Groundcover, rootstock and root restriction effects on vegetative growth, crop yield components, and fruit composition of Cabernet Sauvignon.

Tremain Archer Hatch

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Tony K. Wolf (committee chair)
Gregory E. Welbaum
Bruce W. Zoecklein

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ABSTRACT

Wine vineyards in humid environments like the mid-Atlantic United States are characterized by vines that develop too much vegetative growth for optimum quality wine production. Cover crops, rootstocks and rootzone restriction were evaluated for their effect on vegetative and reproductive growth on Cabernet Sauvignon. Treatments were arranged in a strip-split-split plot arrangement with under-trellis cover crops (UTCC) compared to row-middle only cover crop combined with 1-m weed-free strips in the vine row as main plots. Rootstocks riparia Gloire, 420-A, and 101-14 were sub-plots, while sub-sub-plots comprised two treatments: vines were either planted in root-restrictive (RR), fabric bags (0.016 m^3) at vineyard establishment (2006), or were planted without root restriction. All three factors were effective in suppressing vegetative development as measured by rate and extent of shoot growth, lateral shoot development, trunk circumference, and dormant pruning weights. Canopies of vines with UTCC and RR had reduced leaf layer values by approximately 21% and 23% compared to conventional controls. The principal effect of the UTCC and the RR treatments was a sustained reduction in stem (xylem) water potential. UTCC and RR caused significant 7 and 10% reductions in berry weight, compared to their conventional controls. Berry weights of vines grafted to riparia were greater than those of vines grafted to other rootstocks. Wine made from UTCC and RR treatments increased red wine color compared to herbicide UTGC and NRR, respectively. This study identified treatments that improve vine balance while simultaneously improving grape composition and potential wine quality.

Dedication

This thesis is dedicated to all the friends and family members whom have helped make Zephaniah Farm Vineyard a reality.

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Grapevine balance

Grapevines are perennial plants that have both vegetative growth and reproductive growth, i.e. fruit, occurring in the same growing season. The vegetative growth provides structural support and develops the photosynthetically active leaf area that makes maturation of crop possible. Grapevines, like all plants, are affected by the environmental conditions in which they are grown. The ratio of vegetative growth to reproductive growth is a key factor in quality fruit production (Howell 2001; Kliewer and Dokoozlian 2000). Ecological components of the vineyard, such as climate, soil and cultivar can impact the ratio of vegetative and reproductive growth; this ratio is indirectly determined through the influence these ecological factors have upon the vine's water status (van Leeuwen et al. 2004). Vines with too much vegetative growth cannot be economically trained to maximize leaf exposure to full sunlight. Overcropped vines lack enough functional leaf area to ripen their crop. Balance implies equilibrium of vine reproductive and vegetative growth for production of active leaf area that will adequately ripen fruit (Howell, 2001). A ratio of 7-14 cm^2 healthy, exposed leaf area per gram of crop is needed to ripen fruit (Howell, 2001). The Ravaz index is a ratio of crop weight to dormant cane pruning weight. Ravaz index values between 5 – 10 are considered to be in balance (Kliewer and Dokoozlian 2000). Pruning weights between 0.3-1.0 kg per meter of canopy are capable of producing high quality wine grapes without within canopy shading (Kliewer and Dokoozlian 2000).

Excessive vegetative vine growth is a common problem for mid-Atlantic vineyards. Excessive vegetative growth is achieved by higher rates of vine growth or vigor. Trellising and canopy management for these vines is expensive. Vines with poor canopy management decrease vineyard profitability and fruit quality. The excessive vine vigor is attributed to a

surplus of plant available water, warm temperatures, and precipitation during the growing season. Soils common to vineyard sites in the mid-Atlantic are deep with fine textures which have high water holding capacities.

Excessive vegetative growth of grapevines can limit fruit quality by means of canopy shading (Smart and Robinson 1991). Canopy shading in this context is due to canopy congestion, where multiple leaf layers are present in a single canopy transect.. A canopy makes a three dimensional shape (usually rectangular). The surface area of this three dimensional shape intercepts sunlight though the day (Smart 1985). Congested canopies have a greater leaf area than canopy surface area. This situation results in vine organs shading other vine organs, this is called, within canopy shading.

Within canopy shading is positively correlated increased pH and potassium ion concentration [K^+] in grapes (Smart 1985). Wine pH is a component of wine stability. A lower pH wine has more resistance to color fading and microbial spoilage (Mpelasoka et al. 2003). Within canopy shading is inversely related to sunlight exposure on fruit. Berries that intercept direct sunlight will have higher daytime temperatures than shaded fruit. Malic acid is utilized as an energy source through respiration. Rate of respiration will increase with berry temperatures (Conde et al. 2007). Therefore fruit with less within canopy shading and less fruit shading should have lower malic acid content in the fruit at harvest. Biosynthesis of phenolic compounds important to wine color, taste and stability are also influenced by temperature (Downey et al. 2006). Overall wine quality was found to be lower on fruit sourced from more shaded canopies in sensory analysis studies (Smart 1985).

Vine water status

Water is a necessary component for plant growth, development and assimilation of carbon (Taize 2006). Negative pressure in the plant is caused by leaf transpiration and is

conducted throughout the plant to the root surface where water is drawn out of the soil, like tension pulled on a rope (Waisel et al. 2002). This tension is maintained through the plant by the cohesive and adhesive properties of water (Taize 2006).

Soil moisture is subject to multiple forces, which determine in what direction the water will move. These include gravity, the negative force pulling down on the water, matrix potential of water adhering to soil particles, and osmotic potential of solutes driving diffusion. In order for water to enter the plant from the soil, the tension pulling the water into the plant must be greater than the combined matrix, osmotic and gravitational potential pulling the water away from the plant root surface (Black 1968). As the soil moisture content decreases, the thickness of the water film surrounding a soil particle decreases, and the matrix force holding the water film around the soil particle increase. Therefore, the plant must exert more tension to pull water away from the soil particles and into the roots.

The water status of a vine can be measured as the tension with which water is held in a plant organ. This value is called the water potential and is denoted by the Greek letter Psi (ψ). The water potential can be measured in the leaf of a grapevine by using the pressure chamber technique (Scholander et al. 1965). Water potential values are influenced by the time of day, organ or material with which measurement is made. These measurements have been categorized to allow for distinction of the values collected. Plant organs that have water potential values include tissue (ψ_{tissue}), leaf (ψ_{leaf}), stem (ψ_{stem}), and fruit (ψ_{fruit}). Water potential measurements of plant organs are better indicators of plant physiological status than soil water potential measurements (Shackel 2007).

Leaves have stomates and these outlets allow water vapor to escape the leaf and carbon dioxide to enter the leaf. The tension close to the stomates is greater than the tension conducted though vascular tissue of the plant. Leaf water potential measures the ψ of a leaf

while the leaf is subject to sunlight interception and evaporation. To measure the tension within the xylem, leaves are sealed from the environment with an opaque, foil-laminate bag. Once this bag has been on the leaf for more than ten minutes the ψ measured shows the tension conducted though the plant, this ψ measurement is known as ψ_{stem} (Shackel 2007). A grapevine canopy is made up of multiple leaves with different exposure to sunlight, wind and humidity. Leaf water status is affected by sunlight, wind and humidity. Leaves of the same vine in the same canopy have high variability in ψ_{leaf} values but similar ψ_{stem} values.

Measurement time of day influences ψ values, largely due to the influence of transpiration. Water potential ($\psi_{pre\text{-}dawn}$) measurements taken just before dawn indicate of the ψ of a plant with no transpiration driven tension. Of the commonly used measurements, ψ_{stem} is best overall indicator of plant water status (Chone et al. 2001; Shackel 2007).

Vegetative growth of grapevines is more sensitive to water deficits than the rate of carbon assimilation (Schultz and Matthews 1988). The relative sensitivity of tendrils, internodes and leaves to water deficit and the level of deficit needed to stop growth of these organs has been found empirically (Schultz and Matthews 1988). Stem water potential has a significant correlation with shoot growth rate, more negative ψ_{stem} correlating with lower rates of shoot growth (Shackel 2007). These principles can be utilized with irrigation strategies that maintain a vine water status to reduce shoot growth yet not low enough to significantly reduce carbon assimilation.

Irrigation strategies to regulate vine size, vine vigor and reproductive development

Plant available water can be increased with irrigation. Regulated deficit irrigation (RDI) is a practice of imposing water stress on the grapevine after fruit set, then alleviating

this stress during the berry ripening period. The goal of RDI is to reduce the berry size, yet not reduce the berry ripeness at harvest. Accurate irrigation management is necessary for this practice, and stem water potential measurements are a practical tool allowing for an objective view of vine water status (Chone et al. 2001; Shackel 2007). Water potential thresholds for grapevine growth responses have been established empirically (table 1).

Table 1 – ψ values for vine growth thresholds and relationships with gas exchange.

Vine response	**Value**	**Measurement**	**Adapted from**
Cessation of vegetative growth	-1 MPa -0.53MPa	Ψ_{tissue} ψ_{soil}	(Schultz and Matthews 1988; Shellie 2006)
Inhibition of volumetric increase of berries	-1.5 MPa	ψ_{leaf}	(Roby and Matthews 2004)
60% reduction in transpiration	Decrease 0.5 MPa	ψ_{stem}	(Chone et al. 2001)

Arid conditions with limited amounts of plant available water are required for RDI to achieve desired response. Virginia's climate does not consistently limit soil moisture because of high precipitation.

Partial rootzone drying (PRD) is an irrigation strategy that has potential for improving grapevine water use efficiency, maintaining crop production at levels comparable to those of well watered grapevines, and improving fruit quality. Two separate rootzones are created in PRD, these rootzones are irrigated individually. One rootzone is irrigated while the other is allowed to dry. The rootzone treatments are switched on an approximately 14-day interval. Abscisic acid (ABA) is an endogenous hormone and a component of many physiological pathways in the vine, including stomatal regulation. PRD utilizes the principle that roots can generate ABA in drying soil to signal the shoots to slow stomatal conductance and vegetative growth (Stoll et al. 2000). The drying rootzone induces the synthesis of ABA while the moist rootzone keeps the vine hydrated. When ABA is transported to the shoots, the stomatal conductance is decreased and the vegetative growth slows. The decreased stomatal conductance is responsible for the vine's increased water use efficiency. PRD is used in

commercial vineyard operations because irrigation economy is improved and vine size and fruit quality is often improved.

RDI and PRD are different irrigation management strategies that are derived from a shared principle of viticulture. The shared foundation is that vines subjected to droughty conditions have less vegetative growth. RDI succeeds in creating this reduction by creating a deficit water status in the vine, stressing the vine to shut down vegetative growth usually resulting in a smaller crop than vines supplied with surplus plant available water. PRD succeeds in creating a reduction of vegetative growth by tricking the vine into shutting down vegetative growth without sacrificing functional leaf area. PRD and RDI both decrease the water usage in the vineyard; however, PRD ideally decreases water usage without decreasing the crop yield.

Fruit composition

The water status of grapevines has important implications for fruit quality. The relative proportion of berry components (seed, skin, pulp) can be affected by water deficit during the synthesis of these berry parts. The important wine constituents are focused in the skin and seed of the grape berry (Kennedy 2002; Roby and Matthews 2004). Berry growth is modeled with a double sigmoid curve. Berry cell number increases in the first positive slope, at veraison there is a lull in berry development, then after veraison berry development increases again with expansion of pulp cells with sugar and water (Conde et al. 2007). A deficit water status post veraison can reduce pulp expansion (Kennedy 2002; Roby and Matthews 2004). Increased skin to pulp can be favorable for wine quality because the majority of color and aroma precursors are located in the skin and seed, and largely absent in the pulp.

Phenolic compounds are responsible for color, bitterness, astringency and anti-oxidant properties of wine (Harbertson and Spayd 2006). Phenolic compounds have different

properties and spectral signatures, however all phenolic compounds have a aromatic ring structure that absorbs light in the ultraviolet and visible spectra (Downey et al. 2006; Harbertson and Spayd 2006). Absorbance of ultraviolet light at 280nm will give a measure of all the compounds in the solution with an aromatic ring (Harbertson and Spayd 2006). Anthocyanins are responsible for most of the color in red wine, and have a absorption maxima at 520 nm (Harbertson and Spayd 2006). Color density is the sum of A_{420} and A_{520}, and hue is the ratio of A_{420} and A_{520} (Harbertson and Spayd 2006). Color density measures how much color is in the wine and hue will measure brick red color of wine that occurs during wine aging (Harbertson and Spayd 2006).

Cover crops

Common vineyard floor management in the mid-Atlantic makes use of a perennial grass sward in the row middles and a bare soil strip about a meter wide below the trellis. Grass cover crops utilized this way are living mulches, because they are maintained as a living ground cover during the growing season (Hartwig and Ammon 2002). The bare soil strip below the trellis is managed by cultivation, pre- and post-emergent herbicides, or a combination of cultivation and herbicides.

Complete grass covers of the vineyard floor are used on some vigorous vineyard sites. Grass cover crops compete with vines (Ingels et al. 2005; Wolpert et al. 1993). Cover crops are utilized in vineyards for erosion control, nitrogen or organic matter addition, improved soil structure and water penetration, reduction of excessive soil moisture and enhanced pest management (Ingels et al. 2005).

Grass covers in the row middles have not always been utilized in vineyards. Roman vineyards were kept weed-free to reduce weed competition and to ensure high yields (Hartwig and Ammon 2002). Vineyard floor management differs depending on the vineyard site,

vineyard vigor and management objectives. Weed-free vineyard floors are used in more arid environments to minimize weed competition. Perennial cover crops will affect nutrient status of the vineyard especially as the cover crop is established. Cover crops that have established a full perennial sward cover have an equilibrium of nutrient needs and deposits. Cover crops will add organic matter to the soil after full establishment, which will improve vine nutrition and performance. This organic matter will improve soil characteristics leading to improved soil structure, which improves plant productivity (Ingels et al. 2005).

Cover crops compete with grapevines for soil moisture (Celette et al. 2008; Tesic et al. 2007; Wolpert et al. 1993). In a vineyard trial where a grass sward was maintained in the row middles, cover crops utilized water from the shallow soil below the cover crop and the grapevine utilized water from the groundcover bare strip below the trellis as well as the deeper profiles of soil that only the vine roots could explore (Celette et al. 2008). Cover crops improve soil water replenishment during rainfall events due to increased rates of infiltration (Celette et al. 2008). Complete under-vine grasses have reduced vines' vegetative growth; reducing pruning weights, early season rates of shoot growth and shading within the vine canopy compared to partial and full grass-free vineyard floor treatments (Tesic et al. 2007). Under trellis grass covers can significantly reduced berry weight compared to vines with full and partial weed-free zones on the vineyard floor (Tesic et al. 2007). Sunlight interception by nodes improves bud fruitfulness the following year (May et al. 1976), however, cover cropped vineyards in California had reduced canopy density and reduced yields, indicating that bud fruitfulness was negatively affected by cover crops in the vineyard (Wolpert et al. 1993).

Grapevine root systems and rootstocks

Plant roots serve several purposes: anchorage for the above-ground portions of the plant and below ground surfaced area for water/nutrient absorption, hormone synthesis and

provide perennial wood for nutrient and carbohydrate storage (Black 1968; Stoll et al. 2000). Vines utilize tendrils to obtain support from other above-ground structures; therefore trellised grapevines do not depend upon their root structures to support their above ground architecture (Smart et al. 2006). Vineyard management practices and environmental factors including: soil texture, soil bulk density, soil fertility and soil water content affect root growth and distribution (Smart et al. 2006).

Grapevine root systems, being below ground, are inherently difficult to observe. Grapevine root systems explore a larger volume of soil and have a lower root density than many other plants (Smart et al. 2006). A larger volume of soil explored by grapevine roots increases the probability for roots to find nutrient and water resources. The large volume of soil explored and the low density of roots, could make vines competitive in a forest ecosystem where grapevines could find and utilize pockets of soil not explored by the trees that the vines grow upon (Smart et al. 2006). Grapevine roots explored regions of soil space not colonized by fescue roots when tall fescue was grown in the row middles, while in control plots containing no fescue, vine roots explored the shallow soil in the row middles and under the trellis (Celette et al. 2008).

Growing *Vitis vinifera* grapes in Virginia requires grafting of the scion to phylloxera resistant rootstock (Pouget 1987; Wolf 2008). The physical process of grafting grapevines confers a change in vine function. In self-grafted grapevines the physical obstacle of the graft on vascular tissues is evident as a favorable effect on fruit set indicating a grafting effect, however the graft caused no significant differences in yield or vigor (Pouget 1987). Both rootstocks and *Vitis vinifera* varieties have their own genotype-specific vigor; however, the conferred vigor of the vine x rootstock union is independent of either rootstock or scion vigor. Rootstock x scion selection can be used to moderate scion performance on a given site e.g. a

vigorous rootstock on a low vigor site or a low vigor rootstock used at a high vigor site. Root emergence angles of rootstocks have been studied, however, the effect of rootstock on root distribution of mature vines is not fully understood (Smart et al. 2006). The conferred vigor of a rootstock is also attributed to resistances in the rootstock to uptake and transmission of water and nutrients. Root type also influences the uptake of nutrients from the bulk soil.

Table 2- Rootstocks shown with parentage and relative vigor ratings.

Rootstock name[a]	**Common name**	**Parentage**[a]	**Vigor**[b]
Riparia gloire de Montpellier	Riparia Gloire	Vitis riparia	1-2[c]
420-A Millardet et de Grasset	420-A	Vitis berlanieri X Vitis riparia	1-2
101-14 Millard et de Grasset	101-14	Vitis riparia X Vitis rupestris	2-3

[a] adapted from (Pongracz 1983)
[b] adapted from (Wolf 2008)
[c] 1 = low vigor and 5 = high vigor

Riparia Gloire, 420-A, and 101-14 are rated as relatively “low vigor” rootstocks (Wolf 2008). The rootstock Riparia Gloire is known to confer low vigor to the grafted scion (Pongracz 1983; Sampaio 2007; Wolf 2008). The rootstock Riparia Gloire has been credited with shifting scion vine growth toward reproductive biomass and away from vegetative biomass (Ollat et al. 2001). The rootstock 101-14 has higher vigor than Riparia Gloire and 420-A (table 2). The rootstock 420-A is reported to be a higher vigor rootstock than Riparia Gloire and lower vigor than 101-14 (Wolf 2008), however one rootstock trial in Oregon found this rootstock to have higher vigor and yield compared to 101-14 (Sampaio 2007).

Potassium is a key material in plant function. High potassium concentration in grapevine petioles at bloom is correlated with high potassium concentration in the fruit, which can cause high wine pH (Mpelasoka et al. 2003; Ruhl and Fuda 1991). Boulton (1980) suggests that an ATPase pump facilitates the replacement of H^+ with K^+ (Boulton 1980). Replacement of H^+ by K^+ can lower titratable acidity and increase pH values. High pH is

negatively attributed to wine qualities such as lack of acid for taste, and low color and microbial stability (Mpelasoka et al. 2003). Rootstocks with *Vitis berlandieri* ancestors are associated with lower potassium uptake than rootstocks of other Vitis parentage (Wolpert et al. 2005).

Root restriction

Physical restriction of the volume of soil that plant roots explore reduced vegetative growth in apples (Byers et al. 2004), peaches (Boland et al. 2000), and grapevines (Wang et al. 2001). Wang (2001) grew *Vitis vinifera* grapevines cv. Kyoho, in restricted volumes of soil buried in the bulk soil. Treatments that reduced soil volume reduced grapevine vegetative growth and increased the accumulation of skin color, juice soluble solids, and improved fruit set (Wang et al. 2001). The mechanism responsible for this reduced vegetative growth was a quicker depletion of soil moisture content in the fixed soil volume (Wang et al. 2001). The buried soil volumes had similar soil temperatures to the bulk soil (Wang et al. 2001). Root restriction bag materials and volumes were evaluated for apple (Byers et al. 2004) and peach trees (Boland et al. 2000). Restricting roots of apple trees resulted in reduced dormant pruning weights, while increased tree flowering, yield efficiency, fruit color, firmness and soluble solids (Byers et al. 2004). Restricted root volumes coupled with RDI reduced fruit and tree size (Boland et al. 2000).

