THE EFFECT OF COMPLETE VINEYARD FLOOR GROUND COVERS AND ROOT PRUNING ON CABERNET SAUVIGNON

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(ABSTRACT)

Complete vineyard floor cover cropping and root pruning (RP) were evaluated for their ability to regulate excessive vegetative growth and improve berry and wine composition of 'Cabernet Sauvignon' (*Vitis vinifera* L.). Treatments were: tall fescue (*Festuca arundinacea* Shreb.) 'KY-31' and 'Elite II', hard fescue (*Festuca ovina* L.) 'Aurora Gold', perennial ryegrass (*Lolium perenne* L.), orchardgrass (*Dactylis glomerata* L.), and an under-trellis herbicide strip combined with KY-31fescue interrows. Compared to herbicide strip/non-root pruned (NRP), Elite II fescue reduced vine pruning weight (kg/vine) 28%, individual cane weight (g) 20%, and canopy leaf layer number 25%. KY-31 fescue/RP lowered vine pruning weights 29% compared to an 8% reduction in pruning weights of vines grown in herbicide strip/NRP plots from 2005 to 2010. KY-31 fescue produced the greatest biomass and stand density. With the exception of a yield reduction in vines grown with KY-31 fescue in 2006, cover crops minimally decreased grape yield. Yearly climatic variation had a greater effect on berry weight and composition (pH, TSS, TA) than did treatments. Limited treatment differences detected in chemical compounds by gas chromatography–mass spectrometry (GC-MS) analysis in wines made from treatment vines in 2010 were correlated to descriptive sensory terms. Cover crop water use, as evapotranspiration, determined by mini-lysimeter (ML), ranged from 3.28 mm/d for KY-31 fescue to 1.52 mm/d for herbicide-treated plots. In 2008, root biomass of vines grown on KY-31

fescue/RP was increased at the 60 to 80 and 80 to 100 cm soil depths compared to root biomass of KY-31 fescue/NRP vines at those depths. Cover crops minimally impacted vine water potential ($\Psi_{PD,}$ $\Psi_{md,}$ Ψ_{stem}) and grapevine nitrogen levels relative to the herbicide strip, indicating that the grasses were not overly competitive with grapevines. Root pruning and complete vineyard floor cover crops favorably reduced grapevine vegetative growth, although treatment effects diminished over time, possibly in response to redistribution of grapevines' roots and climatic variation at the site.

DEDICATION

To Josephine Ignatowicz who came to America through Ellis Island and her daughter, Ann Marie Olup, my mother. To Bertha Gill Giese of Lancaster Co., Virginia, and her son Willam Gill Giese Sr., my father.

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CHAPTER I

GENERAL INTRODUCTION

Description, Cause and Impact of Excessive Grapevine Vigor

Vitis vinifera has a vigorous growth habit. Excessive vegetative growth of grapevines is an undesirable condition in grape production regions around the world. Such vines may exhibit the following characteristics: dense, shaded canopies, increased incidence of disease, elevated petiole N, delayed fruit maturity, reduced total yields (reduced bud fruitfulness and fruit set and increased bunch stem necrosis), excessive lateral growth, rapid rate of shoot growth, secondary crop borne on laterals, delayed senescence and lack of periderm formation in preparation for dormancy. Fruit from such vines is often of low 'quality': reduced fruit sugar, elevated acidity, reduced levels of phenols and anthocyanins/poor color and tannins, elevated pH, detrimental levels of N, presence of 'vegetative' and lack of varietal character (aroma and flavor) in the concomitant wine. The practical result of this excessive vegetative growth is increased canopy management costs and lower wine quality (Smart and Robinson, 1991).

Deep, fertile soils, long growing seasons ($\geq$ 180 frost free days), and abundant growing season rainfall, which are common to the mid-Atlantic US and other humid regions worldwide, often contribute to excessive vine size and vigor (Caspari et al. 1996, Due 1988, Hatch et al. 2011). Even in more arid regions, wine grape producers invest considerable effort and expense in vine canopy management measures such as shoot, leaf and cluster thinning, shoot hedging, and shoot positioning to remedy poor canopy architecture caused by vigorous shoot growth. This problem can be exacerbated in regions with annual precipitation greater than 700 to 800 mm (Jackson and Lombard 1993) and that have adequate or excessive soil nitrogen. Many grapevines

in North Carolina and Virginia vineyards are characterized as "excessively" vigorous and "out of balance".

Winkler et al. (1974) defined vine vigor as "… the quality or condition that is expressed in rapid growth of the parts of the vine. It refers essentially to the rate of growth." The degree of vigor is influenced by scion and rootstock genetics, temperature, soil moisture, nutrient availability, vine age, vine reserve status and viticultural practices (Keller 2010). Although "vine vigor" is needed to produce an economic crop over a number of years, wines from vines with relatively high shoot vigor and canopy shading have more undesirable sensory attributes and are of lower quality in most cases (Iland et al. 2011). Dry and Loveys (1998) differentiated between vine vigor and excessive vine vigor: "neither 'low' nor 'high' shoot vigor is necessarily undesirable…it is (when) excessive vigor, which competes with the fruit crop for resources (occurs), that there may be undesirable consequences." 'New World' grape plantings have the capacity to produce vines of excessive vigor (Reynolds 2004). The management or control of excessive vine vigor is required to produce "…highest yields of ripe grapes over years" (Howell 2001) i.e. "quality" fruit.

Water is a basic requirement for plant growth. Soil water content has a significant effect on vine performance (Wheeler and Pickering 2003). The water supply to the vine depends on rainfall and irrigation, but plant available water is dependent on a soil's drainage characteristics (Sequin 1986). Well drained soils have little or no water in excess of field capacity 24 hr after a rainfall and provide for a deep rooting system. Such a soil can provide water in case of drought and is able to drain water that can cause berry splitting when heavy rains occur near harvest.

Nutrient deficiency can suppress growth more so than a limitation on photosynthesis due to a degree of water deficit. Nitrogen is the nutrient most extensively taken up from the soil by

plants. N availability limits a plant's growth and yield more than any other nutritional factor (Crawford and Glass 1998). Plants absorb NO_3^- and NH_4^+ to manufacture proteins essential to their metabolism. When nutrient supply limits shoot growth, root growth can actually increase as roots become stronger sinks and improve nutrient uptake in previously unused portions of the soil compartment (Keller 2005).

Soil, via its influence on the water and nutrient supply and availability, is recognized as having varying degrees of influence on the yield and quality of grapes. Soil and its consequent effects on grapes and wine, in the traditional French system, is the predominant determinant of appellation delineation. The French word 'terroir', that includes the effects of a given region's soils, has been variously recognized as a concept to explain differences in wine. Van Leeuwen et.al (2004) systematically studied the effects of various components on 'terroir' in an established vineyard over a five year period. Of the three factors studied: soil, cultivar and climate; climate as "vintage" (rainfall and temperature in a given year) had the greatest effect on most measured parameters. The dominant factor within climate was determined to be its effect on vine water status. Rainfall amount during the growing season and the soils' water holding capacity had the largest influence on the vintage. Negative water balances in the vine from flowering to harvest resulted in the best vintages. Soil water deficits that reduced shoot growth early in development, decreased berry size, and increased grape sugar and anthocyanin concentrations are desired to increase grape quality potential. In a seventeen year study in the Loire Valley of France, organic matter, nitrogen, exchangeable K_2O, pH and soil moisture at field capacity, increased under permanent grass cover compared to an herbicide control over the total soil surface (Morlat and Jacquet 2003). Ground covers reduce bulk density and mechanical resistance of the soil and affect water availability and water relations of the grapevine, which in

turn affects vegetative growth and berry quality. Grapevines exposed to a degree of water stress during fruit development will likely produce grapes with increased wine making potential (Chapman et al. 2005, Matthews and Anderson 1989, Matthews et al. 1990, Ojeda et al. 2002). Vines cropped in an environment without water deficit, specifically, in environments with water levels that remain above that of evapotranspiration the entire growing season, have less potential to produce high quality wines (Dry and Loveys 1998, Pellegrino 2004, Seguin 1983).

Scion and rootstock genetics can affect the vine's uptake of soil water and nitrogen and their consequent effects on vine vegetative vigor (Pongracz 1983). Pool (2004) collected 15 years of data from a Concord grape study and demonstrated that rootstock had the largest effect on measured vine growth parameters relative to nitrogen addition and cover crop in the row middles. Vines grafted to selected rootstocks had a larger root system and increased the water supply to the vine compared to own-rooted vines. In an Australian study, no differences in yield due to rootstock were found between (*Vitis vinifera*) cv Shiraz vines subjected to a 30% reduction in irrigation and those irrigated to industry standards (Stevens et al. 2010). Conversely, rootstocks differentially conferred drought tolerance and recovery ability in Sultana vines subjected to a full growing season without irrigation in South Africa (Sommer et al. 2010).

Given that water and nitrogen, via the soil interface, are the main drivers of vine growth, it is therefore pertinent to this study to characterize a site's climatic and edaphic conditions. This characterization is especially interesting and valid in relation to results of similar studies conducted in different regions with varying environmental conditions. Although researchers often refer to and variously distinguish between "dry" versus "humid" and "hot" versus "cool" growing climates, the definitions or descriptors used for each are inconsistent. For instance, Tesic et al. (2007) describe a warm dry climate as receiving 304 mm of annual precipitation and

2050 growing degree days and a humid climate as one with 492 mm annual precipitation and 1318 growing degree days. Berry weight, cluster number and yield were all reduced to a greater extent in a 'warm' climate as opposed to a 'humid' one when each was exposed to the same cover crop treatment (Tesic et al. 2007). Furthermore, the descriptor; 'Mediterranean' climate is often used to describe a site's climate although it is not precisely defined. Celette et al. (2005) described a 'Mediterranean' climate as receiving ~ 650 mm of annual precipitation. Alternatively, a 'Mediterranean' climate has been described as one with an annual rainfall of 700-750 mm and a water deficit of 150-200 mm per year (Celette et al. 2009) or as 'characterized by severe droughts in summer and by strong year-to-year variation in rainfall with an annual average rainfall of 620 mm' (Ripoche et al. 2011). Other study sites with 'Mediterranean' climates include annual precipitation as low as 409 mm (Pérez-Álvarez et al. 2013). North Carolina vineyards are typically categorized as region IV > 3501-4000 degree days Fahrenheit (> 1941 degree days Celsius) (Amerine and Winkler 1944) and commonly receive rainfall > 1000 mm/year. Soils associated with these vineyards are predominately derived from kaolinite clay. Such soils are moderately well drained and possess a relatively high level of fertility (T. Hambrick, personal communication, NCRS 2007).

A warm and humid climate, deep fertile soils, inappropriate cultivar, rootstock and/or clone, inappropriately applied viticultural practices: irrigation, fertilizer application, pruning schemes, trellis systems, disease control, canopy management and abundant rainfall, can promote excessive vine vigor. Growers with excessively vigorous vineyards face high management costs and reduced income potential due to reduced berry quality. Proactive measures to achieve optimal vine size and canopy architecture, such as more extensive use of

vineyard floor cover crops and or root pruning, are desired in order to reduce the annual canopy management costs, positively impact berry composition and possibly enhance the resultant wine.

Vine Balance

Excessively vigorous vines can be defined as vines with excessive vegetative growth relative to reproductive growth or fruit. A "balanced" vine is one that has sufficient vegetation to ripen a crop to the degree of desired maturity on a "sustainable" basis. Vine balance is desirable and fundamental to the achievement of a quality, economically viable crop over a number of years. The concept of vine balance was first proposed as a quantifiable attribute by M.L. Ravaz in France over a hundred years ago (Dry et al. 2005). Ravaz described the F/V ratio (fruit to wood ratio) and suggested it was the key to fruit quality and longevity of production. Partridge (1925) was probably the first to make practical application of this ratio: he used the weight of prunings collected in year one to indicate or predict a vine's capacity to set and ripen fruit the following year. Later, N. Shaulis, working in New York, developed trellising and refined other practical methods to achieve vine balance (Dry et al. 2005).

Several authors since that early work have described vine "balance" and its impact on grape crop yield and berry composition (Jackson and Lombard 1993). Reynolds (2000) referred to vine balance as a "concept" and the vine as an "unstructured biological entity" that is prone to "overcropping". Overcropping, is the setting of excess fruit, such that maturity is delayed and/or the desired degree of ripeness is not achieved in any particular growing season (Partridge 1925). Reynolds (2000) further stated that the vine should be contained "in a box" (trellis/training system and pruning/hedging regime) in order to maintain fruitfulness and achieve efficient management. Gladstones (1992) defined "balance" as… "when vegetative vigor and fruiting load

are in equilibrium and consistent with high fruit quality". Balance, as described herein, is an elusive goal in many eastern vineyards due to the seasonal availability of rainfall and the depth and fertility of many vineyard sites. The combination of a naturally vigorous cultivar planted on a deep, fertile soil is particularly unsatisfactory with a late-ripening cultivar such as Cabernet Sauvignon. Remedial practices to obtain a more favorable vine balance are widely practiced in the mid-Atlantic and include; shoot trimming, lateral shoot and basal leaf removal, and canopy division (Wolf and Poling, 1995). These practices are, however, expensive and modestly effective. The underlying problem is that warm temperatures and high nutrient and water availability foster excessive, persistent vegetative growth. The persistence of growth directly competes with fruit maturation, delaying veraison and harvest. Vineyards should ideally be sited where the desired mesoclimatic features coincide with a "low vigor potential" soil – soil with very low total available water (Wolf and Boyer, 2003). Such vineyards would have irrigation available to avoid extreme water stress, but would otherwise be subject to mild water stress. This ideal scenario is rarely found. Climatic features of the site cannot be compromised; unfortunately, soil quality often is.

