vine decline and eventual vine death due to secondary pathogens (Johnson et al. 2010). Symptoms of phylloxera root feeding include foliar chlorosis and reduced yield which spreads to other vines in a circular pattern over a few years (Buchanan et al. 2003). Foliar phylloxera symptoms include gall formation, leaf distortion, and early leaf drop which result in reduced photosynthesis, stunted shoot growth, and delayed fruit ripening (Anonymous 2004, Johnson et al. 2010).

The leaf form of phylloxera damage is more common on *Vitis* hybrids and American *Vitis* species (Buchanan et al. 2003, Granett et al. 2001). Scouting and application of insecticides are used to control foliar phylloxera damage. In contrast, rootstocks derived from *V. riparia, V. rupestris, and V. berlandieri* are used to protect against phylloxera root feeding.

2.2.2: Nematodes

Nematodes are microscopic unsegmented roundworms found in soil. Plant parasitic nematodes feed on roots, resulting in restricted growth and secondary disease infection (Walker and Grandison 2003). Root-knot (*Meloidogyne* spp.), dagger (*Xiphinema index* and *X. americanum*), root-lesion (*Pratylenchus* spp.), ring (*Cricionemella* spp.), and citrus (*Tylenchus semipenetrans*) nematodes can cause injury to grapevines.

Root-knot nematodes live and feed inside the roots and induce enlarged root cells and/or galls, which disrupt water and nutrient uptake and restrict vine growth (Walker and Grandison 2003). Root-knot nematodes are most prevalent in coarse, sandy soils and are rarely a problem in fine-textured soils (Hardie and Cirami 1988). Dagger nematodes live outside the roots and feed on root tips, which eventually stunts the root system (Pongrácz 1983). Most importantly, dagger nematode, (*X. index*) is a vector of grapevine fanleaf virus (GFV), which can be devastating in a vineyard (Hardie and Cirami 1988, Walker and Grandison 2003). *X. americanum*, is associated with transmission of tomato ringspot, tobacco ringspot, and peach rosette mosaic virus, etc. Root-lesion nematodes are less common in vineyards, but

when present in high populations they can cause root galls on young vines. (Walker and Grandison 2003). In California and Australia, nematodes are problematic and have been controlled by chemical fumigation and leaving soil fallow for several years. However, there is growing interest in the use of nematode-resistant rootstocks (Howell 1987). In 2008, five nematode-resistant rootstocks, UCD-GRN 1-5, were released from the University of California-Davis breeding program (Covert 2008). Additionally, three root-knot resistant rootstocks (Matador, Minotaur, and Kingfisher) were released in 2010 from USDA-ARS with Cornell University (Hansen 2012).

2.2.3: Bacteria

Crown gall is caused by a bacterium (*Agrobacterium vitis*) that often resides in grape tissue above the soil surface and is expressed in the vine after wounding or low temperature exposure (Margarey and Emmett 2003). This bacterium also resides in plant debris within the soil (Anonymous 2004). *Agrobacterium*-induced galls often form near the graft union of vines (Burr and Otten 1999). Galls reduce vine vigor and can cause vine mortality due to trunk girdling (Walter and Wicks 2003). Although chemical or biological controls for *Agrobacterium* are available, the use of crown gall resistant rootstocks is another option. Burr and Otten (1999) reported that *V. riparia*, *V. rupestris*, and *V. amurensis* are more resistant than *V. vinifera* and recommended the use of resistant scion to maximize protection against crown gall.

2.2.4: Fungi

Phytophthora crown and root rot is caused by *Phytophthora* species that thrive in wet soil conditions. Symptoms of infection include stunted vine growth, sparse foliage, and premature leaf senescence (Walter and Wicks 2003). This disease is most serious on young own-rooted vines (Walter and Wicks 2003) and can be a significant problem in nursery situations (Marais 1986). Grapevine damage is often localized in low spots in the field or near leaking irrigation equipment.

2.3: Abiotic factors affecting grapevine growth

2.3.1: Temperature

Grapevines are typically grown in temperate climates between 34° and 49° latitudes, although there are production regions beyond this zone. In general, *V. vinifera* performs well in warm to hot climates with low humidity, cool winters, and high diurnal temperatures (Winkler et al. 1974). *Vitis* hybrids and American species thrive in regions with humid summers and cold winters (Winkler et al. 1974). Five distinct regions of grape growing have been identified based on their cumulative degree days (DD) from April 1 through October 31, including climatic region I (1700 to 2490 DD), region II (2520 to 2990 DD), region III (3100 to 3480 DD), region IV (3500 to 3990 DD), and region V (4010 to 5900 DD) (Winkler et al. 1974).

Low temperature episodes can cause floral damage, vine dieback, trunk injury, or vine mortality. Cold acclimation of vines begins in response to short day lengths and cool temperatures and corresponds to movement of carbohydrates and

nutrients into the permanent structures of the vine, along with leaf drop, and lignification of green tissues (Keller 2010). Sub-freezing temperatures further acclimate grapevines. During dormancy, grapevines survive low temperature by supercooling. However, after the cold requirement is satisfied, tissues begin to deacclimate. Maximum mid-winter primary bud LT_{50}'s (temperature at which 50% of the buds are dead) are ≤ -40°C for *V. riparia,* -26 to -29°C for *V. labrusca*, -23 to -26°C for interspecific hybrids*,* -15 to -23°C for *V. vinifera*, and -15 to -20°C for *V. rotundifolia* (Munson 1909, Winkler et al. 1974, Zabadal et al. 2007). Among native species, *V. riparia* was ranked the most cold tolerant rootstock, followed by *V. rupestris*, *V. berlandieri*, and *V. champinii* in descending degree of hardiness (Howell 1987, Munson 1909). Among other rootstocks, 3309C is one of the hardiest, 5BB is moderately hardy, and SO4 and Riparia Gloire are less hardy (Munson 1909).

Optimal temperatures for vegetative growth, yield, fruit ripening, and photosynthesis of grapevines are below 30°C (Keller 2010). Heat stress begins at temperatures ≥ 35°C. At about 40°C, stomata close and photosynthesis is limited. Vegetative growth and ripening of fruit is also delayed when vines are heat-stressed (Keller 2010). However, grape cultivars have been selected from growing regions that have adapted to high temperatures.

2.3.2: Soil characteristics

Ideal soil pH for grapevines range from 5.6 to 6.9 and values outside this range can lead to mineral imbalances (Bates and Wolf 2008). Soil pH below 5.5 can lead to Al, Cu, or Mn toxicity and reduced availability of N, P, K, S, Ca, and Mg (Bates

and Wolf 2008, Dry 2007). Conversely, soils > 7.5 pH are considered calcareous and tend to be deficient in Fe and B. Both *V. riparia* and *V. rupestris*, which are native to areas with acidic soils, are sensitive to calcareous soils and leaves can exhibit iron chlorosis (Pongrácz 1983). In the early 1880's, *V. berlandieri* from western Texas was collected and crossed with these pH sensitive species to produce rootstocks tolerant to calcareous soils, such as 41B (*V. vinifera* cv. Chasselas x *V. berlandieri*) and 333 E.M. (*V. vinifera* cv. Cabernet Sauvignon x *V. berlandieri*) (Howell 1987, Pongrácz 1983).

Because American species of grapes are found growing in diverse soil conditions, some are more tolerant of high soil moisture, acidity, and salinity than others. *V. riparia*, which is native to river beds, performs well in wet soils, while *V. rupestris* is better adapted to arid conditions (Pongrácz 1983). Hybrids of these two species, along with some crosses of *V. riparia* x *V. berlandieri* are adapted to a broad range of soil types (Pongrácz 1983). At arid sites, soil salinity values > 1.8 dS/m within the root zone reduce root growth, especially for own-rooted grapevines (Dry 2007). Furthermore, on arid sites, increased soil pH can become problematic for grape production when irrigating with saline water (Dry 2007). Thus, use of sodium-tolerant rootstocks, application of low salt index fertilizers, and water filtration is recommended when growing vines in high salinity conditions (May 1994).

Soil texture impacts root depth and density. Thompson Seedless (*V. vinifera*) on own roots and grafted to Ramsey rootstock had the greatest root lengths (220

cm) in coarse soils followed by moderately coarse soils (100 to 120 cm) and fine soils (60 to 120 cm) (Nagarajah 1987). Furthermore, root distribution was most widespread in coarse soils while finer and intermediate soils had greatest distribution in the top 40 to 60 cm of soil. Conversely, the greatest root density occurred in fine soils and was lowest in coarse soils. In this same study, grafted Ramsey rootstock had higher root density when compared to own-rooted vines in coarse and moderately coarse soils at depths of 40 to 60 cm. In deeper soil profiles, Ramsey rootstock had higher root density in all soil types studied as well as greater root length and number of fine roots than own-rooted vines.

Management practices influence rooting behavior primarily through compaction, soil manipulations, and competition. McKenry (1984) reported that young roots follow the path of least resistance by inhabiting areas of previous root growth, soil fractures, or in areas high in organic matter. It was also shown that the first 60 cm of soil within the drive row had relatively few roots where the soil was compacted. Soil management practices such as tillage and permanent swards between rows of vines reduce roots within the top 20 to 30 cm of soil while no-till or minimal tillage practices increase root density in top 20 cm (Smart et al. 2006).

2.3.3: Water relations

Water is critical for plant growth and impacts vegetative growth, yield, and fruit composition (Iland et al. 2011). Water uptake is driven by transpiration through the leaf stomata and to a lesser extent, berries, while internal water movement is largely driven by pressure potential gradients (Iland et al. 2011, Keller

2010, Smart and Coombe 1983). Typically, the water status within grapevines has a diurnal cycle, in which the stomata close overnight. Thus, leaf water potential increases during the evening, reaching its maximum at pre-dawn, and is lowest at midday (Iland et al. 2011). Also, during most of the growing season, vines have a negative water potential, except for near budburst when there is positive root pressure (Smart and Coombe 1983).

Iland et al. (2011) reported that fruit set is the most sensitive growth stage for water with insufficient amounts affecting percent fruit set and berry size. Throughout the growing season, vines generally require between 406 and 914 mm of water, depending on climate, cultivar, and soil conditions (Winkler et al. 1974). Excessive water during the growing season results in too much vegetative growth and insufficient water reduces berry size and yield (Iland et al. 2011).

Grapevines species which tend to be more tolerant to drought have greater water use efficiency and require less amounts of water. Keller (2010) proposed that drought tolerance is based on species susceptibility to cavitation and rapid stomatal response to soil water potential. Grapevines, even within species, may be classified by the means in which they respond to drought. Vines with an isohydric behavior maintain a strict water balance by maintaining higher midday leaf water potential through reduction in stomatal conductance (Sade et al. 2012). This behavior is characteristic of species that developed in wet climates and are more prone to xylem cavitation (Keller 2010). Vines with anisohydric behavior exhibit more variable leaf water potential and maintain open stomata longer. This results in

greater photosynthetic activity even in times of drought and vines are less susceptible to xylem cavitation (Sade et al. 2012). It has been suggested that anisohydric plants may have a higher root:shoot ratio which aids in drought-avoidance (Keller 2010). Generally, most *V. vinifera* cultivars are considered drought resistant (Pongrácz 1983). American species such as *V. riparia* and *V. rupestris*, are not well adapted to drought conditions, but, *V. berlandieri* and *V. cordifolia* are considered tolerant (Pongrácz 1983). A more recent study has questioned and supported some of the earlier drought tolerance claims (Padgett-Johnson et al. 2003). Using young field grown vines under irrigation and nonirrigated conditions, Padgett-Johnson et al. (2003) demonstrated that *V. californica*, *V. champinii*, *V. doaniana, V. longii*, *V. girdiana*, and *V. arizonica* grapevines were most drought tolerant based upon their high net CO_2 assimilation rate, stomatal conductance, and pruning weights as well as more optimal water status. Grapevines, *V. candicans*, *V. cordifolia*, *V. monticola*, *V. rupestris*, *V. treleasei*, and *V. vinifera* were moderately drought tolerant while *V. berlandieri*, *V. cinerea*, *V. lincecumii*, *V. riparia*, and *V. solonis* grapevines were considered least drought tolerant of all species tested.

