Vines of different capacity and water status alter the sensory perception of Cabernet Sauvignon wines.

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ABSTRACT

Reducing disease and increasing fruit quality in vigorous vineyards with dense canopies is demanding of time and resources; unfortunately, vineyards of this nature are common in humid environments. This study investigated the effectiveness with which vine capacity and water status could be regulated as well as if they related to fruit quality and wine sensory perception. The treatments regulating vine size and water status were under-trellis groundcover, root manipulation, rootstocks, and irrigation. Treatments were arranged in a strip-split-split plot design before the introduction of the irrigation treatment resulted in incomplete replication in each block. Treatment levels were under-trellis cover crop (CC) compared to under-trellis herbicide (Herb); root restriction bags (RBG) compared to no root manipulation (NRM); three compared rootstocks (101-14, 420-A, riparia Gloire); low water stress (LOW) compared to high water stress (HIGH). Vines grown with RBG and CC regulated vegetative growth more so than conventional treatments, resulting in 56% and 23% greater cluster exposure flux availability (CEFA). High water stress (HIGH) and RBG reduced stem water potential and discriminated less against ^{13}C. Vines grown with RBG and CC consistently reduced harvest berry weight by 17 and 6% compared to conventional treatments. Estimated phenolics were consistently increased by RBG and were correlated with berry weight, vine capacity and CEFA. Sensory attributes were significantly distinguishable between wines produced from vines that differed in both vine capacity and water status, amongst other responses. Treatments have been identified that can alter the sensory perception of wines, with the potential to improve wine quality.

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Introduction

A challenge to growing high quality winegrapes in the Eastern U.S. is the humid climate and variable precipitation throughout the growing season relative to more Mediterranean-like climates. Excessive moisture leads to a flourish of vegetative growth in the vine's canopy which leads to undesirable consequences, including preventing canopy light penetration and cluster exposure (Ryona et al. 2008), increased disease pressure (Zoecklein et al. 1992) and decreased canopy penetration of fungicide sprays, and increased vegetative to reproductive growth ratio, leading to a change in source-sink balance of the vine. According to Jones and Goodrich (2008), climate trends that are associated with low quality wine in winegrowing regions of the western U.S. are those associated with ripening period rainfall and above-average bloom and summer rainfall.

Many factors in the vine's environment can be manipulated using viticultural practices to manage excessive vegetative growth and, therefore, change source-to-sink balance and associated indices such as crop load. These factors include, but are not limited to, cultural practices (hedging and leaf pulling), nutrient availability (fertilization), irradiance (by canopy manipulation or training system), and water availability (by irrigation or site selection). However, the growth of plants is reduced more by water deficits than by any other environmental factor (Pallardy 2008) and extremes of water availability have the potential to limit wine quality in the eastern U.S. Further, finding novel ways of decreasing vine vegetative vigor in humid viticulture regions is necessary as the process of physically manipulating vine canopies is highly laborious and costly to growers. Therefore, the field treatments in this study were all aimed at regulating vine size and controlling water status in aim of developing a range of vine sizes (thus,

canopy architectures) and/or water statuses so that their importance in yielding grapes of high wine quality potential could be explored.

Vine capacity and canopy architecture

Vine capacity is the amount of vegetative and reproductive growth a vine is capable of producing within a growing season. Vine capacity is best assessed through pruning weights and yield on a per vine basis. Like the potential bearing capacity of other plant species, vine capacity will vary with genetics and environmental conditions (both past and current). Small vines will have the capacity to ripen a small crop relative to larger vines. Exceeding a vine's capacity for fruit ripening results in overcropping usually manifested as unripe fruit. It also reduces the capacity for ripening in the subsequent growing season (Miller and Howell 1998).

Large capacity vines, characterized by excessively vegetative canopies, are frequently observed in the Eastern USA and other humid viticulture regions. Perhaps the facet of vine capacity that could limit fruit and wine quality is the physical canopy architectural differences that exist between vines of different capacity. This assumes that larger vines have very dense canopies with highly overlapping vegetation and smaller vines have greater sunlight penetration and greater fruit exposure.

Fruit exposure effects on fruit composition and wine quality

Canopy studies have been an active area of viticulture research since the 1960's (Shaulis et al. 1966). Of particular interest has been the influence of sunlight and its impact on berry composition (Dokoozlian and Kliewer 1995) and wine quality. It is generally thought that excessive shading of fruit results in poor varietal aroma/flavor development (Hunter, 1991) and wine quality (Jackson and Lombard 1993), increased herbaceousness (Smith et al. 1988) and methoxypyrazine levels (Ryona et al. 2008) and that shading has the potential to reduce sugar

and color intensity and increase pH (Smart et al. 1985), all of which are undesirable responses. On the other hand, open canopies with well exposed fruit can increase the production of desirable compounds like monoterpenes (Reynolds et al. 1996), increase sugar accumulation (Bledsoe et al. 1988) and anthocyanin and phenol concentration (Carbonneau 1985) and result in more favorable wine sensory analysis (Di Profio et al. 2011; Staff et al. 1997). However, it has been established that excessively open canopies can result in greater sunlight penetration and higher fruit temperatures, which can limit phenols and, specifically, anthocyanins (Carbonneau et al. 1987; Spayd et al. 2002).

Vine water status effects on wine quality

Water deficits change fruit composition (Chalmers et al. 2010; Chaves et al. 2007; Ojeda et al. 2002) and so it is assumed that differences in fruit composition will change wine sensory perception (Matthews et al. 1990). Some form of water deficit is beneficial for wine quality, as long as the stress is not too severe (Keller 1995). Wines produced from grapes of water-stressed vineyards were often preferred in tasting trials (Koundouras et al. 2006). Chapman et al. (2005) found that vine water deficits in Cabernet Sauvignon vines lead to wines with more fruity and less vegetal aromas and flavors.

Indirect effects of vine water status on fruit composition

-via physiological effects

Water availability is critical for photosynthetic efficiency, as it is critical for regulating source strength. Farquhar and Sharkey (1982) suggest that stomata function to minimize water loss and Lakso (1979) and Losivolo et al. (2010) reported a linear relationship between stomatal aperture and stomatal conductance, respectively, and photosynthesis. Long-term water stress in field-grown grapevines leads to a progressive decline of stomatal conductance, accompanied by

a decrease in CO_2 assimilation (Escalona et al. 1999). Thus, water stress limits stomatal conductance and photosynthetic efficiency, resulting in less carbon assimilation. The result is a lower source strength which decreases the allocation of carbon to ripening fruit, resulting in unripe fruit of lower value.

-via vegetative effects

In addition to water's potential influence on fruit quality through physiological processes, such as photosynthesis, water availability can impact cellular expansion and thus vegetative growth, which has the potential to influence fruit composition for several reasons. The growth-restrictive nature of a water deficit may result in a more open canopy architecture as limiting water has the potential to restrict vegetative growth and vine vigor (Chaves 2007, Matthews et al. 1987). Irrigation has to be controlled to optimize source to sink balance and avoid excessive vigor; excess shoot vigor may have undesirable consequences for fruit composition (Chaves 2007).

Direct effects of vine water status on fruit composition

-via compositional effects

In addition to its indirect effects, vine water status has the potential to influence fruit composition directly, either by increasing the synthesis and translocation of flavor and aroma compounds to the fruit or by decreasing their degradation. Depending on the specific phenolic compound of interest and the period and severity of water deficit, biosynthesis of phenols has the potential to be positively impacted by water deficit (Ojeda et al. 2002). Water deficit accelerated sugar accumulation and malic acid breakdown and had beneficial effects on the concentration of anthocyanins and total phenolics in the berry skins (Koundouras et al. 2006). Water limitation, especially pre-veraison, caused a substantial increase of skin anthocyanin

concentration and that limited water supply was associated with increased aroma potential at harvest (Koundouras et al. 2009). Lovisolo et al. (2010) reported that drought caused changes in secondary metabolites in the berry and that polyphenol concentrations increased after water stress conditions, independently from the differences in berry size due to water availability.

-via berry growth effects

Water status can influence berry growth dynamics, which will affect must concentration and wine composition. Roby et al. (2004) found that water deficit increased skin tannin and anthocyanins, but more as a result of the differential growth sensitivity of the inner mesocarp and exocarp than actual effects on phenolics biosynthesis. Shellie (2010) found that vine water deficit was associated with up to a 27% increase in the proportion of seed to total berry fresh weight regardless of berry size, thus altering the proportion of seed-derived relative to skin-derived compounds in the must during fermentation. Roby and Matthews (2004) found that relative proportions of the berry that represented whole-berry mass were changed via water status differences: late-season water deficit resulted in fruit with more skin and seed tissues (relative to whole-berry fresh mass) compared with well-watered control fruit and Ojeda et al. (2002) found that water deficit resulted in a positive effect on the concentration of phenols due to a reduction in berry sizes in Shiraz.

Summary of environmental effects on fruit and wine quality

The previously discussed studies suggest that fruit exposure is an important determinant of fruit and wine quality. Because fruit is exposed to a lesser extent in humid regions where excessively dense canopies can persist, it needs to be achieved through some sort of cultural practice. It is suggested that cultural practices of shoot-tipping and leaf and lateral removal is laborious and, therefore, costly. The previously discussed studies also suggest that water deficits

have great potential to result in relatively greater concentrations of flavor and aroma compounds in fruit, thus having higher wine quality potential. Because vines grown in these same humid regions can have a surplus of water supply, vineyard water management also requires further investigation.

Project: production, physiology, and wine quality potential as affected by vine environment

We desired to manipulate the micro-environment of vines through several applied field treatments so that vines of different size (thus, canopy micro-climate) and water status could be produced and evaluated for several growth and physiology responses as well as fruit and wine quality potential. We understood, through previous research on the same plots (Hatch et al. 2011), that the applied field treatments would result in vines of different vegetative growth capacity and water status. Further, we proposed that, based on previous viticultural research, these responses would be at least partly responsible for imparting differences in fruit composition and sensory perception of the resultant wines.

Three questions were pursued: (1) Will differences in vine size and post-fruit set water status result in detectable sensory differences in wines? (2) Which growth and physiology responses will best correlate with differences in sensory attributes of wines (3) Based on response data and previous viticulture research, why did certain treatments result in sensory differences and/or higher wine quality relative to others?

The specific hypotheses were: (1) Wines produced from vines of different capacity and water status will result in significantly detectable sensory differences; (2) wines compared between treatments which had the greatest magnitude of differences in canopy micro-climate and water status will result in more consistent and significant detectable sensory differences; (3) vines of relatively low capacity and low water stress will result in wines that have the greatest

quality and most desirable sensory characteristics, as confirmed by descriptive analysis and consumer preference tests.

Materials and Methods

Design

The research was conducted at Virginia Tech's AHS, Jr. Agricultural Research and Extension Center near Winchester, VA. Cabernet Sauvignon ENTAV-INRA clone 337 vines, planted in May 2006, in rows running generally northeast/southwest at a 3.0-m x 1.5-m row x vine spacing were used. Vines were trained to bilateral cordons (80 cm above ground) and shoots were vertically positioned upright with the aid of catch wires, otherwise known as vertical-shoot positioning (VSP). The inter-row groundcover, established in 2001, consisted of a mixture of orchard grass (*Dactylis glomerata*) and tall fescue (*F. arundinacea*).

Experimental units were 5-vine plots, each replicated six times. Each block and strip was separated by 5-vine border plots within the row and by continuous buffer rows between each adjacent block. The experimental design was initially a strip-split-split plot design with three different treatments: under-trellis ground cover (UTGC), rootstock (Stock), and root manipulation (RM). The under-trellis groundcover (UTGC) treatment was either an 85-cm wide herbicide-treated strip or the intra-row (under-trellis) area was established to creeping red fescue (*Festuca rubra*); from this point forward, the under-trellis groundcover treatment will be designated by either Herb or CC to convey under-trellis herbicide ground or under-trellis cover crop treatment levels, respectively. The rootstock treatment (Stock, sub-plot) consisted of three different rootstocks: Riparia Gloire (riparia) (*Vitis riparia*), 420-A (*V. berlandieri x V. riparia*), or 101-14 (*V. riparia x V. rupestris*). The root manipulation treatment (RM, sub-sub-plot) consisted of root restriction bags (RBG) (model RCB-12) (High Caliper Products Oklahoma City, OK), with a volume of 0.015 m^3, installed at planting, or no root manipulation (NRM).

Variable irrigation rates were added to the experimental design in May 2010. Three different irrigation treatments were initiated immediately post-fruit set: half of the root-bag vines (those in Blocks 1, 2, and 5) were irrigated by means of drip irrigation (2.27 L per hour emitters on 0.3-m centers) on a 3 day/week basis and generally for 1.5 hours (approximately 5.1 L/vine) at each irrigation (LOW stress); the other half of the root-bag vines (those in Blocks 3, 4, and 6) were irrigated when "stressed," (around times when midday stem water potential, $\psi_{md, stem}$, readings were as low as -1.7 MPa and as high as -0.8 MPa) in 2010 and by a $\psi_{md, stem}$ potential reading of -1.0 MPa or lower in 2011 (HIGH stress); the no root manipulation vines were irrigated once on 26 July (approximately 5.1 L) in 2010 and never irrigated in 2011.

Because variable irrigation rates were not evenly applied to all treatments in the experimental design, but were associated with a specific root manipulation (RM) treatment level, the combination of each irrigation rate and their respective root manipulation (RM) treatment level comprised the root manipulation-differential irrigation (RM-Irr) treatment. Thus, root manipulation-differential irrigation (RM-Irr) treatment levels were: root bag-low water stress (RBG-LOW), root bag-high water stress (RBG-HIGH) and no root manipulation-no irrigation (NRM-None). The amount of water received by each root manipulation-differential irrigation (RM-Irr) treatment level via drip irrigation from post-fruit set until harvest is shown in Table 1.

Table 1. Volume of water applied via drip irrigation by the root manipulation-irrigation (RM-Irr) treatment on a per vine basis, from fruit set through harvest in 2010 and 2011.

	Liters / vine[a]	
Treatment level[b]	**2010**	**2011**
RBG-LOW	233	221
RBG-HIGH	53	56
NRM-None	5	0

[a]Irrigation totals assume that drip irrigation reaches the vines at 90% efficiency and that each vine received irrigation from 1.5 emitters, on average.
[b]RBG = root bag; NRM = no root manipulation; LOW = low water stress; HIGH = high water stress; None = no irrigation.

Meteorological indices

Weather data was logged daily using an ET106 weather station (Campbell Scientific, Inc., Logan, UT) on site at the AHS, Jr. AREC. Two software programs were used to retrieve data. The Virginia Tech Mesonet System was used to log daily minimum and maximum temperatures (˚C), which, along with a base temperature of 10 ˚C, were used to generate growing degree days (GDD) in both 2010 and 2011. Visual Weather 1.0 (Campbell Scientific, Inc., Logan, UT) was used to log daily rainfall (mm) and potential evapotranspiration (ETo). It was assumed that rainfall reached the root-bag and non-root manipulated vines at 80% efficiency early in the season, when there was a less developed canopy. For 5 wks prior to veraison, as canopies developed, rainfall efficiency was assumed to be 70% for the non-root manipulated and still 80% for the root-bag vines. After veraison, rainfall efficiency was assumed to be 60% for the non-root manipulated vines and 70% for the root-bag vines. The efficiencies used were estimated based on 70% to 80% efficiency for overhead sprinkler irrigation, as suggested in The Wine Grape Production Guide for Eastern North America (Ross and Wolf 2008). This reference does not consider canopy maturation in relation to phenology, which likely results in the deflection of relatively more water from the root zone as phenology advances.

Soil moisture

Soil moisture was collected weekly and bi-weekly in both 2010 and 2011. A frequency domain reflectometry soil moisture probe (PR-2, Delta-T Devices, Cambridge, UK) was used to measure volumetric soil water at six depths: 100, 200, 300, 400, 600, and 1000 mm. On each collection date, the probe was inserted into access tubes installed under-the-trellis in NRM panels with vines grafted onto 420-A rootstocks. Six replicates were in panels with under-trellis cover crop and another six replicates in panels with under-trellis herbicide. Each reading comprised

three averaged measurements at each depth, with the probe rotated 120˚ in the access tube between each measure.

Plant tissue analysis

Leaf petioles were collected at bloom and veraison and leaf blades at veraison in 2011. Petiole and leaf samples (50 each/sample) were collected from opposite an inflorescence or, at veraison, opposite a grape cluster. All treatment combinations, except differential irrigation, were sampled in triplicate by combining treatments from two blocks into one sample and replicating three times. Due to combining blocks, only one replicate sample was collected for each treatment combination containing differential irrigation. This meant that six samples were representative of each differential irrigation treatment level, 12 samples for each rootstock treatment level, and 18 samples for each under-trellis groundcover and root manipulation treatment level. Samples were oven dried (60˚C) and sent to Pennsylvania State University's Agricultural Analytical Service's Laboratory (University Park, PA) for analysis of essential mineral nutrients.

Vegetative characterization

Vegetative growth and vigor of vines was characterized by collecting data on lateral shoot growth, shoot-tip activity, canopy architecture and subsequent analysis with enhanced point-quadrat analysis (EPQA) (Meyers and Vanden-Heuvel 2008), fruit zone light interception, and cane pruning weights. All data, except dormant cane pruning weights, were collected at or around veraison in both 2010 and 2011.

Lateral shoot development: Lateral shoot development was assessed by randomly selecting two primary shoots, each originating from spurs midway between the head and end of each cordon,

on two vines per panel (four total shoots/panel) and counting the number of unfolded leaves on each lateral originating from nodes three through seven of each primary shoot.

Shoot-tip activity: Shoot-tip activity was assessed at the time of lateral assessment. The same four primary shoots used in the lateral assessment were assessed for their shoot-tip activity by analyzing shoot tips and tendrils and recording if they were actively growing or not. For no root manipulation (NRM) vines, this meant analyzing lateral shoots, as these vines had previously been shoot-hedged; for most root bag (RBG) vines, this meant analyzing primary shoot tips as most of these vines were never shoot-hedged.

Canopy architecture: Point quadrat analysis (PQA) is a method of assessing canopy architecture and was refined for grapevines by Smart and Robinson (1991). The analysis involves inserting a thin metal rod into the fruiting zone along the transverse axis of the canopy row and using a metal frame to guide spatial insertions. As probe insertions were made through one side of the canopy to the other, contacts with leaves, clusters, or gaps were called out and recorded before the probe was removed for re-insertion through the canopy at the next consecutive insertion guide in the frame. This process was repeated 20 times in each panel, with probe insertions that occurred approximately every 25 cm while moving down the row, ensuring that probe insertion was through the fruit zone. Data were analyzed with enhanced point quadrat analysis (EPQA) software. (Meyers and Vanden-Heuvel 2008).

Fruit-zone light penetration: Canopy sunlight penetration was evaluated using an AccuPAR ceptometer (Model PAR-80, Decagon Devices, Inc., Pullman, WA). Photosynthetic photon flux density (PPFD) was assessed by inserting the ceptometer inside canopy fruit zones in a fashion that was parallel to and directly above the cordon and orienting the light interception side of the ceptometer in three different directions (45˚ east, vertical, 45˚ west) and then averaging these

three readings. Readings were taken at around solar noon (1130-1500 hrs) in both years. Before PPFD readings were taken, an ambient reading was taken of the current, unobstructed light condition; if the sky condition changed before taking another suite of readings, then another ambient reading was taken. The fruit zone PPFD data, along with the probe contacts (from PQA), were used to generate canopy architecture indices with EPQA software.

Dormant pruning weights: Fresh weights of pruned canes were collected by vine each winter.

Components of crop yield

Yield components: Crop yield data were collected at harvest in Sep 2010 and Oct 2011. Yield weight and cluster number were determined on a per-vine basis and average weight per cluster was calculated from those data. Average individual berry weight was determined by collecting 50-berry samples from each panel at harvest and dividing the total weight of each sample by 50. Combining yield per vine with pruning weight per vine allowed for crop load (yield weight: pruning weight) and vine capacity (yield weight + pruning weight) evaluation. In 2011, because of the high disease prevalence, projected yield was calculated by taking the average sound cluster weight and multiplying it by the total number of clusters on the vine at harvest. This was in addition to collecting actual crop weight.