The degree of a vine's balance is commonly assessed allometrically (measurements of relative growth of a part in relation to an entire organism or to a standard) in research and practice. The parts of the grapevine's anatomy so measured typically include: shoots, canes, leaves, yield (berries, clusters). These standard or benchmark measurements that are commonly accepted in the literature and practice are indicative of "balance". The highest wine quality is most consistently obtained from fruit produced on vines that achieve most of these standards and consequently express an optimal balance of leaf area and crop. For instance, "balance" can be quantitatively expressed as crop load (5-7 kg crop per kg of pruned canes) or as leaf area to crop

ratios. For the latter, balance is a steady-state condition at veraison when vines have 1.2 to 1.5 m^2 of healthy, exposed leaf area for each kg of fruit. Smart and Robinson (1991) developed an applied method of grape canopy assessment that utilizes these and other anatomical measurements, including:

- Pruning weight of 0.4 to 0.6 kg/m of canopy
- Mean individual cane weight of 25-40 g
- Canopy characteristics (determined by point quadrat analysis)
    - 1-2 leaf layers, $\leq$ 13 shoots/meter of canopy, 12-20 leaves per shoot, proportion of canopy gaps = 20-40%, exterior fruit = 50-100%, exterior leaves = 80-100%

More recently, remote sensing to generate NDVI (normalized difference vegetation index) images via GPS and GIS systems that estimate plant biomass (vine size) and photosynthetic activity are being used to assess "vine vigor". The correlation of these images with traditional measurements to accurately assess vine growth and balance and their consequent influence on berry phenolics and color on a whole vineyard scale are being investigated, performed and utilized as a vineyard research and management tool (Bramley et al. 2011, Cortell et al. 2005, Hall et al. 2002, Howell 2001, Lamb et al. 2004). Ultimately, the definition and achievement of vine balance implies that vine vigor and size is appropriate to the vineyardist's production goals and thus, no need to trim shoots or remove lateral shoots to obtain those goals.

Root pruning

Root restriction to limit vegetative growth and improve several production parameters has been successfully applied to various fruit crops and ornamentals (Byers et al. 2004, Reiger and Whitcomb 1983). Root pruning applied to fruit trees has only been marginally successful

(Byers et al. 2004). Root manipulation applied to grapevine roots via root restriction or root pruning to limit vine growth in pot and vineyard studies has been variously reported from arid and humid climates (Dry et al. 1998, Ferree et al. 2000, Hatch et al 2011, Pickering et al. 2005, Smart et al. 2006, Wang et al. 2001). Dry et al. (1998) root pruned established, minimally pruned 'Shiraz' vines to a depth of 40-50 cm, 40 cm from the vine trunk for two consecutive seasons. Four root pruning (RP) treatments were applied: one-side or two sides/early (prior to budburst) or one side or two sides/ late (three weeks before flowering). Pruning weight and yield of two-sided RP vines was reduced 20% compared to control vines. Vines root pruned for two consecutive seasons did not produce significantly decreased berry sizes regardless of timing. Dry et al. (1998) measured water use by tracking SWC (soil water content) at various depths both inside and outside the root pruning line with capacitance probes. Although results were inconclusive, water-use of early root pruned vines appeared to be reduced. The authors did not define 'water-stress', but stated that no symptoms (effect on leaf water potential) of water-stress were observed. Early two-sided root pruning treatments resulted in a 28% reduction in vegetative growth relative to the control. This reduction of vegetative growth was a result of fewer shoots per vine and a reduction in mean shoot weight. The fruit weight to pruning weight ratio was greater for the root pruned vines and indicated an improvement in vine "balance". Bunch numbers per shoot increased relative to the control. Since flower primordia were determined before the application of RP treatments the authors state that an explanation for this effect is 'difficult'. They proposed that RP had a stimulatory effect on hormones that in turn caused tendril primordia to differentiate into inflorescence primordia. Post plant ripping of vineyards to alleviate soil compaction, that may also prune vine roots, has been used in an attempt to improve

vine growth (Brown and Goodwin, 1990). The authors recommend a 'winged' ripper that will rip to a depth of 60 cm or greater to maximize the soil loosening effect of the operation.

Smart et al. (2006) conducted a two year study in California on 5 year old vines (*Vitis vinifera*) cv. Syrah grafted on 3309C rootstock with root pruning imposed on two large framework or lateral roots emerging from the each vine trunk, post fruit set (pea-sized berries) the first year. In that study, removal of 25-35% of structural roots, caused some treatment differences; berry weight, berry diameter and leaf area was reduced in root pruned vines compared to the non-root-pruned control.

Water status measurements in both root pruning experiments mentioned above revealed reductions in leaf water potential of root pruned vines. Reduced leaf area is one way a vine can adjust to water stress, the other is stomatal conductance. These adjustments will result in a reduced amount of photosynthetic activity (Winkel and Rambal, 1993). Smart et al. (2006), found that pre-dawn, leaf and stem water status remained lower for root pruned vines compared to the non-root-pruned control vines throughout the course of the season subsequent to root pruning, but did not reach stressful levels regardless of treatment. In the same study; measurements of g_s (stomatal conductance) and A (net photosynthesis) measured in RDI vines (root-pruned, irrigated side of the vines) remained more negative over the growing season compared to both RPD (root-pruned, dry non-irrigated side of the vines) and non-root-pruned control vines. The authors evaluated hydraulic conductance (k_l) and redistribution as a factor in maintaining water status, stomatal conductance and transpiration when vines are exposed to stress. These results suggest that root pruning can have a positive effect on both vegetative growth and berry development in grape. Long-term impacts of the treatments are unknown.

Pickering et al. (2005) in New Zealand found significant differences between root pruned vines and non-root pruned control vines over a three-year period. Seven-year old (*Vitis vinifera*) cv. Cabernet Sauvignon/SO4 were root pruned to a 60 cm depth, 25 cm from each side of the vine trunk or to a 43 cm depth, 25 cm from the vine trunk. Both treatments were done in the dormant season prior to bud break. Vine vigor measured by point quadrat analysis (PQA) was reduced for root-pruned vines and increased light was observed in the canopies of root-pruned vines, although no direct measurements of light levels were taken. This is in contrast to Dry et al. (1998) who determined that root pruning did not increase light interception at the bunch zone. Veraison, beginning of fruit maturation, indicated by color change in red varieties, was advanced somewhat and bunch stem necrosis (BSN) was significantly reduced in root-pruned vines compared to the non-root-pruned control in the Pickering (2005) study. A strong correlation between leaf layer number (LLN) and BSN incidence was established in that study. Dry (1998) found no advancement of maturity due to root pruning. Furthermore, root pruning did not affect berry composition, and berry size was reduced and total crop yield (kg/vine) and bunch weight (g) was significantly lower for treatment vines and anthocyanin levels ncreased in fruit from root pruned vines (Dry et al. 1998). Ferree et al. (2000) working in Ohio, root pruned Seyval and Catawba (3 years) and Concord vines (4 years) at 40-45 cm deep, 40-50 cm from the trunk. Treatments reduced pruning weights and time required to accomplish pruning in some years. However, root pruning did not control vegetative growth or improve juice composition (soluble solids %, pH, TA) of grapes. The authors propose that root pruning may well have stimulated fine root growth in the weak growing Seyval vines that would result in increased vigor. In the case of the vigorous Catawba and Concord vines, the authors state that treatments were not close enough to the vine trunk to sever enough roots in order to significantly affect vine growth.

In a factorial comparison of treatment effects on vegetative growth of Cabernet Sauvignon in Virginia, it was determined that root restriction > under-trellis cover crop (UTCC) > rootstock effects on vine size, shoot vigor, and associated elements of canopy density (Hatch et al. 2011). The study's authors concluded that vine reactions to the treatments were primarily due to a reduction in the vines' water supply and that other factors (hydraulic resistance, hormonal signaling) influenced by rootstock as well as reduced nitrogen availability also likely played a role.

Cover crops

Cover crop competition for water and nitrogen and their consequent effects on grapevine growth, berry composition and resultant wine quality has been studied in many different regions worldwide including: including Europe, Asia, North America and Australasia (Afonso et al. 2003, Celette et al. 2005, Esteve 2003, Ingels 1998, Ingels et al. 2005, Hatch et al. 2011, Lopes et al. 2004, Olmstead et al. 2001, Nieddu et al. 2000, Pieri et al. 1999, Song et al. 2004, and Xi ZhuMei et al. 2004) and widely used by growers (Ingels et al. 1998). The application of root pruning is a straight forward mechanical process, however, implementation and competition from ground covers is more complex.

There is evidence that cover crops compete with vines and perennial orchard crops for mineral nutrients and water. Vineyards with a permanent cover crop cover have been found to use 19 to 46% more water compared to vineyard with a bare floor, (Ingels et al. 1998). Lasko (2005) working in New York, found that row middle cover crops with 0.90 m herbicide strips, used approximately half as much water as did the vines with full, single curtain canopies. Lopes et al. (2004) found that some cover crops and resident vegetation transpired more water than did

25-year old, field grown, Riesling vines. Saayman and Van Huyssteen (1983) working with ungrafted 'Columbard' vines in South Africa determined that a native grass (*Bromus wildenowii*) and deep (30 cm), interrow cultivation treatments reduced pruning weights (kg/vine) over eight seasons. Despite an increase in water infiltration rates for soils treated with deep cultivation and permanent cover crops, yields and growth of vines in those plots were reduced. No differences were detected in TSS between treatments. The soil profile in an apricot orchard planted with either orchardgrass or tall fescue as cover crops, had 33% less water in the winter-early spring period compared to bare soil plots (Stork and Jerie, 2003). Competition from orchardgrass as a complete ground cover reduced growth, yield, and pruning weights of mature peach trees (Tworkoski and Glenn 2001). Interestingly, peach leaf water potential was not affected by grass in that study.

Production viticulture and research and in arid regions indicates that cover crops can result in extreme (undesirable) reductions of vine vigor. For example, Wolpert et.al (1993) measured vine growth and yield that was reduced by 58% and 53% respectively due to Berber orchardgrass row middles in an established Cabernet Sauvignon vineyard in Santa Barbara County, CA. The growth reduction was attributed to ground cover effects on stomatal conductance and transpiration rates that were indicated by treatment vines' water potential. Wheeler and Pickering (2003) measured less soil water content, decreased leaf water potential, stomatal conductance and transpiration as well as less nitrogen uptake due to competition imposed by a vineyard cover crop.

Ultimately, the choice of a vineyard cover crop is contingent on the site and production goals desired or required (Guerra and Steenwerth 2012, Steenwerth et al. 2013). Effects of cover

crops cited in previous studies or used in production viticulture and regarded as beneficial to vine growth include:

- reduced soil erosion
- addition or uptake of nitrogen
- addition of organic matter
- improved soil structure and water penetration/water infiltration rate
- improved wheel traction, and working "platform"
- enhanced pest management, possible attraction of beneficial insects
- suppression of weeds

Effects of cover crops considered detrimental to vine growth include:

- increased water use
- competition with vines for soil moisture and nutrients
- increased frost hazard
- increased pests and incidence of disease
- increased costs and management
- additional equipment required
- decreased aesthetics

The ability to compete with vines is the criteria of precedence in the selection of cover crop to be included in this study. Several species were included to ensure a range of competitive capability. Availability and cost of seed, knowledge of each species' cultural requirements and its ability to thrive under the climatic conditions of the study were also considered. A brief description of selected species is provided below. All ground covers in this study are considered "cool-season" grasses: defined as those that begin their growth cycle and/or are planted in the

autumn or sometimes early spring and make most of their growth during the cooler months of the year, except during the coldest months of winter (Ball et al. 1991, Heath et al. 1973).

1. Orchardgrass (*Dactylis glomerata* L) has been used in both controlled studies under vineyard conditions in California and is used by commercial producers there (Ingel et al. 1998). It is ranked as aggressive as tall fescue and perennial ryegrass in competitiveness. Conversely, in an Iranian greenhouse study orchardgrass produced significantly less dry matter and was less-drought tolerant, relative to both tall fescue and perennial ryegrass (Bahrani et al. 2010).