Grapevines tolerate water-logged soils of short duration but when soils are saturated for longer periods of time, they suffer from hypoxia (Keller 2010). This becomes more damaging during the growing season when vines are actively growing, resulting in root death and insufficient water uptake (Winkler et al. 1974). In a potted vine study, waterlogging caused reduction shoot and leaf dry weight as early as one day after soils were saturated and continued to decline over the seven

week period from 37 g/vine at week 0 to 19 g/vine at week 7 (Stevens and Prior 1994). Additionally, photosynthesis and stomatal conductance were decreased both during and following waterlogging. Under extreme soil moisture conditions, the root zone can suffer from near anoxia, which decreases water uptake and reduces transpiration, stomatal conductance, and photosynthesis (Stevens and Prior 1994). Rootstocks vary considerably in their tolerance to waterlogged soils. *V. riparia* rootstocks can tolerate this situation for several days whereas *V. rupestris* rootstocks are more susceptible to waterlogged soils (Keller 2010, Mancuso and Marras 2006).

Rootstocks which impart high vigor are believed to affect water uptake due to their deeper rooting habits (Stevens et al. 2008). However, growing in restricted soil conditions vines with *V. riparia* rootstock did not enhance water uptake (Padgett-Johnson et al. 2000). In another study by Kodur et al. (2010a), water use increased over time during a 56-day period for potted vines of all ungrafted rootstocks studied, although amount (mL/day) varied by rootstock. Specifically, water use was higher for ungrafted 1103P and Freedom rootstocks than for Schwarzmann, 110R, 140Ru, and 101-14 (Kodur et al. 2010a). However, when grafted, water use for 110R and 140Ru was higher than for 101-14 and Ramsey rootstocks (Kodur et al. 2010b).

2.4: Rootstock characteristics

Rootstock characteristics can be broadly described in terms of species and crosses between them, however each rootstock has horticultural differences and characteristics (Cousins 2005). Specific rootstock selection characteristics are summarized in Table 1.

Table 1. Characteristics of grapevine rootstocks reported in previous studies [y]

Rootstock	Parentage	Phylloxera resistance	Nematode resistance	Crown gall resistance	*Phytophthora* resistance	Drought tolerance	Flooding tolerance	Lime tolerance	Salinity tolerance	Acid soil tolerance	Clay soil tolerance	Sandy soil tolerance	Susceptibility to Mg deficiency	Susceptibility to K deficiency	Scion fruit maturation	Grafted scion vigor	Ease of bench grafting	Ease of rooting
Vitis aestivalis [z]	*Vitis aestivalis*	○				◍	◈	●	◈	◍	◍	◍		N	D	○		●
3309C	*V. riparia x V. rupestris*	◍	●	◍	●	●	●	●	●		◈	◈	N		A	◈	◈	○
101-14	*V. riparia x V. rupestris*	◍	◈	◍	◈	●	●	●	○	○	◈	●			A	○	◈	○
Schwarzmann	*V. riparia x V. rupestris*	◍	○			◈		◈	○						A	○	◍	○
5BB	*V. riparia x V. berlandieri*	◍	◈			●	◈	○	◈		◈	●	Y	Y	D	◈	◈	◈
SO4	*V. riparia x V. berlandieri*	◍	◈	◈	●	●	○	◈	●	○	◈	●	Y	N		○	◈	◈
1103P	*V. rupestris x V. berlandieri*	◍	◈	◈	◈	◍	●	◈	◍	◈	○	○	N	Y	D	○	○	○
110R	*V. rupestris x V. berlandieri*	◍	◈	●	●	◉	●	◈	◈	○	○	○	Y	Y	D	○	◍	●
140Ru	*V. rupestris x V. berlandieri*	◍	●	●	◈	◉	●	○	◍	◍	○	◍	N	Y	D	◍	○	◈
1616C	*V. riparia x V. acerifolia*	○	●		●	○	◈	●	○		●	◈			A	◈	●	○
44-53M	*V. riparia x (V. cordifolia x V. rupestris)*	◍	○			◈	●	●		○	○	●	Y	N	A	○	◉	◍

[y] Adapted from Keller (2010), Peccoux (2011), Christensen (2003), and Dry (2007).
[z] Ratings derived from Hendrick (1908) Main et al. (2002), Pongrácz (1983), USDA (2012a), and Wagner (1945).
◉(Excellent); ◍(High); ○(Medium); ◈(Poor); ●(Low); A: advanced; D: delayed; N: no; Y: yes

2.4.1: *V. aestivalis* Michx.

V. aestivalis (summer grape) is a native to the eastern United States and Canada, including southern Canada through eastern Texas (Moore 1991, Wagner 1945). Vines of this species have large leaves and are extremely vigorous with a climbing growth habit (Hendrick 1908, Moore 1991). In the wild, *V. aestivalis* tends to grow in upland forests away from streams and waterways (Hendrick 1908, Moore 1991). Vines have resistance to several fungal diseases and phylloxera (Wagner 1945). They are also tolerant of dry conditions but less so of wet conditions, calcareous or saline soils, and high soil pH (Hendrick 1908, USDA 2012a, Wagner 1945). *V. aestivalis* is generally difficult to propagate and has low vigor when young (Hendrick 1908, USDA 2012a). The vines are winter hardy and require a long, warm growing season (125 days from bloom to harvest with 165 to 185 frost-free days) to fully ripen fruit (Hendrick 1908, Morris and Main 2010, Wagner 1945).

2.4.2: *V. riparia* Michx.

V. riparia (riverbank grape) is native to parts of Canada to the Gulf of Mexico and east of the Rocky Mountains (Galet 1979). Vines have a relatively shallow root system which makes them intolerant of drought conditions and sandy soils (Galet 1979, Pongrácz 1983). *V. riparia* vines have good resistance to phylloxera and are highly adapted to cold temperatures (Cousins 2005, Howell 1987, Pongrácz 1983). This species is easily propagated and produces fruit that ripens earlier than *V.*

rupestris (Howell 1987, Pongrácz 1983). Riparia Gloire is one of the most well known rootstocks of this species.

2.4.3: *V. rupestris* Scheele.

V. rupestris (rock grape) is primarily found in hot climates and stony soils of south central United States, but also performs well in colder areas (Galet 1979, Pongrácz 1983). Vines perform poorly in shallow, droughty, and calcareous soils (Cousins 2005, Galet 1979, Howell 1987, Pongrácz 1983). *V. rupestris* is resistant to phylloxera, is easily propagated by cuttings (Galet 1979, Pongrácz 1983), and has early budburst and fruit ripening, although not as early as *V. riparia* (Howell 1987). The most common rootstock selection of this species is Rupestris St. George.

2.4.4: *V. berlandieri* Planch.

V. berlandieri (mountain grape) is native to Texas and northeast Mexico (Galet 1979, Pongrácz 1983). Vines have a vigorous climbing growth habit and their relatively deep root systems are drought tolerant (Howell 1987). Fruit is late-maturing, about a month later than *V. riparia* (Galet 1979). Vines are also resistant to phylloxera and calcareous soils, but they are difficult to propagate from cuttings (Galet 1979, Pongrácz 1983). For this last reason, *V. berlandieri* has been crossed with another easier rooting species for rootstock selections.

2.4.5: *V. riparia* x *V. rupestris*

V. riparia x *V. rupestris* rootstocks have a dense but fairly shallow root system which is suitable for loam to clay loam soils (Dry 2007, Pongrácz 1983). Cuttings

root easily, have short growing seasons, and do well in cool soils (Pongrácz 1983). Their main limitation is intolerance to calcareous soils and drought conditions (Cousins 2005, Pongrácz 1983). Commonly-available rootstock selections of this cross are 3309C, 101-14, and Schwarzmann.

2.4.6: *V. riparia* x *V. berlandieri*

V. riparia x *V. berlandieri* rootstocks tend to have a shallow root system but it can become extensive when grown in deep soils under irrigation (Pongrácz 1983). This cross requires less water than *V. riparia* x *V. rupestris*, although it is not suited for drought conditions (Dry 2007, Pongrácz 1983). Rootstock of this cross perform well in clay soils and tolerate calcareous soils, but are relatively intolerant of high salinity conditions (Pongrácz 1983). Additionally, *V. riparia* x *V. berlandieri* rootstocks, such as 5BB and SO4, have phylloxera resistance and generally impart low to moderate vine vigor when grafted (Cousins 2005, Pongrácz 1983).

2.4.7: *V. rupestris* x *V. berlandieri*

V. rupestris x *V. berlandieri* rootstocks have a deep and dense root system and perform well on all soil types (Dry 2007, Pongrácz 1983). Vines of this cross are adapted to deep and well drained soils, are tolerant to drought and calcareous soils, and phylloxera (Cousins 2005, Pongrácz 1983). Vines on this hybrid rootstock require less water than own-rooted vines and all of the hybrid rootstocks described above (Dry 2007). Some of the most common rootstocks from this cross are 110R, 1103P, and 140Ru.

2.4.8: *V. riparia* x *V. acerifolia*

V. acerifolia Raf. (mapleleaf grape) has a bushy growth habit found in drier climates of southern plains states of Texas, New Mexico, Colorado, Kansas, and Oklahoma (Moore 1990). It is relatively cold hardy, drought tolerant, and phylloxera resistant. When crossed with *V. riparia*, this rootstock (1616C) produces intermediate-sized vines with early ripening fruit (Galet 1979, Pongrácz 1983). Unlike most rootstocks, 1616C tolerates wet and saline soil conditions, but is sensitive to drought.

2.4.9: *V. riparia* x (*V. cordifolia* x *V. rupestris*)

V. cordifolia Michaux vines are extremely vigorous and often grow to tops of trees in central and southeastern United States (Galet 1979). Budburst of *V. cordifolia* is slightly later than *V. riparia* and is often confused with this species (Galet 1979). It is highly resistant to phylloxera and performs well in slightly calcareous soils, but it roots poorly when propagated (Pongrácz 1983). The interspecific cross, *V. riparia* x (*V. cordifolia* x *V. rupestris*), has been used as a rootstock (44-53M) to induce drought tolerance and enhance vine performance in high Mg soils (Pongrácz 1983).

2.5: Rootstock – Scion interactions

Movement of carbon and nutrients, and source-sink relationships within the grapevine vary somewhat seasonally; however, they are associated with growth stage of the vine. From budburst to early bloom, roots and permanent woody

structures of the vine provide carbon and sugar from stored reserves to new shoots (Zapata et al. 2004) Thereafter, when root growth is initiated, starch accumulation also occurs in the permanent structures of the vine (Comas et al. 2005, Richards 1983, Zapata et al. 2004). Shoot growth rapidly increases until mid-summer and remains stable for the remainder of the growing season (Richards 1983). Maximum root growth occurs in mid-summer during flowering, fruit set, and fruit development and then declines during the remainder of the growing season (Comas et al. 2005, Richards 1983). This root decline can be attributed to the desiccation of early season root development six weeks following early spring growth and the higher demand for carbon during fruit development and ripening (Comas et al. 2005, McKenry 1984). Root growth is again stimulated in fall after harvest (McKenry 1984).

2.5.1: Root system architecture

The majority of grapevine roots are present within the top 1 m of soil, although they may extend to depths of 6 m (Richards 1983, Smart et al. 2006, Swanepoel and Southey 1989). The most productive of these roots are the lateral ones which occur 100-600 mm below the soil surface (Richards 1983). Lateral growth of grapevines generally extends greater than 1.5 m from the trunk (McKenry 1984, Smart et al. 2006). Highest root densities occur 30 cm from vine trunk (Nagarajah 1987). Distribution of the root system is influenced by species, rootstock/scion combinations, soil characteristics, and management practices (Southey and Archer 1988, Swanepoel and Southey 1989). Swanepoel and Southey

(1989) found differences in root distribution and density by rootstocks grafted onto cv. Chenin blanc (*V. vinifera*) when planted in deep, well irrigated soils. The rootstock, 1103P, had the highest root density, followed by 101-14, 110R, and 140Ru. Root densities corresponded to greater shoot masses and yield. However, in arid conditions, 1103P had a low root density and 140Ru had high root density (Southey and Archer 1988).