Manipulation of the volume of soil that grapevine roots can explore changes the normally diffuse rooting patterns of the grapevine. Byers (2004) believed that reduced vegetative growth of apple trees was an effect of excessive restriction of roots to a smaller soil volume. Restricted root volumes decreased vegetative growth and total water use in peach trees (Boland et al. 2000). Restriction of peach tree vegetative growth by root restriction was not severe when precipitation was above normal (Boland et al. 2000),

indicating that water deficit was important to reductions in vegetative growth. Root to shoot signaling could be partially responsible for the plant response to a restricted volume of soil. Root meristems may be in contact with root restriction materials or dry soil could alter root meristematic hormone production.

Methods and materials

Research objectives

The objectives of this study were to determine if vegetative growth and vigor of Cabernet sauvignon could be altered. The second objective was to determine how changes to vine growth impacted fruit composition and potential wine quality.

Research methods

Site details

The experiment site was located at the Alson H. Smith Jr. Agricultural Research and Extension Center, near Winchester, VA. Soil was Frederick-poplimento sandy loam, with an approximate rooting depth of 0.75 to 1.50 m; site had good topography for cold air drainage resulting in low chance of frost injury. Location averaged 1900 heat units (10˚C base) and 550mm rainfall accumulated April through October (Zoecklein et al. 2008).

The vineyard site was fallow with tall fescue for 3 years before vineyard installation. Soil testing and soil amendments were applied, the trellis was erected and meter wide rows where the vines would be planted was cleared with herbicide in 2005. Rows run northeast/southwest; inter row spacing of 3m with an inter-planting space of 1.5 m. The vines were planted In May of 2006.

Treatments

Three factors: under trellis ground cover (UTGC): a permanent under the trellis cover crop [UTCC] verses herbicide strip below the trellis; 3 rootstocks: Riparia Gloire (riparia) (*Vitis riparia*), 420-A (*Vitis berlandieri X Vitis riparia*), and 101-14 (*Vitis riparia X Vitis rupestris*); and root manipulation (RM): root restriction bags (RR) and no root restriction (NRR) were evaluated in this study. Treatments were organized in a strip-split-split plot design. The main plots comprised a comparison of UTGC, sub-plots comprised a comparison of three rootstocks and the sub-sub-plots evaluated a comparison of root manipulations. Experimental units were panels of 5 vines, and all plots were replicated 6 times in a randomized complete block design. The UTGC plots were separated by border panels of five vines to prevent confounding effects on soil moisture.

All scion wood was Cabernet Sauvignon, clone 337. No root restriction vines were planted in the bulk soil with no restriction imposed on the volume of soil that the vine roots could explore. The planting process for root restriction vines required: auguring a hole, placing a fabric root restriction bag into the augured hole, then planting the vine and replacing the soil into the root restriction bag. The root restriction bags (High Caliper Products Oklahoma City, OK) are made of a UV-stabilized, fabric cylinder with an open top end; they are intended for use in the nursery industry for transplanting. The bags have a volume of 0.015 m^3 with a diameter of 0.24 m and height of 0.32 m.

A 1 m wide soil strip under the trellis was kept clean with herbicides until late-summer of 2007, at that point UTCC plots had creeping red fescue (*Festuca rubra)* seed sown, and then covered with straw. By bud-break in 2008, these treatments had a full sward established below the trellis. The UTCC plots were not mowed however a circular weed-free area with a radius of approximately 0.13 m was maintained around the vine trunks using pre-emergent

and contact herbicides.

Vineyard management

Vines were established and managed following commercial recommendations for the mid-Atlantic region (Wolf 2008). Vines were cordon-trained and spur-pruned, with vertical shoot positioned canopies. Twelve shoots per m of cordon were retained by dormant pruning and spring shoot thinning. Pest management for the plots followed Virginia Tech's commercial Pest Management recommendations (Pfeiffer et al. 2009). Nitrogen fertilizer was applied both years at a rate of 22.4 kg/hectare. Application of soluble $CaNO_3$ was split between two applications, the first two weeks before bloom and the second two weeks after bloom.

Crop level

Crop levels were controlled so that the crop load was similar between the treatments. Crop load is the ratio of crop to vegetative growth, such as cane pruning weights (Howell 2001). Crop levels in 2008 were reduced to 10 bunches per vine while the non-restricted vines were kept at 20 bunches per vine. Crop was thinned to balance the pruning weights from the previous winter in 2009. Crop thinning took place both years at pea berry size BBCH 75, the extended BBCH scale is a grapevine specific phenology scale (Lorenz et al. 1995).

Irrigation

Irrigation was utilized in the vineyard to avoid severe drought stress. The irrigation was used at the same rate (2.27 liters per hour emitters on 0.3 m centers) to all the treatment plots in 2008, with RR vines water status as the indicator to initiate the irrigation. Adaptations were made to the irrigation line in August of 2009, to enable watering only RR vines, or all vines if desired. Irrigation control specific to the treatments was enabled because some treatments

caused water stress.

Irrigation was applied beginning 15 August 2008 on a weekly schedule with the goal of avoiding water stress greater than –1.0 MPa. Irrigation was applied for one hour at a rate of 2.27 Liters per hour.

Irrigation applications began in mid-July 2009 using a irrigation strategy that watered RR vines every week and all vines every other week. When vines received supplemental irrigation they received about 2.3L. The irrigation pattern continued until late-September when significant (>20 mm) rainfall events occurred.

Data collection

Shoot growth

Shoot growth rates were obtained by repeated measures of shoot length between shoot emergence and shoot hedging. Ten shoots per replicate (2 representative shoots per vine) were measured with a flexible measuring tape on a bi-weekly basis. Measurements were made from the base of shoot to the apical meristem. Shoots were selected from the middle of the cordon, had at least one inflorescence, and were representative in length for the treatment.

Pruning weights

Cane pruning weights were collected by vine each winter.

Trunk circumference

Trunk circumference measurements were made to characterize the amount of perennial wood produced by the different treatment combinations. The perennial wood in this case is used to measure the vines capacity of growth (Trought et al. 2008). A vine with more vegetative growth has a larger trunk girth. Trunk circumferences were measured at bloom

with flexible tape. The vines in this trial were all double-trunked. So both trunks were measured at the third node above the graft union, and the circumferences of the two trunks were summed.

Leaf area

Leaf area was evaluated 80 days post-bloom using the relationship of leaf length to leaf area. A regression equation (equation 1) that related leaf length to leaf area was first obtained by sampling 200 leaves and measuring both leaf length and leaf area. Leaf length was measured as the length of the leaf mid-rib while the area of the leaf was measured using a belt-driven leaf area meter LI-3000 (LI-COR, Lincoln, NE). Equation 1 was used to calculate the leaf area based upon measurements of the leaf mid-rib length.

Equation 1

Leaf area= 17.034[leaf length] +56.769; $R^2 = 0.759$

Leaf length was measured non-destructively on the shoots that had been tagged for shoot growth measurements (10 shoot per replication). The number of nodes was recorded along with the mid-rib length of the primary and lateral leaves developing from each node for these shoots. These measurements allowed for a calculation of the primary, lateral, and total leaf area per node. These leaf area per node values were compiled with primary node counts for vines. The leaf area per node and the node count per vine were combined to create primary and secondary leaf area per vine figures. The purpose of this measurement was to compare the leaf area of treated vines.

Leaf area per node was used as a foundation of leaf area estimation rather than leaf area per shoot (Smart, 1991) because there was significant variability in shoot length between vines of the same treatment. This variability made a leaf area per shoot value inadequate to describe the canopy as a whole.

Canopy architecture

Canopy transects or canopy point quadrat analysis provides a quantitative description of the canopy density and fruit exposure. The general approach was similar to that outlined in Smart and Robinson (1991) adding the more detailed data assessment of Meyers and Vanden Heuvel (2008). Twenty canopy insertions were made per treatment replicate using a probe insert frame. Probe insertions were made at 20 cm intervals in the canopy fruit zone. The PQA and EPQA analyses were used to analyze this canopy transect data. The calculated values that were used for this study are defined in table 3.

To characterize the fruit exposure to sunlight, light measurements within the canopy were made using a ceptometer (AccuPAR Model 80, Decagon Devices, Inc.) within the hours surrounding solar noon on a cloudless day at veraison BBCH 81. The light measurements included a measurement of ambient, unobstructed light collection on the sensor surface, and measurement of the light collection on the sensor surface when placed within the fruit zone of the canopy (15 cm above the cordon wire). This pair of measurements provides a means of estimating the light attenuation by the canopy.

The PQA analysis enables canopy characteristics to be quantified. The PQA is a powerful tool for vineyard operators and researchers. The EPQA utilized the same insertion with one new insertion value, a mid-canopy ‘wire’ and calculates values to describe symmetry of biomass in the canopy. EPQA can also integrate with light measurements in the fruit zone and outside the canopy to calculate the light attenuation by the canopy.

Table 3 Calculated canopy parameters from PQA adapted from (Smart and Robinson 1991) and EQPA adapted from (Meyers and Vanden Heuvel 2008).

Metric	Abbreviation	Unit of expression	Value range	Description	Analysis
Percent gaps	PG	gaps	0 to 100%	The total number of gaps divided by the number of insertions.	PQA
Leaf layer number	LLN	contacts	0 to ∞	The total number of leaf contacts divided by the number of insertions.	PQA
Percent interior clusters	PIC	None	0 to 100%	The number of interior clusters divided by the total number of clusters.	PQA
Percent interior leaves	PIL	None	0 to 100%	The number of interior leaves divided by the total number of leaves.	PQA
Occlusion layer number	OLN	Contacts	0 to ∞	Number of shade-producing contacts (leaves and clusters) per insertion.	EPQA
Cluster exposure layer	CEL	Occlusion layers	0 to ∞	Number of shading layers between clusters and nearest canopy boundary.	EPQA
Leaf exposure layer	LEL	Occlusion layers	0 to ∞	Number of shading layers between leaves and nearest canopy boundary	EPQA
Canopy cluster symmetry	CCS	None	-1to 1	Ratio of the number of occlusion layers between a cluster and the insertion side of the canopy.	EPQA
Cluster exposure flux availability	CEFA	None	0 to 1	Percentage, expressed as a decimal, of above-canopy photon flux that reaches clusters.	EPQA
Cluster exposure flux symmetry	CEFS	None	-1 to 1	Ratio of the photons flux that clusters receive from the insertion side of the canopy vs. the exit side of the canopy.	EPQA
Leaf exposure flux availability	LEFA	None	0 to 100%	Percentage of above-canopy photon flux that reaches leaves.	EPQA
Leaf exposure flux symmetry	LEFS	None	-1 to 1	Ratio of the photon flux that leaves receive from the insertion side vs. the exit side of the canopy.	EPQA
Trellis contact symmetry	TCS	None	-1 to 1	Ratio of the number of biomass contacts on the insertion side vs. the exit side of the trellis center.	EPQA

Lateral development

Development of lateral shoots is a critical component of canopy density. Vines were evaluated to give a relative score to the degree of lateral development.

Lateral evaluations were made at veraison, BBCH 81 in 2008 and 2009. Evaluation of laterals took place on the center vine of the five-vine experimental unit. The two shoots that had previously been selected and marked for shoot length measurements were evaluated.

Count nodes three though seven from the shoot base were inspected and laterals were scored by the number of completely unfolded leaves. A lateral with no unfolded leaves was given a value of zero, a lateral with one unfolded leaf was given a value of 1, and a lateral with 10 or more unfolded leaves was given a value of 10. *Lateral evaluations were made on treatments that had herbicide strip UTGC in 2008. All treatment combinations had lateral evaluations in 2009.*

Leaf gas exchange

Transpiration (E), photosynthesis (A), and stomatal conductance (g_s) were measured at different phenological stages during the growing season using a CIRAS-1 (PP Systems, Cambridge, UK])portable, closed system, infrared gas analyzer, fitted with an environmental cuvette. The leaves selected for gas exchange measurements were primary, mature leaves, well exposed to sunlight. Gas exchange conditions were as follows: ambient temperature of 25 to 35˚C, under clear or hazy light conditions; CIRAS operating conditions had a CO_2 supply of 370-410ppm, and internal pump rate of 200mL/min. RH and CO_2 were calibrated monthly per manufacturer's instructions. Gas exchange measurements were performed both seasons but more consistently in the 2009 season, from which data will be presented. When a measurement was taken, the cuvette had been attached to the leaf for 90 seconds to allow an equilibrium to be reached in the cuvette. Gas exchange measurements were taken at bloom (BBCH 60), pea-sized berries (BBCH 75), veraison (BBCH 81), and mid-maturity (BBCH 87). These measurements were taken in combination with ψ measurements to correlate gas exchange and vine water status.

Water potential

Leaf water potential and ψ_{stem} measurements were obtained using a pressure chamber (Model 600, PMS Instrument Co.,Corvallis, OR) (Sholander, 1965). Mid-day leaf water

potential (ψ_{leaf}) was measured by bagging leaves then immediately cutting and placing the leaf in the pressure chamber for analysis. Stem water potential (ψ_{stem}) measurements consisted of bagging the leaf one hour before the leaf was cut and placed in the pressure chamber; the bag eliminates the atmospheric demands from the leaf, and reflects the sunlight. Stem water potential measurements were made between 1200 and 1400 HR.

Leaf water potential measurements were taken in 2008. The intention of this measurement was to create a snapshot of the vines' water status between the two RM treatments. These values were used to create a seasonal view of vine water status; this also provides information to schedule irrigation.

Water potential measurements in 2009 were focused on profiling how the different treatments affected ψ_{stem} measurements. Stem water potential measurements were collected at bloom (BBCH 60), pea-sized berries (BBCH 75), veraison (BBCH 81) and mid-maturity (BBCH 87).

Soil moisture

Frequency domain reflectrometry-type soil moisture probes [PR-2, Delta-T Devices, Cambridge UK] were used to measure soil water contents at five different depths: 10cm, 20cm, 40 cm, 60 cm, and 100cm. Soil moisture content was recorded as volumetric water (m^3 H_2O m^{-3} soil). Sampling was performed in access tubes that were installed in 2006. Two access tubes were installed in each block in plots with NRR, 420-A with and without UTCC. Measurements were conducted on a biweekly basis during both growing seasons. A Delta-T devices representative stated that moisture within plant roots will not be measured with this soil moisture sensor.

Plant nutrient analysis

Leaf petioles and juice samples were analyzed for nutrient content. Petiole samples

were processed and analyzed by A&L Laboratories in Richmond, VA. Petioles from the two RM treatments were evaluated in 2008. Petioles were collected at cluster-close (BBCH 77) in 2008. Petiole sampling was performed at bloom, (BBCH 60) in 2009. Two replicates of all treatment combinations had petioles sampled in 2009.

Juice samples were analyzed for yeast assimilable nitrogen by the Virginia Tech Enology Service Lab in 2009. Four treatment combinations were analyzed: RR with herbicide strip, RR with UTCC, NRR with herbicide strip, and NRR with UTCC.

Fruitfulness

Node fruitfulness was evaluated in 2009 when inflorescences were clearly visible, (BBCH 53). All shoots and inflorescences were counted on one vine per treatment replicate. Shoots were classified as either “count” shoots or “base” shoots. “Count” shoots emerged from a one-year-old spur with an internode visible between the perennial cordon wood and the first spur node. “Base” shoots did not have one-year-old internode visible between the perennial cordon wood and the node, but rather emerged from the base region of the spur. Inflorescences were then classified as to whether they originated from a base shoot or a count shoot.

Fruit sampling and components of yield

Twenty-five-berry samples were collected both seasons at veraison, mid-maturity and harvest for analysis of primary fruit chemistry and berry mass. Fruit sampling was completed to determine how berry size was affected by treatment over time and monitor the rate and extent of fruit ripening so that plots could be harvested at similar maturity levels. Components of yield data were collected at harvest. Vines were harvested individually with the number of clusters and fruit mass recorded for each vine. Average cluster weight was calculated for each vine from these values.

Maturity sampling

Primary fruit chemistry was determined on fresh (non-frozen) berry samples within 24 HR of collection at the AHS AREC in Winchester, VA. Fruit maturity was evaluated on twenty-five-berry samples before harvest. Harvest fruit maturity was evaluated on fifty-berry samples. Soluble solids were measured using an optical refractometer (10430, Reighert Scientific Instruments, Buffalo, NY). pH was measured using an electrode and bench monitor (Orion 3 Star, ThermoFisher scientific, Beverly MA). Titratable acidity was determined by titration with 0.1 N NaOH until reaching an endpoint of pH 8.2.

Glucose-glycosides

Twenty-five- berry samples were collected at harvest in 2008, sampling was performed on plots that had herbicide below the trellis to compare the three rootstock treatments and the two RM treatments. Total Glucose-Glycosides (TGG) were measured from punches of skin extracted in ethanol using procedures of (Whiton and Zoecklein 2002).

Color

Estimates of total phenolics (Absorbance at 280nm, A_{280}), A_{420}, and total anthocyanins (A_{520}) were measured spectrophotometrically [Genesis 8, ThemoFisher Spectronic] from frozen fruit samples. These measurements utilized 25 x 9mm disks of berry skins, which were homogenized and extracted in a 50% v/v anhydrous ethanol solution acidified with HCl to pH 2.0. The sample was extracted for 2 hours, centrifuged then diluted 20:1 in 1M HCl for one HR before spectroscopy (Iland et al. 2000).

Wine-making

Fruit from UTGC and RM treated vines was made into wine to observe the quantitative and qualitative effects of the viticulture treatments on the wine. Fruit from the 2009 vintage

UTGC and RM treatments was combined in a factorial design then subsample to create 4 treatment combinations with 3 x 31kg replication of each lot. The treatments groups were fruit from vines with: herbicide UTGC and NRR, herbicide UTGC and RR, UTCC and NRR, and UTCC and RR.

Fruit processing and wine making occurred at the Virginia Tech Enology-Grape Chemistry Group's facilities in Blacksburg, VA. Fruit was de-stemmed and crushed into separate cylindrical fermentation vessels with the dimensions 33 cm wide and filled 33 cm deep. Must samples were analyzed for soluble solids, pH, titratable acidity (TA), and YAN. Must was cold soaked for 6 days at 4˚C. Yeast Levin ICV D80 was pitched at a rate of 500g yeast/20hL must, fermentation temperature (~21˚C) and rate were recorded and caps were punched down 3 times a day. Wine lots were juiced without significant pressure. Wines were settled for two days post-fermentation and then racked off the heavy lease into 11L glass carboys. Post fermentation wine analysis including alcohol, malic acid, pH, TA, volatile acidity (VA) and free and total sulfites were completed by The Enology Analytical Services Laboratory at Virginia Tech. Wine color was measured spectrophotomically. For measurements at 280 nm, 1mm path-length curettes were used. Wine samples were diluted until absorbance values were below 1.5, dilutions were made with distilled water with pH corrected to 3.5 with citric acid. Wine lots will be used for sensory evaluation in the spring of 2010.

Data analysis

Analysis of variance (ANOVA) was computed for the data collected using SAS proc mixed analysis (SAS Institute; Cary, NC). A strip-split-split plot design was used to analyze the significance of treatment effects and their interactions (equation 2). The fixed effects in

this model are UTGC, rootstock, and RM. The random effect is block. ANOVA tests the probability of measured variable to reflect a situation where there are no treatment effects. The lower the p-value the more likely there are treatment effects. In this study p-values less than 0.05 were considered statistically significant.