Cluster thinning: Vines were thinned 4-7 days before veraison, retaining 24 and 26 clusters per vine for under-trellis herbicide and under-trellis cover-crop vines, respectively. In 2011 vines were thinned 7-10 days before veraison, retaining the respective number of clusters for each treatment level (Table 2).

Table 2. Grape cluster number retained per vine by the root manipulation-differential irrigation + under-trellis ground cover (RM-Irr + UTGC) treatment levels in 2010 and 2011.

	Cluster no. / vine	
Treatment level[a]	**2010**	**2011**
NRM-None + CC	26	28
NRM-None + Herb	24	23
RBG-LOW + CC	26	25
RBG-LOW + Herb	24	21
RBG-HIGH + CC	26	27
RBG-HIGH + Herb	24	20

[a] RBG = root bag; NRM = no root manipulation; LOW = low water stress; HIGH = high water stress; None = no irrigation; CC = under-trellis cover crop; Herb = under-trellis herbicide.

Berry geometry: The lone measure of average individual berry weight in 2010 was from weighing 50-berry samples, randomly collected at harvest. In 2011, in order to better characterize the effect that root manipulation (RM) and differential irrigation (Irr) had on berry weight and geometry during different stages of berry development, 50-berry samples were randomly collected once every three weeks beginning one week post-fruit set; five data sets were collected in all. The 50-berry samples were weighed and 20 berries were randomly chosen in order to measure their diameter with calipers. Assuming a sphere, the surface area and volume of each berry could be calculated from diameter, providing relative skin: pulp ratios.

Grape and wine composition: Juice samples from the 50-berry samples taken at harvest were analyzed for soluble solids (˚Brix), pH and titratable acidity (TA). Juice samples were prepared by uniformly hand-pressing the 50-berry samples with a crusher/strainer and collecting the juice in a test tube. Soluble solids were measured with a digital refractometer (Pocket PAL-1, ATAGO USA, Inc., Bellevue, WA). Juice pH was measured with a Ross Ultra pH electrode and Orion Star pH meter (Thermo Fisher Scientific, Beverly, MA). Juice TA was measured using the titrametric procedure using NaOH as by Zoecklein et al. (1995). Additionally, twelve 50-mL juice samples were obtained from the musts of treatment level lots post-processing and crushing of fruit. Processing and crushing was done by adjusting the wheels of a destemmer/crusher

(Wottle Type 2; Wottle Maschinen & WeinPressenbau, Austria) to accommodate treatment effect on berry size and break the skins as uniformly as possible. Juice samples from must lots were analyzed by the Enology Services Lab in the Food Science Deptartment at Virginia Tech using the following procedures: malic acid was analyzed using a L-malic acid test kit, UV method (R-Biopharm, Darmstadt, Germany) and following the manufacturer's instructions; TA was analyzed using the Association of Official Agricultural Chemists (AOAC) Method 962.12, with modifications: titrated to pH 8.2 using a pH probe (Metler Toledo, Columbus, OH) for endpoint detection; pH was analyzed using the AOAC Method 960.19, using standards of 2.00, 4.00, 7.00, and 10.00; yeast-assimilable nitrogen (YAN) was analyzed using K-PANOPA and K-LARGE kits (Megazyme Inc, Bray Business Park, Bray, Co. Wicklow, Ireland.) and following the manufacturer's instructions. Wine samples from the treatment lots were analyzed by the Enology Services Lab in the Food Science Department at Virginia Tech using the following procedures: residual sugar was analyzed using Clini-Test Reagent Tablets (Bayer AG, Leverkusen, Germany); alcohol percentage was estimated by fourier transform infrared spectroscopy (FTIR).

Grape color: Absorption spectroscopy was used to evaluate the differences in estimated total phenolic and anthocyanin levels in the berry skins from different treatments. Samples of 30 berries each were randomly collected at harvest in both 2010 and 2011 and frozen at -80C˚ until tests commenced. At time of testing, 6 mm diameter skin discs from each thawed berry were punched using a leaf hole punch tool which were then homogenized with a 50% ethanol/distilled water solution for 60 sec using a Bio-Homogenizer (BioSpec Products, Inc., Bartlesville, OK). In 2010, the homogenate was then put into test tubes and gently hand swirled for 3-5 sec every hr for three hrs (hand swirling on the first two hours and then proceeding to the next step on the

third hour). In 2011, the homogenate was hand-swirled for 3-5 sec every hr for the first three hrs (hand swirling on the first three hrs) and then let stand an additional 32.5 +/- 10.5 min (depending on what order each homogenate was made in). The homogenate was then transferred into a 15-mL centrifuge tube and then centrifuged for 5 min at 3500 rpm. One mL of the supernatant was pipetted into 15 mL of 1 M HCl and mixed thoroughly. This solution was left to stand for at least one hr after which it was poured into a Hellma quartz cuvette (14-385-906C, Thermo Fisher Scientific Inc., Pittsburgh, PA) with a path length of 10 mm and measured with the Genesys 8 ThermoSpectronic spectrophotometer (Cambridge, UK). Readings were taken for 420 nm and 520 nm wavelengths and, with the deuterium lamp on, the 280 nm wavelength. Samples were diluted with a 2:1 sample to hydrochloric acid (1N) ratio in order to read absorbance at 280 nm; pipettes were used for uniform amounts of HCl and the sample.

Ecophysiology

Mid-day stem water potential: Starting in May 2010, mid-day stem water potential ($\psi_{md,stem}$) was measured wkly for the first five wks and then bi-wkly until early-September. Starting in Jun 2011, $\psi_{md,stem}$ was measured bi-wkly until late-Aug. On each date, aluminum foil-covered plastic bags were placed on exposed primary leaves in the mid-shoot range at least an hr and up to five hrs before the $\psi_{md,stem}$ was assessed on a given vine. Given the large data set (one vine per panel, 72 total readings) collected, the time-span over which stem water potential data were collected varied between data sets and depended mostly on how stressed vines were. In general, data collection started at 1100 hr and ended around 1600-1630 hr. Stem water potential was measured by excising the bagged leaf and within 10-20 sec placing the bagged leaf in the chamber of the pressure bomb (Model 600 Pressure Chamber Instrument, PMS Instrument Co.,

Albany, OR), after which the chamber was pressurized at a rate of approximately 0.04 MPa/sec. At the moment sap began to be exuded from the end of the petiole, the pressure increase to the chamber was stopped and the pressure reading was recorded.

Leaf gas exchange: Gas exchange measurements were collected on the same days and at the same times as $\psi_{md,stem}$ in both 2010 and 2011, with the exceptions being 14 and 21 Jun 2011, when $\psi_{md,stem}$ and gas exchange were collected on alternate dates. This was done to limit the potential day-to-day environmental influence on gas exchange and/or stem water potential, and thus increase the potential of correlating water status with gas exchange parameters. Net photosynthetic rate (A), stomatal conductance (g_s), internal [CO_2] (C_i), and transpiration (E) were measured with a CIRAS-1 portable, closed system infrared gas analyzer (PP Systems, Amesbury, MA), fitted with an environmental cuvette. Operating conditions were a CO_2 reference supply of approximately 365-400 ppm (infrequently as low as 325 ppm) and an internal pump rate of ~200 mL/min. Gas exchange conditions were: ambient temperature of ~20-35 ˚C, under generally clear or partly-cloudy conditions. The cuvette light source (provided by LED lamp) provided a photosynthetic photon flux density (PPFD) of ~1100 to 1200 μmols·m^{-2}·s^{-1}, but was infrequently as lows as 600 μmols·m^{-2}·s^{-1} or as high as 1900 μmols·m^{-2}·s^{-1}. However, on a given data collection event, the range of PPFD did not very much more than 100 μmols·m^{-2}·s^{-1}, thus limiting the influence of highly fluctuating light conditions on gas exchange between treatment readings. For each measurement, the chamber was clamped on one exposed, healthy, green leaf and readings were recorded after 60 sec; two leaves were measured per panel.

Carbon isotope discrimination: At harvest in 2010, 12 different samples, each containing 50 berries each, were collected from vines grown on 420-A rootstocks and from all RM-Irr + UTGC factor levels. After frozen at -80˚C, the juice was extracted from the berries and the centrifuged

at 3500 rpm for five min. The supernatant was poured off and then lyophilized. Stable carbon isotope analysis was performed at the lab of Augustana College in Sioux Falls, South Dakota, using procedures comparable to those of Jensen et al. (2002) with the exception that the standard for sample comparison was Vienna Pee Dee belemnite.

Winemaking

Wines were made at the Virginia Tech Food Science Department's winemaking lab. Fruit for the wine lots was selected by combining grapes from lugs of the same root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatment level, six of which existed, and randomly selecting across the rootstock treatment to obtain 36.3 kg of fruit per replicate lot, for a total of 12 wine lots. Fruit was processed and crushed using the de-stemmer/crusher (Wottle Type 2; Wottle Maschinen & WeinPressenbau, Austria) in the winemaking lab in the Virginia Tech Food Science Department. This was done by adjusting wheel separation to break berry skins from different treatment levels as uniformly as possible. After fruit was processed into a bin, cluster stems were removed from the fruit by hand.

Winemaking included a post-crush cold soak period for 10 days in 2010 and 8 days in 2011 that was preceded by potassium metabisulfite (PMBS) and dimethyl dicarbonate (DMDC) addition at rates of 30 mg/L and 250 mg/L, respectively. Musts of approximately equal volume (30.3 L) remained in the same vessels (55 L Nalgene 11100-0015 high density polyethylene cylindrical tanks with covers, Nalgene Nunc, Rochester, NY) from cold soak through fermentation. After cold soak and before yeast inoculation, musts were amended with tartaric acid for TA adjustment and ameliorated with water in 2010 and chaptilized with cane sugar in 2011 for Brix adjustment. Tartaric acid was added at a rate of 1.5 g/L in 2010 and 1.0 g/L in 2011. In 2010, musts were ameliorated with water to reduce ˚Brix levels to 23.2. In 2011, musts

were chaptilized to increase ˚Brix levels to 22.5. Musts were inoculated with Lalvin BM 4x4 yeast (Lallemand, Inc. Montreal, Canada) at a rate of 0.24 g/L on 28 Sep 2010 and at a rate of 0.30 g/L on 29 Oct 2011 using standard protocol for yeast re-hydration (Scott Labs) and adding the yeast re-hydration supplement GoFerm (Lallemand, Inc. Montreal, Canada) at a rate of 0.3 g/L in both years. During early fermentation, musts were amended with diammonium phosphate at a rate of 240 mg/L in 2010 and Fermaid K (Lallemand, Inc. Montreal, Canada) at a rate of 0.3 g/L in 2011, for yeast nutrition and based on YAN analysis from the respective years.

Fermentation temperatures were monitored three times a day during fermentation using a bulb thermometer and placing it into the must for 10-15 sec. before taking a reading. Grape skin cap punch down was done three times a day during fermentation with a stainless steel punch down tool. Soluble solids measurements were done once a day throughout fermentation using a hydrometer and until soluble solids levels were measured to be around 1.0 ˚Brix, at which time Clini-Test Reagent Tablets (Bayer AG, Leverkusen, Germany) were used. When wines finished fermenting, as indicated by a 0.25% sugar reading using Clini-Test Reagent Tablets, they were siphoned off the primary lees and then analyzed for percent alcohol and residual sugar. While the 2010 vintage was being held in cold storage (at approximately 8.4 ˚C) from Oct 2010 through Apr 2011, DMDC was added twice at a rate of 250 mg/L and SO_2 (via PMBS) was added twice at a rate of 50 mg/L and 10 mg/L. While the 2011 vintage was being held in cold storage (at approximately 4.3˚C) from Nov 2011 to present, SO_2 (via PMBS) was added once at a rate of 50 mg/L. Before sensory analysis, after determining that there was no existence of sulfur-like odors in the wines, composite wine samples were made by bottling enough wine for each particular session. Eventually, all 2010 vintage wines were racked off the secondary lees by siphoning into one common glass vessel and then siphoning this composite wine into bottles on 6-7 Jun 2011.

Wine sensory analysis

Triangle difference test: Triangle difference tests were conducted with the 2010 wines in April 2011 at the Virginia Tech Food Science Department's sensory analysis lab. Panelists were male and female students, ≥ 21 years of age, and enrolled in the "Wines and Vines" class at Virginia Tech, where they learned about sensory analysis, but had not received any previous formal sensory training. In each session, panelists were asked to distinguish the sensory attributes of pairs of wines from different treatment levels that were unique to that session. The sensory attributes evaluated were aroma, color and flavor. Each panelist in each session was given a set of three clear wine glasses; two of the three glasses contained the same treatment level's wine and one glass contained a different treatment level's wine. International standards organization (ISO) wine glasses were used, each with approximately the same amount of wine (around 25-28 mL), which was kept at consistent temperatures as best as possible (aiming for around 15.6 ˚C). The panelists were asked to identify the one wine that was different in each session and for each sensory attribute. After each panelist evaluated one attribute (i.e. aroma), wine glasses were tranferred from the "panelist room" through the window to the "prep kitchen," rotated or exchanged for different glasses, and transferred back to the panelist, who would be asked to evaluate the next attribute (i.e. color). This was repeated until all panelists in each session attempted to distinguish each attribute of the wines. There were eight total sensory sessions in all with varying numbers of panelists (26-40), each performing three evaluations of the uniquely paired wines in each session. Future plans will be to have descriptive analysis and consumer preference tests performed with the wines[1]

[1] *Descriptive analysis:* After identifying if differences existed or not with triangle difference analysis, descriptive analysis will be performed with the wines. Descriptive analysis uses a trained sensory panel to characterize the attributes of the wines and to identify qualitative differences among wines.

Statistical analysis

Field data were analyzed using JMP, versions 8 and 9 (SAS; Cary, NC). For data sets in which all treatment levels in the project design were of high interest, incomplete factorial models were developed and analyzed using standard least squares with restricted maximum likelihood (REML, for scaling of standard errors for models with random effects - blocks herein) and an emphasis on effect leverage (for details on significance of each effect). From the primary analysis of fixed effects using standard least squares with REML, the separation of means of treatments (UTGC, Stock, RM-Irr) and the root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatment were further analyzed using Student's T-test (for pairwise comparisons of least square means) or Tukey's HSD test (for all differences among least square means). Significant interactions were also further analyzed using plots of least squares means and referring back to the mean separation of factor levels of interest.

Responses that were not collected in a fashion that could be evaluated with the developed model, either for collection-based reasons (berry geometry) or combination of experimental units from different blocks (berry skin color data) were analyzed with one-way ANOVA in JMP. Because of the design of this study and for statistical model reasons, root manipulation (RM) and irrigation (Irr) had to be combined to produce the root manipulation-differential irrigation (RM-Irr) treatment for model analysis. However, the separate treatments, root manipulation and differential irrigation, were analyzed using one-way ANOVA in JMP. It is important to note that the differential irrigation treatment could only be analyzed between root bag (RBG) treatment levels, as these were the only root manipulation (RM) treatment levels in which differential

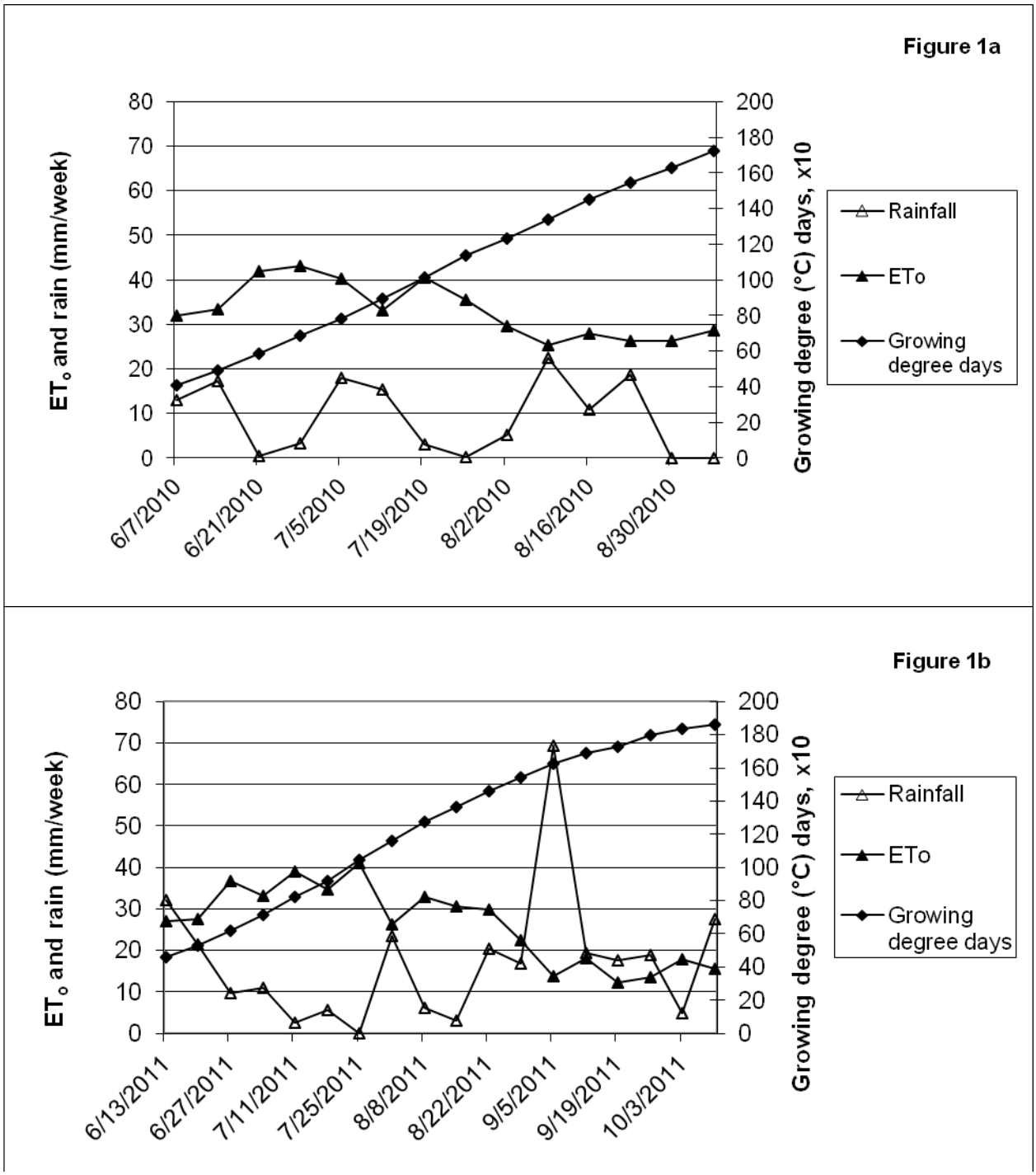
irrigation (Irr) was implemented. All tests evaluated the responses for significance at the 95% confidence ($\alpha = 0.05$) level and levels of significance for each result were reported.

Correlation analysis was done using multivariate analysis in JMP, version 9 (SAS; Cary, NC). Pairwise correlations used the pairwise deletion method to determine correlations and significance probabilities. "Critical Number of Correct Responses in a Triangle Test" (Meilgaard et al. 2006) was used for analysis of the triangle difference test. If panelist number was not provided in the triangle test critical number table, then the z-value was calculated and a T-table was used for assessment of significance.