2.5.2: Nutrient uptake

Uptake of nutrients by roots is dependent upon their proximity to nutrients, movement of water, and nutrient mobility within the soil. Nutrients are taken up by the roots either by mass flow, root interception, or diffusion. Movement by mass flow is through water movement and nutrients from bulk soil and uptake is driven by leaf transpiration (Wang et al. 2006). Diffusion is driven by a concentration gradient near the roots, and root interception is direct contact of nutrients by actively growing shoot tips (Schreiner 2009). Uptake of N, Ca, Mg, S, Cu, B, and Mn is usually by mass flow while uptake of P, K, Zn, and Fe is by diffusion. Small amounts of Ca, Mg, Zn, and Mn are taken up by root interception. Fine roots are primarily responsible for nutrient uptake and their ability to do so is dependent on environmental factors such as soil temperature, pH, and oxygen (Schreiner 2009).

In addition to soil and environmental factors, rootstocks influence the mineral nutrient status of vines. Grapevines require all of the essential mineral elements, but the nutrients of highest demand are N, K, P, Ca, Mg, and S (Bates and Wolf 2008). Research conducted on nutrient status has shown significant

differences among rootstocks and cultivars, although the extent to which rootstocks or cultivars are influenced by specific nutrients is highly variable (Lambert et al. 2008, Wolpert et al. 2005).

Grapevines have a high N demand because it is essential for vegetative growth and development, specifically the building of amino acids, nucleic acids, proteins, and pigments (Bates and Wolf 2008). Nitrogen also is critical for fruit yield, ripening, and adequate berry and wine quality (Perez-Alvarez et al. 2013, Schreiner 2005, Shaulis and Kimball 1955). The N required for grapevines ranges from 30 to 80 kg/ha (Conradie 1980, Hanson and Howell 1995). About 8 to 30 kg N/ha is typically lost due to crop removal (Schreiner et al. 2006).

Nitrogen, along with carbon is stored within the roots and permanent above-ground woody structures of dormant vines. Early in the growing season little N is taken up into the vines (Zapata et al. 2004). From first leaf to early bloom N was remobilized from roots and woody structures to vegetative and reproductive tissues with minor uptake from the soil solution, resulting in depleted root N. Other researchers (Williams and Biscay 1991), found a similar trend with the highest root, shoot, and cluster N early in summer, which then steadily declined throughout the season, except for root N which increased around harvest. Uptake of N by roots greatly increases from early flowering to berry development while accumulation of N increased for shoots and clusters following bloom and leveled off 75 days after bloom to meet demands of vegetative and reproductive growth (Williams and Biscay 1991, Zapata et al. 2004).

The application of N increased whole plant biomass of cvs. Cabernet Sauvignon and Muller-Thurgau (*V. vinifera*) vines when grafted onto specific rootstocks (Keller et al. 2001b, Zerihun and Treeby 2002). Although root N content was similar, leaf N was greatest for vines with 1103P rootstock and lowest for vines on Ramsey (*V. champinii*) rootstock (Zerihun and Treeby 2002). In another study, 5BB rootstock had greater concentrations N within xylem sap than 3309C and 140Ru rootstocks (Keller et al. 2001b).

Phosphorus is relatively immobile within the soil, requiring nearby roots for uptake. Greatest phosphorus uptake occurs within the top 10 cm of soil which allows uptake by shallow root systems and results in the production of lateral and adventitious roots within that zone (Wang et al. 2006). The greatest P uptake occurs between budburst to bloom during drier conditions, while in wetter conditions or potted vines, greatest uptake is between bloom and veraison (onset of ripening) (Conradie 1981, Schreiner 2005, Schreiner et al. 2006). A second, smaller degree of P accumulation was observed postharvest and was stored in permanent structures (Conradie 1981, Schreiner et al. 2006).

Studies have shown than P uptake varies among rootstocks (Grant and Matthews 1996a, 1996b). Vines on Freedom rootstock had greater P uptake and translocation when this nutrient was sufficient in the soil (> 8 mg/kg of air dry soil by the Bray 1 procedure) when compared to St. George even though there was little difference in root morphology (Grant and Matthews 1996a). In a companion study, Freedom and 110R rootstocks produced acceptable vine growth in low and

adequate P soil conditions, while vines on St. George rootstock had inhibited growth when soil P was low (Grant and Matthews 1996b).

Potassium has multiple functions within vines, including the production of carbohydrates, protein synthesis, solute transport, and plant water regulation (Bates and Wolf 2008). Additionally, these authors reported that K may account for up to 5% of vine dry matter. Nearly half of the K was taken up by vines between late bloom and veraison (Conradie 1981, Schreiner et al. 2006). Following veraison, K uptake was reduced although bunches continued to accumulate K, suggesting that it was transported from the leaves, shoots, and roots during ripening (Williams and Biscay 1991). Following harvest, K was transported from the leaves to the roots and trunk (Conradie 1981, Schreiner et al. 2006).

Rootstocks have the ability to influence K uptake. Using hydroponics to grow cuttings of grafted rootstocks, Ruhl (1989) found that as shoot to root ratio increased, higher shoot K concentrations were obtained. They also showed that 140Ru and 1103P rootstocks had lower shoot to root ratios and lower vine shoot K when grown in a high K nutrient solution, suggesting that these two rootstocks limited K uptake. Kodur et al. (2010b) also reported that vines grafted with Freedom and 101-14 rootstocks accumulated greater concentrations of K than those grafted with 140Ru, 1103P, and Ramsey. They attributed this to higher root length and root systems with a high percentage of fine roots. They further concluded that the rootstock was primarily responsible for K uptake, while the scion or rootstock/scion interaction regulated K accumulation.

Calcium is present in cell walls and is important in providing cell structure (Keller 2010). Similar to N, P, and K, Ca uptake is greatest between bloom and veraison with early transport from roots (Conradie 1981, Schreiner et al. 2006). From veraison to harvest, Ca is primarily present in leaves with a significant amount in bark (Conradie 1981). During berry ripening, Ca decreases within the fruit, although the greatest whole-plant loss is due to leaf fall and pruning (Conradie 1981, Schreiner et al. 2006).

Magnesium is a structural component of chlorophyll and is involved in protein synthesis (Bates and Wolf 2008). Uptake of Mg is continuous throughout the growing season with peak uptake from pre-bloom to veraison and then again post-harvest (Conradie 1981). Leaves were the greatest importer of Mg during the growing season while the roots, shoots, and permanent woody tissues were greatest post-harvest (Conradie 1981, Schreiner et al. 2006).

Sulfur is a key element in amino acids, lipids, and metabolites and is involved in energy production and tissue protection from oxidative stress (Kopriva 2006). Since elemental S is routinely applied as a fungicide in vineyards, it is not typically deficient. However, S applications are not used on sensitive cultivars, such as Norton, Concord, and Chambourcin, so this nutrient may be deficient when these are grown.

Micronutrients, such as Fe, Mn, Zn, B, and Cu are generally present in low concentrations within grapevines. Concentrations of these nutrients change throughout the year, although not consistently among years (Schreiner et al. 2006).

Additionally these authors found that greatest accumulation of Fe, Cu, and Zn and B were present in the woody roots, fine root, and trunks, respectively.

2.6: Yield

Grapevine yield is determined by multiple factors including rootstock and scion genotype, soil characteristics, climate, trellis and training system, cultural practices, irrigation, and pest and disease pressure (Keller 2010). Yield potential for a given year is determined by numbers of buds per vine after pruning, shoots per bud, clusters per shoot and berries per cluster, as well as berry weight (Coombe and Dry 2001). Yield parameters typically measured at harvest to calculate yield are clusters per vine, cluster weight, berries per cluster, and berry weight.

Rootstocks have been shown to affect yield or its various components in several studies (Benz et al. 2007, Edwards 1988, Ezzahouani and Williams 1995, Main et al. 2002, Ruhl et al. 1988). 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). In another study, Muller Thurgau grafted onto 3309C rootstock had lower berry weight than 5BB, SO4, and 140Ru (Keller et al. 2001a). Other studies have shown that berry weight is also influenced by scion cultivar, site, and year (Benz et al. 2007, Main et al. 2002, Reynolds and Wardle 2001). Cluster weight appears to be less affected by rootstock, although the number of berries per cluster can be influenced by rootstock (Hedberg et al. 1986, Main et al. 2002, Reynolds and Wardle 2001). Walker et al. (2010) showed that two different scions (Chardonnay and Merbein) grafted onto

eight rootstocks generally had higher berry weight, cluster weight, clusters per shoot, and overall yield when compared to own-rooted vines. In other studies, Muller Thurgau grafted onto 5BB and SO4 rootstocks had higher yields than 3309C rootstock (Keller et al. 2001a). In another study, Chardonnay and Cabernet franc vines grafted on 5BB rootstock had higher yields than these cultivars grafted onto Riparia Gloire (Vanden Heuvel et al. 2004). However, several studies found that the scion cultivar or site had a greater influence on yield than rootstock (Lipe and Perry 1988, Morris et al. 2007, Reynolds and Wardle 2001).

2.7: Factors influencing fruit composition

Fruit development and ripening are critical factors when determining optimal harvest times. The grape berry is composed of skin, pulp, and seeds, which range from 5 to 20, 74 to 90, and 0 to 6% by weight, respectively (Rankine 2007). Berries also contain sugars, organic acids, tannins, anthocyanins, minerals, and aroma compounds, which are important components of wine (Kennedy 2002). The accumulation of these compounds varies by berry developmental stage, climatic conditions, water availability, and light. Berry growth occurs in a double sigmoid curve pattern (Figure 1) (Coombe and McCarthy 2000, Kennedy 2002, Robinson and Davies 2000). In Phase I (berry formation), berry size increases rapidly and organic acids, tannins, minerals, and other substances rapidly accumulate in the fruit. During Phase II or lag phase, cell expansion does not occur. In Phase III, berry ripening (veraison) begins and berry expansion resumes. Also, during Phase III,

anthocyanins accumulate in the berry skins, glucose and fructose content increases, and organic acids decline.

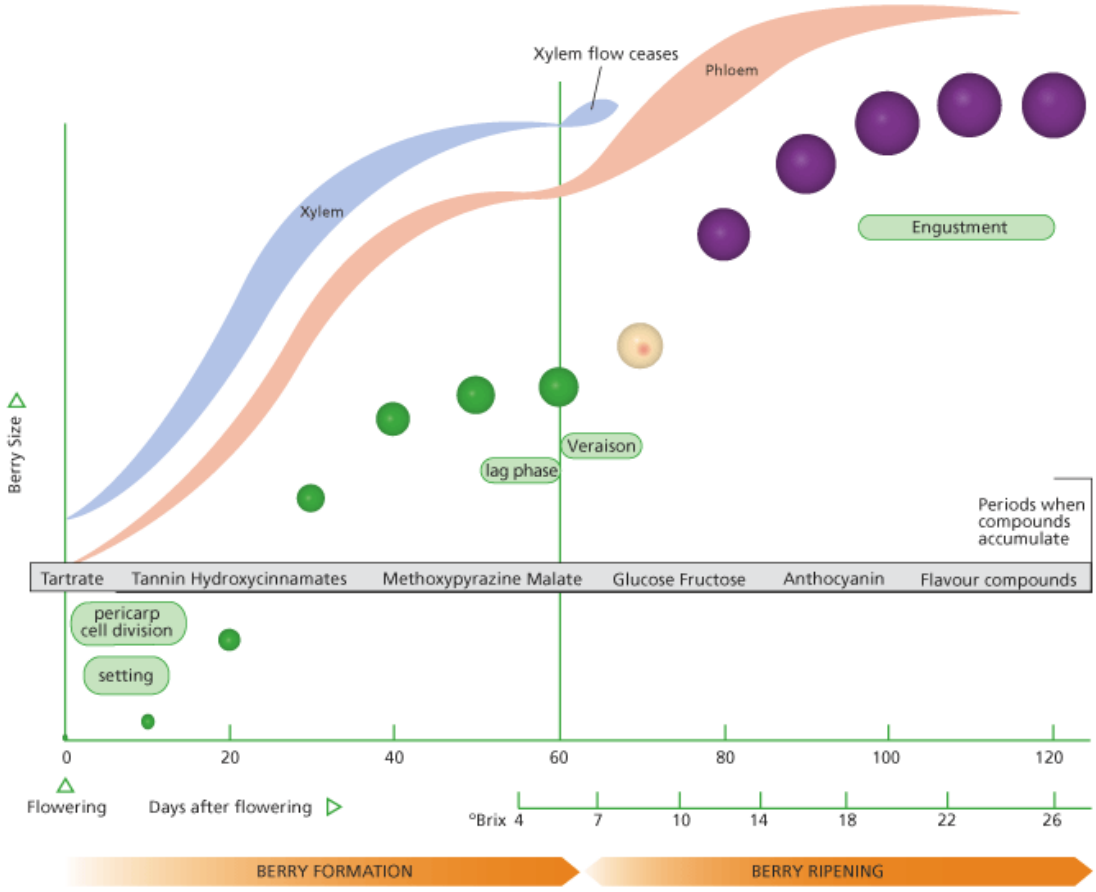

Figure 1. Grape berry development. Depiction of grape berry development after bloom at 10 day intervals. Reproduced from (Kennedy 2002).