Equation 2- Model used for ANOVA

$\mu_{ijk} = \mu + G_i + R_j + GR_{ij} + M_k + MG_{ik} + MR_{jk} + MGR_{ijk}$

μ is the mean

G_i is the i^{th} UTGC effect

R_j is the j^{th} Rootstock effect

GR_{ij} is the ij^{th} UTGC X Rootstock interaction

M_k is the k^{th} RM effect

MG_{ik} is the ik^{th} RM X UTGC interaction

MR_{jk} is the jk^{th} RM X Rootstock interaction

MGR_{ijk} is the ijk^{th} RM X UTGC X Rootstock interaction

Blocks are random effects

Differences of least square means from proc-mixed was utilized to find significant differences between the rootstocks. Differentiating between the rootstocks was necessary because there were three different rootstocks in this treatment level.

Results:

Temperature and rainfall

This study took place during two growing seasons that were representative of the mid-Atlantic (figure 1, figure 2). The 2009 season had greater than average rainfall in May and early June, and below average precipitation in August-September (figure 2). However, the total seasonal rainfall in both years was similar (table 4), and very close to long-term averages from Winchester, VA.

Irrigation was applied beginning 15 August 2008 on a weekly schedule lasting until harvest. Irrigation was applied for one hour per week at a rate of 2.27 Liters per hour. Irrigation applications began in mid-July 2009 with all RR vines receiving about 2.5 Liters of water. The following week all vines received an hour of irrigation at rate of 2.27 Liters/hour. The following week only RR vines received supplemental irrigation. This irrigation pattern continued until late September when significant (>20 mm) rainfall event occurred.

Table 4 - Heat accumulation and precipitation from growing seasons 1 April -31 October 2008 and 2009.

Season	Growing degree days (base 10)	Total precipitation (mm)
2008	1742	731
2009	1757	721
historic average	1981	647

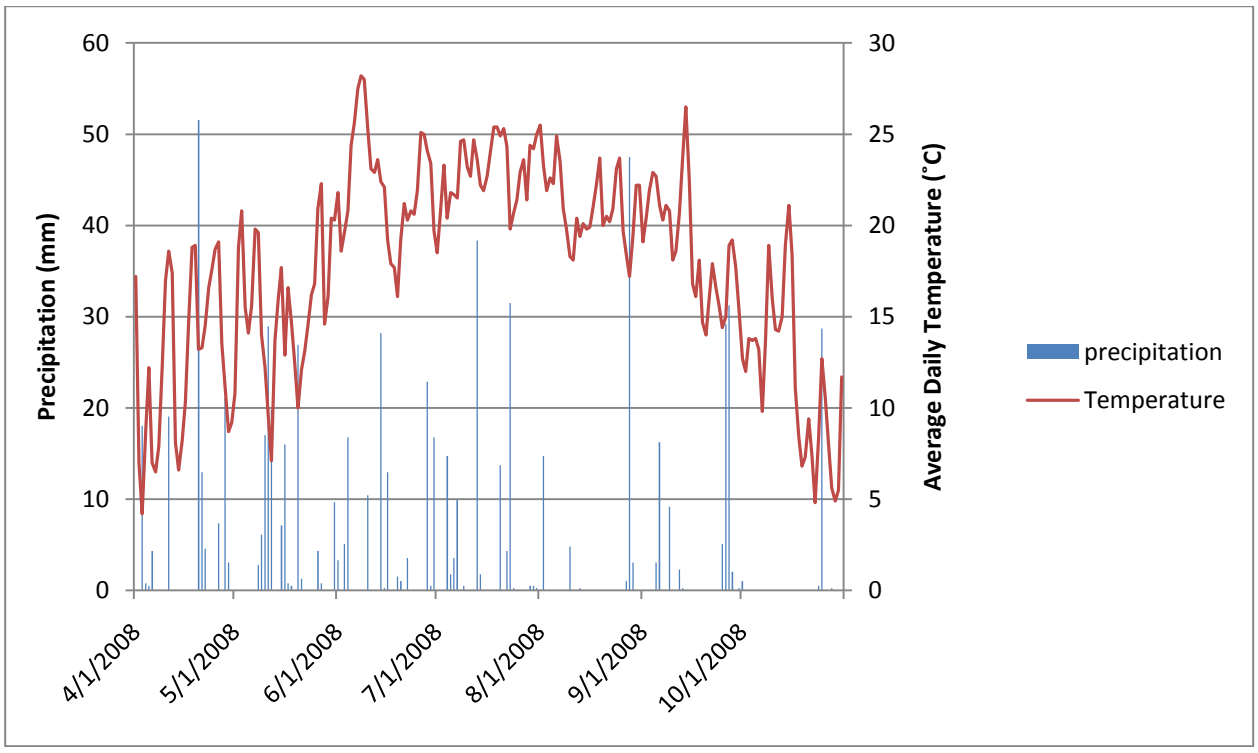


Figure 1 - Daily rainfall and temperature data from the AHS AREC 2008 growing season.

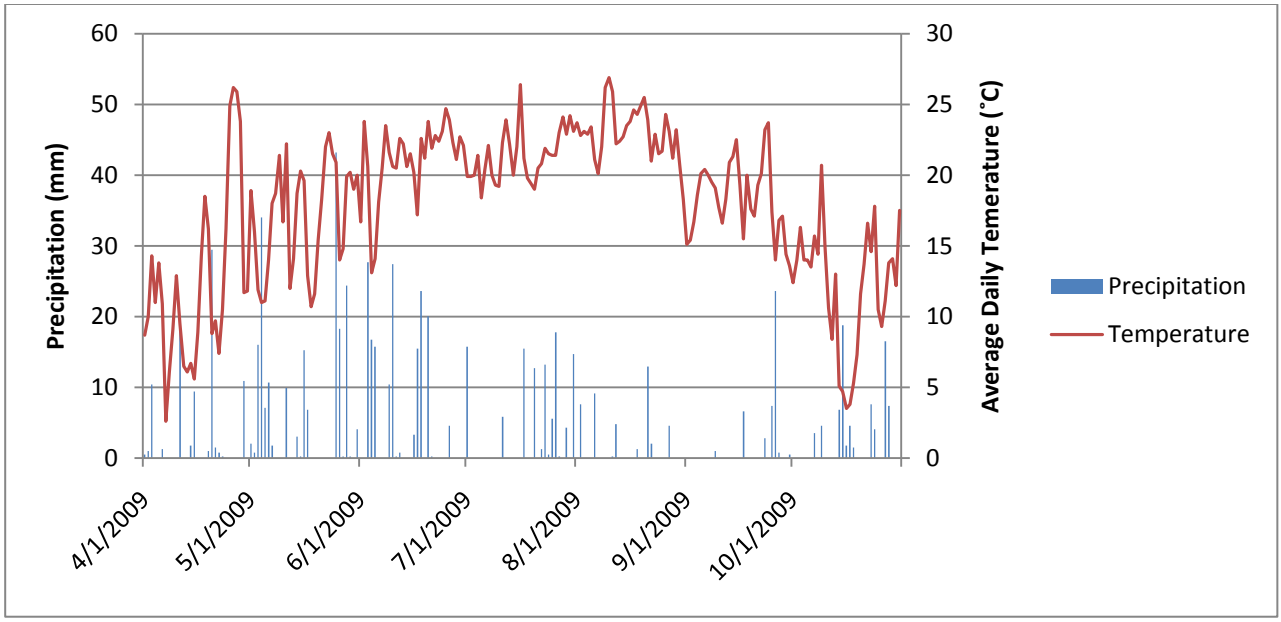


Figure 2 - Daily rainfall and temperature data from the AHS AREC, 2009 growing season.

Shoot growth

Both the rate and duration of shoot growth was influenced by rootstock (figure 3) and root manipulation (figure 4) in 2008. Vines grafted to Riparia Gloire had significantly slower rates of shoot growth in comparison with the other rootstocks (table 5). RR significantly

reduced the rate shoot growth compared to NRR (table 5). Compared to NRR vines, RR vines have a much lower rate of shoot growth between 16 June and 14 July.

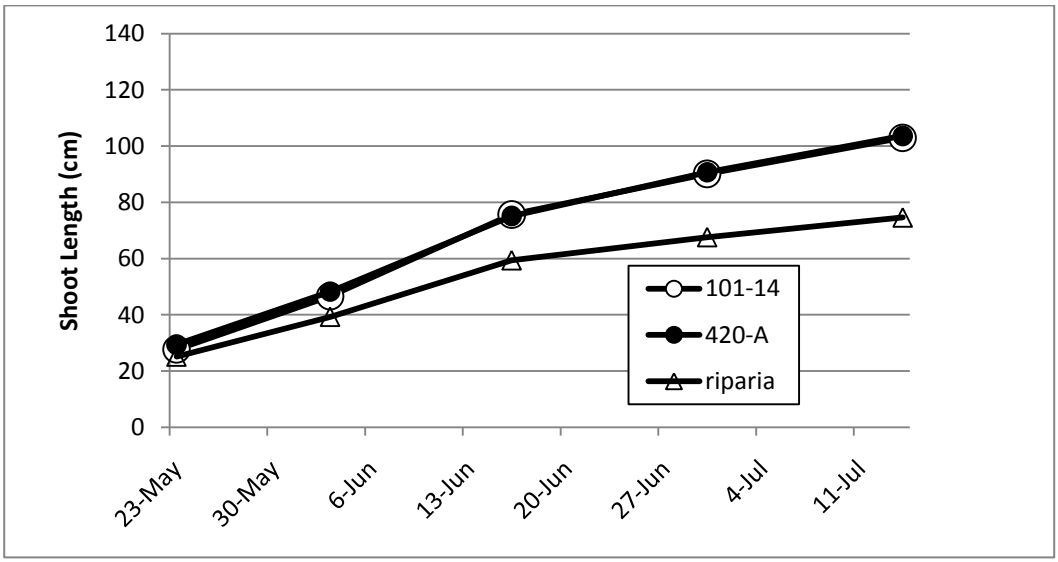


Figure 3 - Average shoot growth shown by rootstock treatment in 2008.

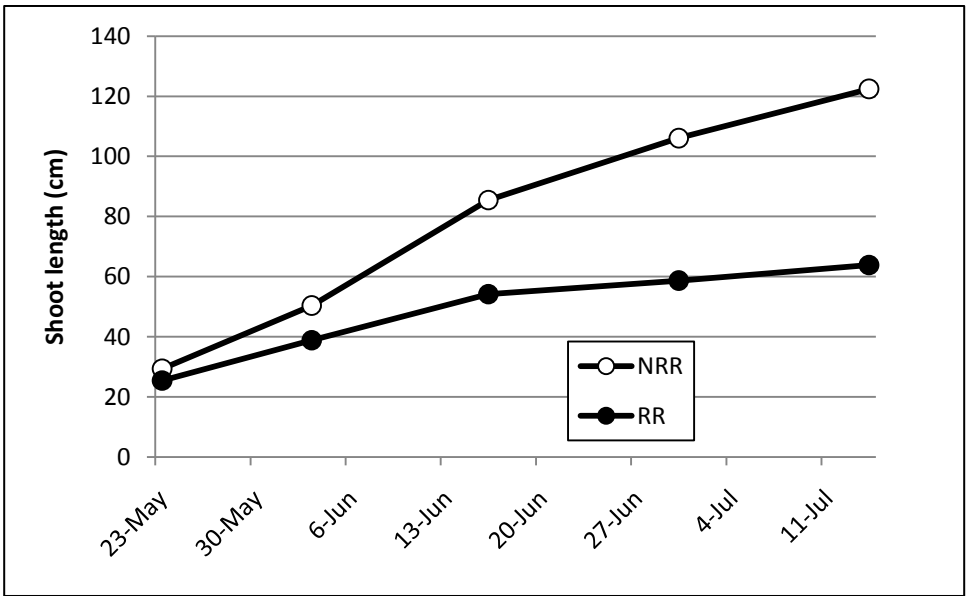


Figure 4 - Average shoot growth shown by root manipulation in 2008.

Table 5 - Shoot growth rate (cm/day) from 23 May to 16 June 2008 show with ANOVA p-values.

Rootstock	NRR	RR	Average*
101-14	2.6	1.4	2.0 a
420-A	2.5	1.3	1.9 a
riparia	1.9	0.9	1.4 b

Effect	p-value
Rootstock	<0.0001
RM	<0.0001
Rootstock X RM	0.0381

*Values not bearing the same lowercase letter differ at p= 0.05

High rainfall in the spring of 2009 (figure 2) caused rapid shoot growth, high growth rates resulted in a need to hedge shoots before the end of July. The UTCC treatment resulted in a reduced shoot growth rate compared to herbicide plots (figure 5). There were no significant effects of rootstock in 2009 (table 6), however, Riparia Gloire tended to have slower rates of shoot growth compared to the other two rootstocks. Treatments with RR also had significantly slower rates of shoot growth than did treatments with NRR (figure 6).

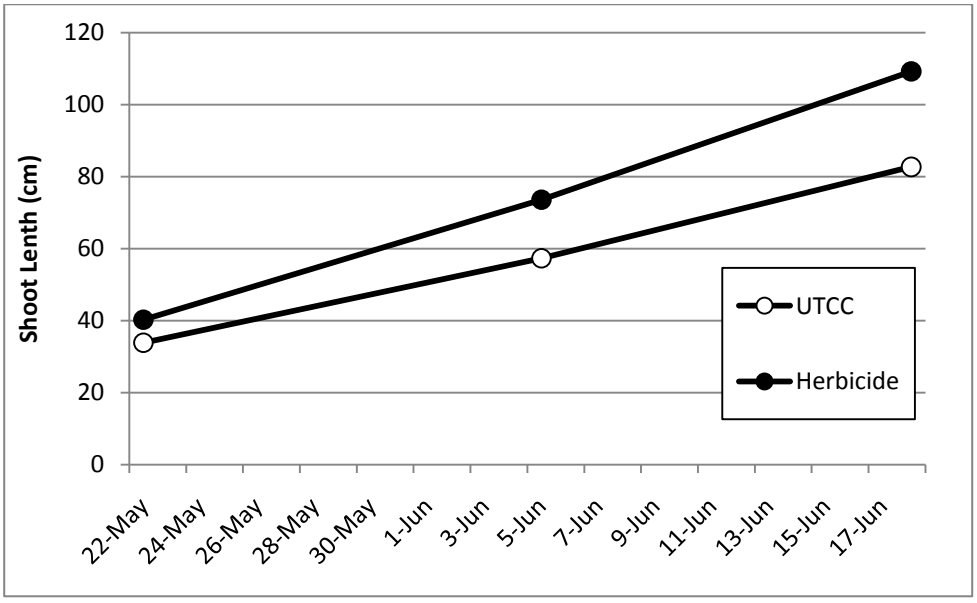


Figure 5 - Average shoot growth shown by under trellis ground cover in 2009.

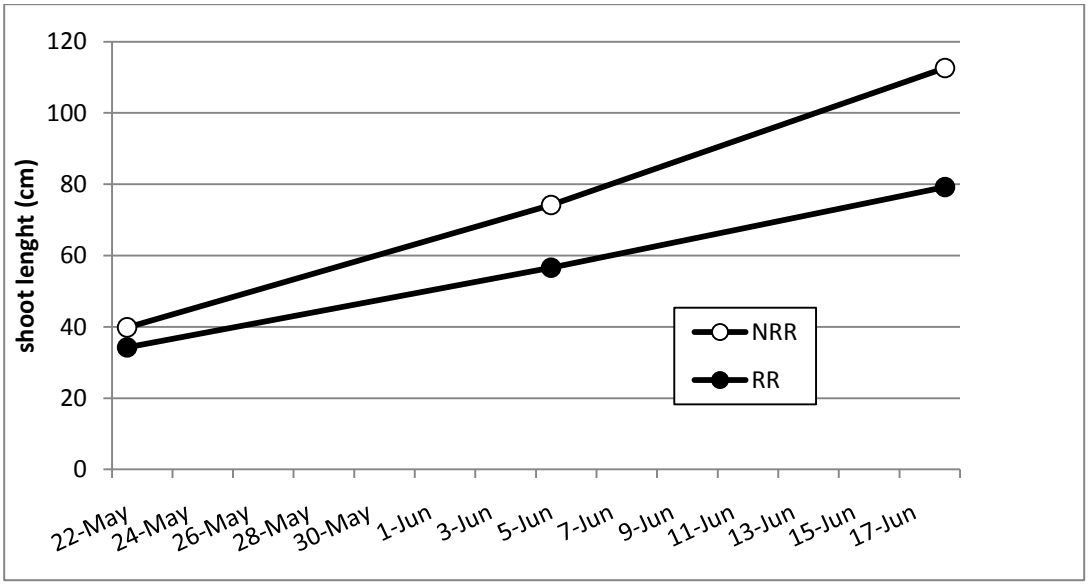


Figure 6 - Average shoot growth shown by root manipulation in 2009.

Table 6 - ANOVA p-values for shoot growth rate from 22 May – 18 June 2009.

Effect	P-value
UTGC	<0.0001
Rootstock	ns
UTGC X Rootstock	ns
RM	<0.0001
UTGC X RM	<0.0001
UTGC X Rootstock X RM	ns

Pruning weights

UTCC, Riparia Gloire rootstock and RR all significantly depressed vine pruning weights in 2008 (figure 7, table 7, table 8). Vines with UTCC, on average, had 47% less cane pruning weights than those grown with herbicide strips below the trellis (figure 7). Vines with Riparia Gloire rootstock, on average, had 32% and 28% less cane pruning weights than those grown on the rootstocks 101-14 and 420-A, respectively (figure 7). RR vines had 66% reduced pruning weights than those vines with NRR (figure 7).

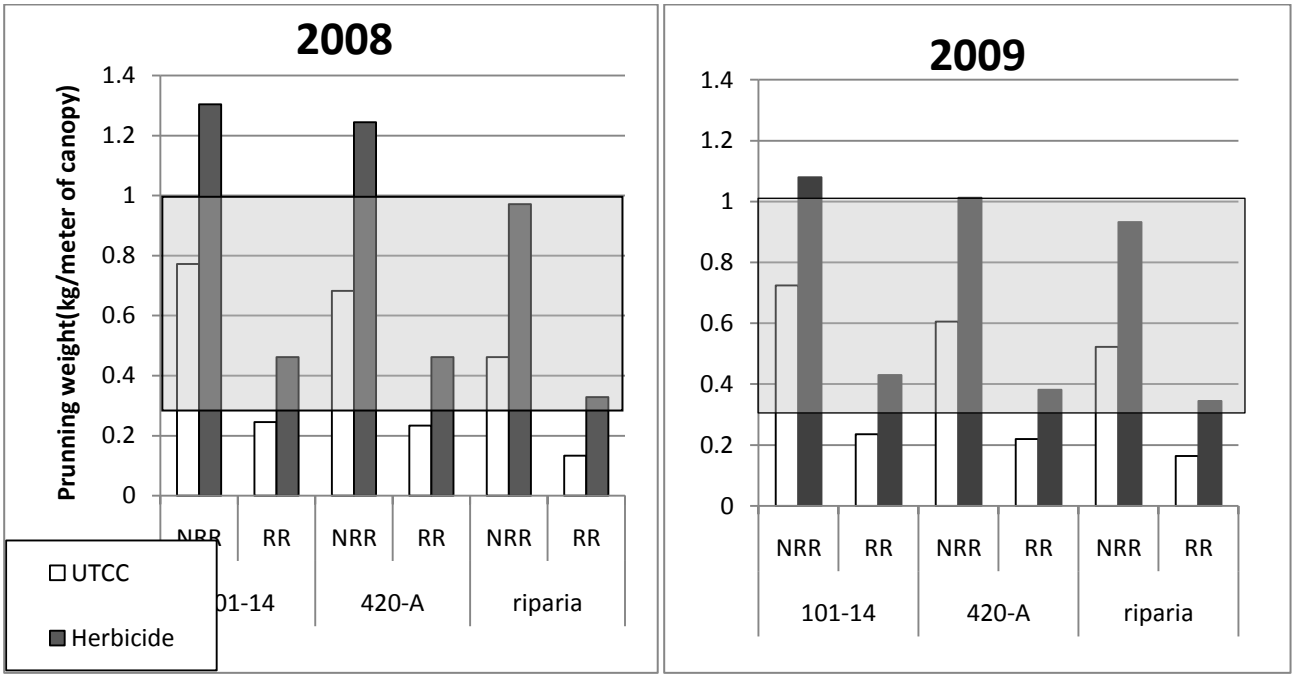


Figure 7 - Pruning weights per meter of canopy from 2008 and 2009*.