Results

Meteorological indices

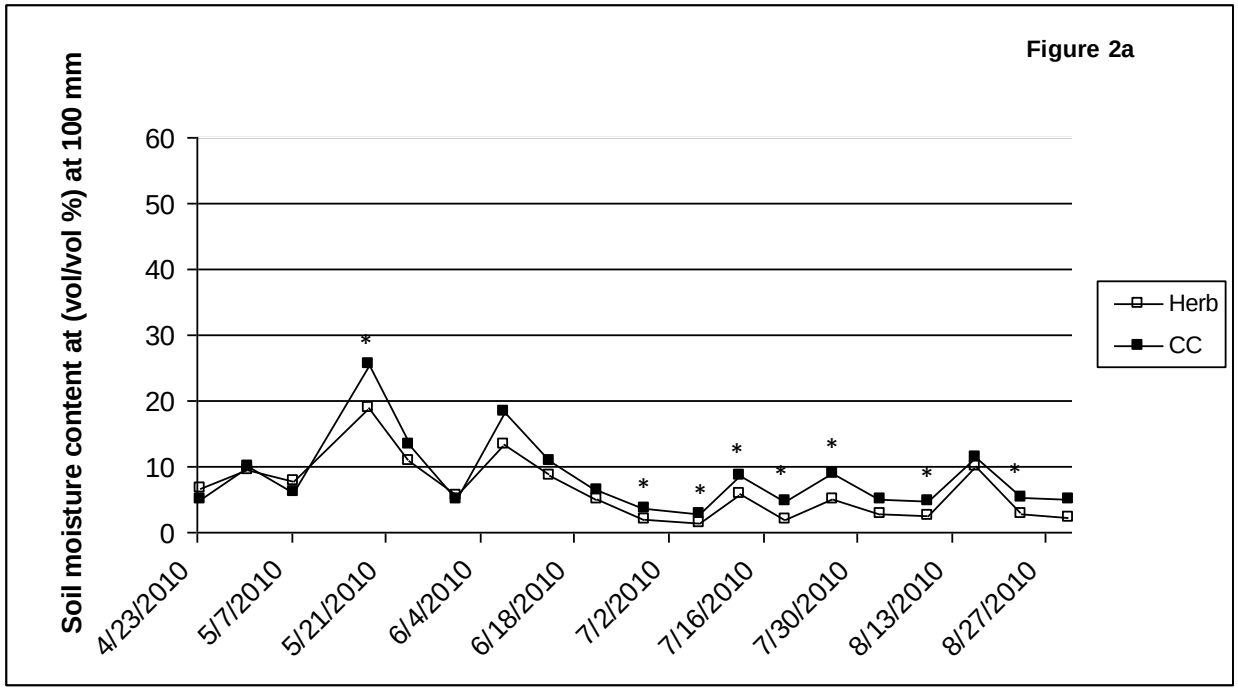
In general, 2010 was dry and relatively warm compared to 2011 (Figures 1a and 1b). The accumulated growing degree days reached in the week of 6 Sep 2010 (the week of harvest) were the same as those reached two wk later on 19 Sep 2011. Further, the rate of weekly growing degree day accumulation was almost 20 growing degree days lower in 2011 than in 2010. Cumulative rainfall from fruit set to harvest was 180 mm greater in 2011 than in 2010 and 140 mm more rain fell between veraison and harvest in 2011 than in 2010 (Figures 1a and 1b). Potential evapotranspiration (ET_o) followed similar trends in both years. However, average weekly ET_o in the fruit set to six-week pre-harvest period was almost 6mm/wk greater in 2010 than in 2011 (Figures 1a and 1b). The greatest seasonal differences in average weekly ET_o occurred in the six wk before harvest: 12mm/wk greater in 2010 than in 2011.

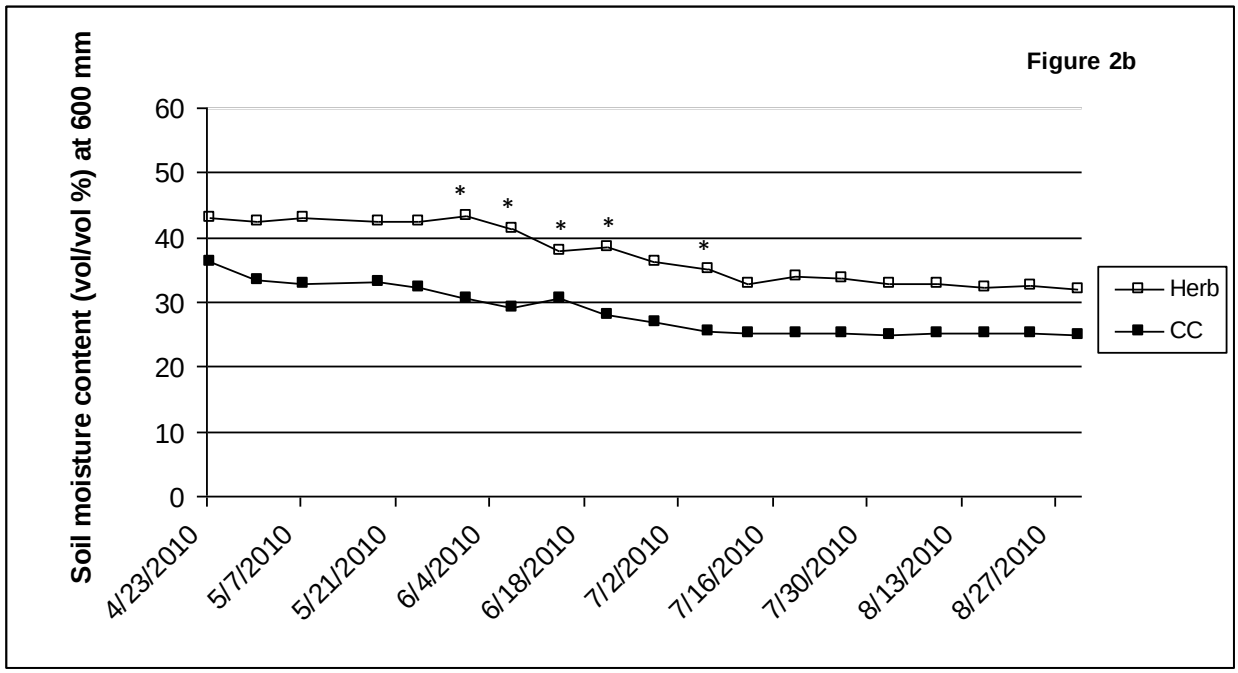


Figures 1a and 1b. Weekly rainfall (mm), potential evapotranspiration (ET_o, mm), and growing degree days (base 10 ˚C) experienced at the Alson H. Smith, Jr. Agricultural Research and Extension Center in Winchester, VA from fruit set through harvest (Cabernet Sauvignon, clone 337) in 2010 and 2011.

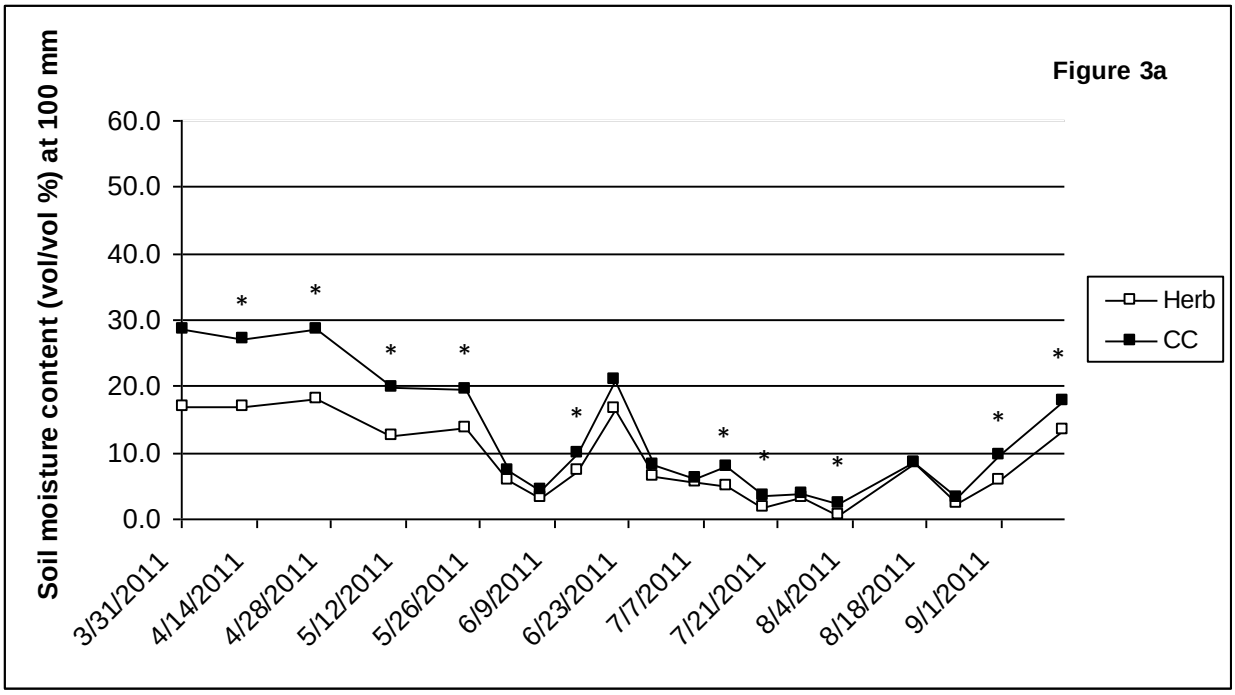
Soil moisture

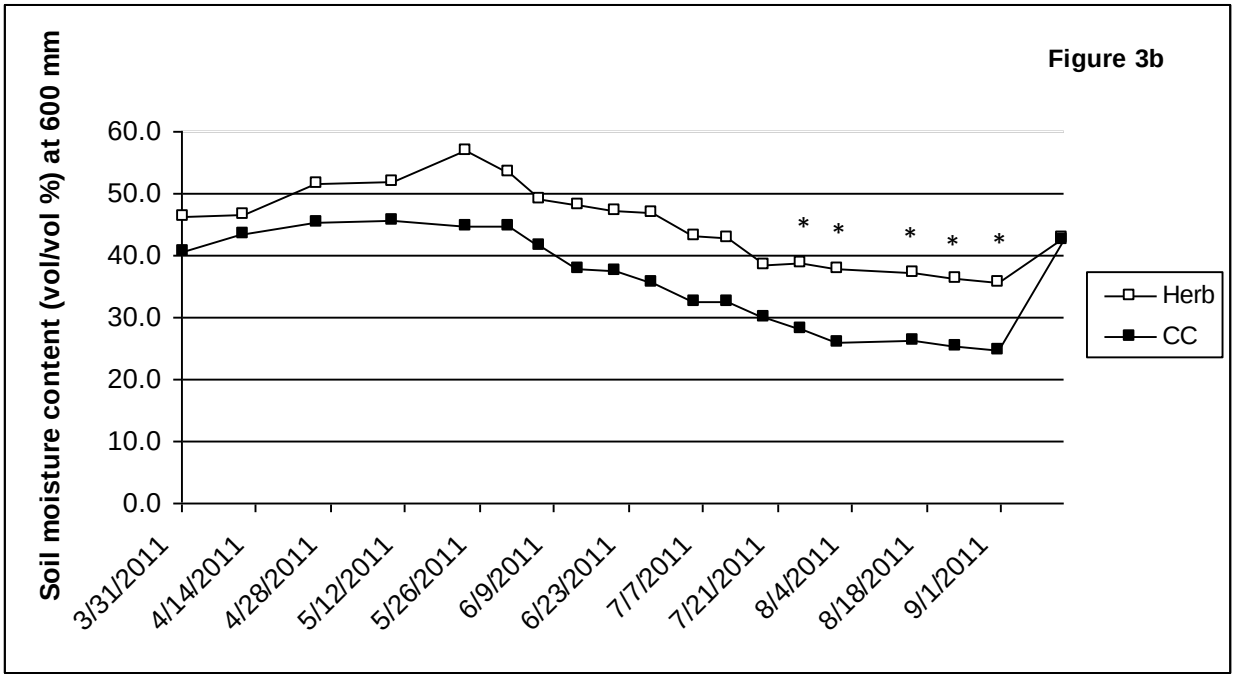
Similar soil moisture trends, as affected by under-trellis groundcover (UTGC), were evident in both years (Figures 2a, 2b, 3a, and 3b). On several dates, volumetric soil water content (vol/vol %) was higher in under-trellis cover crop (CC) plots than under-trellis herbicide (Herb) plots (Figures 2a and 3a). The differences in soil water content at 100 mm in between under-trellis groundcover (UTGC) treatment level content tended to be greater in the early part of the season in 2011 relative to 2010; after Jun, differences were similar. While under-trellis cover crop (CC) plots had lower volumetric soil water content at 600 mm, trends were different between the two years (Figures 2b and 3b). In 2010 (Figure 2b), under-trellis herbicide (Herb) had significantly higher soil water content than under-trellis cover crop (CC) on several dates in the middle of the season. In 2011 (Figure 3b), however, the difference in soil water content increased as the season progressed; the under-trellis herbicide (Herb) had significantly higher soil water content than under-trellis cover crop (CC) on several dates toward the end of the season.





Figures 2a and 2b. Volumetric soil water content at 100 and 600 mm depths for plots with under-trellis herbicide (Herb) and under-trellis cover crop (CC) in 2010. Asterisks denote significant (p > F) under-trellis groundcover (UTGC) effects.





Figures 3a and 3b. Volumetric soil water content at 100 and 600 mm depths for plots with under-trellis herbicide (Herb) and under-trellis cover crop (CC) in 2011. Asterisks denote significant (p > F) under-trellis groundcover (UTGC) effects.

Plant tissue analysis

Under-trellis cover crop (CC) decreased nitrogen content in leaves and petioles relative to under-trellis herbicide (Herb) (Table 3). Nitrogen was also reduced in no root manipulation (NRM) leaf samples relative to root bag (RBG) samples. Phosphorous was reduced at bloom and increased at veraison by root bag (RBG) and was always reduced by the high water stress (HIGH) treatment level (Table 3). Potassium levels at bloom were increased by under-trellis cover crop (CC) and decreased by 420-A. At veraison, potassium levels were decreased by the root bag (RBG) treatment level. Calcium and magnesium levels were consistently affected by root manipulation (RM) rootstock (Stock) treatments at both phenological stages (Table 3).

Table 3. Treatment effect on percent macronutrient composition of petioles at bloom and veraison and leaves at veraison in 2011.

	Percent (%) macronutrient composition in petioles									
	Bloom					Veraison				
Treatment effects[ab]	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
UTGC										
Herb	0.79 a	0.43	2.01 b	1.91	0.46 a	0.45	0.11	3.84	2.15	0.68
CC	0.69 b	0.38	2.61 a	1.78	0.34 b	0.42	0.14	3.8	2.02	0.62
RM										
NRM	0.75	0.54 a	2.12	2.11 a	0.47 a	0.37 b	0.10 b	5.45 a	1.99	0.47 b
RBG	0.72	0.27 b	2.5	1.58 b	0.33 b	0.50 a	0.15 a	2.20 b	2.18	0.83 a
Irr										
LOW	0.7	0.38 a	2.7	1.69 a	0.32	0.49	0.24 a	1.84	2.17	0.83
HIGH	0.74	0.19 b	2.3	1.48 b	0.37	0.57	0.10 b	1.89	2.15	0.95
Stock										
420-A	0.75	0.39	1.47 b	1.84	0.42 a	0.46	0.14	3.05	2.35 a	0.81 a
riparia	0.74	0.43	2.59 a	1.87	0.30 b	0.41	0.12	4	2.16 a	0.48 b
101-14	0.72	0.39	2.86 a	1.82	0.48 a	0.44	0.12	4.41	1.74 c	0.66 ab

	Percent (%) macronutrient composition in leaves				
	Veraison				
	N	**P**	**K**	**Ca**	**Mg**
UTGC					
Herb	2.56 a	0.17	0.9	2.39	0.29
CC	2.32 b	0.18	1.01	2.19	0.28
RM					
NRM	2.22 b	0.17 b	1.16 a	2.53 a	0.24 b
RBG	2.67 a	0.18 a	0.75 b	2.05 b	0.33 a
Irr					
LOW	2.56	0.20 a	0.75	2.11	0.34
HIGH	2.82	0.18 b	0.65	2.05	0.33
Stock					
420-A	2.47	0.18	0.82	2.53 a	0.32 a
riparia	2.4	0.17	0.98	2.34 a	0.24 b
101-14	2.45	0.18	1.05	2.00 b	0.30 a

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for Stock ($\alpha = 0.05$).

Vegetative characterization

Lateral shoot growth and shoot activity: Many treatments had a significant effect on both the mean sum of unfolded lateral leaves and mean percent shoot-tip activity, at veraison in both years (Table 4). In general, under-trellis cover crop (CC), root bag (RBG), and high water stress (HIGH) all depressed both responses in both years (Table 4). Root bag (RBG) and under-trellis cover crop (UTCC) suppressed lateral development between treatment levels to a greater extent than did high water stress (HIGH). High water stress (HIGH) and root bag (RBG) suppressed shoot-tip activity between treatment levels to a greater extent than did under-trellis cover crop (CC) (Table 4).

Table 4. Treatment effect on mean sum of unfolded lateral leaves originating from primary shoot nodes 3-7 and mean percent shoot-tip activity assessed at the time of veraison in 2010 and 2011.

	Unfolded leaves (n)		Shoot-tip activity (%)	
Treatment effects[ab]	**2010**	**2011**	**2010**	**2011**
UTGC				
Herb	12.3 a	16.9 a	24 a	35 a
CC	8.8 b	13.1 b	12 b	31 a
RM				
NRM	14.9 a	24.5 a	39 a	69 a
RBG	8.1 b	10.2 b	8 b	14 b
Irr				
LOW	9.1 a	10.5 a	14 a	27 a
HIGH	7.3 b	9.8 a	1 b	2 b
Stock				
420-A	9.7 a	13.4 a	22 a	33 a
riparia	10.2 a	15.6 a	16 a	33 a
101-14	11.6 a	16.0 a	17 a	32 a
RM-Irr				
NRM-None	15.0 a	24.6 a	40 a	70 a
RBG-LOW	9.0 b	11.1 b	12 b	27 b
RBG-HIGH	7.6 b	9.2 b	4 b	3 c
RM-Irr + UTGC				
NRM-None+Herb	18.5 a	28.9 a	48 a	75 a
NRM-None+CC	11.5 b	20.3 b	32 ab	64 a
RBG-LOW+Herb	9.8 bc	12.3 c	18 bc	29 b
RBG-HIGH+Herb	8.6 bc	9.9 c	7 c	24 b
RBG-LOW+CC	8.1 bc	9.5 c	5 c	4 b
RBG-HIGH+CC	6.6 c	8.9 c	1 c	1 b
Significance[c]				
UTGC	0.009	0.0014	0.0072	ns
RM	<0.0001	<0.0001	<0.0001	<0.0001
Irr	<0.0500	ns	<0.0500	<0.0500
Stock	ns	ns	ns	ns
RM-Irr	<0.0001	<0.0001	<0.0001	<0.0001
Stock*UTGC	ns	ns	ns	ns
RM-Irr*UTGC	0.0175	0.026	ns	ns
RM-Irr*Stock	ns	ns	ns	ns
RM-Irr*UTGC*Stock	ns	ns	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for all others, ($\alpha = 0.05$).

[c] Significance of factor and treatment effects on response variables using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors ($p > F$; ns = not significant).

The rootstock (Stock) treatment never had a significant effect on lateral leaf number or shoot-tip activity in either year (Table 4). The treatment levels of both root manipulation-differential irrigation (RM-Irr) and root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) all resulted in a greater range of responses than any of the root manipulation (RM), differential irrigation (Irr), or under-trellis groundcover (UTGC) treatment levels alone (Table 4). The interaction between root manipulation-differential irrigation (RM-Irr) and under-trellis groundcover (UTGC) revealed that no root manipulation-no irrigation (NRM-None) vines responded more to under-trellis cover crop in terms of reduced lateral leaf number relative to the other two root manipulation-differential irrigation (RM-Irr) treatment levels in both years (data not shown and obtained from plots of least squares means).

Enhanced PQA: Under-trellis groundcover (UTGC), root manipulation (RM), and root manipulation-differential irrigation (RM-Irr) had the most consistent and significant affects on all EPQA values in both years (Table 5). Differential irrigation (Irr) effects were less consistent and rootstock (Stock) effects were highly inconsistent (Table 5). Under-trellis cover crop (CC) generally opened the canopy, as revealed by consistent effects on leaf exposure layer (LEL), cluster exposure flux availability (CEFA) and leaf exposure flux availability (LEFA). The root bag treatment level (RBG) affected every EPQA value in both years, resulting in a canopy that was much more open relative to no root manipulation (NRM) (Table 5). The addition of differential irrigation to root manipulation, to give the RM-Irr treatment, did not result in any further significant effects on any EPQA value (Table 5).