2. Perennial ryegrass (*Lolium perenne* L.), is similar to annual ryegrass although it maybe longer lived than annual ryegrass under conditions in the current study. Annual ryegrass (*Lolium multiflorum*) has been characterized as a vigorous competitor "regardless of where it is planted in the vineyard floor" (Ingels et al. 1998). Perennial ryegrass has been shown to reduce the foliar concentrations of sulfur, calcium and boron in grapevines Tan and Crabtree (1990). Perennial ryegrass, Brome grass and creeping red fescue have been found to induce water stress in grapevines in arid regions and perennial ryegrass has been shown to alter the mineral analysis of vines (Ingel et al.1998).

3, 4. Tall fescue (*Festuca arundinacea* Shreb) cv 'Kentucky 31' (KY-31) is commonly used as a forage/pasture grass and is the standard inter-row ground cover used in the mid-Atlantic region. The cv 'Elite II' is a 'turf-type' tall fescue with a finer leaf blade relative to KY-31 and is used in turf applications. Tall fescue has been described as being widely adapted and grows best in the "transition zone" that separates the southern and northern United States. Surry County, North Carolina, the location of the current study, has been characterized as being located in that transition zone (D. Bowman, NCSU, personal communication, 2005). KY-31 is the predominant grass ground cover in North Carolina vineyards, typically used in row middles. The

seed is relatively inexpensive compared to “turf type” fescue seed. Tall fescue is described as ‘aggressive’ and is recommended for use in vigorous vineyards in Italy and California (Guerra and Steenwerth 2012)

5. Hard fescue (*Festuca ovina* L) cv ‘Aurora Gold’, commonly referred to as ‘hard fescue’ or “sheep” fescue is short-statured and more difficult to establish compared to tall fescue (Ingels et al. 1998). The cultivar ‘Aurora Gold’ has demonstrated tolerance to Round-up® application. Additional phosphorus and lime may be needed to ensure establishment. Advantages to Aurora Gold’s use include the ability to apply over-the-top applications of affordable generic glyphosate formulations for weed control following cover crop establishment. In Germany, it is described as less aggressive than tall fescue and is recommended for use in hillside vineyards and those with shallow soils (Guerra and Steenwerth 2012).

Celette et al. (2005) found that tall fescue (*Festuca arundinacea* Shreb.) interrows caused vine roots to increase under the vine row and to move deeper into the soil profile and increased water infiltration into the vineyard soil. This vine root reaction was evident in the lack of treatment differences in Ψ_{PD} and stomatal conductance (Celette et al. 2005). A permanent cover crop of tall fescue competed more strongly with grapevines than did barley (*Hordeum vulgare* L.) in the direct uptake of nitrogen and in reduction of nitrogen mineralization via soil drying. This competition reduced N reserves in grapevine storage organs (Celette et al. 2009). Therefore, the study’s authors concluded that vine growth and yield reductions were not solely a result of competition for water by the cover crops and that other factors should be considered.

Alternative or lesser-used cover crops include forage chicory (*Chicorium intybus* L. var *sativum*) that has been shown to reduce leaf petiole nitrate content in Cabernet Sauvignon. In New Zealand chicory has been shown to reduce soil water levels (Wheeler and Pickering 2003).

Krohn and Ferree (2004) used container grown Seyval vines and reported no effect on total dry weight, dry weight of shoots, petioles or roots of grapevines or any measured fruit characteristic when vines were exposed to several ornamental species used as ground covers.

It has been shown that a reduction in vine growth can be attributed to ground cover effects on vine water status associated with reductions of: soil water content, leaf water potential, stomatal conductance, nitrogen uptake and transpiration rates. Competitiveness is judged by the plant's ability to deplete water and nutrients in the soil over time. Cover crops that compete with vines for soil moisture and nutrients can be utilized to advantage in the mid-Atlantic and other humid regions to regulate vegetative growth and positively influence berry composition (Hatch et al 2011, Tesic et al. 2007) and consequently, quality of the resultant wine. The purpose of this component of the study was to determine the potential competitiveness of the various ground cover species used in the study.

Hypothesis

The central hypothesis of this work is that vine balance would be favorably affected through aggressive root manipulation and soil moisture deprivation. With previous work as a reference, albeit largely from more arid regions, it was expected that complete vineyard floor cover crops and root pruning would affect vine water relations of established field grown grapevines. Furthermore, this work investigated if treatment imposed water and nutrient deficits would restrict vegetative growth, improve the canopy microclimate, and positively affect grape berry composition and sensory attributes and chemistry of the resultant wine without compromising targeted yield levels or vine sustainability. The benefits, if successful, would include mitigation of soil erosion, increased carbon sequestration, enhanced vineyard

biodiversity including possible beneficial insects and soil microfauna, suppression of weeds and maintenance of soil structure.

Study Objectives

1. Examine the effect and interactions of 6 different under-trellis floor management schemes including complete ground covers and a conventional herbicide strip with sward interrows, each combined with or without root pruning on various vegetative and reproductive parameters of field grown *Vitis vinifera* cv. Cabernet Sauvignon / SO4 rootstock in a humid environment.
2. Investigate 5 ground cover species' ability to compete with the grapevine for water and nutrients. The agronomic suitability of the various cover crop species used as ground covers was evaluated and described. This included: biomass per unit area, stand density, persistence under traffic and over time, water use measured as evapotranspiration and degree of competitiveness with companion grapevines.
3. Analyze and describe treatment effects on berry compositional attributes: berry size, TA, Brix, pH, anthocyanins, YAN, sensory attributes of flavor and aroma and associated chemical compounds that may impact and interpret consequent wine quality.
4. Document and describe the effect of treatment combinations: 'KY-31' fescue/RP, NRP and herbicide strip/RP, NRP on the density and distribution of grapevine roots.

Literature Cited

Afonso, J., M. Monteiro, C.M. Lopes, and J. Lourenco. 2003. Cover crops in vineyards of the Vinho Verdes region. A three-year study of variety Alvarinho. Ciência e Técnia Vitivinicola. 18: 47-64.

Amerine, M. A. and A.J. Winkler. 1944. Composition and quality of musts and wines of California grapes. Hilgardia, 15: 493-675

Bahrani, M.J., H. Bahrami, and A. A. K. Haghighi. 2010. Effect of water stress on ten forage grasses native or introduced to Iran. Grassl. Sci. 56:1-5.

Ball, D.M., Hoveland, C.S., and Lacefield, G.D. 1991. Southern Forages. Potash and Phosphate Institute, Norcross, GA

Bramley, R.G.V., M.C.T. Trought and J.P. Praat. 2011. Vineyard variability in Marlborough , New Zealand: Characterizing variation in vineyard performance and options for the implementation of Precision Viticulture. Aust. J. Grape Wine Res. 17:72-78.

Brown B. and Goodwin M. 1999. Post-plant ripping of vineyards. Nov. Aust. Grapegrower and Winemaker. 34-37

Byers, R.E., D.H. Carbaugh, and L.D. Combs. 2004. Root restriction, an alternative to rootstocks for control of flowering, fruiting, tree growth, yield efficiency and fruit quality of apple trees. J. Tree Fruit Prod. 3:11-31.

Caspari, H.W., Neal, S., Naylor, A., Trought, M. and Tannock, S. 1996. Use of cover crops and deficit irrigation to reduce vegetative vigour of 'Sauvignon Blanc' grapevines in a humid climate. Proc. 4th Int. Symp. Cool climate Vitic. Enol. II 63-II 66.

Celette, F., J. Wery, E. Chantelot, J. Celette, and C. Gary. 2005. Below ground interactions in a vine (*Vitis vinifera* L.) tall fescue (*Festuca arundinacea* Shreb.) intercropping system: water relations and growth. Plant and Soil. 276:205-217.

Celette, F., A. Findeling, and C. Gary. 2009. Competition for nitrogen in an unfertilized intercropping system: The case of an association of grapevine and grass cover in a Mediterranean climate. Eur. J. Agron. 30:41-51.

Chapman, D.M., G. Roby, S.E. Ebeler, J. Guinard, and M. Matthews. 2005. Sensory attributes of Cabernet Sauvignon wines made from vines with different water status. Aust. J. Grape Wine Res. 11:339-347.

Cortell, J.M., M. Halbleib, A.V. Gallagher, T.L, Righetti, and J.A. Kennedy. 2005. Influence of Vine Vigor on Grape (Vitis vinifera L. Cv. Pinot Noir) and Wine Proanthocyanidins. J. Agric. Food Chem. 53: 5798-5808

Crawford, N.M. and A.D.M. Glass. 1998. Molecular and physiological aspects of nitrate uptake in plants. Trends Plant Science. 3: 389-395.

Dry, P.R. and B.R. Loveys. 1998. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. Aust. Jour. Grape and Wine Res. 4:140-148.

Dry, P.R., Loveys, B.R., Johnstone, A. and Sadler, L. 1998. Grapevine response to root pruning. Aust. Grapegrower and Winemaker. 414:73-78.

Dry, P.R., Iland , P.G., and R. Ristic. 2005. What is vine balance? In Proceedings of the twelfth Australian Wine Industry Technical Conference, Melbourne, 2004. R.J. Blair, P.J.Williams and I.S. Pretorius (Eds). (Australian Wine Industry Technical Conference Inc. Adelaide): 68-74.

Due, G. 1988. Excessive vine vigour in mild climates. Aust. New Zeal.Wine Ind. J. 3(1):37-41.

Esteve, J. 2003. Cover crops in vineyards. Actas IX Congreso 2003 Sociedad Española de Malherbologia, Barcelona, Apain, 4-6 de novienmbre de 003:160-166

Ferree, D.C., Scurlock, D.M., Johns, G.R. and Riesen, R. 2000. Root Pruning Has Little Effect on Seyval, Catawba or Concord Grapevines. Small Fruits Review, Vol.1(2):19-27.

Gladstones, J.S. 1992. Viticulture and the Environment, Winetitles, Adelaide, Australia.

Guerra, B., and K. Steenwerth. 2012. Influence of floor management technique on grapevine growth, disease pressure, and juice and wine composition: A review. Am. J. Enol. Vitic. 63:149-164.

Hatch, T.A., C.C. Hickey, and T.K. Wolf. 2011. Cover crop, rootstock and root restriction regulate vegetative growth of Cabernet Sauvignon in a humid environment. Am. J. Enol. Vitic. 62:298-311.

Heath, M.E., D.S. Metcalfe, R.F. Barnes. 1973. Forages, the Science of Grassland Agriculture, third edition, The Iowa State University Press, Ames Iowa.

Howell G.S. 2001. Sustainable grape productivity and the growth-yield relationship: A Review. Honorary Research Lecture ASEV Annual Meeting 1999, Reno, Nevada. Am. J. Enol. Vitic. 52:3.

Iland, P., Dry, P., Proffitt, T. and S. Tyerman. 2011. Sources and Sinks, Concepts and Practices. *In* The Grapevine From The Science To The Practice Of Growing Vines For Wine: 265-277. Patrick Iland Wine Promotions Pty Ltd., Adelaide, Australia.

Ingels, C.A., Bugg, R.L., McGourty, G.T. and L.P. Christensen. 1998. Cover Cropping in Vineyards, A Grower's Handbook. University of California, Publication 3338.

Ingels C.A., Scow K.M. and Whisson D. A. 2005. Effects of cover crops on grapevines, yield, juice quality soil microbial ecology and gopher activity. Am. J. Enol. Vitic. 56: 19-29.

Jackson, D.I. and P.B. Lombard 1993. Environmental and management practices affecting grape composition and wine quality—a review. Am. J. Enol. Vitic., 44: 409-430.

Keller, M. 2005. Deficit irrigation and vine mineral nutrition. *In* Proceedings of the Soil Environment and Vine Mineral Nutrition Symposium. P. Christensen and D.R. Smart (eds): 91-107. Am. Soc. Enol. Vitic., Davis, CA.

Keller, M. 2010. The Science of Grapevines. Academic Press, Elsevier Inc, Oxford, UK.

Krohn, N. and Ferree, D. 2004. The effects of ornamental ground covers on the growth and fruiting of containerized Seyval blanc grapevines. Proc. XXVI IHC- Viticulture-Living with Limitations., Eds. A.G.Reynolds and P.Bowen. Acta Hort. 640: 341-345.

Lamb, D.W., M.M. Weedon, and R.G.V. Bramley. 2004. Using remote sensing to predict grape phenolics and colour at harvest in a Cabernet Sauvignon vineyard: Timing observations against vine phenology and optimising image resolution. Aust. Jour. Grape and Wine Res. 10: 46-54.

Lasko, A. and T. Martinson. 2005. Vine water use and getting a “feel” for water stress. Finger Lakes Newsletter #6, August, Cornell Cooperative Extension., Finger Lakes Grape Program.

Lopes, C. A. Monteiro, F.E. Ruckert, B. Gruber, B. Steinberg, and H.R. Schultz. 2004. Transpiration of grapevines and co-habitating cover crop and weed species in a vineyard. A "snapshot" at diurnal trends. Vitis 43: 111-117.

Matthews, M.A. and M.M. Anderson. 1989. Reproductive development in grape (*Vitis vinifera* L.) responses to seasonal water deficits. Am. J. Enol. Vitic. 40:52-59.