*Shaded area shows optimal pruning weight range for producing high quality fruit adapted from (Kliewer and Dokoozlian 2000).

Table 7 – ANOVA p-values for pruning weights in 2008.

	2008	2009
Effect	P- Value	
UTGC	<0.0001	<0.0001
Rootstock	0.0064	0.035
Roostock X UTGC	ns	ns
RM	<0.0001	<0.0001
RM X UTGC	<0.0001	<0.0001
RM X Rootstock X UTGC	0.0009	ns

Table 8 - Pruning weight averages by rootstock treatment 2008 and 2009.

	Pruning weight per vine (kg)			
Rootstock	2008		2009	
101-14	1.2	a	0.9	a
420-A	1.2	a	0.9	ab
riparia	0.9	b	0.8	b

*Values not bearing the same lowercase letter differ at the p=0.05 level

2008
2009
Effect
P- Value
UTGC
<0.0001
Pruning weight per vine (kg)
Rootstock
2008
2009
0.0064
101-14
1.2
a
0.9
a
420-A
1.2
a
0.9
ab
riparia
0.9
b
0.8
b
Roostock X UTGC
ns
ns
RM
<0.0001
<0.0001
RM X UTGC
<0.0001
<0.0001
RM X Rootstock X UTGC
0.0009
ns

Trunk circumference

These measurements showed that treatments in this trial significantly altered trunk circumference. Under the trellis cover crops reduced trunk circumference by 11%, significantly compared to herbicide strips (table 9, table 10). The rootstock Riparia Gloire reduced trunk circumference by 12%, significantly compared to the other rootstocks (table 11). RR reduced trunk circumference by 23%, significantly compared to NRR (table 10, table 10).

Table 9 - Trunk circumference at bloom 2009, BBCH stage 60.

UTGC	Rootstock	RM	Trunk circumference (cm)
UTCC	101-14	NRR	13
		RR	10
	420-A	NRR	13
		RR	10
	riparia	NRR	11
		RR	8
Herbicide	101-14	NRR	14
		RR	11
	420-A	NRR	14
		RR	12
	riparia	NRR	13
		RR	10

Table 10 – ANOVA p-value for trunk circumference, measured at bloom 2009, BBCH stage 60.

Effect	P-value
UTGC	0.0004
Rootstock	0.0021
Rootstock X UTGC	ns
RM	<0.0001
RM X UTGC	ns
RM X Rootstock X UTGC	ns

Table 11 - Trunk circumference by rootstock, bloom 2009 BBCH stage 60.

Rootstock	Trunk circumference (cm)*		
101-14	12.2	a	
420-A	12.1	a	
riparia	10.6		b

* Values not bearing the same lowercase letter differ at p=0.05

Leaf area

Leaf area was estimated on the herbicide plots in 2008. Rootstock was a significant (p <0.0063) factor, with vines grafted to 101-14 having more leaf area. Leaf area was significantly (p <0.0001) less on RR vines compared with NRR vines (figure 8).

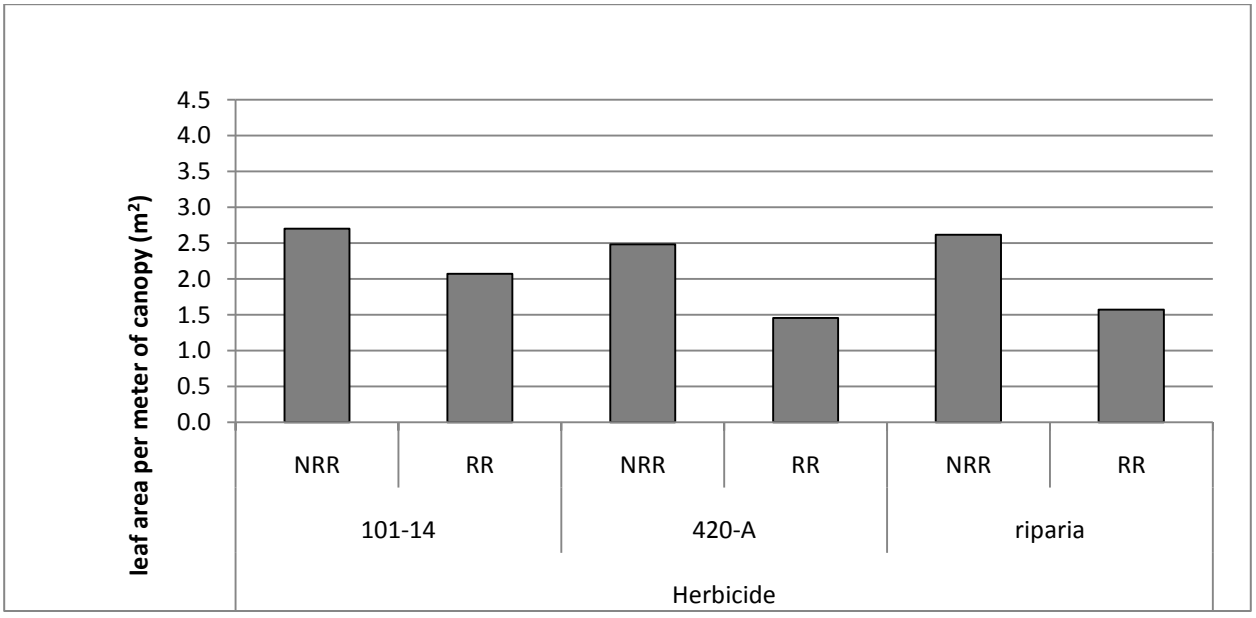


Figure 8 - Primary leaf area shown for treatment combinations*, veraison 2008 BBCH 81.
*In 2008 only vines with under the trellis herbicide strips had their leaf area inspected.

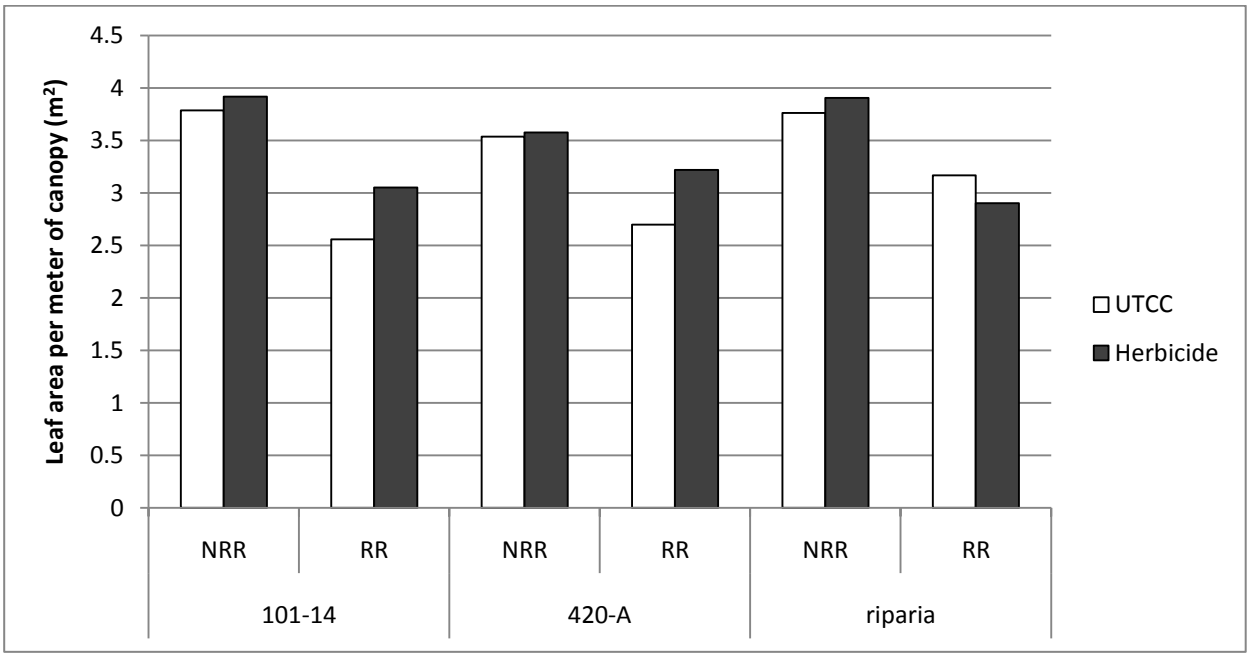


Figure 9 - Primary leaf area for treatment combinations, veraison 2009 BHCC 81.

Leaf area was assessed for both UTGC treatments during veraison 2009. Although no statistically significant treatment effects were found for leaf area values in 2009 there were trends for cover crop and RR treatments to reduce the leaf area (figure 9).

Canopy architecture

Canopy architecture was measured at veraison BBCH 81 in 2008 and 2009. Vines with UTCC were not evaluated in 2008 (Figure 10A). Under the trellis cover crops reduced occlusion layer number by 23% and reduced cluster exposure layer number by 52% compared to herbicide strips in 2009 (figure 10B). RR reduced canopy density in 2008 (figure 10A) and 2009 (figure 10B). Rootstocks did not have significant effects on PQA or EPQA values in 2008 or 2009 (table 12, table 13). RR significantly reduced occlusion layer number by 33% in 2008 (figure 10A) and 23% in 2009 (figure 10B). Cluster exposure layer values were lower for RR vines in 2008 however this was not statistically significant (figure 10A, table 12). Vines with cover crop had significantly lower cluster exposure layers than vines with a herbicide strip below the trellis in 2009 (table 13). Vines with cover crop and RR had significantly lower percent interior leaf values in 2009 than vines with UTGC herbicide and NRR, respectively (table 13). Interior leaves are those that will be shaded by the exposed leaves. Cluster exposure flux availability was significantly 37% higher for UTCC vines that those with herbicide UTGC in 2009 (table 13, figure 11). Cluster exposure flux availability was not significantly different for the RM treatments, but RR vines had 26% higher values than NRR vines (table 13, figure 11).

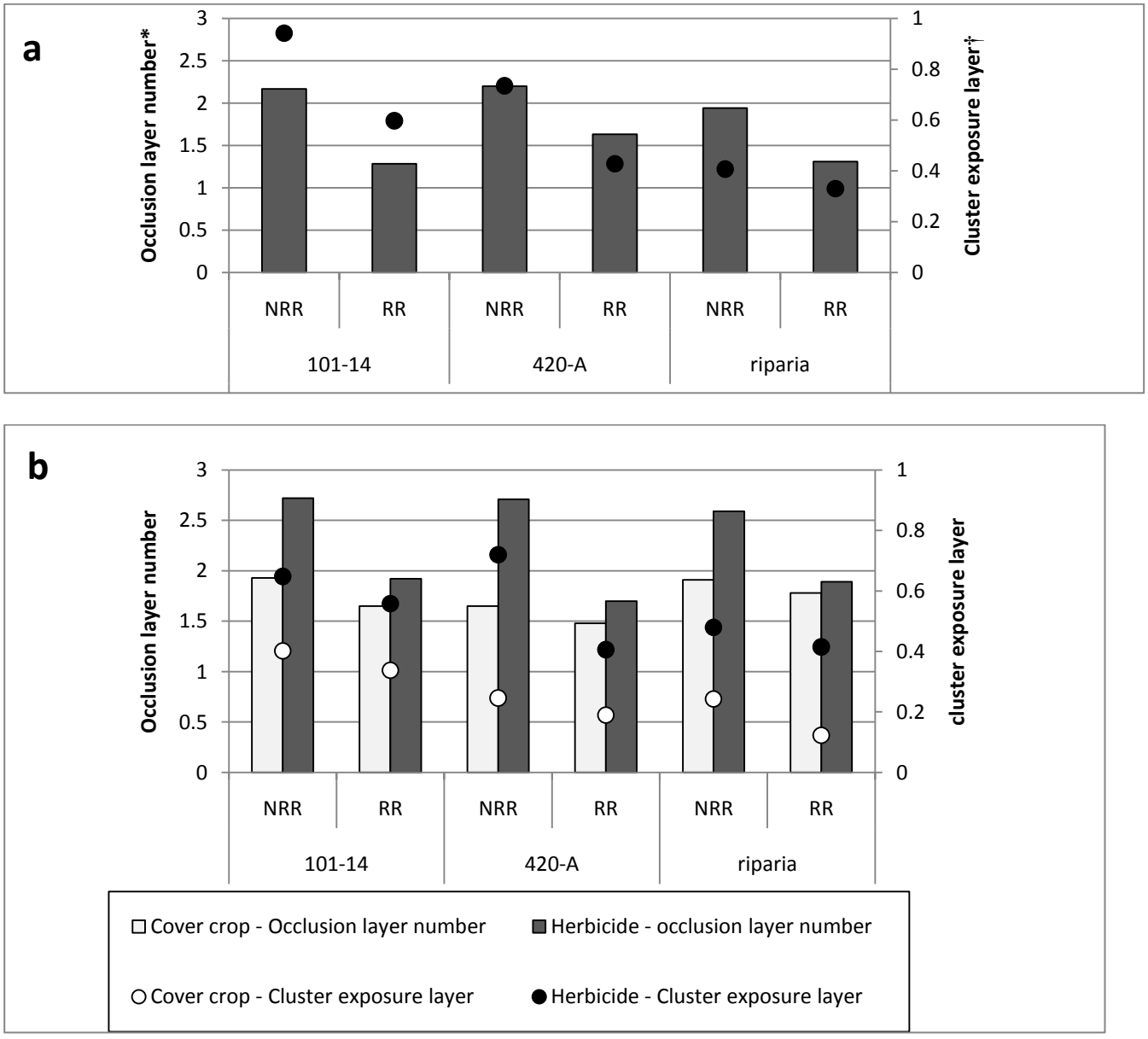


Figure 10 - A B. Calculated canopy parameters from veraison 2008, BBCH 81(A) and, veraison 2009, BBCH 81(B).

*Occlusion layer number relates the number of the shade producing layers in the canopy. †Cluster exposure layers relates the number of shade producing layers between the clusters and canopy boundary.

Table 12 – ANOVA P-values for calculated values of canopy parameters, veraison 2008 BBCH 81.

	PQA*				EPQA†			
	Percent gaps	Leaf layer number	Percent interior leaves	Percent interior clusters	Occlusion layer number	Cluster exposure layer	Leaf exposure layer	Canopy cluster symmetry
Effect	p-values							
Rootstock	ns	ns	ns	ns	ns	ns	ns	ns
RM	0.0067	0.0086	ns	ns	0.003	ns	ns	ns
Rootstock X RM	ns	ns	ns	ns	ns	ns	ns	ns

*PQA values are calculated from the point quadrat analysis (Smart and Robinson 1991) and †EPQA values are calculated from the enhanced point quadrat analysis (Meyers and Vanden Heuvel 2008)

Table 13 ANOVA P-values for calculated values of canopy parameters veraison 2009 BBCH 8.

	PQA*				EPQA†							
	Percent gaps	Leaf layer number	Percent interior clusters	Percent interior leaves	Occlusion layer number	Cluster exposure layer	Leaf exposure layer	Canopy cluster symmetry	Cluster exposure flux availability	Cluster exposure flux symmetry	Leaf exposure flux availability	Leaf exposure flux symmetry
Effect	p-values											
UTGC	ns	0.0056	0.0281	0.003	0.0066	0.0167	0.0105	ns	0.017	ns	0.0053	ns
Rootstock	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Rootstock X UTGC	ns	0.0056	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM	0.0284	0.0056	ns	0.0155	0.0069	ns	0.013	ns	ns	ns	0.0038	ns
RR X UTGC	ns	0.0068	ns	0.0021	0.0045	ns	0.0328	ns	ns	ns	ns	ns
RM X Rootstock X UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*PQA values are calculated from the point quadrat analysis (Smart and Robinson 1991) and †EPQA values are calculated from the enhanced point quadrat analysis (Meyers and Vanden Heuvel 2008)

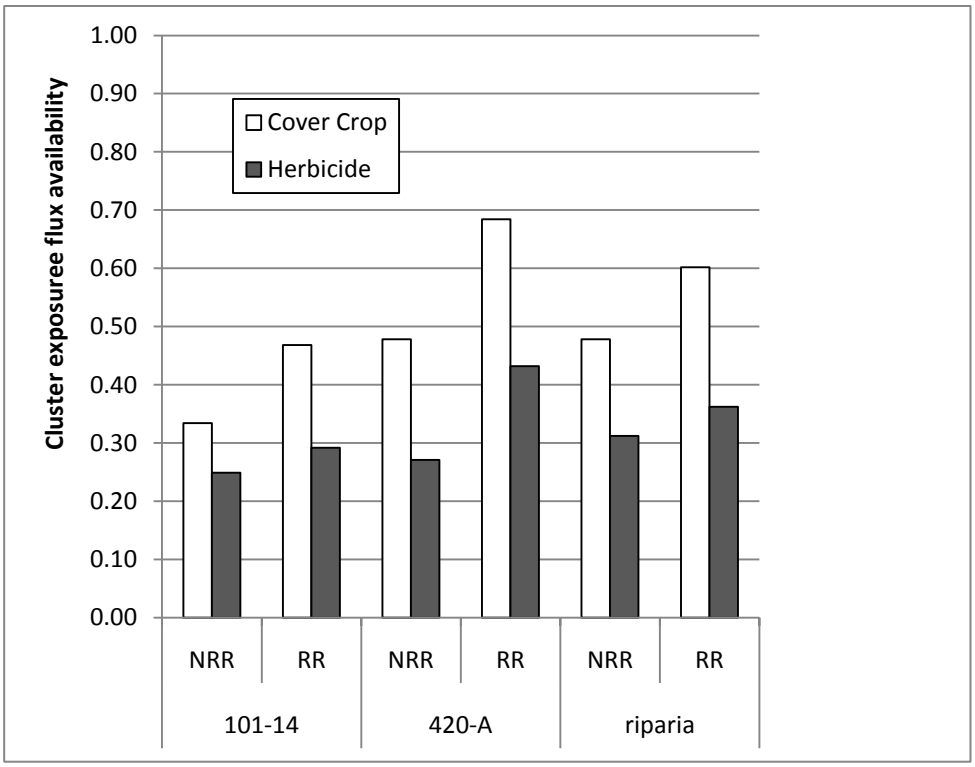


Figure 11 - Canopy exposure flux availability is the percentage of ambient light reaching the clusters, veraison 2009 BBCH 81.

Lateral evaluation

Rootstocks 101-14 and 420-A resulted in 45% and 33% higher lateral scores, respectively, than the rootstock Riparia Gloire in 2008 (table 14, table 15, table 16). Vines with NRR had 51% higher lateral scores than vines with RR (table 14). Rootstock and RM treatments had significant effects upon lateral score (table 15).

Vines with UTCC tended to have lower lateral scores than vines with herbicide strips in 2009 (table 14). Rootstocks did not have consistent influences on lateral score. Root manipulation had a treatment effect where RR vines had a 41% lower lateral score than NRR (table 14). Root manipulation had the only significant ($p < 0.0336$) effect on lateral score in 2009.

Table 14 - Lateral evaluation values shown by treatment combination, veraison 2008.