In both years, the trend for root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatment levels was that root bag-differential irrigation + under-

trellis cover crop (RBG-Irr + CC) had lowest OLN, CEL and LEL, root bag-differential irrigation + under-trellis herbicide (RBG-Irr + Herb) had the second highest levels and no root manipulation-no irrigation + under-trellis groundcover (NRM-None + UTGC) the highest (Table 5). The opposite order of these treatment levels was the result for CEFA and LEFA, with root bag-differential irrigation + under-trellis cover crop (RBG-Irr + CC) resulting in the highest levels and no root manipulation-no irrigation + under-trellis groundcover (NRM-None + UTGC) the lowest (Table 5). The root manipulation-differential irrigation*rootstock (RM-Irr*Stock) interaction in 2010 revealed that riparia vines were more responsive to differential irrigation (Irr) on occlusion layer number (OLN) compared to other rootstocks. Cluster exposure layer (CEL) was affected differently by differential irrigation (Irr) between 420-A and riparia in 2010, such that riparia experienced the canopy-opening benefits of high water stress (HIGH) whereas 420-A did not. The three-way root manipulation-differential irrigation*under-trellis groundcover*rootstock (RM-Irr*UTGC*Stock) interaction revealed that root bag-low water stress (RBG-LOW) vines responded more to under-trellis cover crop (CC) when grafted on 101-14 relative to the other two rootstocks, as evidenced by greater CEFA values in 2011.

Table 5. Select enhanced point quadrat analyses as affected by treatment levels at veraison in 2010 and 2011.

	Occlusion layer number (OLN)		Cluster exposure layer (CEL)[c]		Leaf exposure layer (LEL)		Cluster exposure flux availability (CEFA)		Leaf exposure flux availability (LEFA)	
Treatment effects[ab]	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**
UTGC										
Herb	2.13 a	2.27 a	0.46 a	0.44 a	0.21 a	0.24 a	0.35 b	0.38 b	0.47 b	0.46 b
CC	1.90 a	2.07 b	0.30 b	0.34 a	0.12 b	0.17 b	0.46 a	0.44 a	0.54 a	0.52 a
RM										
NRM	2.44 a	2.78 a	0.55 a	0.62 a	0.23 a	0.32 a	0.31 b	0.28 b	0.43 b	0.38 b
RBG	1.80 b	1.86 b	0.29 b	0.28 b	0.13 b	0.15 b	0.46 a	0.47 a	0.54 a	0.55 a
Irr										
LOW	1.91 a	1.87a	0.30a	0.33 a	0.16 a	0.14 a	0.42b	0.46 a	0.51b	0.54 a
HIGH	1.70 a	1.85a	0.28a	0.23 a	0.10 a	0.15 a	0.50a	0.49 a	0.58 a	0.55 a
Stock										
420-A	1.93 a	2.07 b	0.39 a	0.37 a	0.14 a	0.19 a	0.41 a	0.43 a	0.52 a	0.51 a
riparia	2.08 a	2.16 ab	0.40 a	0.42 a	0.16 a	0.2 a	0.39 a	0.39 a	0.51 a	0.49 ab
101-14	2.04 a	2.28 a	0.34 a	0.39 a	0.18 a	0.23 a	0.42 a	0.40 a	0.49 a	0.47 b
Significance[d]										
UTGC	ns	0.003	0.0104	ns	0.003	0.01	0.0151	0.0068*	0.0092	0.0024
RM	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irr	ns	ns	ns	ns	ns	ns	<0.0500	ns	<0.0500	ns
Stock	ns	0.0174	ns	ns	ns	ns	ns	ns	ns	0.0058

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test ($\alpha = 0.05$) for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Cluster exposure layer data analyzed using standard least squares with EMS and an emphasis on effect leverage (i.e. no random effects taken into account; p > F; ns = not significant).

[d] Significance of factor and treatment effects on response variables using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors (p > F; ns = not significant).

Table 5 (cont.). Select enhanced point quadrat analyses as affected by treatment levels at veraison in 2010 and 2011.

Treatment effects[ab]	Occlusion layer number		Cluster exposure layer[c]		Leaf exposure layer		Cluster exposure flux availability		Leaf exposure flux availability	
	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
RM-Irr										
NRM-None	2.44 a	2.78 a	0.55 a	0.62 a	0.23 a	0.32 a	0.31 b	0.28 b	0.43 c	0.38 b
RBG-LOW	1.91 b	1.87 b	0.30 b	0.33 b	0.16 b	0.14 b	0.42 a	0.46 a	0.51 b	0.54 a
RBG-HIGH	1.70 b	1.85 b	0.28 b	0.23 b	0.10 b	0.15 b	0.50 a	0.49 a	0.58 a	0.55 a
RM-Irr + UTGC										
NRM-None+Herb	2.55 a	2.93 a	0.62 a	0.70 a	0.26 a	0.37 a	0.25 c	0.25 b	0.42 d	0.36 d
NRM-None+CC	2.34 ab	2.63 b	0.48 ab	0.53 ab	0.20 ab	0.28 ab	0.36 bc	0.30 b	0.45 cd	0.41 c
RBG-LOW+Herb	2.02 bc	1.92 c	0.40 abc	0.33 bc	0.21 ab	0.18 c	0.34 bc	0.45 a	0.47 bcd	0.52 ab
RBG-HIGH+Herb	1.83 c	1.95 c	0.34 bc	0.28 bc	0.15 bc	0.19 bc	0.47 ab	0.45 a	0.53 abc	0.51 b
RBG-LOW+CC	1.80 c	1.83 c	0.19 c	0.32 bc	0.11 bc	0.11 c	0.49 ab	0.46 a	0.55 ab	0.57 ab
RBG-HIGH+CC	1.56 c	1.75 c	0.22 c	0.18 c	0.06 c	0.11 c	0.53 a	0.54 a	0.63 a	0.59 a
Significance[d]										
RM-Irr	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001*	<0.0001	<0.0001
Stock*UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM-Irr*Stock	0.0093	ns	0.0100	ns	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC*Stock	0.0013	ns	ns	ns	ns	ns	ns	0.0229*	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test ($\alpha = 0.05$) for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Cluster exposure layer data analyzed using standard least squares with EMS and an emphasis on effect leverage (i.e. no random effects taken into account; p > F; ns = not significant).

[d] Significance of factor and treatment effects on response variables using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors (p > F; ns = not significant).

Fruit-zone light interception: In both years under-trellis cover crop (CC) and root bag (RBG) significantly increased average fruit-zone PPFD relative to the corresponding levels of each treatment (Table 6). High stress (HIGH) increased fruit-zone PPFD only in 2010 and 101-14 did the same only in 2011 (Table 6). In both years, root bag-high water stress (RBG-HIGH) resulted in the greatest levels of fruit-zone PPFD, followed by root bag-low water stress (RBG-LOW) (Table 6).

Root bag-high water stress + under-trellis cover crop (RBG-HIGH + CC) resulted in 376% and 658% increases in fruit-zone PPFD relative to no root manipulation-no irrigation + under-trellis herbicide (NRM-None + Herb) in 2010 and 2011, respectively (Table 6). The interaction between root manipulation-differential irrigation*under-trellis groundcover (RM-Irr*UTGC) revealed that root bag-high water stress (RBG-HIGH) vines responded more to under-trellis cover crop (CC) than the other two root manipulation-differential irrigation (RM-Irr) treatment levels, as evidenced by higher fruit-zone PPFD values. The root manipulation-differential irrigation*rootstock (RM-Irr*Stock) interaction revealed that vines grafted to riparia were more responsive to differential irrigation than were vines grafted to either of the other two rootstocks.

Table 6. Treatment effects on mean fruit-zone PPFD measured during midday at veraison in 2010 and 2011.

	PPFD (μmol sec^{-1} m^{-2})	
Treatment effects[ab]	**2010**	**2011**
UTGC		
Herb	4.9 b	6.4 b
CC	6.6 a	8.6 a
RM		
NRM	2.6 b	2.2 b
RBG	7.5 a	10.3 a
Irr		
LOW	6.1 b	10.0 a
HIGH	8.7a	10.6 a
Stock		
420-A	6.2 a	8.8 a
riparia	5.6 a	7.0 ab
101-14	5.5 a	6.7 b
RM-Irr		
NRM-None	2.6 c	2.2 c
RBG-LOW	6.1 b	10.0 b
RBG-HIGH	8.7 a	10.6 a
RM-Irr + UTGC		
NRM-None+Herb	2.1 d	1.7 c
NRM-None+CC	3.1 cd	2.6 c
RBG-LOW+Herb	5.3 bc	9.3 b
RBG-HIGH+Herb	7.4 ab	8.2 b
RBG-LOW+CC	6.8 ab	10.1 ab
RBG-HIGH+CC	10.0 a	12.9 a
Significance[c]		
UTGC	0.0171	0.004
RM	<0.0001	<0.0001
Irr	<0.0500	ns
Stock	ns	0.0161
RM-Irr	<0.0001	<0.0001
Stock*UTGC	ns	ns
RM-Irr*UTGC	ns	0.0202
RM-Irr*Stock	ns	0.0061
RM-Irr*UTGC*Stock	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors ($p > F$; ns = not significant).

Dormant pruning weights: Under-trellis cover crop (CC) and root bag (RBG) reduced pruning weights in both years and root manipulation (RM) resulted in a greater separation of this response relative to under-trellis groundcover (UTGC) (Table 7). Differential irrigation (Irr) and rootstock (Stock) treatments had significant effects on pruning weight only in 2011 (Table 7). Root bag-low water stress (RBG-LOW) and root bag-high water stress (RBG-HIGH) both reduced pruning weight relative to no root manipulation-no irrigation (NRM-None) in both years, but not relative to each other in either year (Table 7). Greater separation between all root bag-differential irrigation + under-trellis groundcover (RBG-Irr + UTGC) treatment levels existed in 2010 relative to 2011 (Table 7). The significant interaction between root manipulation-differential irrigation*under-trellis groundcover (RM-Irr*UTGC) revealed that no root manipulation-no irrigation (NRM-None) vines were more responsive to under-trellis cover crop (CC) than either of the other two root manipulation-differential irrigation (RM-Irr) treatment levels.

Table 7. Treatment effect on mean dormant cane pruning weights collected in the winters of 2010 and 2011.

	Cane pruning weight / vine (kg)	
Treatment effects[ab]	**2010**	**2011**
UTGC		
Herb	0.93 a	0.89 a
CC	0.61 b	0.65 b
RM		
NRM	1.27 a	1.42 a
RBG	0.51 b	0.44 b
Irr		
LOW	0.54 a	0.49 a
HIGH	0.48 a	0.39 b
Stock		
420-A	0.89 a	0.72 b
riparia	0.86 a	0.73 b
101-14	0.96 a	0.85 a
RM-Irr		
NRM-None	1.28 a	1.43 a
RBG-LOW	0.54 b	0.47 b
RBG-HIGH	0.48 b	0.40 b
RM-Irr + UTGC		
NRM-None+Herb	1.47 a	1.63 a
NRM-None+CC	1.06 b	1.23 b
RBG-LOW+Herb	0.66 c	0.58 c
RBG-HIGH+Herb	0.61 cd	0.46 c
RBG-LOW+CC	0.40 d	0.36 c
RBG-HIGH+CC	0.37 d	0.35 c
Significance[c]		
UTGC	0.0005	0.0021
RM	<0.0001	<0.0001
Irr	ns	<0.0500
Stock	ns	0.0468
RM-Irr	<0.0001	<0.0001
Stock*UTGC	ns	ns
RM-Irr*UTGC	0.0292	ns
RM-Irr*Stock	ns	ns
RM-Irr*UTGC*Stock	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors ($p > F$; ns = not significant).

Components of crop yield

Yield components: Under-trellis cover crop (CC) significantly reduced yield (18%) in 2010 but not in 2011 (Table 8). Root bag (RBG) and high water stress (HIGH) both significantly reduced yield in both years, but root manipulation (RM) vines had relatively greater separation for this response (Table 8). The root bag-high water stress (RBG-HIGH) vines had significantly lower yields than root bag-low water stress (RBG-LOW) vines in both years. Rootstock (Stock) had no significant affects on yield. No root manipulation-no irrigation + under-trellis herbicide (NRM-None + Herb) vines had the highest yields and root bag-high water stress + under-trellis cover crop (RBG-HIGH + CC) the lowest in both years (Table 8).

Table 8. Treatment effect on yield per vine and average cluster and berry weight at harvest in 2010 and 2011.

	Yield / vine (kg)		Projected yield / vine[d] (kg)	Cluster weight[e] (g)		Berry weight (g)	
Treatment effects[ab]	**2010**	**2011**	**2011**	**2010**	**2011**	**2010**	**2011**
UTGC							
Herb	3.36 a	3.30 a	3.69 a	139 a	164 a	1.20 a	1.31 a
CC	2.76 b	3.52 a	3.49 a	110 b	136 b	1.09 b	1.26 b
RM							
NRM	3.60 a	5.09 a	5.21 a	141 a	207 a	1.27 a	1.47 a
RBG	2.80 b	2.58 b	2.80 b	116 b	122 b	1.08 b	1.19 b
Irr							
LOW	3.16 a	2.85 a	3.03 a	137 a	126 a	1.17 a	1.21 a
HIGH	2.43 b	2.34 b	2.58 a	96 b	119 a	0.98 b	1.18 a
Stock							
420-A	3.04 a	3.45 a	3.62 a	123 ab	150 a	1.12 b	1.27 a
riparia	3.22 a	3.49 a	3.71 a	133 a	159 a	1.20 a	1.33 a
101-14	2.92 a	3.27 a	3.43 a	118 b	145 a	1.12 b	1.26 a
RM-Irr							
NRM-None	3.60 a	5.09 a	5.18 a	141 a	207 a	1.27 a	1.47 a
RBG-LOW	3.16 b	2.85 b	3.03 b	137 a	147 b	1.17 b	1.21 b
RBG-HIGH	2.43 c	2.34 c	2.22 c	96 b	97 c	0.98 c	1.18 b
RM-Irr + UTGC							
NRM-None+Herb	3.84 a	5.15 a	5.25 a	153 a	218 a	1.29 a	1.49 a
NRM-None+CC	3.36 ab	4.98 a	5.11 a	129 b	194 a	1.25 ab	1.45 a
RBG-LOW+Herb	3.35 ab	3.57 b	3.72 b	150 a	172 ab	1.24 abc	1.22 b
RBG-LOW+CC	2.96 b	2.91 bc	3.01 b	124 b	123 bc	1.12 bc	1.20 b
RBG-HIGH+Herb	2.89 b	2.00 c	2.23 b	114 b	102 c	1.06 cd	1.24 b
RBG-HIGH+CC	1.96 c	1.84 c	2.21 b	78 c	93 c	0.9 d	1.12 b
Significance[c]							
UTGC	0.0096	ns	ns	0.0005	0.0104	0.0046	0.0398
RM	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irr	<0.0500	<0.0500	ns	<0.0500	ns	<0.0500	ns
Stock	ns	ns	ns	0.0304	ns	0.0047	ns
RM-Irr	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Stock*UTGC	ns	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	ns	ns	ns	ns	ns	ns	ns
RM-Irr*Stock	ns	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors ($p > F$; ns = not significant).

[d] Mean projected yield was calculated by taking average "sound cluster" (clusters with minimal to no rot) weight and multiplying this number by the total number of clusters on the vine at harvest; only in 2011.

[e] Mean cluster weight was calculated using only sound clusters.

Vine Capacity: In general, under-trellis cover crop (CC), root bag (RBG) and high water stress (HIGH) all decreased vine capacity and increased crop load in both years (Table 9). The root bag-low water stress (RBG-LOW) treatment level always resulted in the greatest crop load, but not the lowest capacity. Rootstock (Stock) had no effect on vine capacity, but consistently affected crop load in both years such that 101-14 had lower crop loads relative to the other two rootstocks (Table 9). Only in 2010 did the addition of differential irrigation (Irr) to root bag-differential irrigation-under-trellis cover crop (RBG-Irr-CC) result in a significant difference in vine capacity and crop load (Table 9).

In 2010, the root manipulation-differential irrigation*under-trellis ground cover (RM-Irr*UTGC) interaction revealed that root bag-low water stress (RBG-LOW) was much more responsive to under-trellis ground cover (UTGC) as made evident by a greater increase in crop load with under-trellis cover crop (CC) than the other two root manipulation-differential irrigation (RM-Irr) treatment levels. In both 2010 and 2011, the root manipulation-differential irrigation*rootstock (RM-Irr*Stock) interaction revealed that 101-14 was less responsive to differential irrigation (Irr) as made evident by a lesser difference in crop load than the other two rootstocks. In 2011, the three-way root manipulation-differential irrigation*under-trellis groundcover*rootstock (RM-Irr*UTGC*Stock) revealed that crop load in root bag-high water stress-420-A (RBG-HIGH-420-A) vines and root bag-low water stress-riparia (RBG-LOW*riparia) vines was highly responsive to UTGC.

Table 9. Treatment effects on mean vine capacity and crop load in 2010 and 2011.

	2010		2011	
Treatment effects[ab]	**Vine capacity (kg)**	**Crop load**	**Vine capacity (kg)**	**Crop load**
UTGC				
Herb	4.29 a	4.4 b	4.52 a	4.8 b
CC	3.37 b	5.5 a	3.97 a	5.9 a
RM				
NRM	4.88 a	3.0 b	6.60 a	3.7 b
RBG	3.31 b	6.0 a	3.04 b	6.2 a
Irr				
LOW	3.61 a	6.4 a	3.36 a	6.5 a
HIGH	3.02 b	5.6 b	2.76 b	5.9 b
Stock				
420-A	3.79 a	5.3 a	4.19 a	5.8 a
riparia	3.95 a	5.2 a	4.26 a	5.6 a
101-14	3.74 a	4.3 b	4.27 a	4.5 b
RM-Irr				
NRM-None	4.88 a	3.0 c	6.58 a	3.6 c
RBG-LOW	3.67 b	6.4 a	3.76 b	6.7 a
RBG-HIGH	2.94 c	5.5 b	2.39 c	5.6 b
RM-Irr + UTGC				
NRM-None+Herb	5.33 a	2.7 c	6.71 a	3.1 d
NRM-None+CC	4.42 b	3.3 c	6.45 a	4.1 c
RBG-LOW+Herb	4.00 bc	5.4 b	4.27 b	6.1 ab
RBG-HIGH+Herb	3.53 c	5.2 b	2.57 bc	5.1 bc
RBG-LOW+CC	3.35 c	7.4 a	3.24 bc	7.3 a
RBG-HIGH+CC	2.35 d	5.7 b	2.21 c	6.1 ab
Significance[c]				
UTCC	0.0043	0.0011	ns	0.0016
RM	<0.0001	<0.0001	<0.0001	<0.0001
Irr	<0.0500	<0.0500	<0.0500	<0.0500
Stock	ns	<0.0001	ns	<.0001
RM-Irr	<0.0001	<0.0001	<.0001	<.0001
Stock*UTGC	ns	ns	ns	ns
RM-Irr*UTGC	ns	0.0021	ns	ns
RM-Irr*Stock	ns	0.0189	ns	0.0386
RM-Irr*UTGC*Stock	ns	ns	ns	0.0196

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors ($p > F$; ns = not significant).

Seasonal berry weight and geometrics: The root manipulation-differential irrigation (RM-Irr) and root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) factors both had significant and consistent effects on seasonal berry surface area: volume ratios (SA: Volume ratios) as well as berry weight (Table 10). No root manipulation-no irrigation (NRM-None) resulted in the lowest berry SA: Volume ratios on all dates. The only two dates in which root bag-low water stress (RBG-LOW) and root bag-high water stress (RBG-HIGH) were significantly different from one another were 12 Jul and 2 Aug, when root bag-high water stress (RBG-HIGH) had significantly higher berry SA: Volume ratios than root bag-low water stress (RBG-LOW) (12% and 13% higher, respectively) (Table 10). Root bag-low water stress + under-trellis cover crop (RBG-LOW + CC) vines had significantly higher berry SA: Volume ratios than root bag-low water stress + under-trellis herbicide (RBG-LOW + Herb) vines on 14 Sep, which is the only time that a different under-trellis groundcover (UTGC) resulted in a significant difference in berry weight or SA: Volume ratio. Focusing on extremes, the root bag-high water stress + under-trellis cover crop (RBG-HIGH + CC) treatment level resulted in berry SA: Volume ratios that were 18% and 23% greater than no root manipulation-no irrigation + under-trellis herbicide (NRM-None + Herb) on 12 Jul and 2 Aug, respectively (Table 10).