Matthews, M.A., R. Ishii, M.M. Anderson, and M. O'Mahony. 1990. Dependence of wine sensory attributes on vine water status. J. Sci. Food Agric. 51:321-335.

Morlat, R. and Jacquet, A. 2003. Grapevine root system and soil characteristics in vineyard maintained long-term with or without interrow sward. Am. J. Enol. Vitic. 54:1-7.

Nieddu, G., O. Graviano., C. Porqueddu and P.P. Fiori. 2000. Effects of ground cover on grapevines. Informatore Agrario 56:63-78.

NRCS (Natural Resource Conservation Service). 2007. Soil Survey of Surry County, North Carolina (http://Soil Data Mart.ncrs.usda.gov).

Ojeda, H., C. Andary, E. Kraeva, A.Carbonneau and A. Deloire. 2002. Influence of pre- and postveraison water deficits on synthesis and concentration of skin phenolics compounds during berry growth of *Vitis vinifera* cv. Shiraz. Amer. J. Enol. Vitic. 53:261-267.

Olmstead, M.A., R.L. Wample, S.L. Greene, and J.M. Tarara. 2001. Evaluation of potential cover crops for inland Pacific northwest vineyards. Am. J. Enol. Vitic. 52: 292-303.

Partridge, N.L. 1925. The use of the growth-yield relationship in the field trials with grapes. Proc. Am. Soc. Hort.Sci. 23:131-134.

Pellegrino, A., E. Lebon, M. Voltz, and J. Wery. 2004. Relationships between plant and soil water status in vine (*Vitis vinifera* L.). Plant and Soil 266:129-142.

Pérez-Álvarez, E. P., J. L. Perez-Sotes, E. Garcia-Escudero, and F. Peregrina. 2013. Cover crop short-term effects on soil NO_3−N availability, nitrogen nutritional status, yield, and must quality in a calcareous vineyard of the AOC Rioja, Spain. Comm. Soil Sci. and Plt. Anal. 44: 711-721.

Pickering, A.H., I.J. Warrington, and D.J. Woodlley. 2005. Root pruning of Cabernet Sauvignon (*Vitis vinifera* L.) decreases bunch stem necrosis. Limiting factors for primary production, June 2005, Lincoln, New Zealand. (conference presentation)

Pieri, P., C.F.Riou, and C. Dubois. 1999. Competitions for nitrogen and water in two vine-grass systems-application of a water balance model. Acta Horticulturae. 493: 89-96.

Pool, R.M. 2004. Vineyard Balance- What is it? Can it be Achieved? Proc. XXVI IHC-Viticulture-Living with Limitations., Eds. A.G.Reynolds and P.Bowen. Acta Hort. 640:285-302. ISHS

Pongracz, D.P. 1983. Rootstocks for Grapevines. David Phillip, Cape Town.

Reiger, R. and C. E. Whitcomb. 1983. A root control system for growing trees in the field. SNA Research Conference: 100-102.

Reynolds, A. 2000. Impact of trellis/training systems and cultural practices on production efficiency, fruit composition and vine balance. Proc. ASEV 50th Ann. Annual meeting Seattle, Washington. June 19-23:309-317.

Reynolds, A. 2004. Canopy management adaptations to climatic constraints. 29th ASEV/ES Annual Technical Meeting & Symposium "Grapes, Wine and Environment" Roanoke, Va July 14-16, 2004.

Ripoche, A., A. Metay, F. Celette, and C. Gary. 2011. Changing the soil surface management in vineyards: immediate and delayed effects on the growth and yield of grapevine. Plant and Soil 339: 259-271.

Saayman, D. and L. Van Huyssteen. 1983. Preliminary studies on the effect of a permanent cover crop and root pruning on an irrigated Colombar vineyard. S. Afr. J. Enol. Vitic. 4:7-12.

Seguin, G. 1986., "Terroirs' and pedology of wine growing. Experientia 42:861-873.

Smart, R. and M. Robinson. 1991. Sunlight into Wine, Winetitles, Adelaide, Australia.

Smart, D., A. Breazeale, and V. Zufferey. 2006. Physiological changes in plant hydraulics induced by partial root removal of irrigated grapevine (*Vitis vinifera* cv. Syrah). Am. J. Enol. Vitic. 57: 201-209.

Sommer, K.J., F. Hancock and M.O. Downey. 2010. Resilience of Sultana (*Vitis vinifera*) to drought and subsequent recovery: field evaluation of nine rootstock scion combinations. S. Afr. J. Enol. Vitic. 31:181-185.

Song, G.C., M.S. Ryou, and M.D. Cho. 2004. Effects of cover crops on the growth of grapevine and underground environment of vineyards. Proc. XXVI IHC- Viticulture-Living with Limitations., Eds. A.G.Reynolds and P.Bowen. Acta Hort. 640:347-352.

Stevens, R.M., J.M. Pech, M.R.Gibberd, R.R. Walker and P.R. Nicholas. 2010. Reduced irrigation and rootstock effect on vegetative growth, yield and its components, and leaf physiological responses of Shiraz. Aust. J. Grape Wine Res. 16: 413-425.

Stork, P.R. and P.H. Jerie. 2003. Initial studies of the growth, nitrogen sequestering, and de-watering potential of perennial grass selections for use as nitrogen catch crops in orchards. Aust J. Agric. Res. 54:27-37.

Tan, S. and G.D. Crabtree. 1990. Competition between perennial ryegrass sod and Chardonnay wine grapes for mineral nutrition. Hortscience 25(5):533-535.

Tesic, T., M. Keller, and R.J. Hutton. 2007. Influence of vineyard floor management practices on grapevine vegetative growth, yield and fruit composition. Am. J. Enol. Vitic. 58:1-11.

Tworkoski, T.J. and D.M. Glenn. 2001. Yield, shoot and root growth, and physiological responses of mature peach trees to grass competition. HortScience 36:1214-1218.

Van Leeuwen, C., Ph. Friant, X. Chone, O. Tregoat, S. Koundouras, and D. Duboudieu. 2004. The influence of climate, soil, and cultivar on terroir. Am. J. Enol. Vitic. 55:207-217.

Wang, S., G. Okamoto, K. Hirano, J. Lu, and C. Zhang. 2001. Effects of restricted rooting volume on vine growth and berry development of Kyoho grapevines. Am. J. Enol. Vitic. 52:248-253.

Wheeler S.J. and G.J. Pickering 2003. Optimizing grape quality through soil management practices. Food Agri.Env. Vol. 1 (2):190-197.

Winkel, T. and S. Rambal. 1993. Influence of water stress on grapevines growing in the field: from leaf to whole-plant response. Aust. J. Plant Physiol., 20:143-157.

Winkler, A.J., J.A. Cook, W.M. Kliewer, and L.A. Lider. 1974. General Viticulture, University of California Press, Berkeley.

Wolf, T.K. and J. Boyer. 2003. http://www.ext.vt.edu/pubs/viticulture/463-020/463-020.html

Wolf, T.K. and E. B. Poling.1995. The mid-Atlantic Wine Grape Grower's Guide. Dept. of Communication Services. North Carolina State University, Raleigh, NC.

Wolpert, J.A., P.A. Philips, R.K. Striegler, M.V. McKenry, and J.H. Foot. 1993. Berber orchardgrass tested as cover crop in commercial vineyard. Calif. Agri. 47:23-25.

Xi ZhuMei, Li Hua, Liu YanLin, Fang YuLin. 2004. The effect of vineyard green cover on wine quality in grape cultivar Cabernet Sauvignon. Scient.Agri. Sin. 37:1527-1531.

CHAPTER II

ROOT PRUNING AND UNDER-TRELLIS COVER CROP IMPACTS ON CABERNET SAUVIGNON VEGETATIVE GROWTH, CROP YIELD COMPONENTS, AND BERRY CHEMISTRY

Abstract: Complete vineyard floor cover cropping and vine root pruning were evaluated as tools to restrict vegetative growth of vigorous *Vitis vinifera* cv. 'Cabernet Sauvignon' grapevines over a six-year period. Treatments were arranged in a split-plot, randomized, complete block experimental design with vineyard floor management (cover crop schemes) as main plots and annual vine root pruning (RP), or not (NRP), as splitting factors. Cover crop treatments compared five perennial grasses as complete floor cover crops that included: tall fescue (*Festuca arundinacea* Shreb.) 'KY-31' and 'Elite II', hard fescue (*Festuca ovina* L.) 'Aurora Gold', perennial ryegrass (*Lolium perenne* L.), orchardgrass (*Dactylis glomerata* L.), and an under-trellis herbicide strip combined with 'KY-31'fescue interrows, as a conventional floor management scheme. We found that all of the complete floor cover crop schemes reduced the rate and extent of 'Cabernet Sauvignon' shoot growth relative to the conventional herbicide strip treatment. However, the magnitude of this difference varied among the perennial grasses tested; KY-31 fescue and orchardgrass each reduced shoot growth rate > 30% in 2006 and >20% in 2007. Root pruning consistently reduced 'Cabernet Sauvignon' shoot growth rates independent of cover crop treatment. The combination of cover crop and RP decreased vine size to a greater extent than did the additive effects of either factor applied alone. Vine size was reduced 8% due to RP, 15% due to cover crop and 38% when both treatments were applied compared to the herbicide strip treatment in 2010.

Leaf petiole N at bloom was ~11% lower in RP vines in 2 of 3 years evaluated but did not differ among vines exposed to cover crop treatments, indicating that cover crops were not overly

competitive with vines for nitrogen. Vine water potential (ψ_{stem}) was not affected by treatments. Crop yield was comparable among cover cropped vines with the exception of a yield reduction with vines grown with KY-31 fescue in 2006. Berry weights were slightly reduced by treatments in some years. Juice attributes: pH, TA and SS at harvest, were minimally impacted by treatments. While complete vineyard floor cover cropping and root pruning were effective tools to reduce vine size and vigor, effects on canopy architecture and primary fruit chemistry were minimal and more influenced by climatic variation.

Introduction

Excessive vine vigor is a significant management issue for many eastern U.S. vineyards where long growing seasons and substantial rainfall contribute to vines with annual pruning weights in excess of 0.6 kg/m of canopy, more than 2 leaf layers in the fruit zone, and inadequate fruit exposure (Smart and Robinson 1991). The consequences of inferior fruit exposure include increased disease incidence and reduced wine quality potential. Large, vigorous grapevines also increase vine management costs if the grower elects to use remedial measures to improve canopy architecture.

Proactive vine management measures, such as cover cropping and root pruning, are sought to favorably restrict vegetative vine development. In particular, the intensive use of cover crops has become more common in recent years, particularly in vineyards situated on relatively steep, erodible sites (Battany and Grismer 2000). Benefits of complete floor cover crops have been observed by growers and measured in research plots (Hatch et al. 2011, Tesic et al. 2007), although questions about the long-term response of vines to specific cover crops and vineyard cover crop sustainability are still being explored (Giese et al. 2014, Steenwerth et al. 2013).

The mechanisms of cover crop competition and degree of cover crop impact on vines will likely vary with the environmental conditions. For example, in Virginia, Hatch et al. (2011) showed that cover crops reduced long-term stem water potential of Cabernet Sauvignon, leading those authors to conclude that the primary mechanism of reduced vine vigor was lower water availability. In apparent contrast, companion cover crops had little or no effect on vine water potential in other studies (Celette et al. 2005, Ingels et al. 2005, Monteiro and Lopes 2007, Sweet and Schreiner 2010), suggesting that mechanisms other than competition for water, such as competition for nitrogen and other nutrients, may also reduce vegetative growth (Celette et al. 2005, Celette et al. 2009, Saayman and Van Huyssteen 1983). Vine vigor constraint due to limited nitrogen resources can be comparable to that due to water deficits (Celette 2005, Keller 2005, Schultz and Matthews 1988). Planted cover crops and weeds can deprive grapevines of nitrogen by direct sequestration and by drying the soil, which lowers the rate of nitrogen mineralization and, consequently, vine uptake (Celette et al. 2009, Keller 2005). The threshold where negative effects of cover crops begin to outweigh benefits is dependent on grapevine and cover crop genotype, the extent of vineyard floor comprised of cover crop, the particular climate and soil characteristics of the site, and vineyard management goals (Hatch et al. 2011, Steenwerth et al. 2013, Wolpert et al. 1993).