2.7.1: Sugars

The primary sugars within grape berries are glucose, fructose, and sucrose. Sugars are required for fermentation by yeast to produce alcohol. In finished wine, residual sugars, either added before bottling as sucrose or remaining in the wine due to stopping yeast metabolism of glucose and fructose, add to complexity of wine and are perceived to soften acidity. These sugars primarily accumulate within the

pulp, but they are also present in grape skins (Coombe and McCarthy 2000, Possner and Kliewer 1985). Sucrose from leaf photosynthesis is transported into the berries via the phloem although accumulation within the berries does not begin until veraison (Coombe and McCarthy 2000, Hrazdina et al. 1984, Possner and Kliewer 1985, Robinson and Davies 2000). During berry ripening, sucrose is converted primarily to glucose and fructose that continue to develop throughout Phase III (Ribereau-Gayon et al. 2000). At harvest, glucose and fructose concentrations are between 150 to 250 g/L (Ribereau-Gayon et al. 2000). Sugars are typically measured as percent total soluble solids (degrees Brix) using a refractometer. This is one of the primary measurements used to determine grape maturity and optimal harvest date.

Rootstocks influenced sugar concentrations in berries when compared to own-rooted vines in some studies; however, results have been variable. Because many factors contribute to sugar accumulation (vine health, nutritional status, crop load, etc.), the rootstock effect may be obscured by other factors. In spite of this difficulty, Reynolds and Wardle (2001) found that when all cultivars were combined, grafted vines with 5BB rootstock produced fruit with higher percent soluble solids than own-rooted vines, although 3309C and SO4 rootstocks were similar to own-rooted vines. Similarly, Ezzahouani and Williams (1995) found that percent soluble solids of berries varied when Ruby Seedless was grafted onto 8 rootstocks over a three year period. They found that soluble solids of berries from vines with 101-14 and 1103P rootstocks were similar to that of fruit harvested from

vines with SO4 rootstock, but had higher percent soluble solids than that from vines with Rupestris du Lot, 140Ru, 110R, 41B, and 99R rootstocks. When Chardonnay and Cabernet franc were grafted onto 5BB and Riparia Gloire rootstocks, berries on vines with Riparia Gloire rootstock tended to produce higher percent soluble solids, however, this varied by year and could have been a result of higher crop load of 5BB (Vanden Heuvel et al. 2004).

Climate is another factor that influences soluble solids in berries. In warm climates, fruit harvested from Chardonel grafted onto Freedom and 110R rootstocks had higher percent soluble solids than that fruit harvested from vines on Norton and 5BB rootstocks in Arkansas (Main et al. 2002). However, when the study was duplicated in California, rootstocks produced berries with similar percent soluble solids. Ruhl et al. (1988) reported that rootstocks had only minor effects on percent soluble solids while scion cultivar and site were more important in determining sugar content. In another study, Muller Thurgau grafted onto 3309C and 110R rootstocks produced fruit with greater soluble solid contents than that of Muller Thurgau berries harvested from vines on 5BB and SO4 (Keller et al. 2001a). Walker and Blackmore (2012) recently found that berries from own-rooted Chardonnay vines had consistently lower soluble solids than Chardonnay grafted on 101-14 and St. George rootstocks planted in four different Australian locations.

2.7.2: Acids

Tartrate, malate, and citrate are major organic acids present in grape pulp and skin (Coombe and McCarthy 2000, Possner and Kliewer 1985). These acids,

along with those formed during winemaking, are critical for wine balance, microbial stability, color, and aging rate (Margalit 1997). Tartaric acid content peaks during Phase I and remains fairly stable until Phase III when concentrations decline. Malic acid accumulates at the end of Phase I and then begins to decline with berry ripening (Coombe and McCarthy 2000, Possner and Kliewer 1985). Although both acids decline during Phase III, the loss of tartaric acid is not as rapid and has been associated with increase in berry size. In contrast, degradation of malate is primarily due to metabolites and reduced rate of acid synthesis (Possner and Kliewer 1985). Titratable acidity of grape juice, which includes organic acids, inorganic acids, and amino acids is commonly used to assess grape maturity and to determine harvest date (Ribereau-Gayon et al. 2000). Organic acids can be analyzed individually, with typical concentrations at harvest ranging from 2 to > 6 g/L, 1 to 6.5 g/L, and 0.5 to 1 g/L for tartaric, malic, and citric acids, respectively (Ribereau-Gayon et al. 2000).

Similar to sugars, acids vary depending on climate, soils, scion cultivars, and rootstocks with scion cultivar, but year and soil type may have more impact on titratable acidity than rootstock (Keller et al. 2001a, Main et al. 2002, Reynolds and Wardle 2001, Ruhl et al. 1988, Vanden Heuvel et al. 2004). However, research conducted in warmer climates has shown that rootstock influences titratable acidity (Ezzahouani and Williams 1995, Keller et al. 2001a, Main et al. 2002).

2.7.3: pH

Juice pH is an important maturity index measured at grape harvest due to its influence on color, taste, microbial stability, sulfur, and cloudy wine (Amerine and

Ough 1980). Ideally, pH for table wine should be between 3.1 to 3.6 because greater values often lead to poor color and wine stability, which in turn results in a negative perception of wine flavor (May 1994, Somers 1975, Wolpert et al. 2005). The increase of pH follows a similar pattern as sugar accumulation in berries with stable concentrations early in the season until veraison, when pH begins to increase due to cation and acid concentrations (Hrazdina et al. 1984). This increase in berry pH coincides with the decrease in acids (Amerine and Ough 1980).

Rootstocks have been suggested as a potential tool in reducing the amount of K and resulting pH in juice and wine. Ruhl et al. (1988) tested this theory with several rootstock-scion combinations. They found that Riesling grafted on Schwarzmann and Ramsey, Ruby Cabernet grafted on Schwarzmann and Freedom, and Shiraz grafted on Harmony and Dog Ridge rootstocks had higher juice pH than that from berries harvested from own-rooted vines. Additionally, among rootstock combinations, the authors found that certain scion-rootstock combinations produced berries with lower pH when compared to the combinations above, including Ruby Cabernet grafted on 101-14 and Ramsey rootstocks and Shiraz grafted to Ramsey rootstocks. Of these rootstocks, Harmony, Dog Ridge, and Freedom also produced fruit with high juice K. Additionally, Chardonel grafted onto Freedom rootstock had berries with higher juice pH than that from fruit harvested from vines on 110R rootstock in California (Main et al. 2002). Foott (1989) also reported reduced pH for vines grafted on 110R rootstock. Other authors have reported variable results on the effect of rootstock on juice pH (Reynolds and

Wardle 2001, Ruhl et al. 1988, Vanden Heuvel et al. 2004, Walker and Blackmore 2012).

2.7.4: Polyphenols

The main polyphenolic compounds measured in grapes are anthocyanins and tannins due to their influence on wine color, astringency, bitterness, stability, and structure (Kennedy 2002, Margalit 1997). Nearly all polyphenolic compounds in grapes are components of the skin and seeds, with anthocyanins mostly occurring in skins and tannin present in both seeds and skin (Kennedy 2002, Margalit 1997). Anthocyanins begin to form after berry set but the greatest accumulation is during Phase III (Hrazdina et al. 1984). Tannins accumulate during Phase I and decline during Phase III, primarily due to oxidation of the more bitter seed tannins (Kennedy 2002).

Research on the effect of rootstock on polyphenols is limited and inconsistent. Satisha et al. (2007) found that berries from vines grafted with 110R and 1103P rootstock (*V. rupestris* x *V. berlandieri*), had higher phenolics, flavon-3-ols, flavanoids, proline, and total proteins than that of berries harvested from vines grafted with *V. champinii*, *V. rupestris*, and *V. riparia* x *V. berlandieri.* Although, when Cabernet Sauvignon was grafted onto 1103P and SO4 (*V. riparia* x *V. berlandieri*) rootstocks, phenolic concentrations of fruit were similar among rootstocks (Koundouras et al. 2009).

2.7.5: Minerals

Minerals primarily accumulate during berry development (Kennedy 2002). Nitrogen compounds in must (juice pressed from grape berries prior to fermentation) are amino acids, polypeptides, proteins, amines, ammonia, nitrates, and vitamins, which are important for yeast to complete fermentation, and for clarification and stability in wine (Margalit 1997, Zoecklein et al. 1999). Nitrogen is taken up by the plant in form of nitrate, ammonia, and urea. Nitrate is reduced to ammonia, which is needed for amino acids and protein synthesis, and yeast metabolism (Zoecklein et al. 1999).

Anions within grapes are primarily phosphate, sulfate, and borate (Ribereau-Gayon et al. 2000). Phosphate is present in inorganic and organic forms within the grape berry, although diammonium phosphate may be added to musts to ensure adequate nutrients for complete fermentation (Amerine and Ough 1980). Sulfur compounds are important to yeast in protein biosynthesis of vitamins and coenzymes, especially in form of sulfate (Zoecklein et al. 1999). Only 5 to 10 mg/L sulfate is required for yeast growth, although much higher concentrations are often present in grapes and wine (Zoecklein et al. 1999). Foliar application of elemental S to vines resulting in residual S on fruit, in combination with inadequate juice N and pH, has been associated with the presence of a hydrogen sulfide taint within wine (Zoecklein et al. 1999). Borate is present in low amounts within berries, but it is not typically analyzed in must and wine (Amerine and Ough 1980, Zoecklein et al. 1999).

Other minerals, K, Na, Ca, Mg, Fe, Cu, Mn, and Zn, are important cations within the grape berry (Amerine and Ough 1980), with all but Fe and Zn influencing pH (Hrazdina et al. 1984). Additionally, K, Ca, Mg, Fe, Cu, Mn, and Zn are important for cell metabolism (Ribereau-Gayon et al. 2000). However, excessive amounts of these minerals affect wine quality and can be obtained due to environmental conditions, nutrient and fungicide applications to vines, as well as additions to wine during the winemaking process. When K and Ca concentrations are excessive, these nutrients precipitate in the juice and form K and Ca tartrate crystals in wine (Amerine and Ough 1980). Magnesium may play a role in tartrate stability and the perception of wine acidity. High concentrations of Fe (7 to 10 mg/L) have been associated with wine cloudiness and color stability. Also, high Cu (> 5 mg/L in musts) can cause cloudiness in wine.

Possner and Kliewer (1985) reported that K was present in early Phase I and steadily increased through Phase III of berry growth. Sodium content was inconsistent throughout berry growth (Hrazdina et al. 1984). Throughout berry ripening, Ca continued to decline while Mg remained constant through harvest (Hrazdina et al. 1984). Copper and Mn were present in much lower concentrations than K, Na, Ca, and Mg, and concentrations of these nutrients also declined throughout berry ripening.