Table 10. Mean berry surface area to volume ratio and weight assessed at five different dates during the 2011 growing season.

	Berry SA: Volume (mm^2/mm^3)				
Treatment effects[a]	**22 Jun**	**12 Jul**	**2 Aug**	**23 Aug**	**14 Sep**
RM-Irr					
RBG-HIGH	1.04 a	0.67 a	0.68 a	0.57 a	0.52 a
RBG-LOW	1.00 a	0.59 b	0.59 b	0.56 a	0.51 a
NRM-None	0.90 b	0.55 c	0.53 c	0.52 b	0.48 b
RM-Irr + UTGC					
RBG-HIGH+CC	1.05 a	0.67 a	0.69 a	0.57 a	0.52 ab
RBG-HIGH+Herb	1.04 a	0.67 a	0.67 a	0.57 a	0.52 a
RBG-LOW+CC	1.02 a	0.59 b	0.60 b	0.56 a	0.53 a
RBG-LOW+Herb	0.97 ab	0.59 b	0.57 b	0.57 a	0.50 bc
NRM-None+CC	0.90 b	0.54 c	0.53 c	0.52 b	0.49 c
NRM-None+Herb	0.90 b	0.55 c	0.53 c	0.51 b	0.48 c
Significance[b]					
UTGC	ns	ns	ns	ns	ns
RM-Irr	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
RM-Irr + UTGC	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
	Berry weight (g)				
Treatment effects[ab]	**22 Jun**	**12 Jul**	**2 Aug**	**23 Aug**	**14 Sep**
RM-Irr					
RBG-HIGH	0.15 b	0.45 c	0.49 c	0.90 b	1.11 b
RBG-LOW	0.17 b	0.61 b	0.69 b	0.94 b	1.15 b
NRM-None	0.22 a	0.76 a	0.84 a	1.16 a	1.36 a
RM-Irr + UTGC					
RBG-HIGH+CC	0.14 c	0.44 c	0.48 c	0.89 b	1.13 b
RBG-HIGH+Herb	0.16 bc	0.46 c	0.51 c	0.92 ab	1.08 b
RBG-LOW+CC	0.15 bc	0.59 b	0.63 bc	0.94 ab	1.10 b
RBG-LOW+Herb	0.18 b	0.62 b	0.75 ab	0.93 ab	1.21 ab
NRM-None+CC	0.23 a	0.76 a	0.86 a	1.15 ab	1.35 a
NRM-None+Herb	0.22 a	0.77 a	0.83 a	1.18 a	1.37 a
Significance[c]					
UTGC	ns	ns	ns	ns	ns
RM-Irr	<0.0001	<0.0001	<0.0001	0.0002	0.0002
RM-Irr + UTGC	<0.0001	<0.0001	<0.0001	0.0087	0.0020

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress).

[b] Separation of means using Tukey's HSD ($\alpha = 0.05$).

[c] Significance of factor and treatment effects on response variables, using One-Way ANOVA ($p > F$; ns = not significant).

Those treatment levels that resulted in low SA: Volume ratios resulted in relatively greater berry weights. As with the berry SA: Volume ratio response, the greatest separation of berry weights between treatment levels was realized on 12 Jul and 2 Aug, when, regardless of under-trellis groundcover (UTGC), root bag-high water stress (RBG-HIGH) resulted in berry weights that were on average 41% less than those of no root manipulation-no irrigation (NRM-None) treatments levels (Table 10). At the last recorded measurement, which was about one month before harvest, both root bag-high water stress + under-trellis ground cover (RBG-HIGH + UTGC) treatment levels resulted in significantly lower berry weight (average of 19% lower) than the no root manipulation-no irrigation + under-trellis groundcover (NRM-None + UTGC) treatment levels.

No root manipulation-no irrigation (NRM-None) resulted in the slowest berry SA: Volume ratio decreases during the post-veraison period as well as for the season (Table 11). There were no significant differences in the rate of berry SA:Volume ratio decrease between root manipulation-differential irrigation (RM-Irr) treatment levels in the pre-veraison period, but root bag-differential irrigation (RBG-Irr) treatment levels were significantly different from each other during the post-veraison period and from no root manipulation-no irrigation (NRM-None) over the course of the season. Post-veraison rates of SA: Volume ratio decrease in root bag-low water stress + under-trellis groundcover (RBG-LOW + UTGC) and no root manipulation-no irrigation + under-trellis groundcover (NRM-None + UTGC) treatment levels were not significantly different from each other, but all were significantly different from both root bag-high water stress + under-trellis groundcover (RBG-HIGH + UTGC) treatment levels. Root bag-high water stress + under-trellis cover crop (RBG-HIGH + CC) decreased berry SA: Volume ratio 69%

greater than occurred with no root manipulation-no irrigation + under-trellis herbicide (NRM-None + Herb) (Table 11).

Where SA: Volume ratio rates were significantly affected post-veraison, the rates of berry weight increase were significantly affected pre-veraison (Table 11). No root manipulation-no irrigation (NRM-None) vines exhibited the greatest rates of berry weight increase during the pre-veraison period as well as during the entire season (Table 11). There were no significant differences in the rate of berry weight increase between root manipulation-differential irrigation (RM-Irr) treatment levels in the post-veraison time period, but root bag-differential irrigation (RBG-Irr) treatment levels were significantly different from each other during the pre-veraison time period and from no root manipulation-no irrigation (NRM-None) over the course of the season. The two root bag-high water stress + under-trellis groundcover (RBG-HIGH + UTGC) treatment levels resulted in significantly lower rates of berry weight increase than root bag-low water stress + under-trellis herbicide (RBG-LOW + Herb) as well as both no root manipulation-no irrigation + under-trellis groundcover (NRM-None + UTGC) treatment levels (Table 11).

The general trend with berry SA: Volume ratio and berry weight was that significant differences were indistinct at one-week post-fruit set, became more apparent during the pre-veraison period, and then became blurred again during the post-veraison period (Table 11). As berries expanded, especially post 2-August, or post-veraison, the differences in both the mean berry weight and the mean berry SA: Volume ratio between the root bag-differential irrigation (RBG-Irr) treatment levels and the root bag-differential irrigation + under-trellis groundcover (RBG-Irr + UTGC) treatment levels became insignificant (Table 11).

Table 11. Mean weekly rates of grape berry surface area: volume decrease and berry weight increase in three periods of vine phenology in 2011: post-fruit set to veraison, veraison to one month before harvest, and post-fruit set to one month before harvest.

	Berry SA: Vol. decrease (mm^2/mm^3 / week)			Berry wt. increase (g/week)		
Treatment effects[ab]	**Pre-veraison**	**Post-veraison**	**Post-fruit set**	**Pre-veraison**	**Post-veraison**	**Post-fruit set**
RM-Irr						
RBG-HIGH	0.061 a	0.026 a	0.043 a	0.06 c	0.10 a	0.08 b
RBG-LOW	0.068 a	0.013 b	0.040 a	0.09 b	0.08 a	0.08 b
NRM-None	0.061 a	0.008 c	0.035 b	0.10 a	0.09 a	0.09 a
RM-Irr + UTGC						
RBG-High+CC	0.060 a	0.029 a	0.044 c	0.06 b	0.11 a	0.08 a
RBG-High+Herb	0.062 a	0.023 a	0.043 c	0.06 b	0.10 a	0.08 a
RBG-LOW+CC	0.070 a	0.013 b	0.042 bc	0.08 ab	0.08 a	0.08 a
RBG-LOW+Herb	0.066 a	0.012 b	0.039 abc	0.09 a	0.08 a	0.09 a
NRM-None+CC	0.061 a	0.008 b	0.034 c	0.11 a	0.08 a	0.09 a
NRM-None+Herb	0.061 a	0.009 b	0.035 bc	0.10 a	0.09 a	0.10 a
Significance[c]						
UTGC	ns	ns	ns	ns	ns	ns
RM-Irr	0.0406	<0.0001	<0.0001	<0.0001	ns	0.0045
RM-Irr + UTGC	ns	<0.0001	<0.0001	0.0002	ns	0.0283

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress).

[b] Separation of means using Tukey's HSD ($\alpha = 0.05$).

[c] Significance of factor and treatment effects on response variables, using One-Way ANOVA ($p > F$; ns = not significant).

Fruit Composition: Treatment effects on soluble solids (˚Brix) were more consistent and significant in 2010 than 2011; opposite factor effects between years were common (Table 12). Under-trellis cover crop (CC), no root manipulation (NRM) and low water stress (LOW) all increased ˚Brix in 2010 and high water stress (HIGH) increased ˚Brix in 2011 (Table 12). Rootstock (Stock) did not effect ˚Brix in 2010, but 420-A vines had fruit with the greatest ˚Brix in 2011. Fruit from root bag-low water stress (RBG-LOW) vines had the greatest ˚Brix in 2010 and the lowest in 2011 (Table 12).

Both pH and total acidity were less affected by year than was ˚Brix, resulting in more consistent factor effects over both years (Table 12). Under-trellis ground cover (UTGC) and RM vines did not affect fruit pH or total titratable acidity (TA) in 2010 or 2011, but NRM fruit had higher pH and TA in 2011 (Table 12). High stress (HIGH) vines had significantly lower pH and TA in both years. Rootstock (Stock) had inconsistent effects on TA in both years and 420-A had lower pH than riparia and 101-14 did in both years. Root bag-low water stress (RBG-LOW) fruit had the lowest pH in both years, and TA that trended higher, but was not different from other treatment levels in 2011 (Table 12).

Table 12. Treatment effects on soluble solids (˚Brix), pH, and total acidity (TA) as measured at harvest in 2010 and 2011.

	Soluble solids (˚Brix)		pH		Total titratable acidity (g/L)	
Treatment effects[ab]	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**
UTGC						
Herb	24.6 b	21.0 a	3.41 a	3.38 a	5.54 a	5.3 a
CC	25.0 a	20.9 a	3.43 a	3.41 a	5.25 a	5.4 a
RM						
NRM	25.5 a	21.3 a	3.44 a	3.44 a	5.43 a	5.80 a
RBG	24.5 b	20.8 a	3.41 a	3.37 b	5.36 a	5.13 b
Irr						
LOW	25.2 a	20.2 b	3.38 b	3.32 b	5.61 a	5.77 a
HIGH	23.8 b	21.5 a	3.44 a	3.43 a	5.12 b	4.49 b
Stock						
420-A	24.6 a	21.5 a	3.38 b	3.36 b	5.76 a	5.25 a
riparia	25.1 a	20.7 b	3.44 a	3.39 ab	5.03 b	5.70 a
101-14	24.7 a	20.7 b	3.44 a	3.43 a	5.38 ab	5.11 a
RM-Irr						
NRM-None	25.5 a	21.3 a	3.44 a	3.44 a	5.43 ab	5.80 a
RBG-LOW	25.5 a	20.2 b	3.37 b	3.34 b	5.65 a	5.77 ab
RBG-HIGH	23.5 b	21.5 a	3.45 a	3.41 ab	5.10 b	4.49 b
RM-Irr + UTGC						
NRM-None+Herb	25.5 ab	21.2 ab	3.45 ab	3.45 a	5.41 ab	5.74 a
NRM-None+CC	25.6 a	21.3 a	3.42 bc	3.42 ab	5.45 a	5.87 a
RBG-LOW+Herb	24.9 b	20.5 ab	3.37 c	3.32 b	5.75 a	5.71 a
RBG-LOW+CC	26.0 a	19.9 b	3.37 c	3.35 ab	5.55 ab	5.83 a
RBG-HIGH+Herb	23.5 c	21.4 ab	3.42 bc	3.37 ab	5.45 ab	4.47 a
RBG-HIGH+CC	23.5 c	21.6 ab	3.49 a	3.45 a	4.74 b	4.52 a
Significance[c]						
UTGC	0.0136	ns	ns	ns	ns	ns
RM	<0.0001	ns	ns	0.0087	ns	0.0235
Irr	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500
Stock	0.0489	0.0134	0.0007	0.0427	0.0148	ns
RM-Irr	<0.0001	0.0057	0.0003	0.0273	ns	0.0219
Stock*UTGC	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	0.0064	ns	0.0039	ns	ns	ns
RM-Irr*Stock	ns	0.0120	0.0232	ns	ns	ns
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors ($p > F$; ns = not significant).

In 2010, the root manipulation-differential irrigation*under-trellis groundcover (RM-Irr*UTGC) interaction revealed that root bag-low water stress (RBG-LOW) vines were much more responsive to under-trellis groundcover (UTGC) than the other two root manipulation-differential irrigation (RM-Irr) treatment levels, as evidenced by a much greater increase in ˚Brix with under-trellis cover crop (CC). Contrarily to ˚Brix, the pH levels in both no root manipulation-no irrigation (NRM-None) and root bag-high water stress (RBG-HIGH) were more responsive to under-trellis groundcover (UTGC) than root bag-low water stress (RBG-LOW) in 2010. The root manipulation-differential irrigation*rootstock (RM-Irr*Stock) interaction in 2010 revealed that pH levels of root bag-high water stress (RBG-HIGH) and no root manipulation-no irrigation (NRM-None) were differentially affected by rootstock (Stock) and this interaction in 2011 revealed that ˚Brix in no root manipulation-no irrigation (NRM-None) was less responsive to rootstock (Stock) than the other two root manipulation-differential irrigation (RM-Irr) treatment levels.

Juice composition from must lots: Treatment levels that resulted in small vines of high stress (RBG-HIGH + UTGC) had the lowest TA levels and, in all cases, under-trellis cover crop (CC) vines had less TA relative to under-trellis herbicide (Herb) vines within each root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) factor level (Table 13). The same trends for TA existed for malic acid levels, with the exception of the root bag-high water stress + under-trellis groundcover (RBG-HIGH + UTGC) treatment levels, when under-trellis cover crop (CC) resulted in slightly greater malic acid levels relative to under-trellis herbicide (Herb) (Table 13). Trends in pH were less evident, but, generally, treatment levels that involved root bag-low water stress (RBG-LOW) had the lowest pH while factors that involved no root

manipulation-no irrigation (NRM-None) had the greatest pH, regardless of under-trellis groundcover (UTGC) (Table 13). Under-trellis cover crop (CC) resulted in lower YAN levels relative to under-trellis herbicide (Herb) for each root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatment level. For each treatment level, TA and malic acid levels were higher and pH levels lower in 2011 relative to 2010 (Table 13).

Table 13. RM-Irr + UTGC treatment effects on composition of juice samples taken from must lots in 2010 and 2011.

		2010		
Treatment effects[ab]	Total titratable acidity (g/L)	Malic acid (g/L)	pH	Yeast assimilable nitrogen (mg/L N)
RBG-LOW + CC	4.28	1.37	3.79	62
RBG-LOW + Herb	5.21	1.75	3.79	73
RBG-HIGH + CC	3.86	1.23	3.89	65
RBG-HIGH + Herb	4.47	1.3	3.77	97
NRM-None + CC	4.84	2.34	3.97	69
NRM-None + Herb	5.5	2.71	3.98	85
		2011		
RBG-LOW + CC	5.47	1.99	3.5	53
RBG-LOW + Herb	5.95	2.24	3.52	73
RBG-HIGH + CC	4.94	1.57	3.69	59
RBG-HIGH + Herb	5.73	1.46	3.58	80
NRM-None + CC	5.37	2.83	3.78	69
NRM-None + Herb	6.51	3.44	3.75	92

[a] Herb = under-trellis herbicide; CC = under-trellis cover crop; NRM = no root manipulation; RBG = root bag; None = no irrigation, LOW = low water stress; HIGH = high water stress.
[b] In 2010, means for TA, and pH were derived from a total of 4 samples; all other compositional means in 2010 and all in 2011 were derived from 2 samples.

Alcohol and sugar content of wine lots: Although chaptilization and amelioration were performed in 2010 and 2011, respectively, differences in alcohol still existed in treatment level wine lots (Table 14). Those treatment levels that resulted in higher ˚Brix in 2010 also resulted in slightly higher wine alcohol, but there was no evidence of this trend for the 2011 vintage. Residual sugar levels were less than 1 g/L for all treatment level lots in both years (Table 14).

Table 14. Alcohol and residual sugar analysis of wine lots from 2010 and 2011.

Treatment[a]	Alcohol (%, v/v)[b] 2010	Alcohol (%, v/v)[b] 2011	Residual sugar (g/L)[b] 2010	Residual sugar (g/L)[b] 2011
NRM-None + Herb	14.1	12.8	<1	<1
NRM-None + CC	14.3	12.3	<1	<1
RBG-LOW + Herb	14.2	12.1	<1	<1
RBG-LOW + CC	14.4	12.5	<1	<1
RBG-HIGH + Herb	13.7	12.3	<1	<1
RBG-HIGH + CC	13.7	12.3	<1	<1

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress).
[b] Alcohol % and residual sugar are an average of two wine lot replicates in 2010 and from one of two wine lots in 2011 (other lot replicate not submitted for analysis in 2011).

Berry skin color: Root bag (RBG) significantly increased berry skin absorbance at 280 nm, 420 nm and 520 nm (A280, A420, and A520) in both years while under-trellis cover crop (CC) significantly increased absorbance at those wavelengths in 2010 (Table 15). Differential irrigation (Irr) had inconsistent effects on berry skin absorbance (Table 15). High water stress (HIGH) slightly increased absorbance in 2010 and low water stress (LOW) increased absorbance in 2011, but only significantly for A280. Excepting when 420-A resulted in significantly higher A520 in 2011, the rootstock (Stock) treatment rarely had a significant affect on berry skin absorbance at any wavelength (Table 15). In 2010, root bag-high water stress (RBG-HIGH) resulted in significant increases in A280 and A420, but not A520 while, in 2011, root bag-low water stress (RBG-LOW) resulted in the greatest color absorbance at all wavelengths, being significant at the 280 nm and 420 nm wavelengths, but not at the 520 nm wavelength (Table 15).

Table 15. Treatment effect on berry skin color absorbance at 280 nm, 420nm, and 520 nm wavelengths in 2010 and 2011.

	2010			2011		
Treatment effects[abc]	**280 nm**	**420 nm**	**520 nm**	**280 nm**	**420 nm**	**520 nm**
UTGC						
Herb	1.79 b	0.67 b	2.35 b	2.01 a	0.72 a	2.39 a
CC	2.11 a	0.75 a	2.63 a	2.13 a	0.74 a	2.45 a
RM						
NRM	1.79 b	0.68 b	2.40 b	1.95 b	0.69 b	2.33 b
RBG	2.12 a	0.75 a	2.58 a	2.20 a	0.76 a	2.51 a
Irr						
LOW	2.12 a	0.73 a	2.54 a	2.34 a	0.79 a	2.54 a
HIGH	2.13 a	0.76 a	2.62 a	2.06 b	0.74 a	2.49 a
Stock						
420-A	1.89 a	0.71 a	2.44 a	2.16 a	0.76 a	2.52 a
riparia	1.96 a	0.70 a	2.45 a	1.97 a	0.68 a	2.26 b
101-14	2.01 a	0.73 a	2.58 a	2.09 a	0.74 a	2.49 ab
RM-Irr						
NRM-None	1.79 b	0.68 b	2.40 a	1.95 b	0.69 b	2.33 a
RBG-LOW	2.12 a	0.73 ab	2.54 a	2.34 a	0.79 a	2.54 a
RBG-HIGH	2.13 a	0.76 a	2.62 a	2.06 b	0.74 ab	2.49 a
RM-Irr + UTGC						
RBG-LOW+CC	2.44 a	0.82 a	2.81 a	2.46 a	0.82 a	2.64 a
RBG-HIGH+CC	2.26 ab	0.79 a	2.74 a	2.15 abc	0.76 a	2.55 a
RBG-HIGH+Herb	1.99 abc	0.72 ab	2.50 ab	1.98 bc	0.71 a	2.43 a
NRM-None+CC	1.89 bc	0.70 b	2.49 ab	1.97 bc	0.69 a	2.31 a
RBG-LOW+Herb	1.80 bc	0.65 b	2.27 b	2.22 ab	0.76 a	2.44 a
NRM-None+Herb	1.68 c	0.66 b	2.30 b	1.93 c	0.70 a	2.35 a
Significance[d]						
UTGC	0.0030	0.0017	0.0006	ns	ns	ns
RM	0.0017	0.0071	0.0309	0.0072	0.0277	0.0364
Irr	ns	ns	ns	<0.0500	ns	ns
Stock	ns	ns	ns	ns	ns	0.0356
RM-Irr	0.0079	0.0234	ns	0.0018	0.0420	ns
RM-Irr+UTGC	<0.0001	<0.0001	0.0004	0.0084	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Tukey's HSD ($\alpha = 0.05$) for all but UTGC, RM and Irr (Student's T-test, $\alpha = 0.05$).