Root pruning may reduce grapevine vegetative and reproductive growth in both field (Dry et al. 1998, Giese and Wolf 2009, Pickering et al. 2005, Smart et al. 2006) and greenhouse container (Mc Artney and Ferree 1999) studies. Root pruning performed at budburst had no effect on vine water potential but caused a 20% reduction in vegetative growth the first year in a South Australian vineyard (Dry et al. 1998), suggesting that root pruning may be a useful technique in regions with high rainfall and excessive vine vigor. Similarly, root pruning of

Cabernet Sauvignon vines reduced vine canopy size and incidence of bunch stem necrosis (BSN) in New Zealand (Pickering et al. 2005). Contrary to Dry et al. (1998), who found no evidence of a carryover effect from root pruning conducted in the previous season, Pickering et al. (2005) demonstrated a multi-year reduction in vine vigor and the incidence of BSN subsequent to a single application of root pruning. In their investigation of water relations of root pruned vines, Smart et al. (2006), found that stomatal conductance, net photosynthetic carbon assimilation, and leaf-specific hydraulic conductance, decreased following removal of 25 to 35% of framework roots relative to non-root-pruned *Vitis vinifera* cv. Syrah vines. Consequent to these physiological impacts, canopy leaf area of treated vines was substantially lowered and vine water potential reduced, though not to stressful levels. Water deficit, which can be indicated by reductions in vine water potential, has been positively connected with improved berry composition that enhances wine quality (Matthews et al. 1990). Therefore, vineyard manipulations trialed for potential impact on vegetative growth and wine potential are also assessed for effect on vine water potential

To my knowledge, the combined effect of root pruning and complete vineyard floor cover cropping has not been evaluated as a means of suppressing vegetative growth of excessively vigorous grapevines. It is hypothesized that this aggressive treatment combination would decrease the amount of water and nutrients available to vines, reduce vine vegetative growth, decrease canopy density and increase light and air penetration into the fruit zone of the canopy. This report includes the individual and combined effects of complete vineyard floor cover crops and root pruning on vegetative growth, yield components, and primary fruit chemistry of mature, field-grown Cabernet Sauvignon in a North Carolina, U.S.A. vineyard.

Materials and Methods

Vineyard description: The study used Cabernet Sauvignon vines (*Vitis vinifera* L., clone FPS 8; SO4 rootstock, *Vitis berlandieri x Vitis riparia*) in a mature, commercial vineyard (7.3 ha, 2.74 m x 1.83 m spacing) planted in 1999 within the Yadkin Valley American Viticultural Area, Surry County, North Carolina (36^{o} 21'N; 80^{o} 46' W). Vine rows were oriented approximately north/south. The vineyard was chosen because its grapevines chronically exhibited excessive vigor and vine size, necessitating repeated summer pruning of shoots and thinning of leaves and lateral shoots from the fruit zone. Hourly temperatures and daily rainfall were recorded with a meteorological station located at the vineyard. Heat summation, as growing degree days (GDD), was approximated as the mean monthly temperature, minus 10^{o}C, multiplied by the number of days in a month, and summed for the period April through October. The vineyard soil was a Fairview complex clay loam [well drained, kaolinitic, mesic, Typic Kanhapludults (NRCS 2007)] with a rooting depth that ranged from 0.75 to 1.50 m.

Experimental design: The experiment was a split-plot field study with vineyard floor management as the whole plot factor with six levels of cover crops: tall fescue (*Festuca arundinacea* Shreb) cv. KY- 31, turf-type tall fescue cv. Elite II, Round-up® tolerant hard fescue (*Festuca ovina* L.) cv Aurora Gold, perennial ryegrass (*Lolium perenne* L.) or orchardgrass (*Dactylis glomerata* L) and vine root pruning as the subplot factor with two levels; annual root pruning (RP) or none (NRP). The treatments were arranged in randomized, complete blocks replicated six times across 13 adjacent rows (6 study rows and 7 buffer rows) in the vineyard (Figure 2.1). The five complete vineyard floor cover crops were planted in the vine row directly beneath the trellis as well as in adjacent interrows; subplots were used for the two root pruning levels. Experimental units were 8-vine cover crop plots and 4-vine root pruning subplots, with a

single guard vine on each end of each subplot (Figure 2.1). There were six main plots separated by 4-vine border plots within the row, and by buffer rows between each study row of within each block.

Cover crops: To establish cover crop treatments, glyphosate herbicide was applied to all vineyard floor vegetation in August 2004. In August 2005, interrows on either side of each identified main plot were seeded exclusively with one of the corresponding cover crops using a Truax Inc. (New Hope, MN) sod seeder. Seeding rates for the cover crops were ~56 kg/ha (fescues), ~45 kg/ha (orchardgrass) and ~68 kg/ha (perennial ryegrass). These rates were approximately 2x the recommended rate for pasture establishment in order to ensure a dense, uniform stand. The under-trellis portion of each main plot, except the herbicide strip plots, was also seeded with respective cover crops and raked in by hand. Interrows were mowed several times per season and the grass clippings were left in place. The under-trellis portions of the cover crop plots were cut twice a year with hand-held line trimmers when the tallest cover crop (orchardgrass) reached the cordon wire.

Herbicide strip: At budbreak, a 90-cm wide, under-trellis strip (herbicide strip) was treated with glufosinate at 3% concentration and flumioxazin at 0.70 kg/ha in 420 l of water per ha. Glufosinate was re-applied to these plots as needed during the season to maintain the weed-free strip. Tall fescue (*Festuca arundinacea* Shreb*)* cv. KY-31 cover crop was established in adjacent interrows of these plots.

Root pruning: Root pruning (RP) was performed annually at or immediately after vine budbreak. In 2005, a ditch-trenching machine was used in 2005 to excavate 10 cm wide by 60 cm deep trenches approximately 45 cm from vine trunks, on both sides of the RP vines, parallel to the vine rows. The trenches were dug and refilled the same day. In subsequent years, root pruning

was accomplished with a sharpened steel shank mounted on a vibratory, trenching machine commonly used for underground cable installation. The root pruning shank was operated to a depth of 50 cm, 45 cm from each side of the RP vine trunks, parallel to vine rows, between modified Eichorn-Lorenz growth stages E-L 4 and E-L 12 (Coombe, 1995)

Management practices: Vines were cordon-trained and spur-pruned, with upright shoots vertically shoot-positioned with the aid of catch wires. Vines were thinned to 10 shoots per m of cordon shortly after budbreak each year. With the exception of 2006, vines were cluster-thinned each season pre-veraison, to 36 clusters per vine. Leaf removal in the fruit zone prior to E-L 31 achieved < 1 leaf layer in the fruit zone and fully expose > 40% of the fruit clusters. In most seasons, a second pass removed additional leaves in the fruit zone post-veraison. Vines were mechanically hedged whenever shoot growth reached approximately 0.60 m beyond the top catch wires. Typically, hedging was applied twice per season; initially just prior to veraison and then up to a month prior to harvest. Pest management and cultural practices were typical for the region. No nutrient additions were made to the experimental plots from 2005 to 2008. Two applications of calcium nitrate, each at a rate 17 kg/ha actual N, were applied in 2009; the first applied one week before bloom, and the second applied one week post-bloom. Calcium nitrate was applied once in 2010, one week pre-bloom, at a rate of 17 kg/ha actual N. At each application, the fertilizer was distributed by hand in a ring ~46 cm around the base of each vine.

Vegetative measurements: Shoot lengths were repeatedly measured in 2006 and 2007 to obtain growth rates. Sixteen representative (for starting length) shoots per plot (4 shoots per vine on each of 2 vines per subplot) were selected, tagged and measured in length from base to shoot tip every 7 to 10 days from pre-bloom until hedging was applied in the most vigorous plots. Although shoots continued to grow after hedging was applied, final shoot measurements were

taken just before vines were initially hedged on 29 June 2006 and 8 July 2007. Due to the consistency of those 2 years' results, despite representing extremes in seasonal rainfall totals (Table 2.1) shoot length and growth rates were not assessed in subsequent years. The two years of measure coincidentally represented the extremes in seasonal rainfall totals. Vines were dormant-pruned to 40 buds and pruning weights recorded each winter. Canopy point quadrat analyses (PQA) were conducted post-veraison and after canopy management operations each year (see *Management Practices* above) from 2006-2011 (Smart and Robinson 1991). Fifty probe insertions per subplot were made 5 cm apart, at a right angle to the canopy fruit zone (~20 cm above the cordon wire) using a level guide, parallel to the vine row.

Crop yield and berry composition: Crop yield components of all treatments were collected on the same date each year, within 1 to 7 days of the commercial harvest each year and included crop weight per vine and individual cluster weight. Harvest fruit chemistry data were obtained from 100-berry samples randomly collected from each subplot shortly before commercial harvest. All treatment subplots (n = 72) were sampled in 2010 and 2011; however, Aurora Gold and Elite II fescues were not sampled from e 2007 to 2009. Following individual berry weight determination, the berry samples were crushed by hand in a filter bag (Model 400, Steward Stomacher Lab Systems, London), and juice expressed. Juice total soluble solids (TSS) (PAL-1 Pocket Refractometer, Atago USA, Bellevue, WA) and pH (Accumet pH meter, Model 20; Fisher Scientific, Pittsburgh, PA) were measured and titratable acidity (TA, g/L tartaric acid) was determined using standard protocol (Zoecklein et al. 1999).

Tissue nitrogen: Nitrogen concentration was measured in leaf petioles collected at bloom (E-L stage 23) in 2007, 2009 and 2010. A total of 25 petioles were collected from leaves opposite an inflorescence from all treatment subplots. Petioles were dried at 50^{o} C for 72 hr and submitted to

the North Carolina Department of Agriculture and Consumer Services, Raleigh, NC for elemental analysis.

Vine water potential: In order to assess cover crop and root pruning impact on degree of water deficit in treatment vines, stem water potential (Ψ_{stem}) was measured between 1100 and 1500 h using a pressure chamber (Model 670; PMS Instrument Co, Albany, OR). At each sample date, two recently mature, fully exposed leaves showing no visible signs of damage were selected from two individual vines of each subplot. Leaves were covered with an opaque Mylar® bag for a minimum of one hour prior to severing the leaf petiole at the stem and the bagged leaf was immediately placed in the pressure chamber. The chamber was sealed and pressurized with nitrogen gas at a rate of approximately 0.03 MPa per second and pressure recorded when moisture was first evident on the cut petiole. Vine water potential was measured on three replicates of all treatment combinations on: 6 July, 7 August, 6 and 15 September, 2009 and on six replicates of KY-31 fescue and herbicide strip plots on 22 June, 2006, 2 August, 2008 and Ψ_{stem} was measured throughout the growing season in 2010; on 25 May, 2, 9, 22 and 30 July, 5 August and 4 September. Water potential readings were averaged per subplot for statistical analysis.

Soil water measurements: To explore treatment effects on soil hydrology, volumetric soil water (θ_v) was periodically measured with a capacitance probe (Model PR-2; Delta-T Devices Inc., Cambridge, UK) at depths of 10, 20, 30, 40, 60 and 100 cm at each of four access tubes installed in the KY-31 fescue RP/NRP and the herbicide strip RP/NRP subplots. Volumetric soil water (θ_v) readings from 10 and 20 cm soil depths were combined to represent the 'shallow' soil profile and those from 40 to 100 cm were combined to represent the 'deep' soil profile. The probe access sampling tubes were installed in early April 2006, as per the manufacturer's instructions.

Two access tubes were installed within each instrumented subplot; one located under-trellis, mid-way between two vines in the vine row and the other located approximately 1.40 m into the interrow, perpendicular to the under-trellis sampling tube location. Each measurement was an average of three readings per date, sample tube location and soil depth, with the capacitance probe rotated 120^{o} between readings at each soil depth.

Water retention curves generated from soil cores collected from 15, 30 and 45 cm depths in January 2009 were established to align and interpret soil water content (θ_v) data measured with the capacitance probe. Soil samples were collected to determine gravimetric soil water content measured simultaneously in order to relate the capacitance probe readings to actual soil water content (Giese et al. 2014). For example, when the volumetric soil water content was determined to be 0.35 with the PR-2 capacitance probe at the 15 cm depth, the water content at that soil depth was considered to be at field capacity.

Statistical analysis: Treatment main effects and their interactions were analyzed as a split-plot experimental design using a mixed model with repeated measures (SAS 9.2, 2002-2008, SAS Institute Inc., Cary, NC). The mixed model was performed within year or growth intervals (shoot growth rate) and treatment combinations' interaction with time (years) included as a model factor. The fixed effects in this model were cover crop treatment, root pruning, and the cover crop x root pruning interaction. Block, and block interactions with main effects were treated as random variables. When interaction was evident, the SLICE option was used to isolate each independent variable effect at a fixed level of other variables (Littell et al. 2006). Cover crop and root pruning treatments and their interactions were compared using the Tukey-Kramer adjustment for multiple comparisons.

The soil volumetric water content and time relationship was modeled non-parametrically with the local regression technique known as LOESS for the model fit of each treatment and depth combination (Ruppert et al. 2003). A 95% confidence interval (CI) was computed for the fitted model in order to assess the significance of treatments at each depth (Figure 2.4).

Results

Mean annual precipitation and air temperature representative of the Yadkin Valley, NC were 1191 mm and 13^{o}C, respectively, from 1971 to 2000 (NC State Climate Office). Rainfall at the experiment site averaged 584 mm during the growing season (1 April to 30 October) and 1000 mm per year (Table 2.1). Average rainfall per month from April to October was > 75 mm every year of the study and was > 100 mm per month, April to October in 2006, 2008 and 2010. Seasonal heat summation (2005 to 2011) averaged 2013 GDD (base of 10°C) April through October (Table 2.1). The earliest harvest date was 3 October in 2007; the latest was 18 October in 2008. The 2008 growing season was cooler than average and received 129 mm of rainfall in the 30 days prior to harvest.