Much of the research on mineral content of rootstocks and their influence on fruit composition have focused on K and N, but limited work has been done on P, S, and the remaining macronutrients. Huang and Ough (1989) reported that

rootstocks that induce vigor, such as St. George, Harmony, SO4, and 5A produce fruit with higher levels of total amino acids compared to fruit harvested from vines grafted with 110R rootstock. Stockert and Smart (2008) also reported that juice from Merlot on 1103P (high vigor-inducing rootstock), had nearly double the yeast assimilable nitrogen (YAN) than that from Merlot on 101-14 (low vigor-inducing rootstock). Potassium concentrations within fruit may also be influenced by rootstock selection. In two studies with different rootstock/scion combinations, berry juice from vines grafted with 140Ru, 1103P, and 110R had lower K concentrations than that from juice from vines grafted with Freedom, Dog Ridge, St. George, and 101-14 (Ruhl et al. 1988, Walker and Blackmore 2012).

In addition to K, Ruhl et al. (1988) studied the influence of rootstocks on Mg, Ca, Na, and Cl in juice. Both Mg and Ca content in juice varied little among rootstocks, scion cultivars, and soils. Ruby Cabernet grafted onto Freedom rootstock had higher Mg and Ca concentrations in juice than that in juice from own-rooted vines and from vines with all other rootstocks. When Shiraz was grafted onto five different rootstocks, Mg juice concentrations from vines grafted with Harmony and Dog Ridge rootstocks were greater than that from vines grafted with Ramsey. Additionally, Mg juice concentrations for Chardonnay grafted onto Rupestris du Lot, Harmony, and 110R rootstocks, and own-rooted vines were higher than that for Chardonnay grafted onto 5BB, SO4, and 5A. Juice Na and Cl concentration also varied by rootstock in this study.

CHAPTER 3: MATERIALS AND METHODS

The effect of various grape rootstocks on vine growth, yield components, fruiting characteristic, and juice characteristics was evaluated. Six-year-old Norton vines grown on their own roots or grafted onto 10 rootstocks planted in a commercial vineyard in Phelps County, MO (38° 1' 20" N, 91° 32' 40" W, elevation 334 m) were used for this study. Rootstocks evaluated were 3309C, 101-14, Schwarzmann, 5BB, SO4, 1103P, 110R, 140Ru, 1616C, and 44-53M. The soil at this site is a Union silt loam (fine, mixed, active, mesic oxyaquic fragiudults) with a fragipan at 0.36 to 0.89 m depth with seasonal saturation problems (USDA 2012b) and the site was tile-drained in alternate rows.

Four rootstock replicates of three vine plots were arranged in a randomized complete block design and trained to a Geneva Double Curtain System with 2.1 m x 3.0 m (vine x row) spacing and north to south row orientation. Vines were balance pruned using a 50 + 10 formula (50 nodes retained for first 0.45 kg of pruning weight and 10 buds left with additional 0.45 kg dormant prunings removed). Buds retained at pruning along the cordon were a combination of 5 node, 2 node, and 1 node spurs per 0.3 m cordon length (Main and Morris 2008). Shoot thinning was performed annually when shoots were ≈ 25 cm long. Downward shoot positioning was done 2 to 3 times per year from June through August. Shoot length was maintained at 0.5 m above soil surface throughout the growing season. Drip irrigation scheduling, pest, and weed management followed local recommendations (Anonymous 2004). Vines were fertilized with N as urea (33.6 kg actual N/ha) in

2010 and 33.8 kg/ha with UAN 32 (45% ammonium nitrate, 35% urea, 20% water) in 2011. Weather data was obtained from a Specware WatchDog (Spectrum Technologies, Inc., Plainfield, IL) weather station located within a commercial vineyard 3.5 km northeast from research plot location. This information was used to determine growing degree days (GDD) (daily max temp + daily min temp/2)-10°C (Winkler et al. 1974). Historical weather data were collected from University of Missouri Science and Technology and National Weather Service COOP weather station (237263) in Rolla, MO, 24 km southwest of plot location.

To assess vine growth, number of shoots before shoot thinning was recorded annually (2010 and 2011) in early spring while dormant pruning weights, number of shoots, and number of nodes retained were collected annually during winter, and average shoot weights were calculated. Fruit, yield and cluster number per vine were collected and clusters per shoot, cluster weight, berry weight, and berries per cluster were determined at harvest. Grapes were harvested on 14 Sept 2010 and 15 Sept 2011 as chosen by the cooperator based on 3.5 pH limit. Following pruning, Ravaz Index for each vine was calculated (kg fruit/kg prunings).

One hundred berry samples for each replication were collected at harvest to evaluate juice characteristics. Juice was pressed by hand and then homogenized at room temperature using a Stomacher Model 400 circulator (Seward, Worthington, West Sussex, UK) and then pressed through two layers of grade 40 cheesecloth and centrifuged at 9000 rpm for 3 min. Soluble solids of fresh juice were measured with a temperature compensating ABBE refractometer (Reichert Mark II Plus, Depew,

NY). Juice pH was measured with a temperature compensating pH probe and Orion 3 Star meter (Thermo Scientific, Waltham, MA) calibrated with 4.01, 7.00, and 10.05 pH buffers. Titratable acidity, expressed as tartaric acid (g/L), was determined using a 5 mL juice sample diluted in 100 mL degassed and deionized water titrated to an endpoint of 8.2 pH with 0.1 N NaCl (Iland et al. 1996).

For mineral analyses, samples were prepared by mixing fresh juice with 2.5% HCl acid (w/v) at a 1:20 ratio and minerals were measured in the solution using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) at the University of Arkansas Agriculture Plant Analysis Laboratory, Fayetteville, AR. For YAN analysis, juice samples frozen at -20 °C and stored up to three months were used to determine nitrate and ammonia contents. Nitrate content (mg/L) were determined utilizing the NOPA method described by Dukes and Butzke (1998). Ammonia was determined using a high performance ammonia ion selective probe (Thermo Scientific, Waltham, MA).

For determination of anthocyanins, tannins, total phenols, organic acids (tartaric, malic, and citric acid), and sugars (glucose and fructose), samples were collected at harvest annually and frozen at -20°C for up to three months before analysis. Anthocyanins and total phenolics were assayed using methods described by Iland et al. (1996) and modified by the Australian Wine Research Institute (AWRI 2006). Tannin content was analyzed using the methyl cellulose precipitable (MCP) tannin assay described by AWRI (2007). A Spectronic Genesys 2 UV-Vis

spectrophotometer (Thermo Scientific, Waltham, MA) was used for determining anthocyanins, tannins, and total phenols.

Samples for organic acid and sugar determination were removed from the freezer and thawed overnight at 4°C and warmed to 70°C in a circulating water bath. For these samples, juice was extracted from berries as previously described then was centrifuged at 4000 rpm for 3 min, supernatant was then diluted to 1 juice : 50 distilled water (v/v) and clarified using a 200 µm filter. Organic acids and sugars were determined by high performance liquid chromatography (HPLC) as described by Jogaiah et al. (2012).

Vine nutritional status was evaluated from 60 petioles from each replicate treatment at veraison. Macro and micronutrient analyses were conducted by the University of Missouri Soil and Plant Testing Laboratory using standard methods (Nathan and Sun 2006).

Vegetative growth, yield, fruit, and juice characteristics data were subjected to an analysis of variance (ANOVA) using the PROC MIXED procedure of Statistical Analysis Software (SAS; version 9.2; Cary, NC, USA). Means were separated by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$. Means with year by rootstock interaction were analyzed by year using PROC MIXED procedure.

CHAPTER 4: RESULTS

Precipitation from April through September of two growing seasons exceeded historical annual rainfall (639 mm) with 970 and 859 mm recorded in 2010 and 2011, respectively (Figure 2). In 2010, periods of excessive rainfall occurred in May, June, and September, which coincided with bloom, berry set, and veraison, respectively. In April and May 2011, rainfall exceeded average monthly precipitation amounts, but was below average in June, August, and September. Average daily temperatures in 2010 often exceeded the historical average temperatures (Figure 3). Additionally, heat accumulation (measured as GDD) was greater than historical averages (3594) during this study. In 2010 and 2011, GDD was 3934 and 3738, respectively. Thus, the 2010 growing season was unseasonably warm with high rainfall.

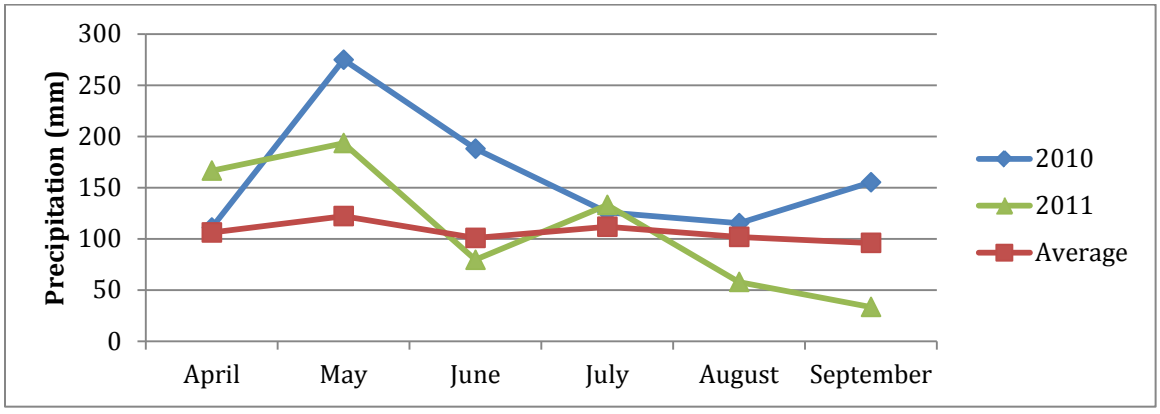

Figure 2. Monthly rainfall for April to September 2010 and 2011 with historical average precipitation (1971-2000) in Phelps County, Missouri.

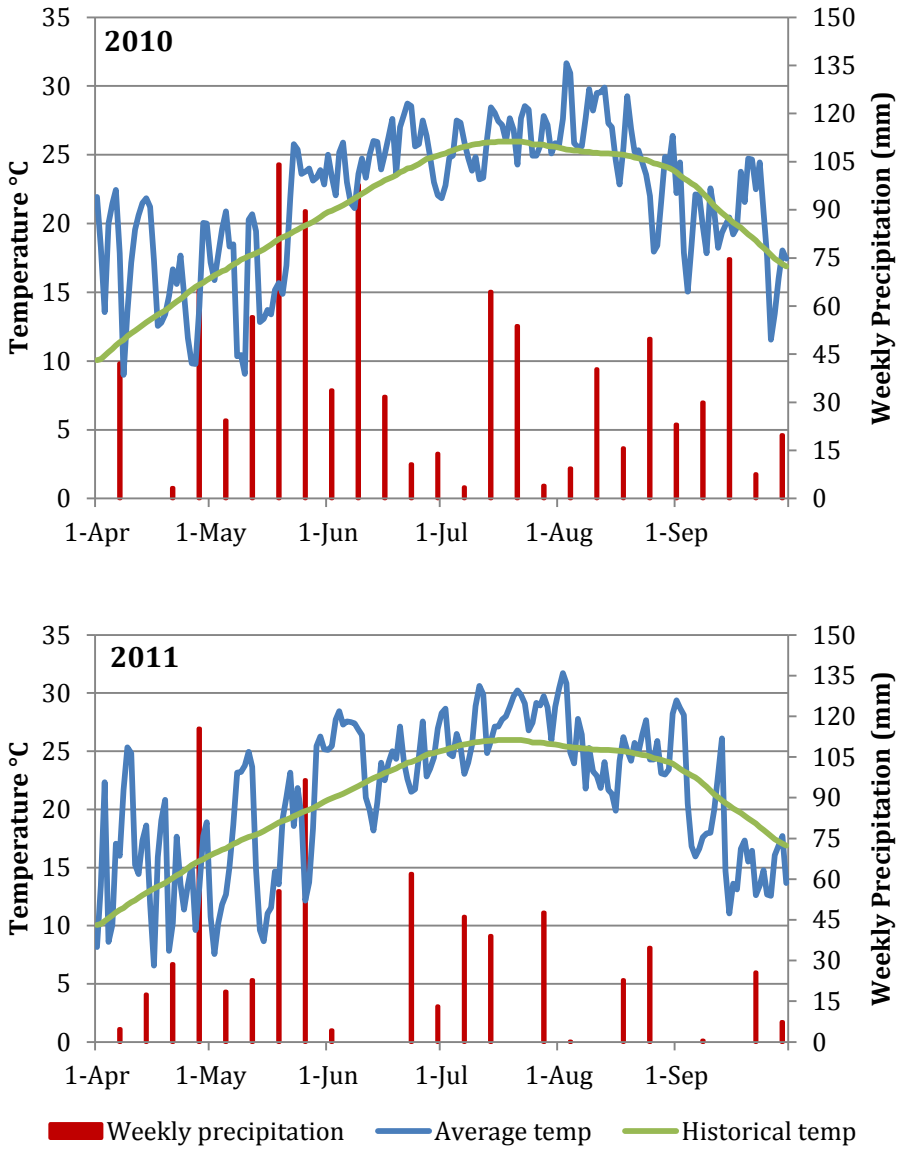

Figure 3. Average daily temperature, historic (1971-2000) average daily temperature, and precipitation from April to September 2010 and 2011 for Phelps County, Missouri.