			Lateral score*	
Groundcover	**Rootstock**	**RR**	**2008**	**2009**
Cover crop	101-14	NRR	nc†	15
Cover crop	101-14	RR	nc	7
Cover crop	420-A	NRR	nc	18
Cover crop	420-A	RR	nc	9
Cover crop	riparia	NRR	nc	15
Cover crop	riparia	RR	nc	11
Herbicide	101-14	NRR	17	17
Herbicide	101-14	RR	9	9
Herbicide	420-A	NRR	15	10
Herbicide	420-A	RR	7	12
Herbicide	riparia	NRR	10	14
Herbicide	riparia	RR	5	8

*Lateral score is the summed number of unfolded lateral leaves from nodes 3 to 7

† data not collected in 2008

Table 15 - ANOVA p-values from lateral score 2008.

Effect	p-value
Rootstock	<.0001
RM	0.0003
RM X Rootstock	ns

Table 16 - Average lateral score by rootstock 2008.

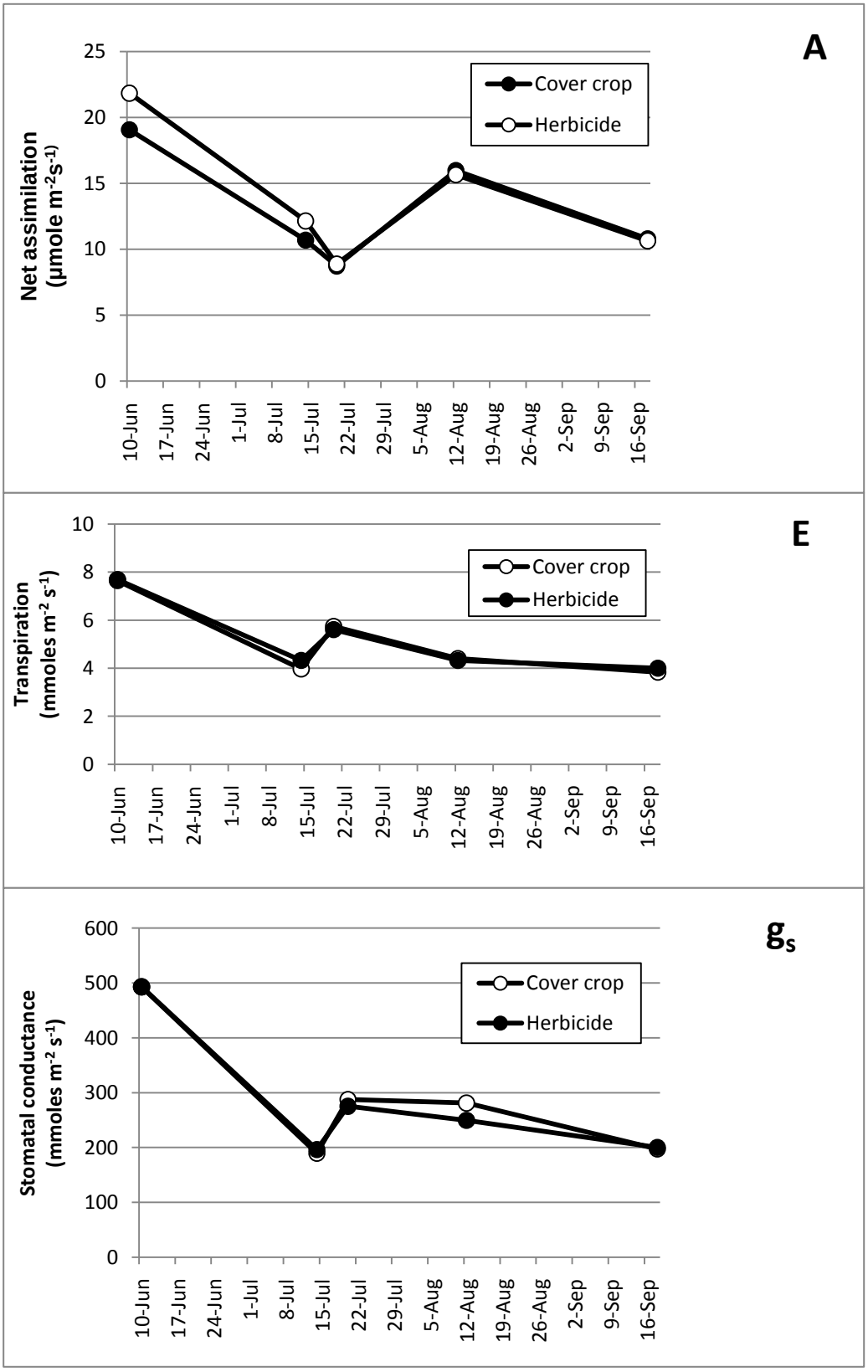
Rootstock	Lateral score*	
101-14	13	a
420-A	11	a
riparia	7	b

* Values bearing a different lower case letter differ at p=0.05

Gas exchange

All the calculated gas exchange parameters had their highest values at bloom on 10 June 2009 (figure 8, figure 9, figure 10). Vines with UTCC had slightly reduced gas exchange values (figure 8). Vines grafted to 420-A had slightly higher gas exchange values than vines grafted to the other rootstocks (figure 9). Vines with RR had reduced gas exchange values compared to vines with NRR (figure 10). Differences in gas exchange values between

rootstocks and RM treatments were clear by the 14 July measurements (figure 9, figure 10).



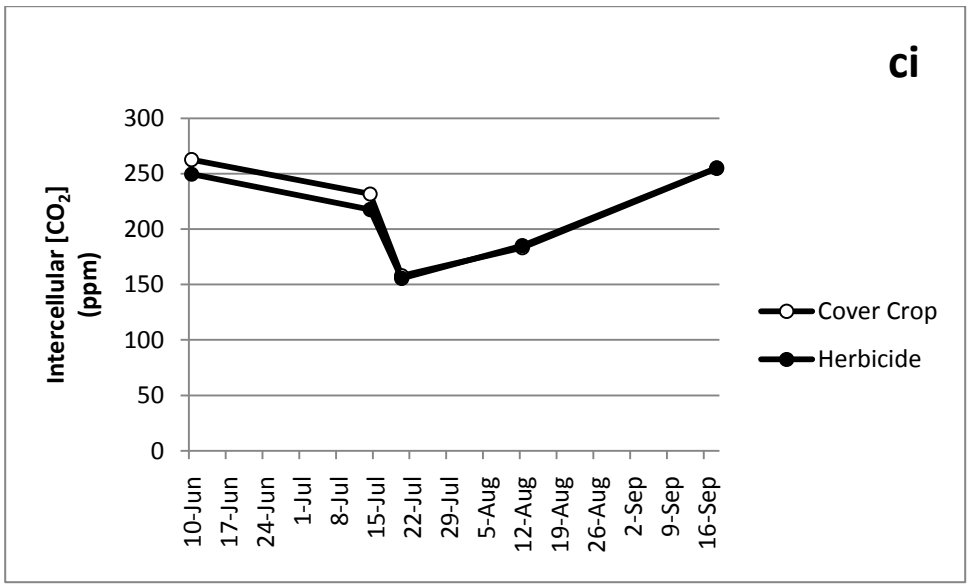
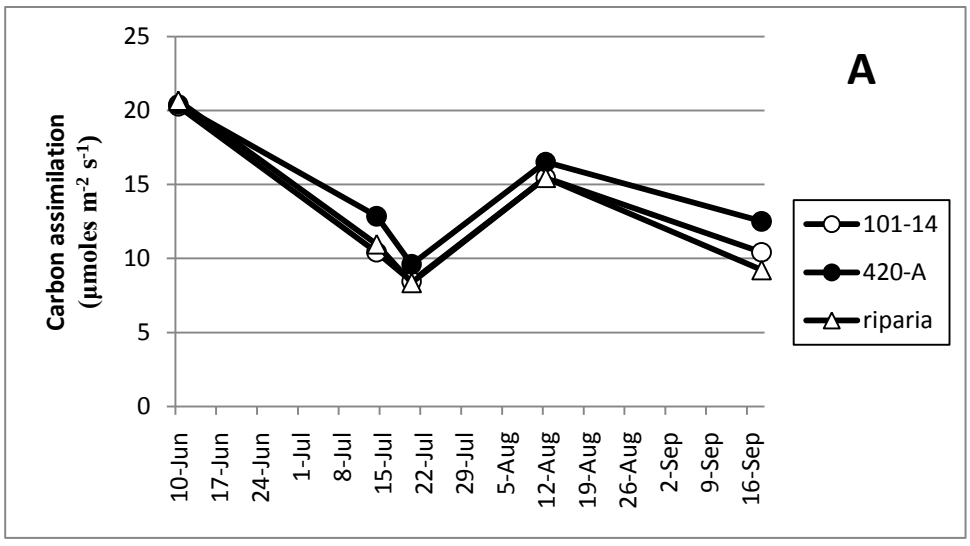
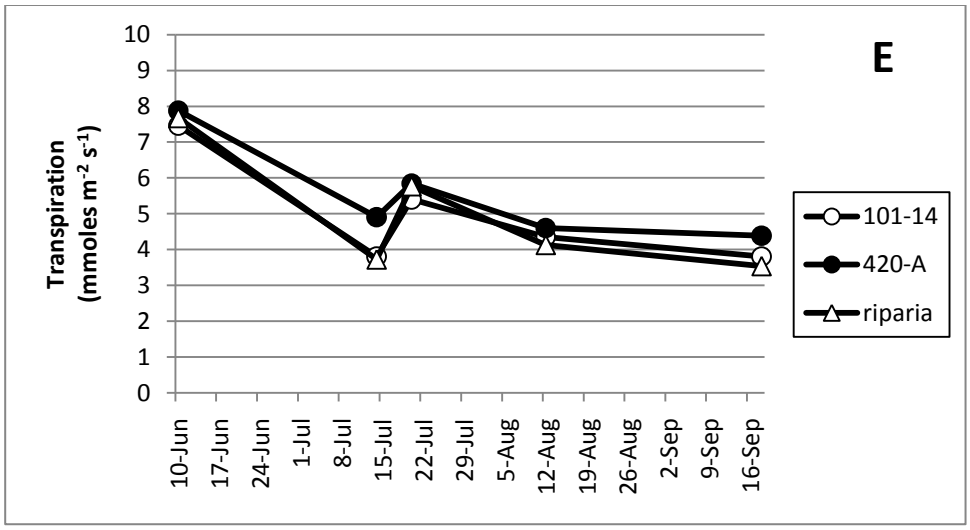


Figure 8- Gas exchange values shown by groundcover 2009.





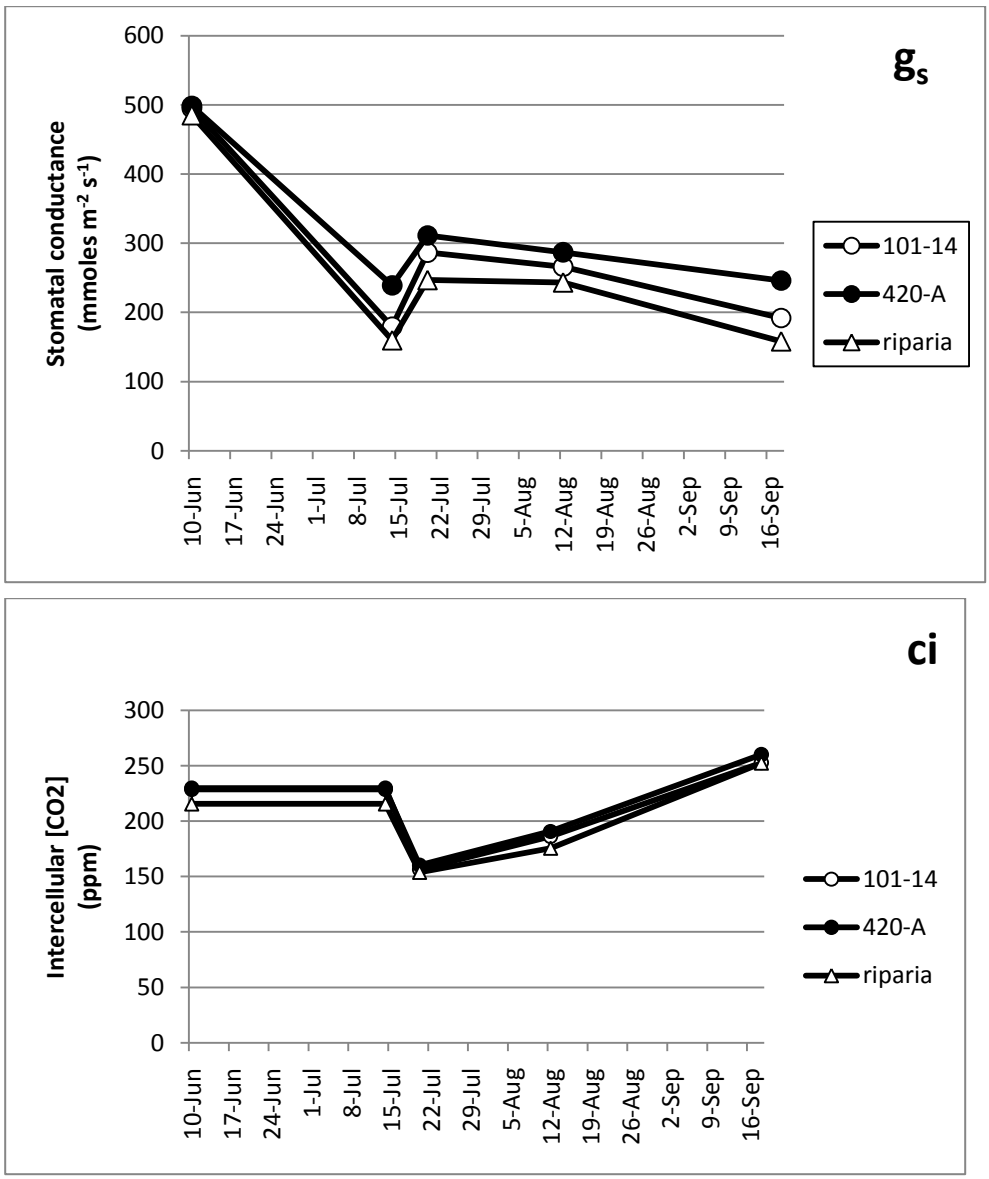
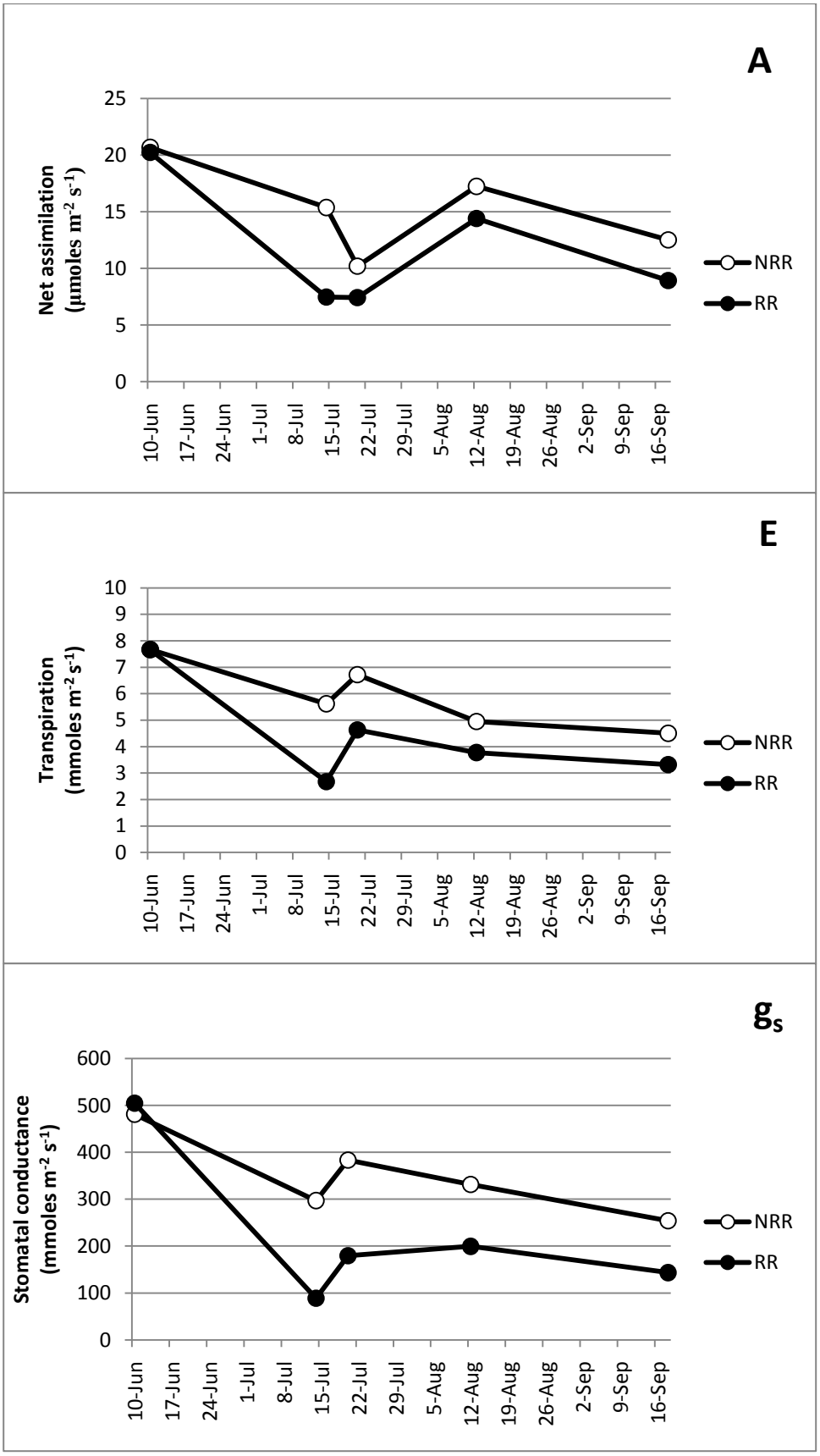


Figure 9 – Gas exchange values shown by rootstock, 2009.


A
Net assimilation (µmoles m-2 s-1)
25
20
15
10
5
0
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
26-Aug
2-Sep
9-Sep
16-Sep
NRR
RR
E
Transpiration (mmoles m-2 s-1)
10
9
8
7
6
5
4
3
2
1
0
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
26-Aug
2-Sep
9-Sep
16-Sep
NRR
RR
gs
Stomatal conductance (mmoles m-2 s-1)
600
500
400
300
200
100
0
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
26-Aug
2-Sep
9-Sep
16-Sep
NRR
RR

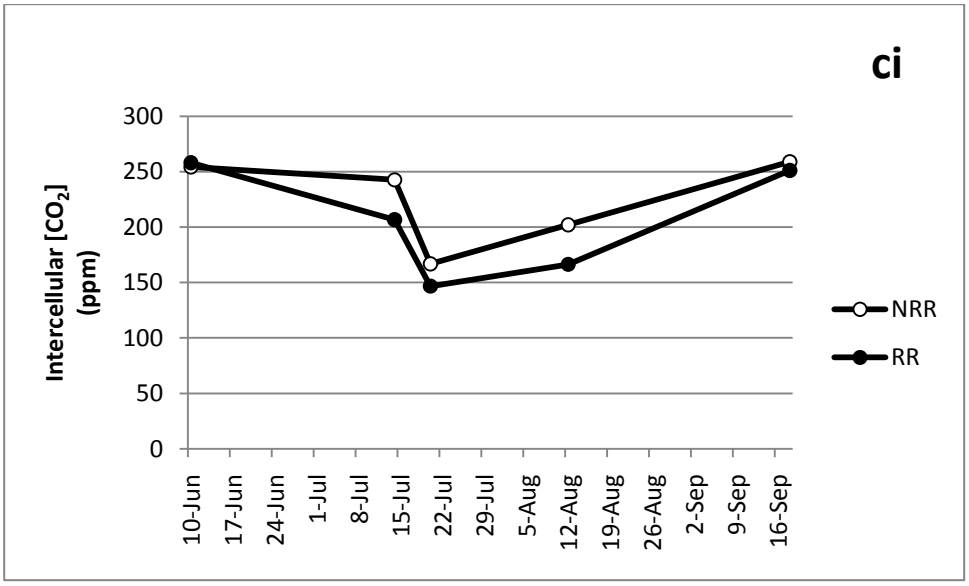


Figure 10 – Gas exchange values shown by RM, 2009.