Root pruning and cover crops independently (all $P < 0.01$) reduced final shoot length in 2006 and 2007. Final shoot lengths of vines grown with KY-31 fescue/RP were 37% less (127 cm) and those in orchardgrass/RP were 39% less (123 cm), relative to final shoot lengths of vines grown with herbicide strip/NRP in 2007 (201 cm). Final measured average shoot lengths of RP vines in 2006 (153 cm) and 2007 (146 cm), were significantly less than the average shoot lengths of NRP vines in those corresponding seasons. There was no significant cover crop by RP interaction on shoot length in either year.

Shoot growth rate of vines in KY-31 fescue/RP and orchardgrass/RP plots was 2.21 and 1.94 cm/day, respectively, compared to 3.22 cm/day for the herbicide strip/NRP vines over a 49-day period in 2006 (Figure 2.2). Between 17 and 25 May in 2007, shoots of KY-31 fescue/RP grew at 2.31 cm/day and orchardgrass/RP vines grew at 2.46 cm/day. These rates were the lowest shoot growth rates during that interval and were significantly less (KY-31fescue P = 0.0242, and orchardgrass P= 0.0094) than that of herbicide strip/NRP vines (3.13 cm/day). Root pruning decreased the rate of shoot growth during the final time intervals in 2006 (20-29 June) and 2007 (27 June-8 July) (Figure 2.2). No cover crop by RP interaction effect on shoot growth rate was detected in either year (Figure 2.2).

Vine pruning weights were reduced in plots with cover crops compared to the pruning weights from vines in the herbicide strip plots (Table 2.2). The degree of vine size reduction amongst cover crops was similar but the most effective cover crop varied from year to year. KY-31 had the greatest depression in 2007 and Elite II the greatest depression of pruning weights in 2008 and 2009 (Table 2.2). Root pruning also significantly reduced pruning weights of all cover cropped vines, but RP did not reduce pruning weights of vines in herbicide strip plots. From 2005 to 2010 there was an ~17% reduction in pruning weights in vines in KY-31 fescue plots and ~7% reduction in in herbicide strip/RP vines (Table 2.2). Pruning weights from the 2005 season, regardless of cover crop or root pruning, were greater than those in any subsequent year of the study (Table 2.2, Figure 2.3). A significant cover crop by year interaction was generated by the non-significant difference in pruning weights between herbicide strip and Aurora Gold fescue plots in 2006, as opposed to significant treatment differences in all other years (Table 2.2, Figure 2.3). In 2006, pruning weights of all cover crop/NRP vines, except those grown with Aurora Gold fescue, were less than those exposed to the herbicide strip/NRP (Figure 2.3).

Pruning weights of vines grown with Elite II fescue were 44% less in 2010 compared to pruning weights from those vines in 2005. There was a 29% drop in pruning weights of vines in the herbicide strip/NRP over the same period.

The significant cover crop by RP interaction (Table 2.2) was due in large measure to the minimal reduction in pruning weights by RP (~0.08 kg/m) in herbicide strip vines compared to the lower pruning weights observed with all cover crop/RP vines (~0.27 kg/m). Furthermore, the pruning weights of vines in the herbicide strip did not fall below 0.60 kg/m in any year, regardless of RP (Table 2.2).

Cover crop by year interactions on pruning weights were more difficult to discern. While all cover crops moderated pruning weights to different degrees in different years, specific cover crops varied in effectiveness from year to year. Orchardgrass, for example, was fairly depressive in 2006 and 2007, but was less depressive than other grasses in 2008 and 2009 (Figure 2.3). Similarly, Aurora Gold was not very depressive in 2006, but was comparable to other grasses in all other years.

Point quadrat analyses illustrated treatment impacts on canopy architecture, particularly in the percent canopy gaps and degree of cluster exposure (Giese et al. 2014). Vine canopy gaps in Aurora Gold fescue (13.9%), KY-31 (14.2%) and Elite II (15.8%) were greater than the percentage of canopy gaps of vines in the herbicide strip (9.5%). There were lower percentages of shaded clusters in all cover crop vines compared to the herbicide strip grown vines. The percent of canopy gaps were greater and percent shaded clusters and shaded leaves trended lower in RP vines compared to NRP vines across all treatments. Root pruning significantly ($P \leq 0.0001$) increased the percent of canopy gaps in vines grown with Elite II and it significantly decreased ($P \leq 0.0001$) the percent of shaded clusters in vines grown with perennial ryegrass.

Additionally, there were fewer shaded leaves on vines grown with perennial ryegrass, KY-31 or Elite II fescue, compared to vines in the herbicide strip plots.

Crop yields were not affected by cover crop but were often reduced by root pruning (Table 2.3). There was not a significant effect of either cover crop or root pruning on crop yield or cluster weight in 2005, the year of study initiation or in 2006 when cluster number per vine was unadjusted. The obviously higher yields in 2006 relative to all other study years were due to the unadjusted cluster numbers per vine that year. However, root pruning reduced crop yield ~16%, and individual cluster weights ~12% across all grass cover cropped vines, from 2007 to 2011. Interestingly, there was no similar reduction in crop yield or cluster weight in the herbicide stripber/RP vines over that same period. A root pruning by year interaction on crop yield was evident in the lower crop yields across all treatments in 2008 relative to other years.

Neither root pruning nor cover crop affected total soluble solids (^{o}Brix) or TA (Tables 2.4 and 2.5). As expected, however, there was a significant year effect on fruit chemistry composition. For example, ^{o}Brix levels were most elevated in 2007, compared to 2008 and 2009. This seasonal variation was also evident in TA and pH levels, which were greater in 2009 compared to TA and pH levels in 2007 and 2008, regardless of treatment. Titratable acidity was also elevated across all treatments in 2011 compared to 2010. A significant cover crop by root pruning interaction appeared to be associated with lower pH of KY-31 fescue/RP berries relative to pH of fruit from KY-31 fescue/NRP vines from 2007 to 2009 (Table 2.6). There was no difference in pH due to RP in the other cover crops or in the herbicide strip vines.

Slightly lower berry weights were associated with the KY-31 fescue from 2007-2009 compared to vines grown with orchardgrass cover crop, while perennial ryegrass elicited the lowest berry weights in 2011 (Table 2.7). A significant root pruning by year interaction was

evident from 2007-2009, as berry weights from RP vines were lower relative to NRP vines in those years. However, berry weights of Aurora Gold and Elite II fescue were not collected from 2007-2009 (see M&M) and there was no root pruning by year interaction on berry weight in 2010-2011.

Cover crop, root pruning affected YAN, NOPA, arginine and ammonium nitrogen levels measured in berries from treatment vines in 2009 (Figure 2.9) and 2010 (Figure 2.10) but treatment effect was not evident in 2011 (Figure 2.11).

Tissue N of petioles collected at bloom in years 2007, 2009, and 2010 did not differ between cover crop treatments and were near or above sufficiency levels in 2010 (Table 2.8). Root pruning did not affect total N concentrations in 2009; however, when averaged across all cover crop treatments, RP significantly depressed petiole N relative to NRP in both 2007 and 2010. There was a significant 9 to 11%, reduction in total N levels due to root pruning (Table 2.8). The significant RP x year and CC x year interactions were likely associated with the N application in 2009 and 2010, which led to elevated tissue N levels across all treatments by 2010 relative to other years. YAN (yeast assimilable nitrogen) levels differed by treatment in 2009 and 2010. In 2009, YAN levels were higher in fruit from vines grown in the herbicide strip treatments compared to that from vines grown with KY-31 fescue, regardless of RP (Table 2.9). In 2010, YAN levels of fruit harvested from vines in the herbicide strip and RP plots were greater than those of fruit from KY-31 fescue or NRP plots, respectively (Table 2.10). In 2011, YAN levels did not differ between treatments (Table 2.11).

Vine water potential (Ψ_{stem}) values were more negative ($P < 0.05$) for the herbicide strip/RP vines on 15 September 2009 (-0.35 MPa) than for the herbicide strip/NRP vines (-0.26 MPa); however, this was the only significant treatment difference measured with vine water

status. Furthermore, there was no case where vine water potential was depressed to a measured value below -0.60 MPa (data not shown).

Under-trellis soil water levels fluctuated with precipitation over the course of each growing season, particularly at the shallower soil depths (Figure 2.4). However, the interrow soil moisture data was not different between treatments (data not shown). The under-trellis soil moisture content did not substantially differ as a function of floor management at 0-20 cm soil depth with the exception of mid-July to mid-August of 2010 when KY-31 fescue plots had significantly less water content at that depth, relative to the herbicide strip. KY-31 fescue tended to have less soil moisture with wider fluctuations that caused occasional treatment separation at the 40-100 cm depth during extended dry periods from late May through early June and again post-veraison, from mid-August through early September of 2007. By August 2007, under-trellis soil water content was reduced to ~12% at the 10 to 20 cm depth (PWP = 23%) and ~27% at the 40 to 100 cm depth (PWP = 33%), respectively. A similar but less pronounced treatment separation occurred in July and late-September 2010 at the 40-100 cm depth, when under-trellis soil water content fell below PWP in KY-31fescue plots but not in the herbicide strip (Figure 2.4).

An interaction of petiole N (%) and pruning weights (kg/m) given the treatment combinations of KY-31 fescue /RP, NRP, Elite II fescue/RP, NRP and herbicide strip/RP, NRP was evident; as petiole N increased the vine pruning weights increased (Figure 2.5). The intercept of Elite II RP was significantly lower compared to those of Elite II/NRP, KY-31 fescue/NRP and both herbicide strip/RP and NRP. The intercept of KY-31 fescue/RP differed from that of KY-31 fescue/NRP, Elite II/NRP as well as that of herbicide strip/NRP. The slope of Elite II/NRP was the most negative and was significantly different compared to that of Elite

II/RP, KY-31 fescue/RP and herbicide strip/RP. The slope of KY-31 fescue/NRP was significantly lower than that of Elite II/RP (Figure 2.5, Table 2.12).

Discussion

Root pruning and under-trellis cover crops were evaluated as tools to reduce vine vigor, vine size and improve canopy characteristics. The study vines could be characterized as "large" or "out of balance", with typical individual cane weights and pruning weights 2x that of desired benchmarks for those parameters. Root pruning and cover crops, each suppressed vine vigor and vine size. Interestingly, root pruning in conjunction with cover cropping exerted synergistic effect on pruning weight and shoot vigor compared to either root pruning or cover cropping alone. There was 23% reduction in pruning weights over six years and 34% reduction in rate of shoot growth in one year compared to vines grown with herbicide strip/NRP. Treatment differences were minimal on canopy density and berry weight and there was little consequent effect on primary berry chemistries (^{o}Brix, TA, and pH). Cover cropping alone had little effect on crop yield. However, crop yield and cluster weights were substantially reduced by root pruning.

For example, in 2007, cover crops (NRP) reduced shoot length by an average of 9%, compared to herbicide strip vines (NRP), and root pruning alone reduced shoot length by an average of 21% across all cover crops compared to NRP vines. By contrast, orchardgrass/RP reduced shoot length by 39% compared to shoot lengths of vines with herbicide strip/NRP in 2007. Differences in final shoot length were likely partially due to lower vine N levels due to a restricted soil volume in RP treatments and limitations of available soil water in cover cropped vines. However, few pronounced treatment differences were evident on shoot growth rate until

both RP and cover crops were applied together. Yearly climatic variation also impacted petiole N levels, which were lowest in 2007, the driest year of the study.

Coincidently, the lowest pruning weights were collected in 2007, but following their nadir in 2007, mean pruning weights increased ~30% by 2010, regardless of floor management. This increase in pruning weights was paralleled by ~30% increase in mean petiole N % levels over the same time period. Despite the relative depression of pruning weights, they seldom fell below 0.60 kg/m, the upper threshold indicative of optimal vine size (Smart and Robinson 1991). Although a pruning weight of 1.00 kg/m is considered acceptable for Cabernet Sauvignon vines in some regions of California (Dokoozlian and Kliewer 1995), we associate pruning weights > 0.60 kg/m with vine canopies subject to increased disease incidence. The mean reduction in pruning weights due to RP was only 8% when vines were grown in the herbicide strip but it was ~27% when the RP vines were grown with a cover crop. A significant cover crop by root pruning interaction, evident in reduction of pruning weights, indicated a possible reallocation of vine resources to support increased root growth over shoot growth when root pruning and cover crop treatments were applied in tandem as discussed earlier.