[c] RM-Irr + UTGC treatment level replication was 9 for NRM-None + UTGC, 5 for RBG-HIGH + UTGC and 4 for RBG-LOW + UTGC in 2010 and 6 for NRM-None + UTGC and 3 for RBG-HIGH + UTGC and RBG-LOW + UTGC in 2011.

[d] Significance of treatment effect on response variable, using One-Way ANOVA ($p > F$; ns = not significant).

Ecophysiology

Mid-day stem water potential: The root manipulation-differential irrigation (RM-Irr) factor, except on 26 Aug 2010, significantly affected mid-day stem water potential ($\psi_{md,stem}$) on all dates in both 2010 and 2011 (Table 16). The root manipulation (RM) treatment significantly affected $\psi_{md,stem}$ on all but the last two dates in 2010 (Table 16). The differential irrigation (Irr) treatment significantly affected $\psi_{md,stem}$ on all dates after inception of this treatment, which was 4 June in 2010 and 13 June in 2011 (Table 16). Other treatments were less consistent in how they affected mean $\psi_{md,stem}$, although under-trellis groundcover (UTGC) often had significant effects. The interactions of several treatment levels were occasionally significant, but not consistently so (Table 16).

Table 16. Treatment significance (p > F) of mid-day stem water potential ($\Psi_{md,stem}$) in 2010 and 2011.

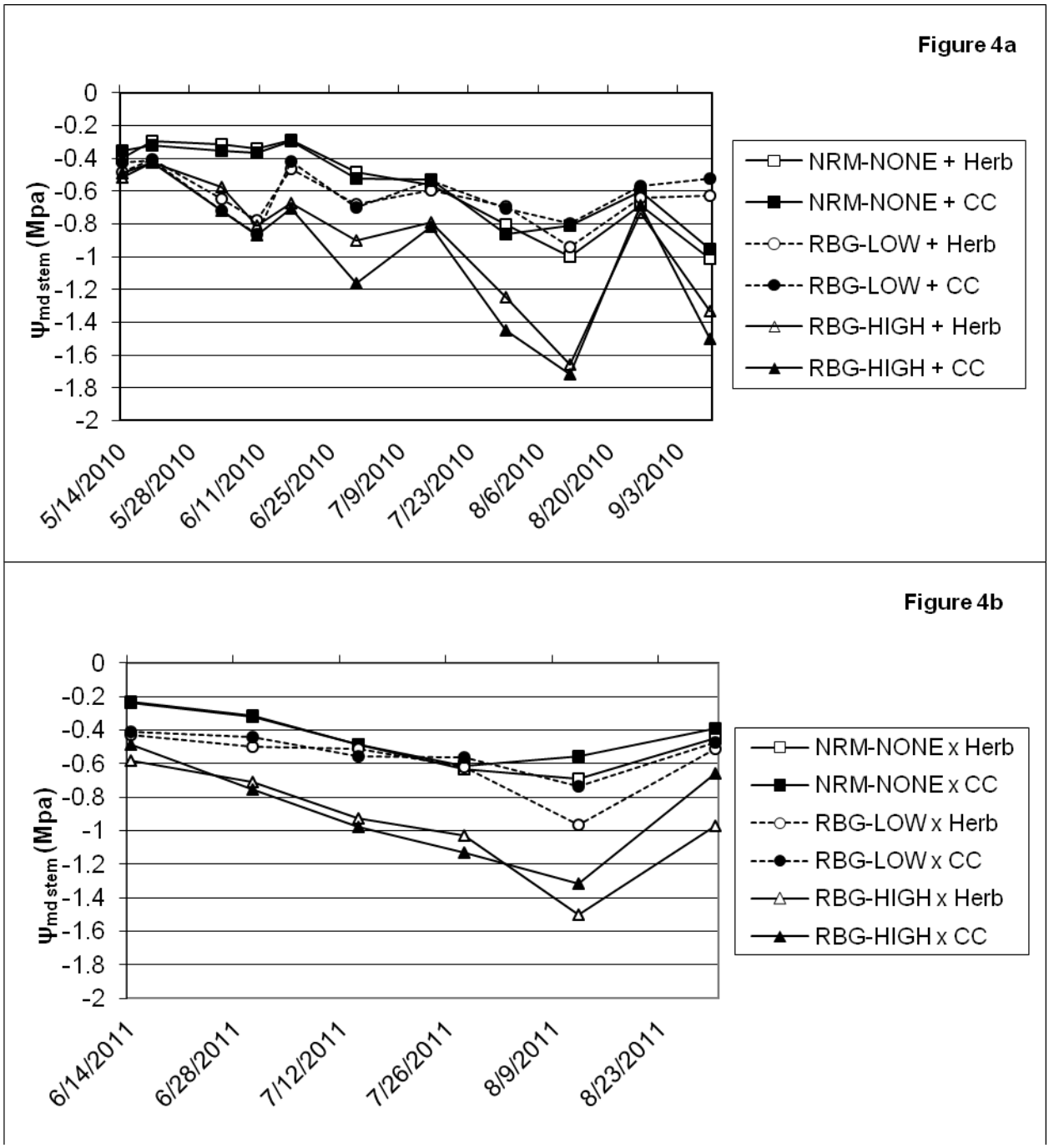
	2010										
Treatment[ab]	14-May	20-May	3-Jun	10-Jun	17-Jun	30-Jun	15-Jul	30-Jul	12-Aug	26-Aug	9-Sep
UTGC	ns	ns	<0.0001	0.0123	ns	0.0105	ns	0.0212	0.0455	ns	ns
RM	0.003	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0005	0.0104	<0.0001	ns	ns
Irr	ns	ns	ns	ns	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500
Stock	ns	ns	ns	0.022	ns	ns	0.0217	ns	ns	ns	ns
RM-Irr	0.002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	ns	<0.0001
Stock*UTGC	ns	ns	ns	ns	0.0331	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	ns	ns	0.0391	ns	ns	0.0347	ns	ns	ns	ns	ns
RM-Irr*Stock	ns	0.0046	ns	0.0128	0.0156	0.0425	0.0063	ns	ns	ns	ns
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

	2011					
	14-Jun	30-Jun	14-Jul	28-Jul	12-Aug	30-Aug
UTGC	ns	ns	ns	ns	<0.0001	0.0064
RM	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irr	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500
Stock	0.0265	ns	ns	ns	ns	ns
RM-Irr	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Stock*UTGC	ns	ns	ns	ns	ns	0.0253
RM-Irr*UTGC	0.0245	ns	ns	0.0391	ns	0.0003
RM-Irr*Stock	ns	ns	ns	0.003	ns	0.0012
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	0.0051

[a] UTGC: under-trellis groundcover treatment; RM: root manipulation treatment; Irr: differential irrigation treatment; Stock: rootstock treatment.

[b] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors (p > F; ns = not significant).

The mean $\psi_{md,stem}$ of the root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatments began to separate after differential irrigation (Irr) initiation (Figures 4a and 4b). In both years, the root bag-high water stress + under-trellis groundcover (RBG-HIGH + UTGC) treatment levels, resulted in the most negative (i.e. stressed) average $\psi_{md,stem}$ throughout the entire season and the "low stress" treatment levels, root bag-low water stress + under-trellis groundcover (RBG-LOW + UTGC) and no root manipulation-no irrigation + under-trellis groundcover (NRM-None + UTGC), resulted in average $\psi_{md,stem}$ values that were very similar to each other (Figures 4a and 4b). The lack of any significant difference in $\psi_{md,stem}$ values on 26 Aug 2010 (the second-to-last data point in Figure 4a) was due to irrigation on 25 Aug 2010. It is also important to note that in 2011 the $\psi_{md,stem}$ was collected with less frequency early in the season and that data collection events ceased more than a month before harvest, due to the weather patterns experienced at this point in the season (Figure 1b).



Figures 4a and 4b. RM-Irr + UTGC treatment effect on mid-day stem water potential ($\psi_{md,stem}$) measured on Cabernet Sauvignon, clone 337 grapevines during the 2010 and 2011 growing seasons.

Gas Exchange: As with the mean $\psi_{md,stem}$ response data, the treatments that most consistently and significantly affected mean net photosynthetic rates (A) in both 2010 and 2011 were root manipulation (RM), differential irrigation (Irr) and root manipulation-differential irrigation (RM-Irr) (Table 17). Root manipulation-differential irrigation (RM-Irr) significantly affected mean A on every date but one, and under-trellis groundcover (UTGC) significantly affected mean A on several dates early in 2010, but was less important on subsequent dates in 2010 and in 2011 (Table 17). Other treatments were less consistent with affects on A, although under-trellis groundcover (UTGC) was often significant in 2010. The interaction of treatment levels was significant on only two dates in 2010 (Table 17).

Table 17. Treatment significance (p > F) of net photosynthetic rate (A) in 2010 and 2011.

	2010									
Treatment[ab]	**20-May**	**27-May**	**3-Jun**	**10-Jun**	**17-Jun**	**30-Jun**	**15-Jul[c]**	**29-Jul**	**12-Aug**	**26-Aug**
UTGC	0.0002	0.0138	ns	0.0053	0.0005	0.0008	ns	ns	ns	ns
RM	0.0217	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	ns	0.0102	0.0124	<0.0001
Irr	<0.0500	ns	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500
Stock	ns	0.003	ns	ns	ns	0.0057	ns	ns	ns	ns
RM-Irr	0.0207	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001	<0.0001
Stock*UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	0.0267	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM-Irr*Stock	ns	0.0342	ns	ns	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

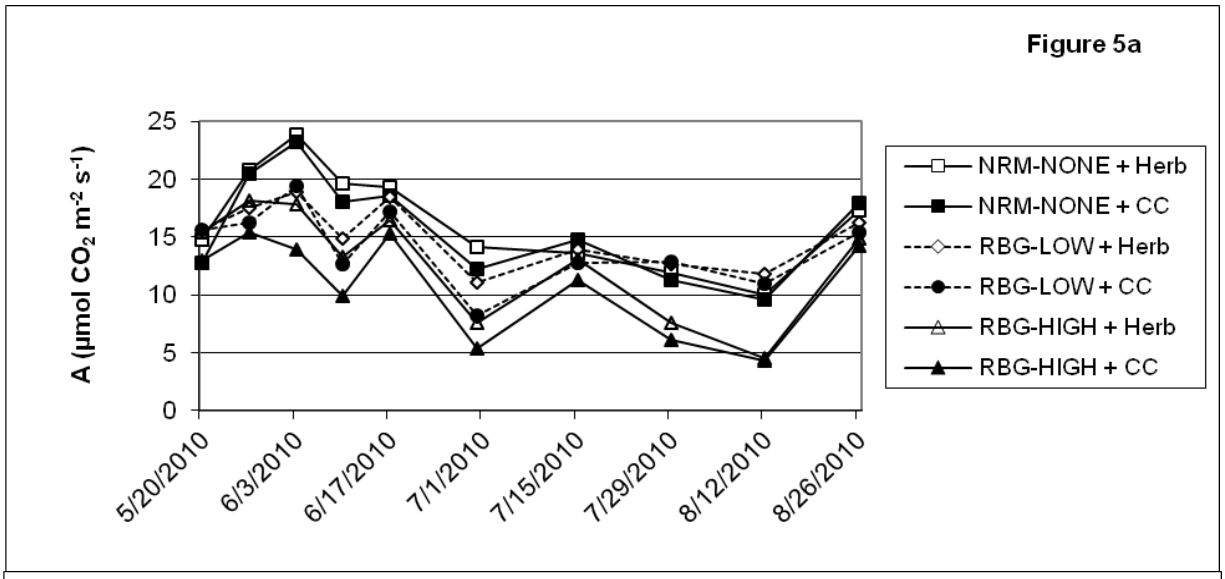
	2011					
	21-Jun	**30-Jun**	**14-Jul**	**28-Jul**	**12-Aug**	**30-Aug**
UTGC	<0.0001	ns	ns	ns	ns	ns
RM	ns	<0.0001	<0.0001	0.0007	0.0004	0.0331
Irr	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500
Stock	ns	ns	ns	ns	ns	ns
RM-Irr	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	0.0054
Stock*UTGC	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	ns	ns	ns	ns	ns	ns
RM-Irr*Stock	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	ns

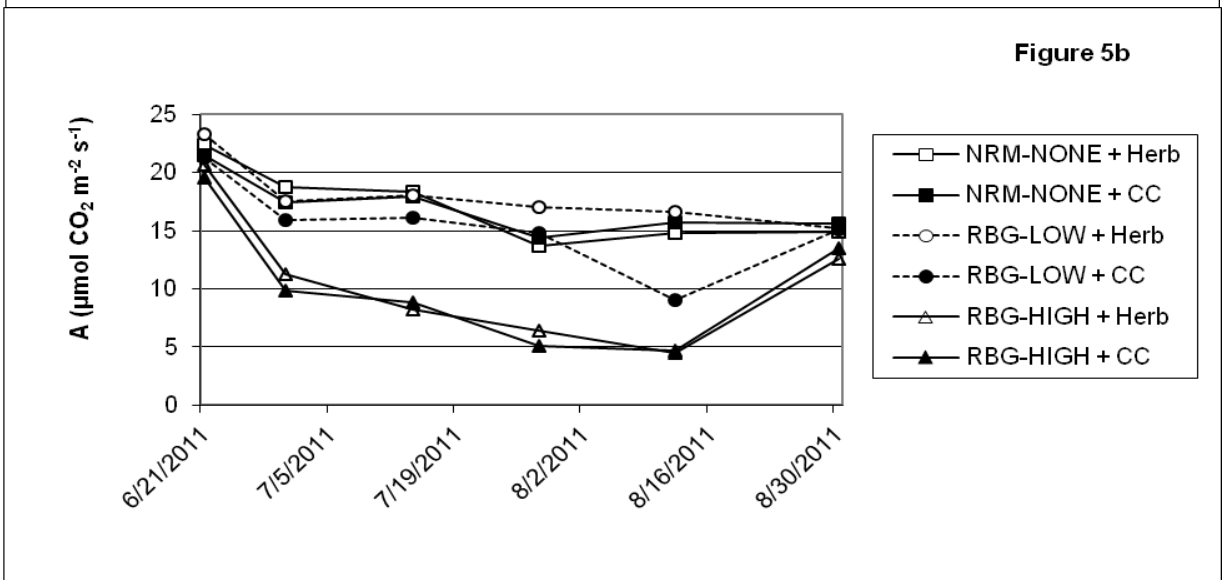
[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors (p > F; ns = not significant).

[c] Insignificance on this date possibly due to incomplete data set, although 3-June was also incomplete.

Root bag-high water stress + under-trellis groundcover (RBG-HIGH + UTGC) treatment levels resulted in lower seasonal rates of A relative to the other root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatment levels in both years (Figures 5a and 5b). In 2010, the separation of A between factor levels was not as consistent as it was in 2011, but it is evident that water status did influence A rates as the general trends were that of relatively lower water stress led to relatively higher seasonal A rates (Figures 4a, 4b, 5a and 5b).





Figures 5a and 5b. RM-Irr + UTGC treatment effect on net photosynthetic rate (A) measured on Cabernet Sauvignon, clone 337 grapevines during the 2010 and 2011 growing seasons.

The treatment that most consistently and significantly affected mean stomatal conductance (g_s) in both 2010 and 2011 was root manipulation-differential irrigation (RM-Irr) (Table 18). Root manipulation (RM) and Irr both significantly affected g_s on six out of the ten dates data were collected in 2010 and five of six dates in 2011. Other treatments had less consistent effects (Table 18).

Table 18. Treatment significance (p > F) of mean stomatal conductance (g_s) in 2010 and 2011.

	2010									
Treatment[ab]	**20-May**	**27-May**	**3-Jun**	**10-Jun**	**17-Jun**	**30-Jun**	**15-Jul[c]**	**29-Jul**	**12-Aug**	**26-Aug**
UTGC	ns	ns	ns	<0.0001	ns	<0.0001	ns	ns	ns	0.0064
RM	ns	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	ns	0.0002	ns	<0.0001
Irr	<0.0500	ns	ns	<0.0500	<0.0500	<0.0500	ns	<0.0500	<0.0500	<0.0500
Stock	ns	ns	ns	ns	ns	0.0443	ns	ns	ns	ns
RM-Irr	0.0049	0.0026	<0.0001	<0.0001	ns	<0.0001	ns	<0.0001	0.0366	0.0002
Stock*UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RM-Irr*Stock	ns	ns	0.0263	ns	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

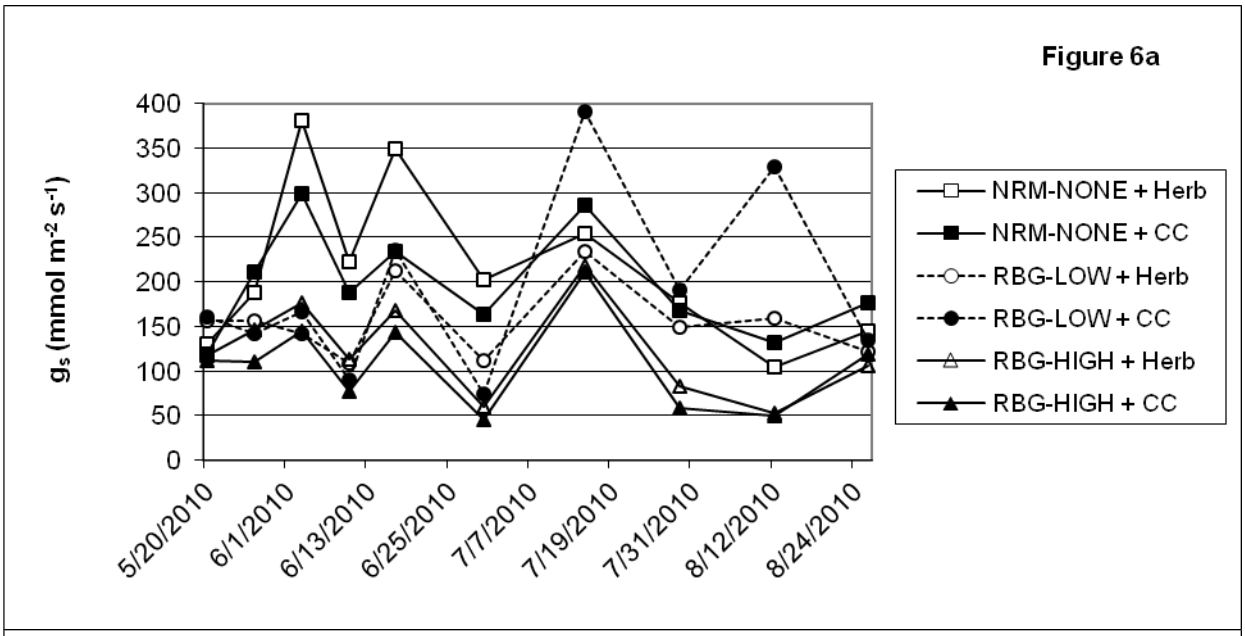
	2011					
	21-Jun	**30-Jun**	**14-Jul**	**28-Jul**	**12-Aug**	**30-Aug**
UTGC	ns	ns	ns	ns	ns	0.0338
RM	ns	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irr	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	ns
Stock	ns	ns	ns	ns	ns	0.001
RM-Irr	ns	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Stock*UTGC	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	ns	ns	ns	ns	ns	ns
RM-Irr*Stock	ns	ns	ns	ns	0.0423	0.0241
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	ns

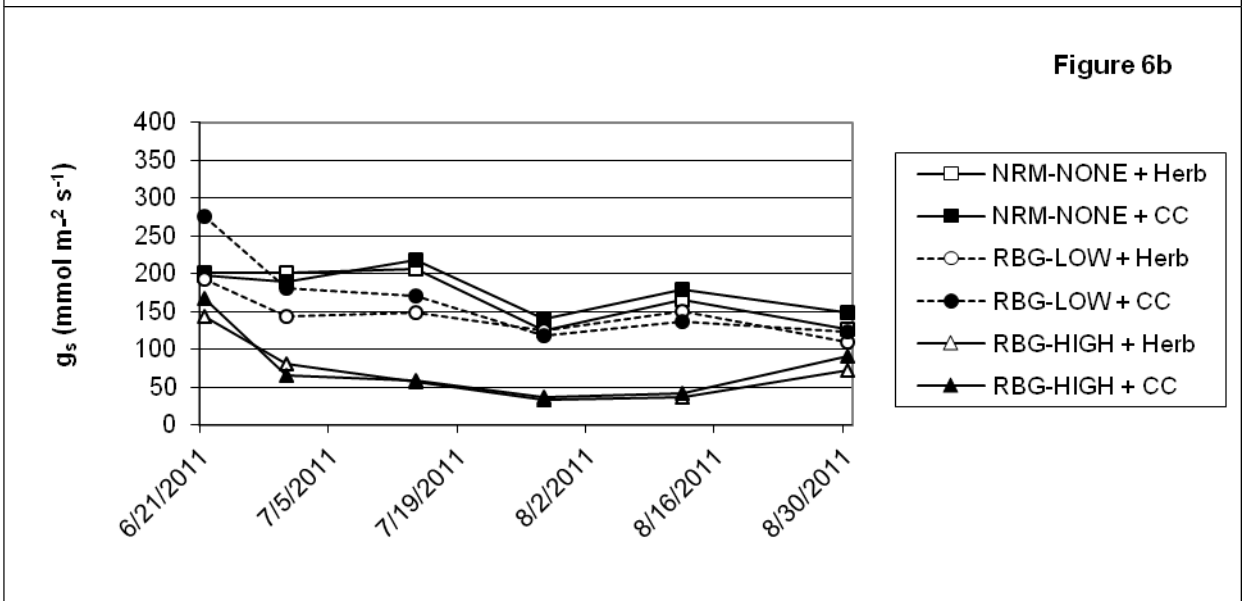
[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors (p > F; ns = not significant).