4.1: Vegetative growth

The number of shoots per vine before shoot thinning in May, number of shoots at pruning, and retained nodes on grapevines after dormant pruning were similar among all rootstocks and own-rooted vines (Table 2). Although not significant, own-rooted vines generally had more vigorous growth than the grafted vines, except for those on rootstock 110R, which had more shoots before thinning in May. Pruning weights and nodes per vine retained were greater in 2010 than 2011. However, pre-thinning shoot numbers and shoots per vine were greater in 2011 than those in the previous year.

Table 2. Vegetative characteristics of Norton grapevines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[v]

Treatment	Pre-thinning shoot no.[w]	Shoot no./ vine [x]	Pruning wt. (kg)[y]	No. of nodes retained/vine
Own-rooted	130	81	0.9	60
3309C	127	72	0.8	57
101-14	129	71	0.8	57
Schwarzmann	124	69	0.8	56
5BB	126	78	0.9	59
SO4	125	75	0.8	58
1103P	129	74	0.8	57
110R	135	74	0.8	58
140Ru	127	73	0.8	58
1616C	128	71	0.9	58
44-53M	121	70	0.8	56
Year				
2010	129	62	1.0	61
2011	126	85	0.6	54
Significance [z]				
Treatment	ns	ns	ns	ns
Year	*	***	***	***
Treatment x year	ns	ns	ns	ns

[v] Means represent 3 vine plots and 4 replications of each rootstock.
[w] Values represent the number of shoots per vine before pruning.
[x] Thinning was performed in May to reduce secondary, tertiary, and basal shoots.
[y] Pruning weight of one year-old canes recorded in February following growing season.
[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

4.2: Petiole nutrient content

Petiole content of N and Mg were similar for all rootstocks (Table 3). However, Ca petiole content was greatest for own-rooted vines and lowest for vines on 101-14, 1103P, and 140Ru rootstocks. N, Ca, and Mg contents were greater in 2011 than those in 2010.

Table 3. Macronutrient content in petioles of Norton grapevines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[x]

Treatment	N (%)[y]	Ca (%)[y]	Mg (%)[y]
Own-rooted	0.91	1.66 a	0.82
3309C	0.89	1.36 cd	0.87
101-14	0.93	1.26 e	1.04
Schwarzmann	0.93	1.42 bc	1.04
5BB	0.95	1.42 bc	1.01
SO4	0.87	1.49 b	0.81
1103P	0.95	1.22 e	1.02
110R	0.87	1.50 b	0.84
140Ru	0.95	1.25 e	1.01
1616C	0.92	1.28 de	0.89
44-53M	0.85	1.48 b	0.93
Year			
2010	0.86	1.28	0.67
2011	0.96	1.51	1.20
Significance[z]			
Treatment	ns	***	ns
Year	***	***	***
Treatment x year	ns	ns	ns

[x] Means represent 3 vine plots and 4 replications of each rootstock. Rootstock values within columns with different letters were significantly different by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.

[y] Petioles collected at veraison. Sufficient ranges for N, Ca, and Mg are 0.8 to 1.2, 1.3 to 2.5, and 0.35 to 0.75%, respectively (Bates and Wolf 2008).

[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

There was a significant interaction of rootstock and year for the petiole contents of P and K (Table 4). P content was highest in vines on Schwarzmann, 1103P, 110R, and 140Ru rootstocks in 2010. In contrast, P content of vines on 44-53M rootstock was low in both years, as well as own-rooted vines in 2011. Potassium petiole content in vines on 1616C rootstock in 2010 was higher than that of all other vines in both years except for those on 101-14 rootstock in 2010.

Table 4. Macronutrient content of P and K in petioles of Norton grapevines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[x]

Treatment	Year	P (%)[y]	K (%)[y]
Own-rooted	2010	0.13 cde	1.90 b
3309C	2010	0.15 bcd	1.75 b
101-14	2010	0.16 bcd	2.18 ab
Schwarzmann	2010	0.25 a	1.76 b
5BB	2010	0.13 cde	1.80 b
SO4	2010	0.16 bcd	1.60 bc
1103P	2010	0.23 a	1.86 b
110R	2010	0.26 a	1.97 b
140Ru	2010	0.23 a	1.77 b
1616C	2010	0.18 b	2.71 a
44-53M	2010	0.11 e	1.71 b
Own-rooted	2011	0.11 e	0.80 d
3309C	2011	0.13 cde	0.81 d
101-14	2011	0.12 cde	0.72 d
Schwarzmann	2011	0.16 bcd	0.71 d
5BB	2011	0.12 cde	0.80 d
SO4	2011	0.12 de	1.01 d
1103P	2011	0.15 bcd	1.12 cd
110R	2011	0.14 bcde	1.03 cd
140Ru	2011	0.13 cde	1.05 cd
1616C	2011	0.12 de	0.88 d
44-53M	2011	0.11 e	0.96 d
Year			
2010		0.18	1.91
2011		0.13	0.90
Significance[z]			
Treatment		***	ns
Year		***	***
Treatment x year		***	**

[x] Means represent 3 vine plots and 4 replications of each rootstock. Rootstock values within columns with different letters were significantly different by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.

[y] Petioles collected at veraison. Sufficiency ranges for P and K are 0.14 to 0.3 and 1.2 to 2.0%, respectively (Bates and Wolf 2008).

[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

Petiole micronutrients, Fe, Cu, and B, were similar among rootstocks and own-rooted vines, although Mn and Zn content differed (Table 5). Vines on 101-14 rootstock had higher Mn petiole content than that of vines on 3309C, 110R, and 44-53M rootstocks. In contrast, vines on 110R rootstocks generally had low Mn in petioles. Vines on Schwarzmann rootstock had higher Zn in petioles than those of all other rootstocks and own-rooted vines except 101-14. Higher concentrations of all petiole micronutrients were present in 2011, although not significantly for Mn.

Table 5. Micronutrient content in petioles of Norton grapevines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[x]

Treatment	Fe (ppm)[y]	Mn (ppm)[y]	Zn (ppm)[y]	Cu (ppm)[y]	B (ppm)[y]
Own-rooted	40.1	483 ab	71.3 bc	6.10	27.9
3309C	37.2	369 bcd	62.1 de	4.63	35.2
101-14	38.0	505 a	77.1 ab	4.94	28.5
Schwarzmann	48.4	476 ab	79.7 a	5.71	29.9
5BB	51.4	499 ab	57.7 ef	5.44	28.9
SO4	52.4	420 abc	51.9 f	5.89	29.9
1103P	39.6	459 ab	68.3 cd	5.03	27.1
110R	38.5	255 d	58.2 ef	5.54	30.2
140Ru	42.6	424 abc	69.0 cd	5.06	23.8
1616C	44.9	386 abc	64.7 cd	4.60	29.8
44-53M	44.1	317 cd	54.6 f	4.82	36.1
Year					
2010	31.8	422	62.1	3.58	20.8
2011	55.0	486	67.8	6.92	38.7
Significance [z]					
Treatment	ns	**	***	ns	ns
Year	***	ns	***	***	***
Treatment x year	ns	ns	ns	ns	ns

[x] Means represent 3 vine plots and 4 replications of each rootstock. Mean separation by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.
[y] Petioles collected at veraison. Sufficiency ranges for Fe, Mn, Zn, Cu, and B are 30 to 100, 25 to 1,000, 25, 5 to 15, and 25 to 50 ppm, respectively (Bates and Wolf 2008).
[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

4.3: Fruiting characteristics

Fruit yield for 2010 and 2011 was affected by rootstock (Table 6). Vines on 110R produced greater yields than own-rooted vines and those on all other rootstocks except for 101-14 and 1616C rootstocks. Own-rooted vines produced 4.4 kg less fruit per vine than those on 110R rootstock. Average clusters per vine, berry weight, and berries per cluster were similar among vines on all rootstocks and own-

rooted vines. In contrast, vines on 1616C rootstocks had greater cluster weights than own-rooted vines and on all other rootstocks except 101-14, 5BB, and 110R. However, vines on 110R had more clusters per shoot than own-rooted vines and those on 5BB, SO4, 1103P, 1616C, and 44-53M rootstocks. Cluster weight, berry weight, and berries per cluster for all rootstocks and own-rooted vines were greater in 2010 than in 2011, but yield, clusters per vine, and clusters per shoot were greater in 2011.

Table 6. Fruiting characteristics of Norton grapevines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011. [w]

Treatment	Yield (kg/vine) [x]	Clusters/ vine [x]	Cluster wt. (g) [x]	Berry wt. (g) [y]	Berries/ cluster	Clusters/ shoot
Own-rooted	12.0 c	187	65.9 e	1.13	58	2.3 c
3309C	13.3 bc	182	75.7 bcd	1.29	59	2.5 abc
101-14	15.0 ab	195	79.7 abc	1.25	64	2.7 ab
Schwarzmann	13.7 bc	182	78.0 bcd	1.26	62	2.6 abc
5BB	14.0 bc	184	78.2 abcd	1.25	63	2.3 c
SO4	13.5 bc	182	76.7 bcd	1.27	61	2.4 c
1103P	13.5 bc	185	74.7 cd	1.21	62	2.5 bc
110R	16.4 a	210	80.4 ab	1.32	61	2.8 a
140Ru	13.1 bc	189	73.3 d	1.25	58	2.6 abc
1616C	14.3 ab	179	82.3 a	1.33	62	2.5 bc
44-53M	13.0 bc	172	76.3 bcd	1.30	59	2.5 bc
Year						
2010	12.2	144	84.5	1.29	66	2.3
2011	15.4	228	68.5	1.23	56	2.7
Significance [z]						
Treatment	*	ns	***	ns	ns	*
Year	***	***	***	***	***	***
Treatment x year	ns	ns	ns	ns	ns	ns

[w] Means represent 3 vine plots and 4 replications of each rootstock. Rootstock values within columns with different letters were significantly different by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.

[x] Cluster wt. = average cluster weight per replication. Reported fruiting characteristics of Norton on a divided canopy system for yield, clusters/vine, and cluster weight are 11.7 kg/vine, 201 clusters/vine, and 58.5 g, respectively (Morris and Main 2010).

[y] Berry wt. = individual berry fruit weight per replication.

[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$ or $P \leq 0.001$, respectively.

4.4: Ravaz Index

Ravaz Index values (yield/pruning wt.) were similar for all rootstocks and own-rooted vines (Figure 3). Numerically, own-rooted vines had the lowest values

and those on 110R rootstock were the greatest. Mean Ravaz Index for all rootstocks and own-rooted vines in 2011 was double (24.8) that in 2010 (12.4).