Water status

Vine water status was measured as mid-day ψ_{leaf} in 2008. Vines with RR had a 15% more negative water status than vines with NRR averaged across the growing season (figure 11). Irrigation began 15 August on a weekly basis with the goal of avoiding a water status more negative than -1MPa. Leaf water potential values were measured on 20 August 2008, both RM treatments exceeded -1MPa. Leaf water potential values from 20 August 2008 show vines with RR had 19% more negative values than vines with NRR (figure 11).

Water potential was measured as mid-day ψ_{stem} in 2009. Vines with UTCC had a 17% more negative water status over the growing season than vines with a herbicide strip below the trellis (figure 12). Vines grafted to the rootstock 420-A had slightly less negative water status values than vines grafted to the other rootstocks (figure 13). Root restricted vines had a 43% more negative water status over the growing season when compared to NRR vines (figure 14). RR vines even had a more negative water staus than the other treatments early in the season when surplus precipitation exsisted (figure 14, figure 2). Irrigation started in mid-July and was used in a weekly rotation which switched watering all the vines to watering only the RR vines. Water potential measurements taken 18 September showed NRR vines

have a slightly more negative water staus than vines with RR.

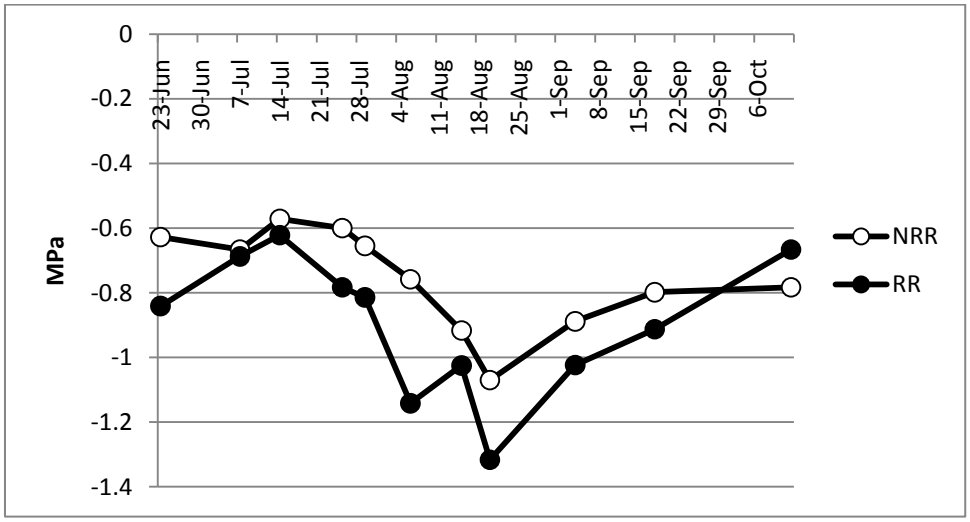


Figure 11- Mid-day ψ_{leaf} by RR, 2008.

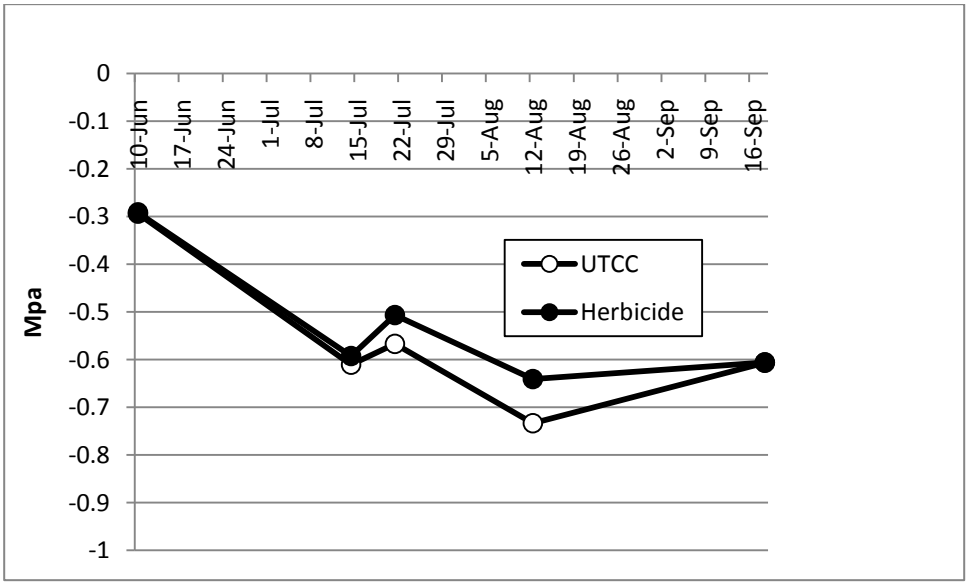


Figure 12- Mid-day ψ_{stem} by groundcover, 2009.

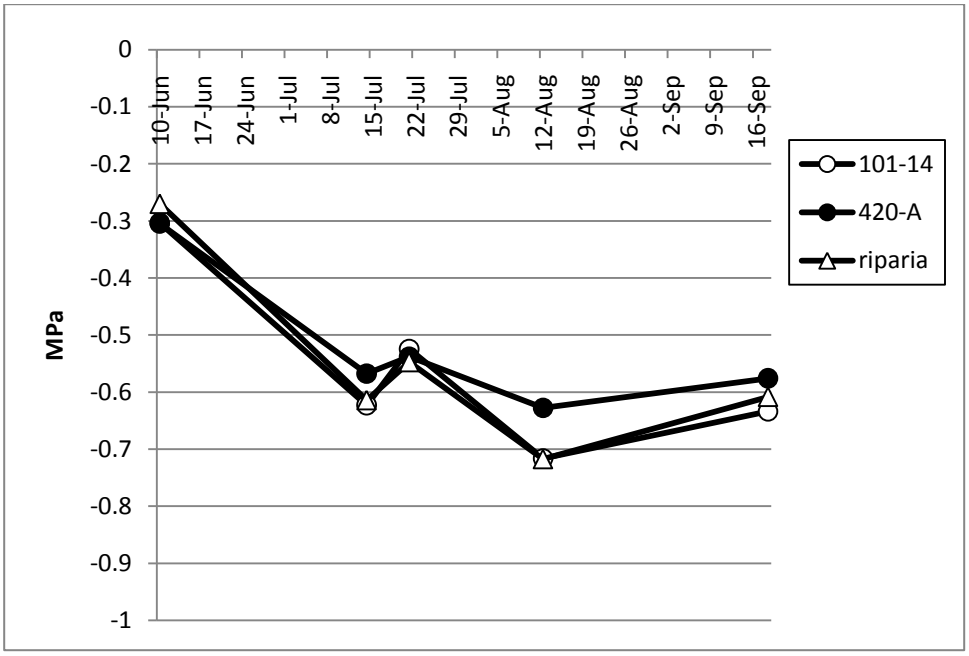


Figure 13 – Mid-day ψ_{stem} by rootstock, 2009.

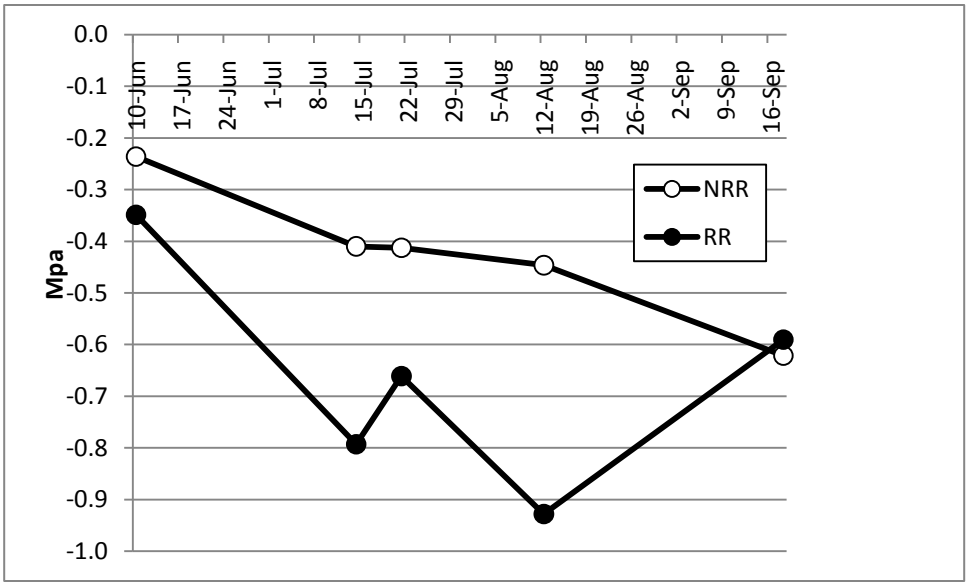


Figure 14 – Mid-day ψ_{stem} by RR, 2009.

Soil moisture

Soil moisture values in 2008 had similar values between the two UTGC treatments.

Herbicide plot soil moisture readings were 6% lower than UTCC plots in 2008 (figure 15).

Herbicide plots had 23% lower soil moisture readings in 2009 (figure 15).

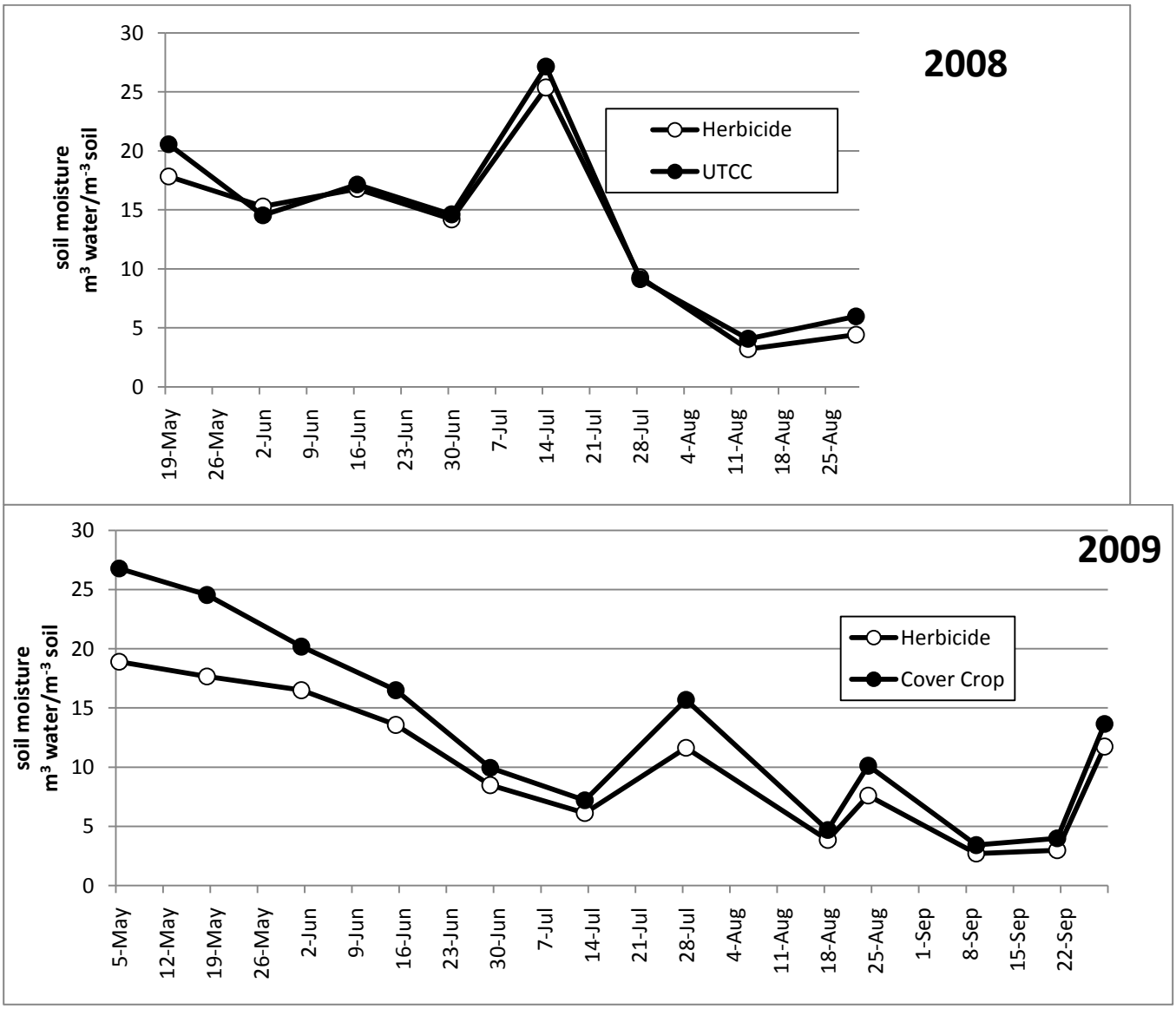


Figure 15- Soil moisture measurements at 100mm below soil surface 2008 and 2009.

Plant analysis

Leaf petioles were collected at BBCH 75, pea sized berries in 2008 and BBCH 60, bloom in 2009 (table 17). Replication of samples (n=24) in 2009 allowed for statistical analysis of the results. No statistical significant differences were caused by UTGC (table 17). Rootstocks did cause statistically significant differences in plant tissue nutrient concentrations (table 17). Vines grafted to the rootstock 420-A had a 38% and 40% lower petiole potassium

concentration compared to vines grafted to 101-14 and riparia, respectively (table 17). Vines grafted to the rootstock 420-A also had a 17% and 12% lower petiole concentration in boron than vines grafted to 101-14 and riparia, respectively (table 17). Vines grafted to the rootstock ripairia Gloire had a 19% and 24% lower petiole concentration of manganese than vines grafted to 101-14 and 420-A, respectively (table 17). Root manipulation had one significant effect on plant nutrient status. Vines with RR had a 60% lower phosphorous concentration in petioles than vines with NRR (table 17).

Vines with cover crop below the trellis tended to have lower yeast assimilable nitrogen (YAN) than vines with herbicide below the trellis, but this difference was insignificant. Fruit from vines with RR had a significantly ($p \leq 0.0345$) more (YAN) that fruit from NRR vines. Vines with RR had 13% more YAN than did vines with NRR (table 18).

Table 17 - Plant tissue analysis nutrient concentrations and ANOVA p-values from 2008, pea sized berries BBCH 75 (n=2) and 2009, boom BBCH 60 (n=24).

	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
UTGC	**Nitrogen (%)**		**Phosphorus (%)**		**Potassium (%)**		**Sulfur (%)**		**Magnesium (%)**		**Calcium (%)**		**Boron (ppm)**		**Zinc (ppm)**		**Iron (ppm)**		**Manganese (ppm)**		**Copper (ppm)**		**Aluminium (ppm)**	
Herbicide	**nc**†	1.18	**nc**	0.30	**nc**	2.49	**nc**	0.19	**nc**	0.33	**nc**	1.56	**nc**	33	**nc**	42	**nc**	55	**nc**	93	**nc**	10	**nc**	1
UTCC	**nc**	0.97	**nc**	0.19	**nc**	2.85	**nc**	0.12	**nc**	0.26	**nc**	1.55	**nc**	33	**nc**	36	**nc**	56	**nc**	104	**nc**	8	**nc**	1
Rootstock	**Nitrogen (%)**		**Phosphorus (%)**		**Potassium (%) ***		**Sulfur (%)**		**Magnesium (%)**		**Calcium (%)**		**Boron (ppm) ***		**Zinc (ppm)**		**Iron (ppm)**		**Manganese (ppm) ***		**Copper (ppm)**		**Aluminium (ppm)**	
101-14	**nc**	1.10	**nc**	0.24	**nc**	3.04 a	**nc**	0.17	**nc**	0.34	**nc**	1.48	**nc**	36 a	**nc**	44	**nc**	54	**nc**	103 a	**nc**	9	**nc**	1
420-A	**nc**	1.02	**nc**	0.29	**nc**	1.87 b	**nc**	0.15	**nc**	0.30	**nc**	1.59	**nc**	30 b	**nc**	40	**nc**	55	**nc**	109 a	**nc**	8	**nc**	1
riparia	**nc**	1.10	**nc**	0.20	**nc**	3.10 a	**nc**	0.15	**nc**	0.24	**nc**	1.59	**nc**	34 a	**nc**	33	**nc**	56	**nc**	83 b	**nc**	9	**nc**	1
RM	**Nitrogen (%)**		**Phosphorus (%) ***		**Potassium (%)**		**Sulfur (%)**		**Magnesium (%)**		**Calcium (%)**		**Boron (ppm)**		**Zinc (ppm)**		**Iron (ppm)**		**Manganese (ppm)**		**Copper (ppm)**		**Aluminium (ppm)**	
NRR	0.56	1.10	0.08	0.35 a	4.14	2.60	0.12	0.17	0.29	0.32	1.87	1.70	32	35	48	41	43	59	94	109	12	10	11	1
RR	0.62	1.05	0.11	0.14 b	3.23	2.74	0.16	0.14	0.31	0.27	1.49	1.41	32	31	45	37	61	52	159	88	19	8	1	1

ANOVA	Nitrogen	Phosphorus	Potassium	Sulfur	Magnesium	Calcium	Boron	Zinc	Iron	Manganese	Copper	Aluminium
Effect	p-value											
UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Rootstock	ns	ns	0.0144	ns	0.0281	ns	0.0259	ns	ns	ns	ns	ns
Rootstock X UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM	ns	0.0462	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM X UTGC	ns	0.0042	0.0335	0.0018	0.0096	ns	ns	0.0273	ns	ns	0.0084	ns
RM X UTGC X Rootstock	ns	ns	ns	ns	ns	ns	0.0209	ns	ns	ns	ns	ns

†not determined in 2008

*represents a significant treatment effect on nutrient concentration in plant tissue

Values not bearing the same lower case letter differ at p=0.05

Table 18 – Juice YAN at harvest, 2009.

UTGC	RM	YAN (mg/L)
UTCC	NRR	132
	RR	150
Herbicide	NRR	139
	RR	164

Fruitfulness

Vines with UTCC had significantly ($p \leq 0.0048$) lower shoot fruitfulness than vines with herbicide UTGC (table 19). No other treatments caused significant differences in shoot fruitfulness.

Table 19 - Shoot fruitfulness (inflorescences/shoot), measured at bloom 2009 BBCH 6.

UTGC	Rootstock	RM	shoot fruitfulness
herbicide	101-14	NRR	1.6
		RR	1.6
	420-A	NRR	1.4
		RR	1.4
	riparia	NRR	1.5
		RR	1.4
UTCC	101-14	NRR	1.3
		RR	1.2
	420-A	NRR	1.1
		RR	1.2
	riparia	NRR	1.1
		RR	1.4

Components of yield

In 2008 there were differences in crop yield at harvest. Under the trellis cover crop had 40% lower crop yield per vine in 2008 than vines with an herbicide strip below the trellis, even though the vines had a similar number of clusters per vine (table 20). Vines grafted to Riparia Gloire had higher yield per vine than vines grafted to the other rootstocks, even though the vines had been thinned to the same number of clusters. Vines grafted to Riparia Gloire had 29% and 16% higher yield per vine than vines grafted to 101-14 and 420-A, respectively (table 20). Vines with RR had a 67% reduction in yield per vine, vines with RR had half the

number of clusters than vines with NRR (table 20).