[c] Insignificance on this date possibly due to incomplete data set, although 3-June was also incomplete.

Relative to seasonal $\psi_{md,stem}$ and A rates, seasonal g_s was highly variable in 2010 (Figure 6a). In general, the two RBG-HIGH + UTGC treatment levels resulted in lower seasonal g_s rates in both years relative to the other treatment levels (Figures 6a and 6b). Tying together water status and gas exchange, the higher stress treatments had lower seasonal $\psi_{md,stem}$ (Figures 4a and 4b), lower seasonal g_s rates (Figures 6a and 6b), and lower seasonal A rates (Figures 5a and 5b).





Figures 6a and 6b. RM-Irr + UTGC treatment effect on stomatal conductance (g_s) measured on Cabernet Sauvignon, clone 337 grapevines during the 2010 and 2011 growing seasons.

Seasonal $\psi_{stem,\ md}$ and leaf gas exchange averages: Under-trellis herbicide (Herb) resulted in significantly lower average seasonal $\psi_{md,stem}$ only in 2011 (Table 19). In both years, root bag (RBG) and high water stress (HIGH) significantly reduced average seasonal $\psi_{md,stem}$ relative to no root manipulation (NRM) and low water stress (LOW), respectively. Rootstock (Stock) did not significantly affect average seasonal $\psi_{md,stem}$ in 2010, but did so in 2011. The root manipulation-differential irrigation (RM-Irr) treatment always significantly affected average seasonal $\psi_{md,stem}$, with root bag-high water stress (RBG-HIGH) reducing this response by 67% and 104% relative to no root manipulation-no irrigation (NRM-None) in 2010 and 2011, respectively.

Under-trellis herbicide (Herb), no root manipulation (NRM) and low water stress (LOW) all increased average seasonal net photosynthetic rate (A) in both years; rootstock (Stock) had inconsistent effects on A (Table 19). The no root manipulation-no irrigation (NRM-None) treatment level resulted in significantly higher A than the other two root manipulation-differential irrigation (RM-Irr) treatment levels in 2010 and only the root bag-high water stress (RBG-HIGH) factor level in 2011. The root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatment further separated mean A between treatment levels, with the addition of under-trellis groundcover (UTGC) to root bag-differential irrigation (RBG-Irr) resulting in further significant differences between factor level means in 2010 but not 2011.

Neither under-trellis groundcover (UTGC) nor rootstock (Stock) affected average seasonal stomatal conductance (g_s), but no root manipulation (NRM) and low water stress (LOW) both resulted in significantly higher g_s in both years (Table 19). Seasonal stomatal conductance (g_s) of all three root manipulation-differential irrigation (RM-Irr) treatment levels

were different from one another in both years and the addition of under-trellis groundcover (UTGC) to these treatment levels resulted in no further differences in g_s.

The root manipulation-differential irrigation*under-trellis groundcover (RM-Irr*UTGC) interaction in 2010 revealed that the $\psi_{md,stem}$ of root bag-high water stress (RBG-HIGH) was more responsive to under-trellis ground cover (UTGC) compared to the other two root manipulation-differential irrigation (RM-Irr) treatment levels. The root manipulation-differential irrigation*rootstock (RM-Irr*Stock) interaction in both 2010 and 2011 revealed that the $\psi_{md,stem}$ of vines grafted on to 420-A were more responsive to RM-Irr treatment levels than were vines grafted to either of the other rootstocks. The root manipulation-differential irrigation*rootstock (RM-Irr*Stock) interaction also revealed that root bag-high water stress (RBG-HIGH) vines responded differently to rootstock (Stock), as riparia and 101-14 had $\psi_{md,stem}$ levels were separated to a greater extent than the other root manipulation-differential irrigation (RM-Irr) treatment levels.

Table 19. Treatment effect on average seasonal mid-day stem water potential ($\psi_{stem\ md}$), photosynthetic rate (A) and stomatal conductance (g_s) in 2010 and 2011.

	$\psi_{stem,\ md}$ (Mpa)		A (µmol CO_2 $m^{-2}s^{-1}$)		g_s (mmol $m^{-2}s^{-1}$)	
Treatment effects[abc]	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**
UTGC						
Herb	-0.78 a	-0.67 a	13.4 a	15.2 a	142 a	129 a
CC	-0.79 a	-0.62 b	12.2 b	14.6 a	132 a	140 a
RM						
NRM	-0.63 b	-0.45 b	15.0 a	17.1 a	180 a	175 a
RBG	-0.86 a	-0.74 a	11.7 b	13.9 b	114 b	113 b
Irr						
LOW	-0.66 b	-0.56 b	14.2 a	17.5 a	150 a	153 a
HIGH	-1.07 a	-0.92 a	9.2 b	10.2 b	78 b	73 b
Stock						
420-A	-0.79 a	-0.65 ab	13.3 a	15.2 a	145 a	138 a
riparia	-0.76 a	-0.61 b	12.8 ab	15.0 a	135 a	133 a
101-14	-0.81 a	-0.67 a	12.2 b	14.5 a	129 a	131 a
RM-Irr						
NRM-None	-0.64 b	-0.45 c	15.0 a	17.1 a	181 a	175 a
RBG-LOW	-0.66 b	-0.56 b	13.3 b	17.1 a	140 b	153 b
RBG-HIGH	-1.07 a	-0.92 a	10.1 c	10.5 b	89 c	75 c
RM-Irr + UTGC						
NRM-None+Herb	-0.65 a	-0.47 ab	15.4 a	17.1 a	185 a	171 ab
NRM-None+CC	-0.63 a	-0.43 a	14.6 ab	17.1 a	177 a	179 a
RBG-LOW+Herb	-0.67 a	-0.58 c	13.8 b	17.8 a	143 b	142 b
RBG-LOW+CC	-0.64 a	-0.53 bc	12.8 c	16.5 a	136 bc	165 ab
RBG-HIGH+Herb	-1.02 b	-0.96 e	10.9 d	10.7 b	97 cd	74 c
RBG-HIGH+CC	-1.11 c	-0.88 d	9.3 e	10.3 b	82 d	77 c
Significance[d]						
UTGC	ns	0.0002	<0.0001	ns	ns	ns
RM	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irr	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500	<0.0500
Stock	ns	0.0437	0.0044	ns	ns	ns
RM-Irr	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Stock*UTGC	ns	ns	ns	ns	ns	ns
RM-Irr*UTGC	0.0040	ns	ns	ns	ns	ns
RM-Irr*Stock	0.0422	0.001	ns	ns	ns	ns
RM-Irr*UTGC*Stock	ns	ns	ns	ns	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Means in 2010 and 2011 derived from data collected on 10-June and 21-June, respectively, and after; means for stomatal conductance and photosynthesis derived without 15 Jul data (incomplete data sets)

[d] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors ($p > F$; ns = not significant).

Water use efficiency: In 2010, under-trellis groundcover (UTGC) did not significantly affect the ^{13}C levels in berry juice but the root bag (RBG) and high water stress (HIGH) treatment levels both resulted in significantly less ^{13}C discrimination ($\delta^{13}C$) relative to no root manipulation (NRM) and low water stress (LOW), respectively (Table 20). Root bag-high water stress (RBG-HIGH) resulted in significantly less $\delta^{13}C$ than no root manipulation-no irrigation (NRM-None) and root bag-low water stress (RBG-LOW) was not significantly different from either (Table 20). Of all the root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatment levels, no root manipulation-no irrigation + under-trellis cover crop (NRM-None + CC) resulted in the most $\delta^{13}C$ and root bag-high water stress + under-trellis herbicide (RBG-HIGH + Herb) the least.

Under-trellis groundcover (UTGC) did not significantly affect average seasonal intrinsic water-use efficiency (WUE_i) in 2010, but under-trellis herbicide (Herb) resulted in significantly greater WUE_i than under-trellis cover crop (CC) in 2011 (Table 20). Both root bag (RBG) and high water stress (HIGH) resulted in significantly greater WUE_i than no root manipulation (NRM) and low water stress (LOW), respectively. The WUE_i was significantly different between all root manipulation-differential irrigation (RM-Irr) treatment levels. The addition of under-trellis groundcover (UTGC) to root manipulation-differential irrigation (RM-Irr), to give the root manipulation-differential irrigation + under-trellis groundcover (RM-Irr + UTGC) treatment levels, did not result in any further significant differences in WUE_i in either year (Table 20). The 2010 interaction between root manipulation-differential irrigation (RM-Irr) and rootstock (Stock) revealed that WUE_i was lowest when root bag (RBG-LOW and RBG-HIGH) treatment levels (regardless of differential irrigation, Irr) were grafted to riparia. WUE_i was highest when no root manipulation-no irrigation (NRM-None) vines were grafted onto riparia.

Table 20. Treatment effect on $\delta^{13}C$ of berry juice in 2010 and average seasonal intrinsic (A/g_s) water-use efficiency (WUE_i) in 2010 and 2011.

	2010		2011
Factor effects[ab]	**$\delta^{13}C$[d]**	**WUE_i[e]**	**WUE_i[e]**
UTGC			
Herb	-25.83 a	0.10 a	0.13 a
CC	-26.11 a	0.10 a	0.11 b
RM			
NRM	-27.37 b	0.09 b	0.10 b
RBG	-24.95 a	0.11 a	0.13 a
Irr			
LOW	-26.27 b	0.10 b	0.12 b
HIGH	-24.30 a	0.12 a	0.14 a
Stock			
420-A	n/a	0.10 a	0.12 a
riparia	n/a	0.10 a	0.12 a
101-14	n/a	0.10 a	0.12 a
RM-Irr			
NRM-None	-27.37 b	0.09 c	0.10 c
RBG-LOW	-26.25 ab	0.10 b	0.12 b
RBG-HIGH	-24.30 a	0.12 a	0.14 a
RM-Irr + UTGC			
RBG-HIGH+CC	-24.4 a	0.12 a	0.14 ab
RBG-HIGH+Herb	-24.21 a	0.12 a	0.15 a
RBG-LOW+CC	-26.47 ab	0.10 bc	0.11 bc
RBG-LOW+Herb	-26.02 ab	0.10 b	0.13 ab
NRM-None+CC	-27.47 b	0.09 bc	0.10 c
NRM-None+Herb	-27.26 b	0.09 c	0.10 c
Significance[c]			
UTGC	ns	ns	0.0198
RM	0.0005	<0.0001	<0.0001
Irr	<0.0500	<0.0500	<0.0500
Stock	na	ns	ns
Stock*UTGC	na	ns	ns
RM-Irr	0.0089	<0.0001	<0.0001
RM-Irr*UTGC	ns	ns	ns
RM-Irr*Stock	na	0.0485	ns
RM-Irr*UTGC*Stock	na	ns	ns

[a] UTGC: under-trellis groundcover treatment (Herb = under-trellis herbicide, CC = under-trellis cover crop); RM: root manipulation treatment (NRM = no root manipulation, RBG = root bag); Irr: differential irrigation treatment (None = no irrigation, LOW = low water stress; HIGH = high water stress); Stock: rootstock treatment (name of rootstock evident).

[b] Separation of means using Student's T-test for UTGC, RM and Irr and Tukey's HSD for all others ($\alpha = 0.05$).

[c] Significance of factor effects and interactions using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for RM and Irr factors ($p > F$; ns = not significant).

[d] Treatment means derived from 50 berry samples, all from 420-A rootstocks, thus why the Stock factor and any interaction is "n/a".

[e] Treatment means derived by averaging across all dates of data collection; ten dates in 2010 and six dates in 2011.

Response correlation analysis

Analysis of response correlation to berry skin color absorbance revealed several significant correlations (Table 21). Cluster exposure flux availability (CEFA) and cluster exposure layer (CEL) were the two EPQA indices that were best correlated with color absorbance at 280 nm and 520 nm wavelengths (other EPQA responses indices not shown) (Table 21). Berry weight and vine capacity were the two responses that were most highly correlated with berry skin absorbance at both wavelengths. Average seasonal photosynthetic rates were negatively correlated to berry skin absorbance (Table 21).

Table 21. Growth and physiology responses and their correlation to berry skin color absorbance at 280 nm and 520 nm wavelengths in 2010.

	Correlation coefficient (and signif.) with absorbance covariate[a]	
Response variable[b]	**280 nm**	**520 nm**
CEL	-0.5221 (0.0011)	-0.4906 (0.0024)
CEFA	0.5721 (0.0003)	0.5491 (0.0005)
Vine Capacity	-0.7173 (<0.0001)	-0.6780 (<0.0001)
A	-0.4867 (0.0026)	-0.5315 (0.0009)
$\psi_{md, stem}$	-0.4309 (0.0146)	-0.4238 (0.0100)
Berry weight	-0.6478 (<0.0001)	-0.6640 (<0.0001)
Crop load	0.5729 (0.0003)	0.4131 (0.0123)

[a] Correlations and significance probabilities ($p > F$) assessed using multivariate analysis and pairwise correlation analysis, using the pairwise deletion method.
[b] CEL = cluster exposure layer; CEFA = cluster exposure flux availability; A = average seasonal net photosynthetic rate; $\psi_{md, stem}$ = average seasonal mid-day stem water potential.

Wine Sensory Analysis

Triangle difference test: Out of the eight total triangle difference test sessions that were conducted, each with a unique comparison of wines, seven sessions included at least one sensory attribute being significantly distinguished between wines. The very first date of sensory sessions was the only session in which no sensory attributes were significantly distinguished and the second date was the only date in which only one sensory attribute was significantly distinguished (Table 22). Aroma was significantly distinguished between compared wines in three out of the eight sessions, including the comparisons made between treatment level wines that were produced from vines with significantly different $\psi_{md,stem}$, A, vine capacity, and berry weight (Table 22). Color was the most consistent and significant distinguished sensory attribute in all unique treatment level wine comparisons. Flavor was significantly distinguished six times in all unique treatment level wine comparisons (Table 22). Sensory attributes of wines were distinguished between RM-Irr + UTGC factors that also differed in several growth and physiology responses. Those responses relating most to significant sensory differences, as determined by number of responses that were significantly different, were A, $\psi_{md,stem}$, crop load (Y:PW), vine capacity and berry weight. In all, seven of eight sensory evaluation sessions revealed at least one significant difference in at least one sensory attribute between wines (Table 22).

Table 22. Triangle difference test results between unique comparisons of RM-Irr + UTGC treatment level wines from the 2010 vintage and significant differences of responses between vines in which fruit was produced to make the treatment level wines in 2010.

Treatment Level Comparison[a]	Date[b]	Aroma[c]	Color[c]	Flavor[c]	A280[d]	A520[d]	CEFA[d]	CEL[d]	A[d]	$\psi_{md,stem}$[d]	Crop load	Vine capacity	Berry wt.
RBG-LOW + CC - RBG-HIGH + Herb	5-Apr-11	ns	ns	ns	ns	ns	ns	ns	s	s	s	ns	ns
RBG-LOW + CC - RBG-HIGH + CC	6-Apr-11	ns	0.0030	ns	ns	ns	ns	ns	s	s	s	s	s
RBG-LOW + CC - NRM-None + Herb	8-Apr-11	ns	<0.0001	<0.0001	s	s	s	s	s	ns	s	s	s
RBG-LOW + Herb - RBG-HIGH + CC	12-Apr-11	0.0021	<0.0001	0.0146	ns	s	s	ns	s	s	ns	s	s
RBG-LOW + Herb - RBG-HIGH + Herb	13-Apr-11	ns	0.0087	0.0207	ns	ns	ns	ns	s	s	ns	ns	ns
RBG-LOW + Herb - NRM-None + CC	15-Apr-11	ns	<0.0001	0.0033	ns	ns	ns	ns	ns	ns	s	ns	ns
RBG-HIGH + CC - NRM-None + Herb	19-Apr-11	0.0007	<0.0001	<0.0001	s	s	s	s	s	s	s	s	s
RBG-HIGH + Herb - NRM-None + CC	20-Apr-11	0.0018	<0.0001	0.0018	ns	ns	ns	ns	s	s	s	s	s
Significant sensory differences[e]					2	3	3	2	6	5	5	5	5

[a] Herb = under-trellis herbicide; CC = under-trellis cover crop; NRM = no root manipulation; RBG = root bag; None = no irrigation, LOW = low water stress; HIGH = high water stress.

[b] Date that each respective triangle difference test was conducted.

[c] Critical Number of Correct Responses in a Triangle Test (Meilgaard et al. 2006) used for testing significance.

[d] A280 and A520 = berry skin color absorbance at respective wavelengths; CEL = cluster exposure layer; CEFA = cluster exposure flux availability; A = average seasonal net photosynthetic rate; $\psi_{md, stem}$ = average seasonal mid-day stem water potential.

[e] Total number of sensory differences between factor level wine lots that were also significantly different in the response listed at the column head; significance of factor effects using standard least squares with REML and an emphasis on effect leverage; one-way ANOVA used for berry skin color responses ($p > F$; s = significant, ns = not significant).

Discussion

Grapevines vary greatly in their growth capacity and vigor due to environment, cultural practices, and management (Dokoozlain and Kliewer 1995). In regions like Virginia and most areas of the Mid-Atlantic USA, where it can be difficult to fully ripen a late maturing variety such as Cabernet Sauvignon, it is the environment which is problematic. The climate in this region lends itself to high vigor vines which are often out of balance, can have highly shaded fruit zones, and often have crop loads lower than optimal for wine quality (Bravdo et al. 1984). Thus, practical, cost-effective ways of producing vines that are of lower vigor and consistently fully mature high quality fruit is desirable.