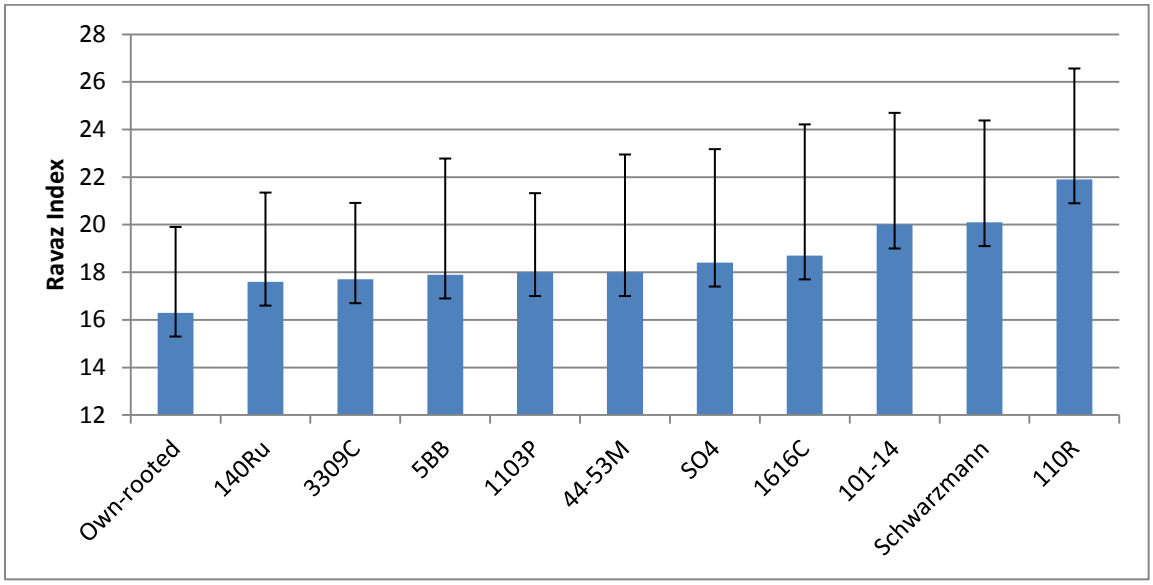

Figure 4. Mean Ravaz Index of Norton grapevines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011. Bars (I) indicate standard deviation of each mean.

4.5: Fruit composition

Percent soluble solids, pH, and titratable acidity (TA) were similar among all rootstocks and own-rooted vines (Table 7). In general, juice from own-rooted vines had higher soluble solids and lower TA while juice from vines on 110R had low soluble solids and higher TA. In 2011, all rootstocks and own-rooted vines had higher soluble solids and TA values and lower pH than those recorded in 2010.

Anthocyanins, total phenols, and tannin contents were similar among rootstocks and own-rooted vines (Table 7). However, juice produced in 2010 had

higher concentrations of anthocyanins and total phenols than in 2011. Tannin content in juice was similar for both years.

Table 7. Juice and berry composition of Norton grapes produced from vines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[y]

Treatment	Total soluble solids (Brix)	pH	Titratable acidity (g/L)	Anthocyanins (mg/g berry wt.)[y]	Total Phenols (AU/ berry wt.)[y]	Tannins (mg/g berry wt.)[y]
Own-rooted	22.7	3.4	8.2	2.20	1.14	1.36
3309C	22.3	3.4	9.0	1.95	1.04	1.63
101-14	21.6	3.4	8.9	1.74	0.95	1.27
Schwarzmann	21.7	3.4	8.4	1.84	0.99	1.37
5BB	22.1	3.4	8.8	1.70	0.94	1.28
SO4	22.1	3.4	8.7	1.90	1.05	1.56
1103P	22.4	3.4	8.8	1.83	1.00	1.47
110R	22.1	3.4	9.0	1.90	1.01	1.34
140Ru	22.3	3.5	8.4	1.79	0.96	1.09
1616C	21.7	3.5	8.7	1.75	0.96	1.35
44-53M	22.2	3.4	8.3	1.99	1.08	1.78
Year						
2010	21.8	3.5	8.3	2.34	1.19	1.47
2011	22.4	3.4	9.1	1.41	0.83	1.35
Significance [z]						
Treatment	ns	ns	ns	ns	ns	ns
Year	**	***	***	***	***	ns
Treatment x year	ns	ns	ns	ns	ns	ns

[x] Means represent 3 vine plots and 4 replications of each rootstock. Mean separation by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.

[y] Berries were collected at harvest, frozen at -20°C, then warmed to 21°C and ground for analysis. AU = absorbance units. Reported ranges of Norton fruit for Brix, pH, TA, anthocyanins, total phenols, and tannins are 20 to 25, 3.3 to 3.9, 7.9 to 15.8 (Main 2005, Main and Morris 2008, Morris and Main 2010), 2.7 to 3.4, 2.6 to 3.2, and 2.7 to 3.4, respectively (Jogaiah et al. 2012).

[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$ or $P \leq 0.001$, respectively.

Organic acids (tartaric, malic, and citric acid) were similar among all rootstocks and own-rooted vines (Table 8). Similarly, glucose and fructose contents did not vary among rootstocks and own-rooted vines. However, tartaric and citric acids, as well as glucose were greater in 2010 than in the following year. Fructose measured in 2011 was greater than that in 2010.

Table 8. Organic acids, glucose, and fructose content in juice and berries of Norton grapes produced from vines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[x]

Treatment	Tartaric acid (g/L)[y]	Malic acid (g/L)[y]	Citric acid (g/L)[y]	Tartaric: malic acid	Glucose (g/L)[y]	Fructose (g/L)[y]
Own-rooted	9.9	4.1	1.0	2.5	97.8	113.6
3309C	9.8	4.6	1.0	2.2	95.9	109.5
101-14	9.7	4.9	1.0	2.0	87.9	102.5
Schwarzmann	9.7	4.3	1.1	2.3	90.1	105.8
5BB	9.8	4.8	1.1	2.0	91.2	105.4
SO4	9.9	4.7	1.1	2.2	92.7	108.5
1103P	9.4	5.0	1.1	1.9	92.8	106.8
110R	9.6	4.6	1.1	2.2	92.2	107.8
140Ru	9.7	4.5	1.1	2.2	90.8	105.7
1616C	9.8	5.1	1.0	2.0	89.7	104.1
44-53M	10.1	4.4	1.0	2.3	94.3	108.5
Year						
2010	10.1	4.6	1.1	2.2	94.2	105.7
2011	9.4	4.7	1.0	2.1	90.5	108.5
Significance[z]						
Treatment	ns	ns	ns	ns	ns	ns
Year	***	ns	***	ns	**	*
Treatment x year	ns	ns	ns	ns	ns	ns

[x] Means represent 3 vine plots and 4 replications of each rootstock. Rootstock values within columns with different letters were significantly different by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.

[y] Juice derived from fruit collected at harvest, frozen at -20°C, and heated to 70°C. Reported ranges of Norton for tartaric acid, malic acid, citric acid, glucose, and fructose are 6 to 10, 3.2 to 7.4, 0.5 to 1.0, 77.6 to 93.6, 79.8 to 137.8 g/L, respectively (Jogaiah et al. 2012, Main and Morris 2004, 2008). Ranges of wine grapes are 1 to7, 1 to 4, 0.15 to 0.3, 80 to 130, and 80 to 130 g/L, respectively (Margalit 1997).

[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$ or $P \leq 0.001$, respectively.

4.6: Juice mineral content

Nitrate and total nitrogen in juice were influenced by an interaction of rootstock and year (Table 9). Nitrate and total nitrogen contents in juice from vines on Schwarzmann were greater in 2011 than that of all other rootstock/year combinations except for vines on 3309C rootstocks in 2011. Nitrate and total nitrogen contents of juice from own-rooted vines generally ranked the lowest in 2010. Ammonia content in juice was not affected by rootstock, but it was much higher in 2010 than in 2011.

Table 9. Yeast assimilable nitrogen concentration in juice of Norton grapes produced from vines on selected rootstocks grown in Phelps County, Missouri in 2010 and 2011.[x]

Treatment	Year	Nitrate (mg/L)[y]	Ammonia (mg/L)[y]	Total N (mg/L)[y]
Own-rooted	2010	260 l	12.0	272 g
3309C	2010	280 ijkl	17.4	298 efg
101-14	2010	271 kl	17.6	289 efg
Schwarzmann	2010	323 defgh	15.8	327 cd
5BB	2010	291 hijkl	17.3	308 defg
SO4	2010	277 ijkl	16.8	294 efg
1103P	2010	273 jkl	15.4	288 efg
110R	2010	272 kl	14.3	286 efg
140Ru	2010	281 ijkl	16.1	297 efg
1616C	2010	276 ijkl	16.4	292 efg
44-53M	2010	268 kl	12.7	280 fg
Own-rooted	2011	360 bcd	6.7	367 bc
3309C	2011	385 ab	6.6	391 ab
101-14	2011	350 bcde	6.7	357 bc
Schwarzmann	2011	406 a	8.9	415 a
5BB	2011	365 bc	7.4	373 b
SO4	2011	344 cdef	6.6	350 c
1103P	2011	333 cdefg	8.2	341 cd
110R	2011	308 fghij	5.7	314 def
140Ru	2011	356 bcd	9.1	365 bc
1616C	2011	305 ghijk	6.6	312 def
44-53M	2011	312 efghi	5.0	317 de
Year				
2010		279	15.6	294
2011		348	7.0	355
Significance[z]				
Treatment		***	ns	**
Year		***	***	***
Treatment x year		*	ns	*

[x] Means represent 3 vine plots and 4 replications of each rootstock. Rootstock values within columns with different letters were significantly different by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.

[y] Juice derived from harvest samples, frozen at -20°C and heated to 40°C. Sufficiency ranges for ammonia and total N at 21 to 23 Brix are at least 20 and 200 to 250 mg/L, respectively (Bisson and Butzke 2000).

[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

In addition to N, juice also varied in P, Ca, Mg, and S (Table 10). Phosphorus was high in juice from vines on 140Ru rootstock but was similar to that produced from vines on Schwarzmann, 1103P, and 110R rootstocks. Juice from vines on 44-53M generally had the lowest concentration of P. Juice from own-rooted vines had a higher Ca content than that from all other rootstocks except SO4 and 44-53M rootstocks. Additionally, juice from vines on 1103P and 140Ru had higher Mg content than that from all other rootstocks and own-rooted vines. Sulfur content in juice was highest for vines on 140Ru rootstock, while it was lowest in juice from vines on 3309C. All rootstocks produced juice with higher concentrations of macronutrients in 2010 than in 2011, except for Ca and S.

Table 10. Macronutrient concentrations in juice of Norton grapes produced from vines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[y]

Treatment	P (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	S (mg/L)
Own-rooted	93.7 bcd	1902	125.8 a	119.3 b	68.9 bcd
3309C	95.2 bcd	1987	109.5 cd	121.7 b	66.8 d
101-14	90.3 cd	1996	105.6 d	128.0 b	73.3 bc
Schwarzmann	100.3 abc	1984	109.5 cd	119.7 b	70.4 bcd
5BB	93.5 bcd	1942	110.3 cd	123.2 b	72.0 bc
SO4	97.2 bcd	1951	117.6 abc	124.8 b	67.5 cd
1103P	102.9 ab	2052	107.8 d	138.8 a	73.6 b
110R	103.0 ab	2004	112.9 bcd	122.4 b	68.2 cd
140Ru	108.8 a	2086	109.9 cd	139.6 a	79.9 a
1616C	95.8 bcd	2082	110.3 cd	124.8 b	67.8 cd
44-53M	86.9 d	1969	119.5 ab	128.0 b	68.7 bcd
Year					
2010	106.2	2257	114.1	132.0	60.6
2011	87.9	1735	111.1	120.7	80.5
Significance[z]					
Treatment	*	ns	**	***	***
Year	***	***	ns	***	***
Treatment x year	ns	ns	ns	ns	ns

[y] Means represent 3 vine plots and 4 replications of each rootstock. Rootstock values within columns with different letters were significantly different by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$. Ranges for P, K, Ca, Mg, and S in wine are 50 to 1000, 200 to 2,500, 10 to 200, 10 to 200, and 100 to 3000 mg/L, respectively (Margalit 1997, Rankine 2007, Zoecklein et al. 1999).
[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, ≤ 0.01, or $P \leq 0.001$, respectively.