With the possible exception of 2007, a drought year, cover crops did not lower crop yield relative to that of vines grown with the herbicide strip. Root pruning significantly decreased cluster weights and crop yield when vines were also exposed to most complete vineyard floor cover crops, but root pruning did not significantly diminish yields in vines grown with an herbicide strip. Somewhat contrary to our results; root pruning did not affect crop yield and berry composition of field grown Catawba, Seyval blanc and Concord vines in Ohio, although pruning weights were reduced (Ferree et al. 2000). Interestingly, root pruning applied to one side of the vines in one year actually *increased* yield of irrigated Shiraz vines in Australia 8-36% due to

increased bunch numbers (Dry et al. 1998) but yield was reduced 20% when RP was applied to both sides of the same vines in two consecutive years. Unfortunately, no description of floor management or cover crops was provided for that study (Dry et al. 1998).

Interrow cover crops were found to be inconsistent and weak competitors with grapevines under relatively cool Oregon conditions; cover crops occasionally lowered soil water content and significantly lowered leaf nutrient concentrations at one site, but did not reduce vine growth, water status or yield of grapes (Sweet and Schreiner 2010). Cover crops in place for three years and partial (interrow) or complete vineyard floor cover crops did not lower yields until the third year of implementation in an Australian, Chardonnay vineyard (Tesic et al. 2007). As expected, vineyards in relatively warmer and more arid regions often have reduced yields when cover crops were used (Tan and Crabtree 1990, Wolpert et al. 1993). Most studies cited here were limited to two or three years in duration, and the fact that floral initiation takes place the year previous to assessment of the treatment effect on yield must be considered (Ripoche et al. 2011). Our long-term study results are unique and allow interpretation of year-to-year variation in a way that previous studies haven't. A comprehensive use of complete vineyard floor cover crops for six years in a humid climate had little effect on available soil water content but did impose a degree of restriction on nutrient availability that likely contributed to a smaller vine size with a minimal impact on crop yield.

No treatment combination achieved ideal vine canopy architecture benchmarks of < 20% shaded leaves and < 50% shaded clusters (Smart and Robinson 1991). Nonetheless, there were significant treatment differences in percent canopy gaps (Giese et al. 2014). Similarly, in a California study, severing 25-35% of the roots of Syrah/101-14 vines resulted in less vine vegetative growth and increased sunlight penetration into the fruit zone (Smart et al. 2006).

Interestingly, the degree of root severance did not consistently decrease Ψ_{PD}, Ψ_{stem} or average Ψ_{leaf} to levels that Smart et al. (2006) considered stressful. In another root pruning study of Syrah, some increased sunlight penetration into the vine canopy was measured but there were no treatment differences on ^{o}Brix, pH or TA (Dry et al. 1998). Under-trellis cover crops and root restriction each improved light penetration into the vine canopy of young Cabernet Sauvignon vines in a related study (Hatch et al. 2011). The modest treatment impacts we measured on canopy architecture were due to lack of water deficit and minimal nutrient stress.

Slightly improved canopy openness in some experimental treatments did not translate into marked improvement in berry composition. For example, vines in both KY-31 and Elite II fescue had lower pruning weights and less dense vine canopies compared to vines in the herbicide strip but did not exhibit a consistent increase of TSS (total soluble solids i.e. Brix levels), or TA (titratable acidity) or a decrease in pH. However, YAN (yeast assimilable nitrogen) levels in this study varied by treatment in 2009 and 2010. There were higher levels of YAN in the herbicide strip vines compared to vines in KY-31 fescue in 2009 and in 2010, YAN levels were higher in RP compared to NRP vines and can fruit from vines in KY-31 fescue were was lower than that from vines grown with herbicide treated soil. In 2011, there were no treatment differences in YAN levels, possibly reflective of the lack of fertilizer nitrogen application in that year. Seasonal variation in this study was often more important than root pruning or cover crop treatment in terms of impacting fruit composition; the most dramatic was the increased ^{o}Brix levels in 2007 compared to other years, regardless of cover crop or RP. Similarly, there was no cover crop effect on fruit composition of Pinot noir in an Oregon vineyard cover crop study although juice N concentrations and YAN levels did vary by treatment and year, contingent on the site (Sweet and Schreiner 2010).

Stem water potential is well correlated with a plant's stomatal conductance and transpiration rate (McCutchan and Shackel 1992) and vine photosynthetic rate was consistently decreased when ψ_{stem} values fell below -0.6 MPa (Patakas et al. 2005). Photosynthetic assimilation (A), stomatal conductance (g_s) and leaf-specific hydraulic conductance (k_1) were decreased when a parallel decrease in vine water potential occurred subsequent to root severance of irrigated grapevines in California (Smart et al 2006). Although, vine shoot growth rate can be attenuated at ψ_{stem} values of -0.6 to -1.1 MPa, and a moderate water deficit has been described to occur at Ψ_{stem} between -0.9 and -1.1 MPa, these ranges vary according to root distribution, vine vigor and yield (Van Leeuwen et al. 2009). For example, Celette et al. (2005) described a "moderate" water deficit to be between -0.39 MPa (Ψ_{PD}) for vines grown with tall fescue (*Festuca arundinacea* L. cv. Centurion) and -0.36 MPa (Ψ_{PD}) in vines grown with bare soil. The authors argued, reasonably, that the cover crop improved soil water infiltration, and with contrasting phenologies of the vine and fescue growth, development of a water deficit in the vines was unlikely. It was further calculated that the fescue produced 4T of DM / ha, used as much as 50 kg / ha of nitrogen and, consequently, exposed the companion vines to a level of nitrogen stress which curtailed vine growth despite a lack of treatment effect on vine water status (Celette et al. 2005). Although we did not measure nitrogen content of experimental cover crops, the KY-31 and Elite II fescues produced as much as 3.10 and 3.75 Mg DM / ha respectively (Giese et al. 2014). In the current study, no measured ψ_{stem} readings were < -0.60 MPa on vines exposed to cover crop/RP or bare soil. Another study in the same vineyard, measured similar levels of Ψ_{stem} (-0.25 to -0.53 MPa) on several dates in vines grown with either a cover cropped interrow or bare soil, over the course of the growing season (Holland et al. 2014). Additionally, Hatch et al. (2011) working in a similar environment, did not measure Ψ_{stem} values more negative

than -0.8 MPa in vines with an under trellis cover crop, nonetheless, substantial reduction of vegetative growth was documented in that study.

Soil water content was monitored in this study in an attempt to correlate it and vine water use (data not shown) to vine water potential that might explain the vine's vegetative and reproductive response. Despite the lack of treatment differences in vine water status (Ψ_{stem}) in 2009 and 2010, θ_v content of KY-31 fescue plots generally trended lower and was more variable than that of the herbicide treated plots. This trend reflected a greater rate of evapotranspiration measured in KY-31 fescue plots compared to that of the essentially bare soil of the herbicide strips (Giese et al. 2014). However, the permanent wilting point (PWP) of soil moisture was only occasionally reached at both the 10 to 20 cm and the 40 to 100 cm soil depths, while Ψ_{stem} did not exceed -0.6 MPa. These results emphasize that a vine's water potential is affected by many interrelated factors and it is difficult to accurately predict a soil water status that will lead to altered vine growth (Pellegrino et al. 2005, Zuffrey and Smart 2012). Hatch et al. (2011), working in a climate similar to ours, concluded that less available soil moisture was the primary, but not sole factor, in vine size reduction associated with root restriction and under-trellis cover crops.

The fact that vegetative growth in our study was constrained in the absence of 'stressful' levels of Ψ_{stem} water potential, does not rule out water deficit as a cause or partial cause of growth regulation. It is well established that vegetative growth, in particular, shoot growth, is highly sensitive to water deficits and can be reduced under mild water reduction without vine Ψ_{stem} being affected (Dry and Loveys 1998, Matthews et al. 1987). The subtle differences in water supply due to treatments, coupled with the possible isohydric behavior of Cabernet Sauvignon grapevines under our study conditions could have potentially masked or limited the

observed range of ψ_{stem} responses (During 1987, Hochberg et al. 2013).

In considering the role of cover crops on vine nutrient status, Tesic et al. (2007), citing Muller et al. 1984, reported "…sward-vine competition for nutrients was more important in soils with ample water availability, while under drier conditions the soil moisture effect became predominant". Keller (2005) suggested that limited N resources could reduce vine vigor to a degree comparable to the effects of water deficits. Permanent grass cover deprives the grapevine of N, either by directly absorbing N, or indirectly by drying the soil and thus reducing the rate of N mineralization (Celette et al. 2009, Keller 2005). As the N mineralization zone near the surface is less populated by vine roots (Celette et al. 2009), less N is taken up, and consequently, shoot growth is limited as more resources are allocated to new root production in a deeper soil compartment. Additionally, Grechi et al. (2007) found that vines deprived of N exhibited enhanced root development at the expense of above ground growth. The decrease of total petiole N of 13 to 17% that we observed in cover crop plots compared to herbicide strip plots is similar to what others have reported (Celette et al. 2009, Ferree et al. 2000, Sweet and Schreiner 2010). Pruning weights generally and positively reflected tissue N concentration in our study.

Despite a lack of treatment effect on vine water status or tissue nutrient concentration, others have also found a reduction in vegetative growth when vines were subjected to mechanical root pruning or a restricted soil volume, (Dry et al. 1998, McClymont et al. 2006). The ability of cover crops to compete with grapevines for water and nitrogen and consequently reduce vine vigor and size is well documented in arid or Mediterranean environments (Celette et al. 2009, Monteiro and Lopes 2007, Morlat and Jacquet 2003, Tan and Crabtree 1990, Tesic et al. 2007, Van Huyssteen et al.1984, Wolpert et al. 1993). Our study generally agrees with and extends findings of those studies, but suggests that responses to cover crops may not be as

dramatic in a warm, humid environment. Seasonal rainfall was adequate for continued vine growth despite occasional reductions in near-surface soil water availability due to root pruning and/or cover crops. More defined treatment effects might have been realized had seasonal rainfall been lower, root pruning more severe, or vine rooting depth more restricted.

We did not explore possible allelopathic effects of cover crops that may have played a role in vine response. Tall fescue (*Festuca arundinacea* Shreb.) cv KY- 31, was allelopathic and exceptionally competitive relative to other ground covers in pecan and black walnut plantings and was more detrimental to pecan tree growth compared to bermudagrass, (*Cynodon dactylon* (L.) Pers.) (Smith et al. 2001).

Given the minimal improvement of canopy characteristics and the reduced crop yield, the slackened vine vegetative vigor due to root pruning is not sufficient to justify its added expense. Annual root pruning, as accomplished in this study, was estimated to increase annual per hectare operational costs ~15%. This estimate is based on a per hectare operational cost of ~$7,410.00, to include: chemical application, mowing, leaf pulling, hedging, moving wires, cluster thinning, harvest, dormant pruning, trellis maintenance and materials and exclusive of interest, taxes, depreciation, management and opportunity costs. Despite some positive effects, root pruning cannot be recommended as a commercial means of regulating vine vegetative growth under the conditions of this experiment. By contrast, under-trellis cover crops reduced vine growth as much or more than root pruning did, and at lower cost. Beyond the desired effects on vine vegetative development, properly managed under-trellis cover crops mitigate soil erosion potential without a substantial reduction in crop yield.

Root pruning, as applied in this study, likely limited the volume of soil available for root exploration and this led to some reduction in vegetative growth. More pronounced depressive

effects on stem water potential and growth were measured relative to those effects observed in the current study, when grapevine roots were restricted to a much smaller soil volume (0.015 m^3) (Hatch et al. 2011). Therefore, it was expected that growth of grapevine roots would acclimate to the presence of cover crops in the current study by occupation of deeper soil horizons in order to forage for water and nutrients. However, these deeper soil horizons can be much less conducive to root foraging and growth; although the soil at depth contains adequate moisture, it typically has fewer nutrients, a much lower pH and higher bulk density relative to soil near the surface.

Indeed, the expected deeper root growth in reaction to cover cropping and root pruning was not confirmed by root intercept observations and vine root biomass data collected from soil pit excavations to ~1.2 m. These pit excavations were accomplished adjacent to six RP vines and six NRP vines, in both KY-31 fescue and herbicide strip plots on two different occasions (May 2008 and October 2010, chapter five of this document). Inspection of these pits revealed very few grapevine roots below 60 cm in either treatment and substantial root regrowth was observed at the point of root pruning severance at < 60 cm. With such an increase in root growth, roots can become stronger sinks for nitrogenous reserves and carbohydrates, and consequently, shoot growth will be reduced (Keller 2005). Consequently, the rooting pattern of treatment vines in our study likely differed somewhat from reports of grapevine roots inhabiting deeper soil horizons as a reaction to cover crop root competition (Ingels et al. 2005, Morlat and Jacquet 2003, Tesic et al. 2007). The observed pattern of root growth likely translated into the minimal observed differences in soil volumetric water content and vine water potential.