Because shoot growth is sensitive to water stress (Smart and Coombe 1983) and the leading cause of excessive vegetative growth is a surplus of plant available water (PAW) (Van Leeuwen and Seguin 1994), all of the applied field treatments in this study had the potential to limit vegetative growth. Using physical root restriction limits the vegetative growth of grapevines (Wang 2001; Hatch et al. 2011) and using rootstocks can affect vine vigor (Dry and Loveys 1998). Tesic et al (2007) found that floor cover could strongly reduce vine vegetative growth. Controlling irrigation or limiting water to the vine also has the potential to limit vegetative growth and overall vine vigor (Chaves et al. 2007; Matthews et al. 1987).

In addition to the applied treatments' effects on vegetative growth, the ability for these treatments to result in more favorable fruit composition has also been demonstrated elsewhere. Naylor et al. (1994) found that cover crop competition can improve fruit composition as well as advance fruit maturity. In this study (Naylor et al. 1994), the management of vines, as by the applied field treatments, altered vine growth (vegetative and reproductive), ecophysiology and

fruit composition in both years. The result was distinguishable sensory differences in the wines made from combinations of treatments.

The use of root bags (RBG) significantly and consistently affected vegetative development, producing vines with more open canopies and greater fruit exposure than vines grown without root restriction (NRM). This was made evident by EPQA analysis as well as fruit-zone PPFD measurements and lateral shoot development. Other studies (Wang et al. 2001, Hatch et al. 2011) found that root restriction did effectively regulate grapevine vegetative development, primarily as a result of more rapid soil depletion of soil water. While root bags did generally result in lower stem water potentials ($\psi_{md, stem}$), the addition of low water stress (RBG-LOW) resulted in average seasonal $\psi_{md, stem}$ that were not significantly different than those of vines grown without root manipulation (NRM) in 2010, yet still had significantly different measures of vegetative development. Though differential irrigation (Irr) resulted in a greater magnitude of separation of $\psi_{md, stem}$ relative to both root manipulation (RM) and under-trellis groundcover (UTGC), differential irrigation (Irr) was less important in affecting vegetative growth.

This suggests that current-season vine water status is not wholly responsible for differences in vegetative growth seen between root restriction treatments. Rather, the growth inhibition could be a result of internal signaling from root to shoot via hormones. Studies in other species support this notion. It was reported that shoot growth in cotton was correlated with root volume and root restriction could result in a decrease in vegetative growth potentially irrespective of water or nutrient status (Carmi and Shalhevet 1983). Rieger and Marra (1994) concluded that growth reduction in peach seedlings was not due to a water deficit or reduction in photosynthesis, but potentially due to root-derived hormone signals.

Vegetative growth of grapevines has been effectively regulated through several irrigation strategies (Chaves et al. 2007, Poni et al. 2007, Reynolds and Naylor 1994; Shellie, 2006), likely because shoot growth is sensitive to water stress (Smart and Coombe 1983). The vegetative devigoration due to irrigation in Chaves et al. (2007) and Matthews et al. (1987) studies could be explained by those climates (Mediterranean, California and Portugal) having a consistently higher evapotransitive demand throughout the growing season; this would result in the depletion soil water resources more rapidly relative to the climate in Virginia. Further, soil water holding capacity would affect the magnitude of vegetative devigoration achievable with water-competitive treatments.

Cover cropping has been shown to limit vegetative growth in vineyards (Celette et al. 2005; Lopes et al. 2008 and 2011) and improve fruit exposure (Tesic et al. 2007; Hatch et al. 2011). While under-trellis cover crop (UTCC) was important in reducing vegetative vigor, it did not reduce vigor to the extent that root bags (RBG) did. Because under-trellis groundcover (UTGC) did not result in relatively great differences in vine water status, but more consistently altered vegetative growth than differential irrigation (Irr), it is suggested that water limitation was not the primary cause of vegetative growth suppression via cover cropping. As suggested in Celette et al. (2005) all factors that may affect vine growth and development must be considered. Nutritionally, nitrogen (N) status was lower in vines grown with cover crops, which may reduce vine shoot growth (Tan and Crabtree 1990), although nitrogen levels were below target values for all samples (Bates and Wolf 2008). Though not yet understood and beyond the scope of this study, allelopathic effects of cover cropping could be partially responsible for limiting vine vegetative growth. Other possibilities are root-to-shoot signaling or the cost of allocating resources for vine root redistribution in cover cropping, both limiting shoot growth. Root

redistribution likely occurred, as the soil moisture characteristics at the 100 and 600 mm soil depths suggest deeper root colonization with cover crops; whether this was costly to the plant and resulted in limiting shoot growth cannot be determined, but is a possibility.

The use of rootstocks has been shown to alter vegetative vigor, as measured by pruning weights (Koundouras et al. 2008; Nuzzo and Matthews 2006; Reynolds and Wardle 2001). There were relatively small differences in cane pruning weights and limited canopy differences between 101-14, 420-A, and riparia. These three rootstocks are considered to be at the lower end of vigor-conferral relative to other rootstocks (Wolf 2008) and, relative to the often dwarfing effects that rootstocks have on other crops, the ability of rootstocks to modify scion vigor in grapevines is low (Dry and Loveys 1998). For these reasons, vegetative growth differences were less likely to be found with the use of rootstocks, especially in comparison to the other treatments.

It was a consistent trend that treatments that resulted in lower yields also resulted in lower cluster and berry weights; these treatments also generally resulted in vines with lower water status. Thus, water status can affect yield through its effects on berry growth and expansion (Matthews et al. 1987; Roby and Matthews 2004). The potential reason that the most effective treatment at altering vine water status (differential irrigation, Irr) did not effect berry and cluster weights in 2011 is likely the weather patterns during phase three of berry development. These weather patterns (relatively lower ET_o and more rainfall) lessened the treatment effects that were more effectively maintained through harvest in 2010, when differential irrigation (Irr) resulted in significantly different berry weights at harvest.

Yield components were related to vine water status more so than vegetative growth was, although root manipulation (RM) still had more consistent effects on berry weight, berry surface

area: volume ratio, and yield than did differential irrigation (Irr). While the treatment levels that resulted in lower vine water status (CC, RBG) generally resulted in vines of lower capacity and higher crop load, this was not the case for high water stress (HIGH), which reduced vine capacity and crop load. Thus, under-trellis cover crop (CC) and root bag (RBG) limited vegetative growth but did not limit berry weight to the extent that high water stress (HIGH) did. This is further evidence that vine water status has a greater effect on components of yield than on vegetative growth, especially when applied during phase three of berry development.

Crop load can affect fruit composition (Bravdo et al. 1984, Kliewer and Dokoozlian 2005) and wine sensory analysis (Chapman et al. 2004). Crop load was affected most by root manipulation (RM) and all root bag (RBG) vines were in the range of 5-12, which was reported ideal for wine quality (Bravdo et al. 1985). Berry size or weight reduction may be desirable as it relates to a higher concentration of phenolics (Ojeda et al. 2002) as well as higher skin (Roby et al. 2004) and seed (Shellie 2010) ratios relative to whole berry mass, thus altering the concentrations of compounds derived from these tissues in musts.

Soluble solids (˚Brix) (Koundouras et al. 2006) and phenols (Chaves et al. 2007; Ojeda et al. 2002; Roby et al. 2004) have been reported to be increased with water deficits. Unlike its relationship to reproductive growth itself, water status did not greatly relate to fruit compositional attributes. However, those treatment levels that did result in lower vine water status tended to have lower ˚Brix in 2010 and lower TA, the former a potential result of lower net photosynthetic rates (A), which was the case for treatments with lower water status in 2010.

Trends were evident that pH levels were higher and TA levels lower in cover crop treatments, which was consistent with other reports studying cover crop effects (Tesic et al. 2007; Lopes et al. 2008 and 2011). This is may be because cover crops promote greater fruit

exposure (Hatch et al. 2011; Lopes et al. 2011) resulting in greater fruit temperatures (Spayd et al. 2002), which hastens organic acid degradation (Jackson and Lombard 1993). The competition between the cover crop and vines for nitrogen was again evidenced by must YAN levels, which were always lower in must from fruit of vines grown with under-trellis cover crop. While lower YAN levels are amendable, they can result in sluggish fermentations if not corrected by the addition of some form of nitrogen available to yeast.

The treatment that always resulted in significant effects on skin color absorbance values at every tested wavelength in both years was root manipulation (RM). Other treatments (i.e. Irr) had highly variable effects on color absorbance data and were dependent on vintage (i.e. under-trellis groundcover, UTGC). This is different than what has been reported previously regarding phenolics, which can be increased due to increased skin: pulp ratios with water deficits (Roby et al. 2004; Ojeda et al. 2002) and, depending on specific phenol, are affected differently due to water deficit timing and severity. Since root bag (RBG) vines had higher levels of estimated phenols (A280) and anthocyanins (A520) than did no root manipulation (NRM) vines, light penetration into the fruit-zone appears important for phenol accumulation (Spayd et al. 2002). Differences in estimated phenol levels will have consequences for sensory analysis as phenols, including anthocyanins, contribute to the olfactory profile and are responsible for red wine color, astringency, and bitterness (Zoecklein et al. 1995).

Potential wine quality characteristics were most common in fruit from root bag (RBG) vines: “more ideal” crop loads, berries with lower mass (and (potentially) greater surface area: volume) at harvest and greater skin color absorbance values. This suggests that phenolics may be more affected by cluster sun exposure (Price et al. 1995) than they are by water deficit either affecting concentration (Roby et al. 2004) or synthesis. This is particularly convincing since

differential irrigation (Irr) affected $\psi_{stem, md}$ more so than did root manipulation (RM) yet did not consistently alter phenolics. While differences in water status attained with differential irrigation may not have been severe enough to result in consistent differences in berry phenolics, water status appeared unimportant, as UTGC altered phenolics without great differences in vine water status. In addition to severity of water stress, the timing of water stress (fruit set through harvest) may have negated positive phenol accumulations, as it was reported that early and late water deficits can have opposite effects on the biosynthesis of phenolics (Ojeda et al. 2002) and levels of phenols and anthocyanins in wine (Matthews et al. 1990). Until methods are developed that allow investigation of continuous water status of field-grown vines, only speculations can be made based on point-in-time measurements of how this highly sensitive response ultimately relates to yield components and fruit composition.

More so than its relatedness to other responses measured in this study, vine water status was important for vine ecophysiology. Water deficit will generally lower photosynthetic rates (A) rates by way of limiting stomatal conductance (g_s), as stomata function to minimize water loss (Farquhar and Sharkey 1982) and a linear relationship exists between stomatal conductance and photosynthesis (Losivolo et al. 2010). While linear relationships were not investigated, the treatment levels that resulted in clear separation of average seasonal water status ($\psi_{stem, md}$) also consistently affected g_s and A to a greater extent.

Under-trellis groundcover (UTGC) did not consistently affect $\psi_{stem, md}$ or g_s, but cover crop tended to lower photosynthetic rates in both years. Because of the cover crop's competition with the vine for nitrogen, as evidenced by leaf tissue analysis, the decrease in A observed could be due nitrogen's limitation of photosynthesis, through reduced chlorophyll synthesis, and level and activity of carboxylating enzyme (Natr, 1975). Rootstock (Stock) did not consistently or

significantly affect $\psi_{stem, md}$, g_s, or A. Soar et al. (2006) reported that rootstock can affect scion gas exchange and water status by its ability to provide the scion with adequate water in times of high stress. While this particular facet of rootstock physiology was not studied, it did not differ between the three rootstocks studied here. While other limitations of A, such as temperature, xylem embolisms, or other non-stomatal limitations cannot be ruled out as causal, they were not evaluated in this study.

Root restriction has been reported to decrease soil water potential and A (Wang et al. 2001) and $\psi_{stem, md}$, g_s, and A (Hatch et al. 2011) and withholding irrigation reduces $\psi_{pd, leaf}$, g_s and A, and increases WUE and berry pulp ^{13}C (Chaves et al. 2007). Similar findings were found in this study. The mechanisms that both high water stress and root restriction limit gas exchange is likely similar, assuming both result from soil drying and ultimately root dehydration. When roots are dehydrated, ABA is produced (Cornish and Zeevart 1985), which increases in xylem sap and causes stomatal closure (Correia et al. 1995). However, other ion or hormonal root-to-shoot signaling that affects stomatal aperture cannot be ruled out as causal either, especially when root growth is confined.

It has been suggested that altering vine water status is a means to alter wine sensory differences (Matthews et al. 1990) by increasing anthoycanin and total phenol concentrations. From strictly a water stress perspective, evidence strongly suggests that root bag (RBG) and high water stress (HIGH) factor levels have greater potential to result in higher quality wines. However, gas exchange and photosynthetic efficiency will be modified by water status, as made evident in this study by WUE_i, $\delta^{13}C$ and A. Ultimately, this means limiting carbon assimilation, thus the potential for full fruit maturity and the production of carbon-based flavor and aroma compounds, all of which can affect fruit quality.

Cover crops have been reported to have a positive impact on wine sensory analysis (Nazrala 2008; Wheeler et al. 2005; Xi et al. 2011). Several studies have suggested that water stress will have a positive impact on wine quality (Chapman et al. 2005; Keller 1995; Koundouras et al. 2006). However, these studies did not have multiple treatments in the design. Because this study did have multiple treatments and wine lots were made from combinations of these treatments, no single treatment's importance in altering wine sensory perception could be evaluated. Rather, the collected responses were considered for their importance of imparting sensory differences of the wines.

Cluster exposure flux availability (CEFA), correlated well with berry skin absorbance (A280 and A520) such that more open canopies resulted in greater absorbance units at each wavelength, in agreement that poor fruit exposure can reduce color intensity (Smart et al. 1985) and open canopies can increase anthocyanin and phenol concentration (Carbonneau 1985). There was limited evidence that EPQA or berry skin color absorbance related to sensory differences. This was determined by the relative number of comparisons in which sensory characteristics were distinguished between wine lots made from the fruit of treatment vines differing in these responses. However, it is possible that EPQA and berry skin absorbance responses did not require significant differences to result in changes in fruit composition that were sensory-perceptible to panelists.

Mid-day stem water potential ($\psi_{md,\ stem}$) values were negatively correlated to berry skin color absorbance, in agreement with Chalmers et al. (2010) and Roby et al. (2004), who found that water deficit increased phenolic concentrations of wine and berry skin tannin and anthocyanins, respectively. Five out of the seven times when there were significant differences in at least one sensory attribute between wines were there also significant differences in $\psi_{md,\ stem}$.

This includes every time that aroma was significantly distinguished. This agrees with both Chapman et al. (2005) and Matthews et al. (1990), who reported that Cabernet Sauvignon vines of different water status resulted in sensory differences in wines, and suggest that altering vine water status can alter wine sensory characteristics, potentially through increasing anthocyanin and phenol concentrations via water deficits, respectively.

Crop load (yield: pruning weight) was positively correlated to berry skin color absorbance levels, suggesting that as crop loads go up, so do berry phenol and anthocyanin levels. While this seems counterintuitive, it is important to note that the highest average crop load was 7.4, which is in the ideal range for wine quality (Bravdo et al. 1984) and wouldn't be considered over-cropped. Further, crop load related to sensory differences; five out of the seven times when there were significant differences in at least one sensory attribute between wines there were also significant differences in crop load. This agrees with literature that crop load can impact wine quality (Bravdo et al. 1984, Kliewer and Dokoozlian 2005) and sensory analysis (Chapman et al. 2004).

Vine capacity (crop weight + cane pruning weight) was negatively correlated to berry skin color absorbance; as vine size decreased absorbance levels increased. Vine capacity was related to wine sensory differences, as five out of the seven times when there were significant differences in at least one sensory attribute between RM-Irr + UTGC wines were there also significant differences in vine capacity.

Crop load and vine capacity may have been correlated to estimated phenol levels and related to sensory differences because both were highly impacted by root manipulation (RM), which resulted in greatly different canopy architectures (EPQA) and berry weights. The confounding responses that exist (i.e. vine capacity and cluster exposure or crop load and berry

weight) cannot be further explored. However, no evidence suggests that vine capacity alone affects sensory differences. Rather, smaller capacity vines have more favorable fruit exposure that enhances fruit composition (all trends with vines grown in root bags, RBG).

Berry size, as determined by weight, was highly and negatively correlated to berry skin color absorbance. This agrees that a reduction in berry size increases skin phenolics, likely as a result of concentration (Ojeda et al. 2002; Roby et al. 2004) rather than biosynthesis. Berry size also related to differences in wine sensory analysis, as five out of the seven times when there were significant differences in at least one sensory attribute between wines were there also significant differences in berry size.

Revisiting the hypotheses set forth, wines that were produced from vines of different capacity and water status did result in significantly detectable sensory differences. There were only two occasions that wines were compared between treatment levels that significantly differed in one of these responses but not the other, neither time in which further sensory attributes were distinguished. The only three times that aroma was significantly distinguished between wines was when comparisons were made between treatment levels that significantly differed in average seasonal $\psi_{md,\ stem}$ and capacity. This suggests that both responses together resulted in changes in aroma compounds that were great enough to be perceptible to panelists.

Wines compared between treatments which had a greater magnitude of difference in water status did result in more consistent and significant detectable sensory differences, but this was not the case for vines differing in canopy microclimate. This suggests that either vine water status affects fruit composition to a greater extent or that greater differences in vine water status may need to occur relative to differences in fruit exposure in order for sensory differences to exist in resultant wines.

The third hypothesis that low capacity vines of low water stress will result in wines that have the most desirable sensory characteristics and/or greatest quality has yet to be tested. This will be done in the near future through descriptive analysis and/or consumer preference tests.

Conclusion

Results have demonstrated that vine growth, water status and physiology can be regulated with the treatments used. Root manipulation and irrigation were the two treatments that regulated growth and physiology to the greatest extent; under-trellis cover crop and rootstock were less significant. Root manipulation and differential irrigation both altered vine water status while root manipulation separated vine capacity and canopy architecture to the greatest extent. Relatively high water stress and greater fruit exposure appeared to be important for increased phenol and anthocyanin levels in berries at harvest. However, estimated levels of these compounds did not relate well to differences in wine sensory perception at the time of testing. Differences in vine water status and capacity appeared to be more important for altering wine sensory perception. Aroma was the sensory attribute most difficult to distinguish, but it was significantly when both vine water status and vine capacity were significantly different. Together, these findings suggest that vine water status and vine capacity altered fruit composition such that wine aroma was more easily distinguished and that phenolics were either unimportant for altering wine sensory perception or were secondary to other compounds that imparted sensory differences in the wines.

Performing descriptive analysis and/or consumer preference testing will provide answers to important questions that remain, such as if vine water status, fruit exposure, or phenol levels relate more to vegetal or fruity characteristics and/or consumer preference. With this information, growers can be informed of treatments that resulted in more preferable wines, thus

the opportunity to make changes in their vineyards that would prove beneficial in terms of decreasing labor costs and increasing wine value.

Future work

In the future, more continuous assessments of fruit-zone micro-climate and berry composition warrant consideration. From a climatic perspective, this means continuously logging fruit-zone temperatures and irradiance. From a fruit composition perspective, this means taking more berry samples over the course of berry development to see not only how treatments affect harvest composition, but also how treatments affect the accumulation or degradation of specific compounds of interest (i.e. acids, sugars, phenols, etc.) at certain phenological stages. This will allow insight into what types of canopy treatments are beneficial or detrimental based on phenology, and if this ultimately relates to fruit composition at harvest. Using gas chromatography to analyze variety-specific compounds that are known to be related to specific sensory characteristics (i.e. methoxypyrazines) would be ideal, but knowledge of this is still embryonic. Ultimately, vineyard cultural treatments and harvest composition must be related to either descriptive analysis, consumer preference (or both) of wines made from respective treatments. This is still the most revealing test, as no one compound makes up a wine's sensory profile, but rather the composition (i.e. primary, secondary and tertiary aroma compounds) and interaction (sugars and acids) of several compounds.

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