Juice micronutrients, Na, Fe, Zn, and Cu, were similar among rootstocks, but different among years. Juice concentrations of Na, Fe, and Cu were higher in 2010 than 2011, but Zn concentration was higher in 2011 (Table 11).

Table 11. Micronutrient concentrations in juice of Norton grapes produced on vines from selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[x]

Treatment	Na (mg/L)[y]	Fe (mg/L)[y]	Zn (mg/L)[y]	Cu (mg/L)[y]
Own-rooted	45.2	5.10	0.74	1.48
3309C	44.9	3.31	0.69	1.29
101-14	45.1	1.84	0.69	1.17
Schwarzmann	47.4	4.28	0.80	1.58
5BB	45.0	3.09	0.51	1.20
SO4	46.8	2.94	0.59	1.31
1103P	46.0	3.18	0.64	1.40
110R	44.0	2.78	0.57	1.23
140Ru	46.4	3.03	0.70	1.39
1616C	46.3	3.70	0.64	1.18
44-53M	46.2	2.56	0.63	1.19
Year				
2010	84.4	4.21	0.36	1.40
2011	7.1	2.30	0.95	1.22
Significance[z]				
Treatment	ns	ns	ns	ns
Year	***	***	***	*
Treatment x year	ns	ns	ns	ns

[x] Means represent 3 vine plots and 4 replications of each rootstock. Rootstock values within columns with different letters were significantly different by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.

[y] Ranges of wine for Na, Fe, Zn, and Cu are 10 to 300, 1 to 10, ≤5, and ≤5 mg/L, respectively (Margalit 1997).

[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

Mn and B concentrations in juice varied among rootstocks and years (Table 12). Juice from own-rooted vines generally had the highest concentration of Mn in 2011, while Mn was relatively lower from vines on 3309C rootstock in 2010 and 110R rootstock in both years. Juice concentration of B was higher from vines on 3309C and 44-53M rootstocks in 2010 than in juice from all other rootstocks except for 101-14, 5BB, 110R, and 1616C in 2010.

Table 12. Micronutrient concentrations of Mn and B in juice of Norton grapes produced from vines on selected rootstocks and own-rooted vines grown in Phelps County, Missouri in 2010 and 2011.[x]

Treatment	Year	Mn (mg/L)[y]	B (mg/L)[y]
Own-rooted	2010	1.82 efghi	6.25 b
3309C	2010	1.48 i	7.53 a
101-14	2010	1.73 fghi	7.02 ab
Schwarzmann	2010	1.78 fghi	6.61 b
5BB	2010	1.65 fghi	7.18 ab
SO4	2010	2.11 cdefgh	6.67 b
1103P	2010	2.13 bcdefgh	6.52 b
110R	2010	1.42 i	6.94 ab
140Ru	2010	1.82 fghi	6.83 b
1616C	2010	1.55 hi	6.97 ab
44-53M	2010	1.58 ghi	7.54 a
Own-rooted	2011	2.75 a	2.03 cd
3309C	2011	2.03 defgh	2.44 cd
101-14	2011	2.70 ab	2.06 cd
Schwarzmann	2011	2.20 abcdef	1.99 d
5BB	2011	2.56 abcd	1.93 d
SO4	2011	2.21 abcdef	1.98 d
1103P	2011	2.62 abc	2.12 cd
110R	2011	1.41 i	2.39 cd
140Ru	2011	2.37 abcde	2.21 cd
1616C	2011	2.16 bcdefg	2.67 c
44-53M	2011	1.89 efghi	2.47 cd
Year			
2010		1.73	6.91
2011		2.26	2.20
Significance[z]			
Treatment		*	ns
Year		***	***
Treatment x year		*	*

[x] Means represent 3 vine plots and 4 replications of each rootstock. Rootstock values within columns with different letters were significantly different by Fischer's protected least significant differences (LSD) test, $P \leq 0.05$.

[y] Average ranges of wine of Mn and B are 1 to 5.5 and 2 to 112 mg/L, respectively (Amerine and Ough 1980).

[z] ns, *, **, *** Non-significant, or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

CHAPTER 5: DISCUSSION

Own-rooted Norton grapevines typically produce vigorous vegetative growth and low yields with small fruit clusters (Hendrick 1908, Wagner 1945, Walker et al. 2003). Fruit yield of Norton grapevines during the two years of this study (Table 6) was higher (12.0 to 16.4 kg/vine) than previously reported (8 to 11.7 kg/vine) on own-rooted Norton vines for both single and divided canopy systems (Main et al. 2002, Main and Morris 2008, Morris and Main 2010). Results from this study also demonstrated that rootstocks influenced Norton yield. Three rootstocks, 101-14, 110R, and 1616C produced 2.3 to 4.4 kg more fruit per vine than own-rooted vines. In other studies, 110R rootstocks grafted to Chardonel in Arkansas (Main et al. 2002) and 101-14 rootstock grafted to Chardonnay and Shiraz in Australia (Walker et al. 2010) also enhanced yield. In the present study, high yields were attained without significant changes in juice or berry composition (Tables 7 and 8). However, concentrations of anthocyanins, tannins, total phenolics, and juice K were lower than previously reported for Norton (Tables 7 and 10), but this may be attributed to high cropping (Jogaiah et al. 2012).

Pruning weights during the 2010 season (1.0 kg/vine) were 40% higher than those in the following season (Table 2). It is likely that the higher rainfall during the 2010 growing season resulted in vigorous vegetative growth. The high number of buds retained after pruning that year resulted in a large crop load in 2011, which limited vegetative growth. This type of growth/yield relationship was described by Partridge (1925). In addition to these differences, pruning weights in both years of

this study were lower than those reported by Morris and Main (2010) for Norton on a divided canopy systems (1.33 kg/vine) which may be attributed to high cropping.

High Ravaz Index ratios (16.3 to 21.9) recorded during this study indicated that all grapevines were overcropped (Figure 4). For example, *V. vinifera* cultivars on various rootstocks trained to a divided canopy system and grown in a warm climate with optimum fruit quality parameters had Ravaz Index values that ranged from 5 to 10 (Kliewer and Dokoozlian 2005). Main (2005) reported the optimum Ravaz Index was 6 to 8.4 for own-rooted Norton vines trained to a single canopy system. However, because this rootstock study was trained to a divided canopy system, the optimum Ravaz Index would be higher than that of a single canopy system.

All nutrients in petioles from own-rooted vines and vines on rootstocks were in sufficient ranges during both years of the study with the exception of Ca, Mg, P, and K (Tables 3, 4, and 5) (Bates and Wolf 2008). Petiole content of Ca, P, K, Mn, and Zn varied among rootstocks. Calcium was slightly insufficient in vines on 101-14, 1103P, 140Ru, and 1616C rootstocks (Table 3). Conversely, Mg was excessive among all rootstocks in 2011 (Table 3). Although high Mg alone is not detrimental to grapevines, it is in direct competition with other nutrients and is known to inhibit the uptake of K, resulting in deficiency of the latter element (Bates and Wolf 2008). Phosphorus was deficient in own-rooted vines and vines grafted onto 5BB and 44-53M for both years, while vines on 3309C, 101-14, SO4, 140Ru, and 1616C rootstocks were P deficient in 2011 (Table 4). The reason for varying nutrient

contents is unclear, but may be related to root numbers and densities among rootstocks. Although net root architecture was not characterized in this study, rootstocks with few roots may limit P absorption from the soil. Heavy cropping in 2010 likely resulted in inadequate P availability for another heavy crop load in 2011.

In contrast, K content in petioles was not only high, but excessive (> 2%) in vines on rootstocks 101-14 and 1616C in 2010 (Table 4). Increased K in petioles of scions grafted onto 101-14 and 1616C rootstocks has been reported by Christensen (2003). In the present study, own-rooted vines and those on all rootstocks were deficient (< 1.2%) in 2011. Because crop removal (i.e., K loss from fruit) was high in 2010, K availability in vines for the following year was most likely inadequate for vines on all rootstocks. Additionally, K content was likely deficient in direct response to excessive Mg content. High rainfall in May and June 2011 may have also caused K to leach out of the root zone, with reduced availability for vine uptake. Potassium deficiency symptoms were observed on leaves of vines with those on 1616C rootstock the most severe. Symptoms ranged from minor leaf chlorosis on the margins which spread interveinally to more severe necrotic and curled leaf margins. Interestingly, only P and K were negatively affected by the higher cropped year. This suggests that supplemental fertilizer may be required in addition to N supplied by urea or ammonium nitrate to produce adequate yield and fruit composition in subsequent growing seasons.

Juice concentrations of N, P, Ca, Mg, S, Mn, and B varied by rootstocks (Tables, 9, 10, and 12). Although sufficiency ranges for juice nutrients (except N) have not been determined, all were within reported ranges for own-rooted vines and vine on all rootstocks, with the exception of ammonia (Table 9) (Bisson and Butzke 2000). Low concentrations of total N (including ammonia) can result in slow or stalled fermentation due to its role in yeast metabolism. However, this situation can be easily mitigated by addition of diammonium phosphate (DAP) before fermentation (Bisson and Butzke 2000, Keller 2010, Zoecklein et al. 1999).

Most juice mineral concentrations were greater in 2010 than 2011, except for N, Zn, and Mn (Tables 9, 10, 11, and 12). Lower concentrations of most juice minerals may be attributed to a dilution effect of minerals in the high number clusters per vine in 2011 (Table 6). Also, there may have been a reduced mineral supply within vines because additional fertilizer containing these nutrients was not applied. In contrast, N, Zn, and Mn concentrations were not limited in 2011 due to urea and fungicide (containing Zn and Mn) applications.

The relationship between petiole nutrients and juice minerals is unclear. Because different methods were used to determine these mineral contents in juice in plant tissue and juice, comparisons are difficult. However, there were no rootstocks that consistently ranked high or low for any specific nutrient.

Although the current study was conducted on young vines at a single site for only two years, Norton fruit yield was enhanced when this cultivar was grafted onto 101-14, 110R, and 1616C rootstocks. With supplemental fertilizer, nutrient

deficiencies can be eliminated and excessive cropping may be reduced by more bud removal during pruning.

CHAPTER 6: SUMMARY AND CONCLUSIONS

The effect of various rootstocks and own-rooted vines on vegetative growth, yield, and fruit composition of Norton grapevines was studied during two seasons. Vines with 101-14, 110R, or 1616C rootstocks had greater yield than own-rooted vines. Organic acids, glucose, or fructose content of berries or their juice were similar among rootstocks. Although N, P, Ca, Mg, S, and Mn concentrations in juice varied among rootstocks, all were within acceptable ranges. Pruning weights and the number of shoots per vine were most likely affected by higher fruit yields, but not by rootstocks. The combination of the high crop load, low pruning weights, and the two-fold increase in Ravaz Index from 2010 to 2011 indicate that the balanced pruning formula utilized in this study did not effectively balance vegetative growth and fruit yield.

Petiole nutrient contents varied among rootstock. In 2010 and 2011, Ca was deficient in grapevines on 101-14, 1103P, 140Ru, and 1616C rootstocks. Phosphorus was inadequate in vines on 5BB and 44-53M rootstocks, and own rooted vines in both years, and in vines on 3309C, 101-14, 140Ru, and 1616C rootstocks in 2011. In contrast, petiole K was excessive for vines on 101-14 and 1616C rootstocks in 2010.

Generally, Norton is grown on its own-roots; however, in this limited study on young vines over two seasons at a single site, fruit yields were enhanced when this cultivar was grown on 101-14, 110R, or 1616C rootstock. However, to maintain

the benefits of Norton on these rootstocks, it may be necessary to apply supplemental fertilizer and remove more buds at pruning to sustain high cropping.

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