Cluster weights were significantly different between all treatments in 2008 (table 20). Vines with UTCC had 37% lower cluster weights than vines with a herbicide strip below the trellis (table 20). Vines grafted to Riparia Gloire had clusters that were 27% and 17% heavier than vines grafted to 101-14 and 420-A, respectively (table 21). Vines with RR had 24% lighter clusters than vines with NRR (table 20).

Berry weights were significantly affected by the UTGC and RM treatments (table 20). Vines with UTCC had 8% lighter berries than those vines with a herbicide strip below the trellis (table 20). Vines with RR had 12% lighter berries than vines with NRR (table 20). Fruit sampling before harvest showed that berries of different RM treatments had slightly different rates of mass increase and decrease before harvest (figure 16). Crop load was kept similar between treatment combinations in 2008 (table 22).

Table 20 - Harvest components of yield by treatment combination with ANOVA p-values. Harvest was on 13-14 October in 2008 and 9 -11 October in 2009.

	Vine yield (kg)		Clusters per vine		Cluster weight (g)		Berry weight (g)		Berries per cluster	
Treatment	**2008**	**2009**	**2008**	**2009**	**2008**	**2009**	**2008**	**2009**	**2008**	**2009**
Herbicide	2.8	2.9	15	21	182	139	1.4	1.5	132	95
UTCC	1.6	1.8	14	20	108	91	1.3	1.4	85	64
101-14	1.8 a	2.1 a	14	20	127 a	102 a	1.3	1.4 a	98	73 a
420-A	2.2 a	2.2 a	15	20	142 ab	109 a	1.3	1.4 a	107	77 a
riparia	2.6 b	2.7 b	14	20	164 b	132 b	1.3	1.5 b	120	88 b
NRR	3.3	2.9	20	24	166	118	1.4	1.5	118	77
RR	1.1	1.8	9	17	124	112	1.2	1.4	99	82
Effect	**p-values**									
UTGC	0.0006	<0.0001	ns	ns	<0.0001	<0.0001	0.0078	0.0074	<0.0001	<0.0001
Rootstock	0.0205	0.0086	ns	ns	0.0487	0.0045	ns	0.0026	ns	0.0252
Rootstock X UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM	<0.0001	0.0006	<0.0001	<0.0001	0.0002	ns	0.0001	0.0003	0.002	ns
RM X UTGC	<0.0001	<0.0001	ns	0.0019	ns	ns	ns	ns	ns	ns
RM X Rootstock X UTGC	<0.0001	<0.0001	ns	ns	<0.0001	ns	ns	ns	0.0004	ns

Table 21- Cluster weight by rootstock, 2008.

Rootstock	Cluster weight (g)*		
101-14	127	a	
420-A	144	a	b
riparia	169		b

* Values not bearing the same lower case letter differ at p=0.05

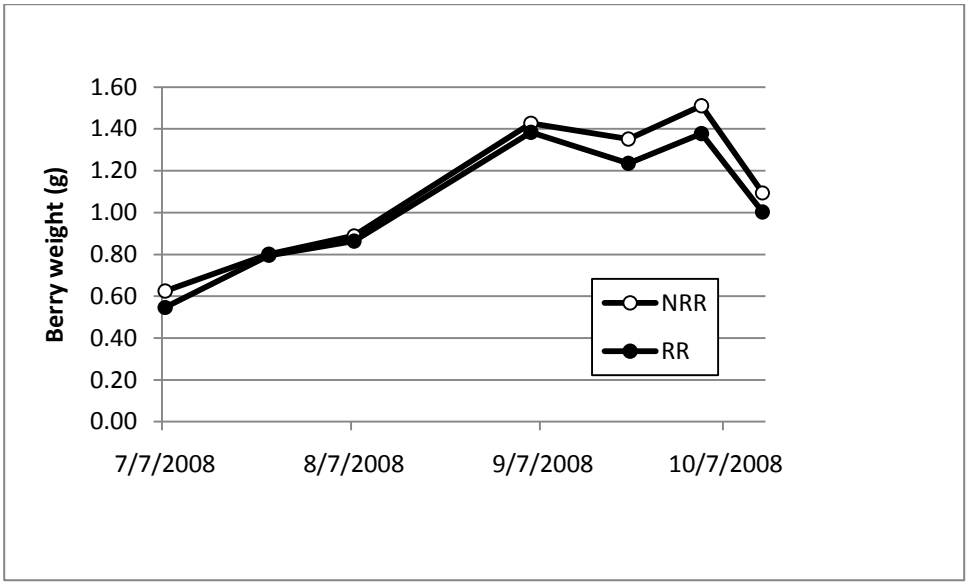


Figure 16 - Berry weight accumulation by RR, 2008.

Table 22 - Crop load values shown from 2008 and 2009.

UTGC	Rootstock	RM	Vine yield (kg)		Pruning weight per vine (kg)		Ravaz index (vine yield/vine pruning weight)		Primary leaf (cm^2) area per g crop	
			2008	2009	2008	2009	2008	2009	2008	2009
UTCC	**101-14**	**NRR**	1.9	1.9	1.2	nc†	1.6	nc	nc	31
		RR	0.7	1.3	0.4	nc	1.9	nc	nc	31
	420-A	**NRR**	2.5	2.0	1.0	nc	2.4	nc	nc	27
		RR	0.8	1.6	0.4	nc	2.4	nc	nc	25
	riparia	**NRR**	3.0	2.7	0.7	nc	4.3	nc	nc	22
		RR	0.7	1.6	0.2	nc	3.6	nc	nc	30
Herbicide	**101-14**	**NRR**	3.5	3.3	2.0	nc	1.7	nc	12	18
		RR	1.3	2.0	0.7	nc	1.9	nc	24	23
	420-A	**NRR**	4.1	3.2	1.9	nc	2.1	nc	9	17
		RR	1.6	2.1	0.7	nc	2.3	nc	14	23
	riparia	**NRR**	5.0	4.2	1.5	nc	3.4	nc	8	14
		RR	1.5	2.4	0.5	nc	3.1	nc	16	18

† data not collected

Crops were harvested on 9 October for the RR treatment combinations and 11 October 2009 for the NRR treatment combinations. Vines with UTCC had 35% less crop than vines with a herbicide strip below the trellis (table 20). Vines grafted to the rootstock Riparia Gloire had 25% and 20% more crop than vines grafted to 101-14 and 420-A, respectively (table 20). Vines with RR had 35% less crop than vines with NRR treatments (table 20).

Cluster weights at harvest were significantly affected by UTGC and rootstock treatments (table 20). Vines with UTCC had 35% lighter clusters than vines with a herbicide strip below the trellis (table 20). Vines grafted to the rootstock Riparia Gloire had 24% and 20% heavier clusters than vines grafted to the rootstocks 101-14 and 420-A, respectively (table 23).

Berry weights were significantly affected by UTGC, rootstock and RM at harvest in 2009 (table 20). Vines with UTGC had 5% lighter berries than vines with a herbicide strip below the trellis (table 20). Vines grafted to the rootstock Riparia Gloire had 7% heavier berries than vines grafted to 101-14 and 420-A (table 20). Vines with RR had 7% lighter berries than vines with NRR (table 20). Crop load was very low for UTCC vines according to measurements of leaf area (table 22).

Table 23 – Cluster weights and berry weights by rootstock, harvest 2009.

Rootstock	Cluster weight *(g)		Berry weight (g)	
101-14	103	a	1.40	a
420-A	109	a	1.40	a
riparia	136	b	1.51	b

* Values not bearing the same lower case letter differ at p=0.05

Fruit chemistry

Vines were harvested due to wildlife threat on 13-15 October in 2008. Vines with UTCC had 6% higher Brix at harvest than vines on herbicide strip treatments (table 24).

Rootstocks had no effect on Brix, while vines with RR had 3% lower Brix at harvest than vines with NRR (table 24). Fruit from vines with UTCC had pH values that were 8% higher than vines grown on herbicide treatments (table 24). Fruit from vines with RR had a 1% increase in pH values over vines with NRR (table 24). Vines with UTCC had 23% lower titratable acidity at harvest than vines with an herbicide strip below the trellis (table 24).

Pre-harvest berry sampling shows early fruit ripening from RR vines had higher levels of soluble solids after veraison. Fruit from RR vines lagged after early September while NRR vines' fruit proceeded with ripening (figure 17).

Root manipulation and an interaction of RM X Rootstock had significant ($p < 0.0001$) effects on total glucosyl-glucose (GG) concentration. Vines grafted to 101-14 had 42% and 31% higher GG levels than vines grafted to 420-A and Riparia Gloire, respectively (figure 18). Vines with RR on average had 11% higher GG concentration than vines with NRR (figure 18).

Treatment combinations were harvested at similar fruit maturity in 2009 (table 24). Vines with RR were harvested on 9 October 2009, and vines with NRR were harvested on 11 October 2009. Significant differences between fruit maturity from different RM treatments were present at harvest (table 24). Vines with RR had 3% lower Brix at harvest than vines with NRR (table 24). Root manipulation had a significant effect on titratable acidity at harvest (table 24). Vines with RR had 19% lower titratable acidity than vines with NRR (table 36).

Berry skin color components were measured at harvest. Fruit from vines with UTCC had significantly ($p \leq 0.0345$) higher A_{280} values than fruit from vines grown on a herbicide UTGC (table 25).

Table 24 - Primary fruit chemistry at harvest with ANOVA p-values, 2008 and 2009.

			2008	2009	2008	2009	2008	2009
UTGC	**Rootstock**	**RM**	**Brix**		**pH**		**TA (g/L)**	
UTCC	**101-14**	**NRR**	24.2	23.6	3.4	3.3	4.9	7.0
		RR	23.3	22.7	3.4	3.4	4.4	5.6
	420-A	**NRR**	23.9	23.2	3.4	3.3	4.4	8.0
		RR	23.9	22.8	3.5	3.4	4.1	5.8
	riparia	**NRR**	23.5	23.4	3.4	3.3	4.8	7.2
		RR	22.8	22.6	3.5	3.4	5.1	6.0
Herbicide	**101-14**	**NRR**	23.1	23.1	3.3	3.4	6.1	6.9
		RR	22.0	22.7	3.3	3.4	5.9	5.7
	420-A	**NRR**	22.4	22.7	3.2	3.3	5.8	7.6
		RR	21.6	22.3	3.2	3.3	5.9	6.3
	riparia	**NRR**	22.4	23.2	3.2	3.4	6.2	7.6
		RR	21.5	22.2	3.2	3.3	6.1	6.4

ANOVA							
Effect	**p-value**						
UTGC	0.0023	ns	0.015	ns	0.0162	ns	
Rootstock	ns	ns	ns	ns	ns	ns	
Rootstock X UTGC	ns	ns	ns	ns	ns	ns	
RM	0.001	0.0044	0.035	0.0109	ns	0.0009	
RM X UTGC	ns	ns	0.0353	0.0003	ns	ns	
RM X Rootstock X UTGC	ns	ns	ns	ns	ns	ns	

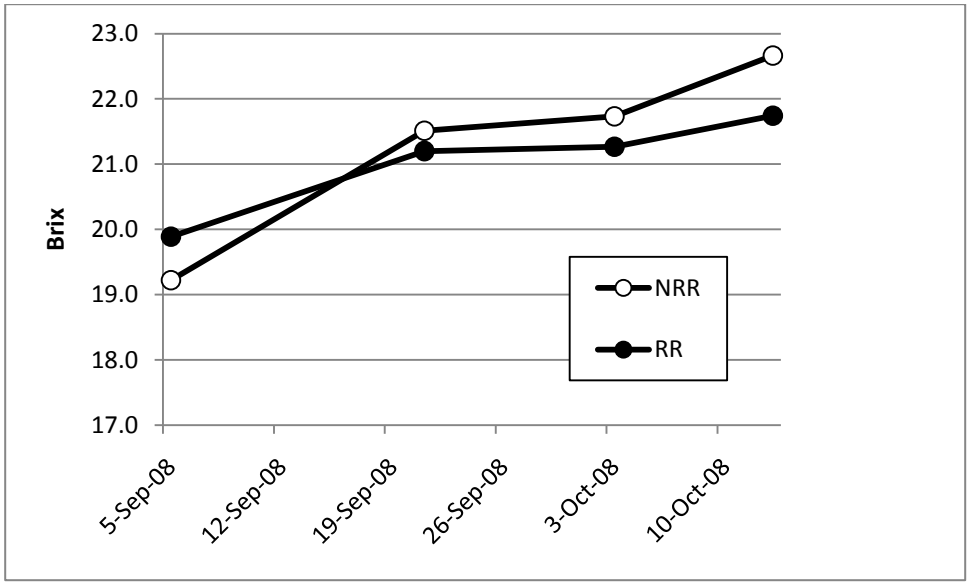


Figure 17 - Brix accumulation in berries, 2008.

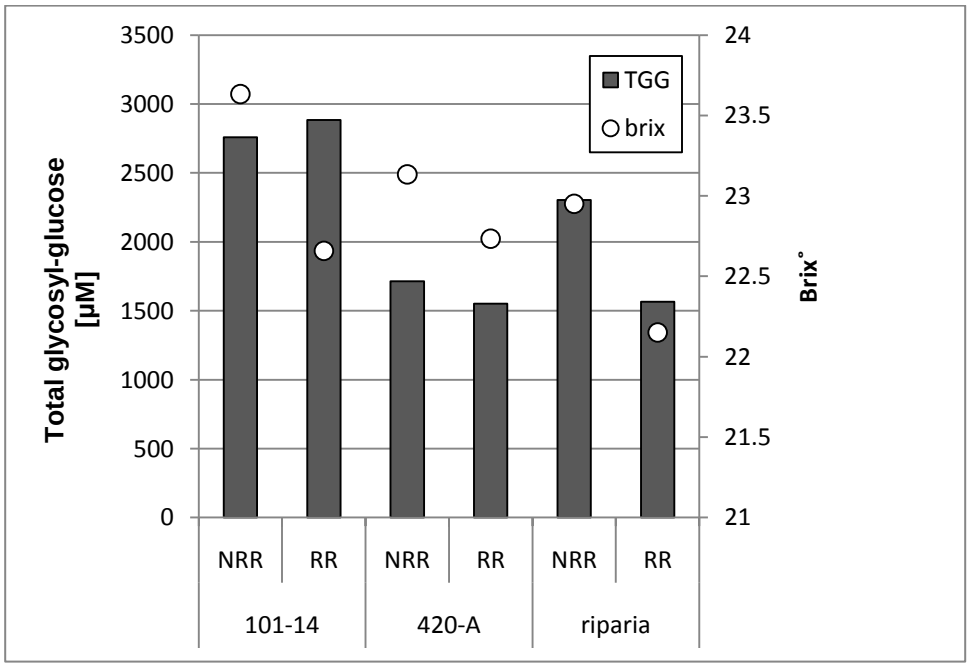


Figure 18- Total glycosyl-glucose and Brix at harvest, 2008.

Table 25 - Berry skin color parameters from harvest 2009 BBCH 89.

UTGC	Rootstock	RM	A_{280}	A_{420}	A_{520}	Color Density (A)	Anthocyanins per unit area of skins (A/cm^2)	Hue (A)
UTCC	101-14	NRR	43	11	38	49	0.009	0.29
UTCC	101-14	RR	43	11	37	47	0.009	0.29
UTCC	420-A	NRR	39	10	34	44	0.008	0.29
UTCC	420-A	RR	45	10	35	45	0.008	0.29
UTCC	riparia	NRR	45	10	35	45	0.008	0.29
UTCC	riparia	RR	42	10	34	44	0.008	0.29
Herbicide	101-14	NRR	38	10	34	44	0.008	0.29
Herbicide	101-14	RR	37	10	36	46	0.009	0.27
Herbicide	420-A	NRR	37	9	32	41	0.008	0.29
Herbicide	420-A	RR	38	9	31	40	0.007	0.28
Herbicide	riparia	NRR	40	9	37	47	0.009	0.25
Herbicide	riparia	RR	39	10	34	44	0.008	0.28

Wine-making

Wines were made from the UTGC and RM treatment combinations in 2009. Fruit harvested in 2009 had little variability in soluble solids and therefore alcohol was similar in the wine made from treatment combinations (table 26, table 27). Malic acid values in finished wine decreased with treatment severity, RR vines had significantly lower levels than vines with NRR (table 26, table 27).

Color analysis post fermentation showed that in this study, smaller vine size results in increased A_{280} values. A_{280} is a measurement of compounds with a aromatic ring that absorbs light in the UV spectrum, which includes all pehnolic compounds (Harbertson and Spayd 2006). Wine made from vines with RR treatments had higher A_{280}, however the difference was not significant (table 27). Wine made from vines with UTCC and RR treatments had significantly higher A_{520} (table 27). Wine made from vines with UTCC and RR had significantly higher color density values (table 27).

Table 26 – Pre-fermentation juice chemistry with ANOVA p-values, 2009.

UTGC	RM	Brix	pH	TA* (g/L)	Malic acid (g/L)	YAN† (mg/L)
Herbicide	**NRR**	23.4	3.8	4.3	3.9	139
UTCC	**NRR**	23.1	3.7	4.3	3.8	132
Herbicide	**RR**	22.6	3.7	3.7	3.0	164
UTCC	**RR**	22.9	3.7	3.7	3.0	150
Effect		p-values				
UTGC		ns	0.0082	ns	ns	ns
RM		ns	ns	0.0065	0.0048	0.0509
UTGC X RM		0.0035	ns	ns	0.018	ns

*Titratable acidity

†Yeast assimilable nitrogen

Table 27 – Post-fermentation wine chemistry with ANOVA p-values, 2009.

UTGC	RM	Alcohol (v/v)	Malic acid (g/L)	pH	TA* (g/L)	VA† (g/L)
Herbicide	**NRR**	13.57	3.75	3.73	7.95	0.49
UTCC	**NRR**	13.43	3.47	3.66	7.95	0.49
Herbicide	**RR**	13.20	2.76	3.54	7.49	0.40
UTCC	**RR**	13.47	2.75	3.55	7.62	0.42
ANOVA						
Effect		**p - value**				
UTGC		ns	ns	ns	ns	ns
RM		ns	0.0044	0.0046	0.0355	0.0237
UTGC X RM		ns	ns	0.0544	ns	ns

*Titratable acidity
†Volatile acidity

Table 28 – Post fermentation color analysis with ANOVA p-values, 2009.

UTGC	RM	A_{280}	A_{320}	A_{420}	A_{520}	color density (A)	Hue (A)
Herbicide	**NRR**	26.3	10.3	2.6	3.5	6.1	0.7
UTCC	**NRR**	30.5	12.4	3.2	4.6	7.8	0.7
Herbicide	**RR**	31.0	11.1	2.7	4.2	6.9	0.6
UTCC	**RR**	35.1	11.9	3.4	5.1	8.6	0.7
ANOVA							
Effect		**p-values**					
UTGC		ns	ns	ns	0.0463	0.05	ns
RM		ns	ns	ns	0.0287	0.03	0.05
UTGC x RM		ns	ns	ns	ns	ns	ns

Discussion

The objectives of this project were twofold. The first objective was to quantify treatments effects on vegetative growth and development. The second objective was to measure the effects, if any, on fruit composition. A grapevine's vegetative growth is largely influenced by the environment in which the vine is grown. To our knowledge this study was the first to inspect the impact of vineyard floor management, rootstock and root manipulation together in a replicated design. These three levels of treatment each influence vegetative growth to varying degrees and through separate mechanisms. These three treatment levels were evaluated because they produce a range of vine vegetative growth response and they required evaluation before practical application.

Treatment level	Treatment	Effect	Compared to
UTGC	UTCC	• Reduced vegetative growth • Reduced canopy density • Reduced components of yield • Reduced fruitfulness • Increase color	Herbicide strip
Rootstock	Riparia Gloire	• Reduced vegetative growth • Increased components of yield	101-14, 420-A
RM	RR	• Reduced vegetative growth • Reduced canopy density • Increased color • Decreased malic acid	NRR

Table 29 – Review of main treatment effects.

Vines with UTCC had lower values for vegetative growth than vines with an herbicide

strip below the trellis. In this study, vines with UTCC had 47% lighter pruning weights than vines with a herbicide strip below the trellis, similar to findings in Australia and California. Cover crops below the trellis have been shown to significantly reduce pruning weights in Australia (Tesic et al. 2007). Vines in California with native grass cover crops grown in between the vine rows had 30% lighter pruning weights than vines which had row middles kept clear of vegetation by disking (Ingels et al. 2005).

Rates of shoot growth were significantly reduced for vines with UTCC in the 2009 growing season of this trial. The spring of 2009 had above average rainfall. Vines had similar ψ_{stem} on 10 June (bloom): vines with UTCC average ψ_{stem} was -0.294 MPa and vines with herbicide strip below the trellis average ψ_{stem} values were -0.291 MPa. These slight differences in ψ_{stem} were measured while there was a significant difference in shoot growth rates between these treatments. Shackel (2007) found a linear relationship between rates of shoot growth and ψ_{stem}. Vegetative growth is highly sensitive to water status (Schultz and Matthews 1988), yet with such small differences in water status, perhaps there was interaction with another factor affecting early season shoot growth. Early season vegetative growth uses carbohydrate reserves to develop the photosynthetically active leaf area necessary to sustain the plant through the remainder of the growing season (Koblet et al. 1994). Vines with UTCC had significantly lower trunk circumference values than vines with herbicide strips below the trellis, indicating that these vines had less perennial wood. Potentially the UTCC vines had fewer carbohydrate reserves than vines with herbicide strips below the trellis and decreased carbohydrate reserves interacted with water status to slow the rate of shoot growth on vines with UTCC. Allelopathy between the cover crops and the grapevines could also be responsible for the reduced rates of shoot growth.

Vines in this study with UTCC had significantly less congested canopies, shown by all

parameters of the PQA (Smart and Robinson 1991) and for most of the parameters of EPQA (Meyers and Vanden Heuvel 2008). Our findings were similar to those in Australia where vines with UTCC had significantly lower canopy density for most PQA parameters (Tesic et al. 2007). Decreased canopy congestion is associated with increased fruit quality and decreased disease pressure (Smart and Robinson 1991). Vines with less dense canopies and more sunlight interception are associated with increased bud fruitfulness (May et al. 1976).

Vines with UTCC in this experiment had significantly lower bud fruitfulness. Lower bud fruitfulness would not be expected for vines with lower canopy congestion. Vines with UTCC had fewer clusters per vine in Australia than vines with a herbicide cleared area below the trellis (Tesic et al. 2007). Vines with orchard grass between the vine rows had reductions in bud fruitfulness compared to vines with a vineyard floor kept clear of vegetation in an arid California vineyard irrigated with overhead sprinklers (Wolpert et al. 1993). These other studies align with our results: UTCC can result in reduced bud fruitfulness.

In our study, vines with UTCC had significantly lower berry weights that vines with herbicide UTGC in 2008 and 2009. Similar research in Australia found vines with UTCC sometimes had significantly lower berry weights than vines with herbicide UTGC (Tesic et al. 2007).

Vines with UTCC in our study had increased maturity at harvest in 2008, but not in 2009. In Australia, vines with UTCC significantly increased fruit maturity 1 time in 6 (Tesic et al. 2007). Native grasses in between vine rows did not have a significant influence on fruit maturity in a California vineyard (Ingels et al. 2005).

Vines with UTCC had reduced ψ_{stem} values in our evaluation. Soil moisture measurements in our study found higher volumetric water content in the shallow soil profiles

under cover crops. Our soil moisture readings are counter-intuitive because vines grown with UTCC had more negative ψ_{stem} values, indicating that there was less plant available water in the soil with UTCC. Our findings were unlike those found in Australia, where volumetric soil moisture content was lower and soil moisture tension was significantly higher under a complete vineyard floor grass cover than under a herbicide cleared vineyard floor (Tesic et al. 2007). Our ψ_{stem} findings are similar to vines with orchard grass in between the vine rows that had significantly more negative ψ_{leaf} values and significantly reduced stomatal conductance and transpiration values in a arid Central coast vineyard, and sometimes significantly lower ψ_{leaf} in a vineyard near Sacramento, California (Ingels et al. 2005; Wolpert et al. 1993).

Cover crops under the trellis caused vines in this study to have lower plant tissue concentrations of nitrogen (N), phosphorous, sulfur, magnesium, calcium, zinc and copper and higher concentrations of potassium and manganese though none of these nutrients were significantly affected by UTCC. However, in Australia vines with UTCC had significantly reduced petiole N and native grasses between the vine rows significantly reduced petiole N concentration in California (Ingels et al. 2005; Tesic et al. 2007). Ingels et al. (2005) did confirm that living ground covers in the vineyard increase soil microbial biomass; microbes are associated with delivery of nutrients to crops, holding nutrients within soil profiles, and improving soil structure. Plant-cover crop interactions with soil nutrients is likely different when a perennial cover crop is being established and when the perennial cover crop is fully established. Further long-term studies are needed to understand how UTCC influence the nutrient balance and how it will affect vineyard nutrition.

Cover crop use in vineyards has great potential for managing vine size (Tesic et al. 2007; Wolpert et al. 1993), and positively influencing vineyard land (Ingels et al. 2005). The mechanism by which cover crops influence vine physiology must still be clarified. Cover

crops are often associated with sustainable management programs and long-term studies are needed to inspect the influence of cover crops on vineyard sustainability. Influence of cover crops on fruitfulness and nutrient status need to be further clarified and demonstrated before cover crops are promoted as the sustainable vineyard floor management option.

Rootstocks influenced vines' vegetative growth and components of yield and nutrient accumulation in this trial. Rootstocks are known to influence scion vigor but the mechanism for this influence is not clear (Sampaio 2007). Rootstocks have genetic characteristics that directly and indirectly influence scion vegetative growth; these include root distribution, vine hormonal status, water and nutrient uptake, and root hydraulic conductivity (Sampaio 2007; Smart et al. 2006). Rootstocks are the link between soil and scion; rootstocks are important for vine response to environmental factors (Pouget 1987). Because rootstock effects are partly a interaction of rootstock with the vineyard ecosystem, interpolation of rootstock effects from trials in different regions are unreliable (Sampaio 2007).

Vines grafted to the rootstock Riparia Gloire had reduced vegetative growth compared to vines grafted to the other rootstocks in this trial. Riparia Gloire is well known to reduce vegetative components of scion growth (Pongracz 1983). Similar to our study, Cabernet Sauvignon vines grafted to Riparia Gloire in Bordeaux had lower pruning weights and lower rates of shoot growth than vines grafted to SO4 and 101-14 (Ollat et al. 2001). The Bordeaux trial used the same rootstocks in two different soils, one gravel and one sandy. Vines with the heaviest pruning weights were grafted to 101-14 on the gravely soil and SO4 on the sandy soil (Ollat et al. 2001); this displays a soil texture influence on rootstock effect. Soil textures control water holding capacity and soil features such as impermeable layers or gravel lenses will influence the depth and distribution of root system (Smart et al. 2006). In our study, vines grafted to 101-14 and 420-A did not have significant differences in vegetative growth, but 101-

14 usually had slightly higher rates of shoot growth, pruning weights and canopy density. Vines grafted to 420-A sometimes had significantly more vegetative growth than vines grafted to 101-14 in a rootstock evaluation in Oregon (Sampaio 2007). Oregon has cooler growing season temperatures than Virginia.

In our trial, the rootstock Riparia Gloire significantly increased cluster weight in 2008 and 2009, and berry weight in 2009. UTCC and RR, the other treatments in our study that reduced vegetative growth, reduced components of yield. Vines grafted to Riparia Gloire had decreased vegetative growth yet increased components of yield. Our findings are similar to those in a 25 year rootstock evaluation in Bordeaux where after 15 years of evaluation, Cabernet Sauvignon vines grafted to Riparia Gloire had an increased Ravaz index compared to vines grafted to 101-14 and SO4, indicating a higher allocation of biomass to reproductive growth relative to vegetative growth (Ollat et al. 2001). Vines grafted to Riparia Gloire in Oregon had reduced components of yield such as berry weight and cluster length and vines grafted to 420-A had stimulated fruit production (Sampaio 2007). Neither of the rootstock effects observed in the cool growing conditions of Oregon agree with our findings in the humid, warm growing conditions of Virginia. The effect that Riparia Gloire had on components of yield was counterintuitive. Reductions in vegetative growth are associated with stress or deficit water status (Schultz and Matthews 1988). Stress and deficit water status can reduce fruitfulness and components of yield (Vasconcelos et al. 2009). Our findings show that Cabernet Sauvignon vines grafted to Riparia Gloire had similar ψ values to other rootstocks, yet decreased vegetative growth and increased components of yield.

The vigor conferred to scion was not completely explained by ψ_{stem} in a rootstock evaluation in Oregon where the author suggested that rootstocks have inherent drought avoidance strategies (Sampaio 2007). Sampaio (2007) noticed that rootstocks like Riparia

Gloire produce smaller canopies yet remain sensitive to drought late in the growing season and rootstocks like 101-14 and 420-A produce larger canopies than Riparia Gloire yet develop water deficit late in the season. Riparia Gloire conferred what appeared to be a similar strategy in Virginia, these vines had less canopy growth, yet vines showed similar water deficit to 101-14 late in the season. Scions grafted to 101-14 in our trial, followed the predictions of Sampaio (2007)- these vines developed larger canopies than Riparia Gloire yet had similar levels of water deficit late in the season. Therefore, we presume 101-14 has greater hydraulic conductance properties than Riparia Gloire which enable the rootstock to keep its larger canopy hydrated. Scions grafted to 420-A grown in Virginia had similar vegetative growth to vines grafted to 101-14, yet these vines had less negative ψ_{stem} values than the other rootstocks. This indicates higher hydraulic conductance, yet vines grafted to 420-A did not have greater lateral development or pruning weights as would be expected for vines with a less negative water status (Schultz and Matthews 1988).

Rootstocks of *V. berlandieri* ancestry have shown reduced potassium accumulation compared to rootstocks of other Vitis parentage (Wolpert et al. 2005). Potassium is important for vine function, but high potassium concentrations in fruit can have deleterious effects on wine color and microbial stability (Mpelasoka et al. 2003). In our trials, rootstock 420-A (*V. berlandieri X V. riparia*) had significantly lower petiole potassium concentrations, 38% and 40% lower concentrations compared to 101-14 (*V.riparia X V.rupestris*) and Riparia Gloire (V*. riparia*), respectively. There was not a significant rootstock effect on fruit pH at harvest in either year.

Rootstocks substantially affected vine growth in this study. However, there were no extreme stresses introduced by any rootstocks in this trial. The effect of rootstock on vine growth varies in different environmental conditions (Ollat et al. 2001; Sampaio 2007; Smart et

al. 2006). Rootstocks studies need to be completed in multiple environments, years and scions varieties to fully characterize rootstock effects on scion growth. Grower planting decisions may be made with more confidence when region specific rootstock research has been completed.

Vines with NRR had more negative ψ values and reduced vegetative growth, components of yield and maturity at harvest in our trial. Apple trees with RR had decreased trunk growth, shoot growth, and pruning weights compared to NRR controls (Byers et al. 2004). The effect of RR on apple trees was related to the excessive restriction of roots to smaller soil volumes (Byers et al. 2004). Water status of apples trees was not measured and no supplemental irrigation was applied (Byers et al. 2004). Supplementary irrigation was applied to vines with RR in this trial. Irrigation was applied specifically to RR vines in the 2009 growing season and fruit maturity was more similar between RR and NRR vines in 2009 than in 2008 when irrigation was applied to all vines at equivalent rates.

Flowering and fruiting as well as fruit quality parameters like fruit firmness, soluble solids and color were improved by RR treatments compared to NRR controls applied to apple trees (Byers et al. 2004). Fruit from RR vines had elevated Brix levels after veraison; however, by harvest Brix was higher in NRR fruit both years of this trial. RR vines had a more negative water status than NRR vines. Severe water stress after veraison has been shown to decrease Brix at harvest (Matthews et al. 1990). Vines grown in RR may have increased root to shoot hormone signaling as vine roots may come in contact with dry soil or girdling by the RR fabric.

Vines with RR had significantly higher titratable acidity in 2009, and tended to be higher in 2008. Increased temperatures result in more malic acid catabolism in the fruit and therefore lower acidity in the fruit at harvest (Conde et al. 2007). It is possible the increased

fruit exposure to sunlight on RR vines led to increased temperatures and therefore decreased malic acid levels at harvest.

RR vines had significantly increased YAN content in the fruit at harvest in 2009. These vines did carry less crop than vines with NRR. Plant tissue analysis from bloom in 2009 shows vines with NRR having a slightly higher concentration of N in their petioles.

Root manipulation has a great deal of potential in reducing vegetative growth and affecting the water status of grapevines in a humid environment. Root restriction treatments subjected peach trees to water stress in Australia (Boland et al. 2000). Accumulated stress over the growing season may increase vine cold tenderness or decrease fruitfulness in subsequent years. Vines with RR had lower phosphorous concentrations in plant tissue analyses. It is possible that reducing the volume of soil that the vine roots can explore will continue to limit the uptake of less mobile nutrients like phosphorous. There are many ways that RR may influence vine physiology, clarifying these influences that RR has on vine physiology is important before any commercial applications are initiated.

Wine made from different treatment combinations showed no significant differences in alcohol yet significant differences in malic acid content and color. Differences in malic acid content could be due to different cluster exposures due to the treatment influences on vegetative growth.

Wine made from UTCC and RR treatments had enhanced wine color compared to herbicide UTGC and NRR. These same treatments UTCC and RR had decreased canopy density, and therefore increased cluster exposure to sunlight.

Phenolic compounds occur in all vascular plants, and are responsible for the color, bitterness, astringency and antioxidant components of wine (Harbertson and Spayd 2006). The biosynthesis of phenolic compounds increases with increasing berry temperatures until a

maximum is reached, estimated to be around 30˚C is reached and biosynthesis is then reduced (Downey et al. 2006). Sunlight interception on dark fruit increases fruit temperature. The treatments UTCC and RR reduced vegetative growth and canopy density. A result of more open canopies is more cluster exposure to sunlight; this may be responsible for the increased color in wine made from vines with these treatments.

Canopy density measurements using PQA allow comparisons of the treatment effects on canopies. Cluster thinning occurred in this trial to maintain similar crop loads between the treatments. Treatment comparisons of the parameter percent exposed clusters from PQA or cluster exposure layer in EPQA is confounded in this study because larger vines with more clusters may have higher values because smaller vines had more clusters removed. The parameter of cluster exposure flux availability in the EPQA allows a comparison of the light zone within the fruit zone of different treatments canopies. This added parameter of EPQA improves canopy comparisons when treatments have different cluster numbers per vine.

Berry weight was significantly influenced by treatments in this study. A popular explanation of wine quality and intensity, explains that wines made from smaller berries have an increased component of skin to pulp thereby increasing the color and aroma of wine. This popular explanation has been proven incorrect by Walker et al. (2005) and Roby and Matthews (2004). These studies found that decreased berry size did not influence the relative components of skin and pulp (Roby and Matthews 2004; Walker et al. 2005). This study did not inspect the relative components of skin and pulp in berries, yet treatments that had decreased berry weights had increased color in wine, indicating differences in wine phenolic composition. More detailed work is needed to clarify how these treatments influence the phenolic composition of fruit.

Cabernet Sauvignon vines with pruning weights in the range of 0.3 – 1.0Kg pruning

weight per meter of cordon have the ability to produce high quality wines (Kliewer and Dokoozlian 2000). Several treatment combinations with UTCC, Riparia Gloire, or RR had pruning weights within this optimum range indicating that these treatments achieved vine balance.

Conclusions

To our knowledge this study was the first to inspect the impact of vineyard floor management, rootstock and root manipulation together in a replicated design. The hypothesis of this experiment was that treatments that reduce the rate and duration of vegetative growth will improve fruit composition and wine potential. On each of the treatment levels one treatment reduced vegetative growth compared to the other treatments at that level. The relative reduction of vegetative growth was different for each treatment level. The reduction in vegetative growth was at least partly due to treatment influence on vine water status, yet the mechanism that treatments used to make this change are quite different between experiment levels. These reductions in vegetative growth resulted in changes to components of yield and fruit composition. Further clarification is needed to assess the influence of these changes on potential wine quality.

This investigation identified practices that can reduce vegetative growth of grapevines. Further studies on these techniques will clarify their mechanisms and allow for predictable application of these vines size regulating practices in warm and humid winegrowing areas where excessive vine vigor is a common problem.

Vines with different treatment combinations had different ψ values during the growing seasons in this trial. The ordinal severity of water deficit the vines were exposed to match the ordinal severity of vegetative growth reduction. Vines with UTCC had more negative ψ than vines with herbicide UTGC. Vines with RR had more negative ψ than NRR. The water deficit

of RR vines was greater than the water deficit of UTCC vines. Vines with RR had more reduced vegetative growth than vines with UTCC.

Different ψ values imposed by these treatments explain most but not all the treatment effects observed in this experiment. The treatments may have influenced the vines by means other than changes to the vines water status. Vines with UTCC had significantly lower fruitfulness values and higher total phenolic compounds in berry skins. Vines with RR had more deficit water conditions than UTCC vines, yet did not show the same degree of lowered fruitfulness or skin phenol content. UTCC must have affected vine properties other than vine water status resulting in alteration to fruitfulness and fruit color. Allelopathic interactions between different species sharing a space or differences in carbohydrate reserves can cause stress.

Vines grafted to different rootstocks had similar ψ values though the growing season. Vines grafted to Riparia Gloire had less vegetative growth during the growing season and larger berries at harvest while maintaining a similar water status to vines grafted to the other rootstocks.

Vines with RR had the most negative ψ values and had the most reduced vegetative growth during the growing seasons. Vines with RR had similar reductions in berry weight to vines with UTCC. Roots can signal shoot response to soil conditions. Root restriction is may alter this root to shoot communication.

This project has followed these treated vines over a two year period. More data is necessary to fully characterize the influences of these treatments on vines. Specifically, evaluations described in the next 4 paragraphs are useful next steps in the study of these treatments on vine size regulation.

Gas exchange and water status measurements could be initiated earlier and repeated

more often. These values would allow for better determination of vine water status influence on vegetative growth and water status influence on gas exchange.

The differences in components of yield could be inspected in more detail. Treatments influenced berry weight and number of berries per cluster. Timing of treatment influence on components of yield may help determine the mechanics by which the treatments influence components of yield and allow predictable use of the treatments. Fruitfulness and flowering could be inspected in more detail to determine if treatments increase floral initiation, branching within inflorescence development or abscission of flowers during bloom.

Root to shoot hormones cause shoot response due to soil conditions. Xylem sap could be collected to compare influences that these treatments have on root to shoot hormone signaling. The types and ratios of hormones in the xylem sap could provide information about the environment roots are exposed to due to treatments.

Treatments influenced the rate of fruit ripening in 2008. Rate of fruit ripening can influence GG concentration which influences fruit quality. GG analysis of fruit or wine will indicate treatment influence on fruit quality.

This study helped identify practices that can aid in improving fruit quality for wine production in winegrowing areas with warm and humid weather that have difficulty managing grapevine vigor to a reasonable vine size. We explored techniques that could be used in the field to manage vine size. These methods are especially attractive if fruit quality is maintained or improved.

This study evaluated three vine growth regulating techniques in a design that allowed comparison of the relative vigor regulation of each of these treatments. On each of the treatment levels one treatment reduced vegetative growth compared to the other treatments at that level. The relative reduction of vegetative growth was different for each treatment.

Further viticulture research using these treatments coupled with research wine production with additional quantification of wine attributes and completion of sensory analysis will show how these treatments impact wine quality.

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