Conclusion

Root pruning and cover crops, in combination, limited vine vigor and size of excessively vigorous, field grown Cabernet Sauvignon vines. RP reduced crop yields, but cover crops did not. Although orchardgrass and KY-31 fescue specifically diminished vine shoot growth rate and shoot length more than did other cover crops, overall, vines grown with Elite II fescue had the greatest and most consistent reduction in pruning weights and in canopy density, compared to other cover crop/RP combinations. However, the practical effects on canopy architecture and berry composition were modest under the high vigor conditions of the experimental site. The interactive effect of root pruning and cover crops on vine growth suppression was likely due to the limited soil volume that results when both cover crops and root pruning are applied, likely intensifying the competition for water and nitrogen. Based on its modest effect and considerable expense to apply, root pruning is not justified with the deep soils present at this study site. Complete cover cropping, especially with Elite II fescue, is an effective and potentially cost-saving management tool to reduce grapevine vigor in high moisture viticulture regions.

Table 2.1 Harvest dates, heat summation, seasonal precipitation, days exceeding 22°C and precipitation for the last 30 days before harvest in seven growing seasons at experimental vineyard site, Dobson, North Carolina.

		Heat summation (10°C base)		Days in last 30 that temp exceeded 22°C	Precipitation (mm)		
Year	Harvest date	Apr-Oct inclusive	Last 30 days before harvest		Jan-Dec inclusive	Apr-Oct inclusive	Last 30 days before harvest
2005	Oct 11,12	2065	307	24	1173	528	116
2006	Oct 8	1899	209	19	1099	717	87
2007	Oct 3	2111	312	28	773	491	100
2008	Oct 18	1910	192	18	881	605	129
2009	Oct 9	2008	222	17	1004	551	69
2010	Oct 6	2045	274	21	1043	600	89
2011	Oct 10	2094	228	23	1030	597	78
Average 2005-2011		2019	249	21	1000	584	95

Table 2.2 Pruning weights as affected by treatment combination, 2005 to 2010.

Cover crop Root Pruning[a]	Pruning wt (kg/m) 2005[b]	2006[b]	2007[b]	2008[b]	2009[b]	2010[b]	Mean[b]	Δ due to RP[c]
KY-31 fescue								
RP	0.84	0.56	0.33	0.48	0.55	0.58	0.55*	
NRP	1.10	0.73	0.55	0.74	0.83	0.75	0.78*	
Mean	0.97 b	0.64 b	0.44 c	0.61bc	0.69 bc	0.67 b	0.67 b	-0.29
Aurora Gold fescue								
RP	0.90	0.78*	0.39	0.49	0.52*	0.55	0.61*	
NRP	1.09	1.07*	0.60	0.77	0.81*	0.79	0.86*	
Mean	0.99 b	0.93 a	0.50 bc	0.63 bc	0.67 bc	0.67 b	0.74 b	-0.29
Perennial ryegrass								
RP	0.95	0.55	0.39	0.55	0.57*	0.67	0.61*	
NRP	1.12	0.82	0.63	0.80	0.92*	0.68	0.83*	
Mean	1.03 b	0.69 b	0.51 b	0.67 b	0.75 b	0.68 b	0.73 b	-0.27
Orchardgrass								
RP	0.90	0.51	0.35	0.61	0.61	0.56	0.59*	
NRP	1.05	0.75	0.55	0.78	0.73	0.73	0.77*	
Mean	0.97 b	0.63 b	0.45 bc	0.69 b	0.67 bc	0.64 b	0.67 b	-0.23
Elite II fescue								
RP	0.92	0.56*	0.33	0.43	0.50	0.58	0.55*	
NRP	1.11	0.86*	0.59	0.65	0.73	0.57	0.75*	
Mean	1.01 b	0.71 b	0.46 bc	0.54 c	0.61 c	0.57 b	0.65 b	-0.27
Herbicide strip								
RP	1.10	0.96	0.60	0.77	0.91	0.84	0.86	
NRP	1.18	1.05	0.63	0.83	1.11	0.79	0.93	
Mean	1.14 a	1.00 a	0.61 a	0.80 a	1.01 a	0.81 a	0.90 a	-0.08

Significance[d]	
CC	<0.0001
RP	<0.0001
YEAR	<0.0001
CC x RP	<0.0001
CC x YEAR	<0.0001
RP x YEAR	0.0002
CC x RP x YEAR	ns

[a] RP: root-pruning; NRP: non-root-pruning; CC: cover crop

[b] Means within a column followed by the same letter are not different at ($P \leq 0.05$) level of significance.

[c] Change in pruning weight (kg/m of canopy) due to root pruning

[d] Significance of treatment effects and interactions ($p > F$; ns = not significant).

***** Means within a within column and individual cover crop or within an individual cover crop across years are different due to root pruning at ($P \leq 0.05$) level of significance when followed by an asterisk.

Table 2.3 Yield components as affected by cover crop and root-pruning treatment combinations, 2005 to 2011.

Cover crop Root Pruning[a]	Vine yield (kg/vine)								Cluster wt (g)							
	2005	2006	2007	2008	2009	2010	2011	Mean[b]	2005	2006	2007	2008	2009	2010	2011	Mean[b]
KY-31 fescue																
RP	4.51	7.11	3.22	3.49	3.63	3.40	4.11	4.21 b	143	190	155	126	133	111	156	145 b
NRP	4.24	7.51	4.01	4.05	5.05	4.36	5.02	4.89 a	137	199	190	139	170	122	175	162 a
Mean	4.38	7.31	3.61	3.77	4.34	3.88	4.57		140	195	173	133	152	116	166	
Aurora Gold fescue																
RP	5.11	8.82	4.30	4.15	4.35	4.05	4.57	5.05	164	216	197	149	154	120	167	167
NRP	4.66	8.07	4.50	4.74	5.28	5.05	5.13	5.34	146	214	219	163	181	130	183	176
Mean	4.89	8.44	4.40	4.45	4.82	4.55	4.84		155	215	208	156	168	125	175	
Perennial ryegrass																
RP	4.87	7.61	3.33	3.61	4.20	4.17	5.22	4.73 b	150	196	160	126	159	123	176	156 b
NRP	4.83	7.98	4.36	4.81	5.38	4.76	5.12	5.32 a	143	200	199	157	179	142	174	171 a
Mean	4.85	7.79	3.84	4.21	4.83	4.47	5.17		146	198	179	141	169	133	175	
Orchardgrass																
RP	4.50	7.25	3.32	3.58	3.62	3.73	4.74	4.40 b	154	195	161	130	143	113	158	151 b
NRP	4.79	7.82	4.08	4.57	4.99	4.36	5.27	5.13 a	147	215	195	153	173	126	179	170 a
Mean	4.64	7.54	3.70	4.08	4.31	4.05	5.07		150	204	178	141	158	120	169	
Elite II fescue																
RP	4.91	7.62	3.86	4.00	3.67	3.59	5.10	4.68	152	210	190	135	141	122	173	160 b
NRP	4.68	7.94	4.43	5.12	4.76	4.20	4.22	5.06	157	216	218	154	172	130	169	174 a
Mean	4.80	7.78	4.15	4.56	4.21	3.90	4.68		155	213	204	145	156	125	125	
Herbicide strip																
RP	4.99	8.73	4.45	3.56	4.45	4.82	4.71	5.10	161	213	206	125	149	139	172	167
NRP	4.39	7.91	4.17	4.16	4.45	4.30	4.82	4.89	148	203	200	137	147	129	167	162
Mean	4.69	8.32	4.31	3.87	4.45	4.56	4.76		155	208	203	131	148	134	169	

Significance[c]		
CC	ns	ns
RP	0.0139	<0.0001
YEAR	<0.0001	<0.0001
CC x RP	<0.0001	<0.0001
CC x YEAR	ns	<0.0001
RP x YEAR	<0.0001	<0.0001
CC x RP x YEAR	ns	ns

[a] RP: root-pruning; NRP: non-root-pruning; CC: cover crop

[b] Means across years within a cover crop followed with different letters are different due to root pruning at ($P \leq 0.05$) level of significance

[c] Significance of treatment effects and interactions ($p > F$; ns = not significant).

Table 2.4 Berry total soluble solids at harvest as affected by complete vineyard floor cover crops, herbicide strip and root pruning, 2007 to 2009, 2010 and 2011[a].

Cover crop Root Pruning[b]	TSS (°Brix)						
	2007	2008	2009	Mean	2010	2011	Mean
KY-31 fescue							
RP	23.2	20.5	21.3	21.7	20.3	19.3	19.8
NRP	23.6	20.3	21.0	21.6	20.0	19.5	19.8
Mean[c]	23.4 a	20.4 c	21.1 b		20.2	19.4	
Aurora Gold fescue							
RP	--	--	--	--	20.3	19.8	20.0
NRP	--	--	--	--	19.9	19.6	19.7
Mean[c]	--	--	--		20.1	19.7	
Perennial ryegrass							
RP	23.0	20.2	20.8	21.3	19.9	19.5	19.7
NRP	23.4	20.6	21.0	21.6	19.8	19.2	19.5
Mean[c]	23.2 a	20.4 bc	20.9 b		19.9	19.4	
Orchardgrass							
RP	23.4	20.2	21.2	21.6	19.9	19.8	19.8
NRP	23.8	20.3	20.6	21.6	20.0	19.5	19.8
Mean[c]	23.6 a	20.2 bc	20.9 b		20.0	19.6	
Elite II fescue							
RP	--	--	--	--	20.3	19.9	20.1
NRP	--	--	--	--	19.8	19.5	19.7
Mean[c]	--	--	--		20.1	19.7	
Herbicide strip							
RP	22.9	20.3	20.7	21.3	19.5	19.9	19.7
NRP	23.4	20.7	20.7	21.6	19.9	19.9	19.9
Mean[c]	23.1 a	20.5 bc	20.7 b		19.7	19.9	

Significance[d]	2007-2009	2010-2011
CC	ns	ns
RP	ns	ns
YEAR	<0.0001	0.0001
CC x RP	ns	ns
CC x YEAR	ns	ns
RP x YEAR	ns	ns
CC x RP x YEAR	ns	ns

[a] Data for Aurora Gold fescue, Elite II fescue collected in 2010 and 2011 only.
[b] RP: root-pruning; NRP: non-root-pruning; CC: cover crop
[c] Means across and within years followed by the same letter are not different at ($P \leq 0.05$) level of significance.
[d] Significance of treatment effects and interactions ($p > F$; ns = not significant).

Table 2.5 Berry titratable acidity (TA) at harvest as affected by complete vineyard floor cover crops, herbicide strip and root pruning, 2007 to 2009, 2010 and 2011[a].

Cover crop Root Pruning[b]	TA (g/L)						
	2007	2008	2009	Mean	2010	2011	Mean
KY-31 fescue							
RP	4.80	4.13	4.93	4.62	3.65	5.58	4.62
NRP	4.24	4.00	4.90	4.38	3.78	5.45	4.62
Mean[c]	4.52 b	4.07 b	4.92 a		3.71 b	5.51 a	
Aurora Gold fescue							
RP	--	--	--	--	3.53	5.03	4.28
NRP	--	--	--	--	3.68	4.88	4.28
Mean[c]	--	--	--		3.60 b	4.95 a	
Perennial ryegrass							
RP	4.88	4.23	4.95	4.69	3.58	5.00	4.29
NRP	4.97	4.40	4.83	4.73	3.80	5.42	4.61
Mean[c]	4.93 b	4.32 b	4.89 ab		3.69 b	5.21 a	
Orchardgrass							
RP	4.20	3.85	4.95	4.33	3.73	4.96	4.35
NRP	4.23	4.28	5.13	4.54	4.35	4.75	4.55
Mean[c]	4.22 b	4.07 b	5.04 a		4.04 b	4.85 a	
Elite II fescue							
RP	--	--	--	--	3.65	5.03	4.34
NRP	--	--	--	--	3.70	5.45	4.58
Mean[c]	--	--	--		3.68 b	5.24 a	
Herbicide strip							
RP	4.43	4.28	5.18	4.63	3.78	4.98	4.38
NRP	4.27	4.32	5.23	4.60	3.75	4.80	4.28
Mean[c]	4.35 b	4.30 b	5.21 a		3.76 b	4.89 a	

Significance[d]	2007-2009	2010-2011
CC	ns	ns
RP	ns	ns
YEAR	<0.0001	<0.0001
CC x RP	ns	ns
CC x YEAR	ns	ns
RP x YEAR	ns	ns
CC x RP x YEAR	ns	ns

[a] Data for Aurora Gold fescue, Elite II fescue collected in 2010 and 2011 only.
[b] RP: root-pruning; NRP: non-root-pruning; CC: cover crop
[c] Means across and within years followed by the same letter are not different at ($P \leq 0.05$) level of significance.
[d] Significance of treatment effects and interactions ($p > F$; ns = not significant).

Table 2.6 Berry pH at harvest as affected by complete vineyard floor cover crops, herbicide strip and root pruning, 2007 to 2009, 2010 and 2011[a].

Cover crop Root Pruning[b]	pH						
	2007	2008	2009	Mean	2010	2011	Mean
KY-31 fescue							
RP	3.42	3.45	3.28	3.38*	3.52	3.45	3.49
NRP	3.62	3.58	3.43	3.54*	3.64	3.58	3.61
Mean[c]	3.52 a	3.52 a	3.35 b		3.58 ab	3.51 abc	
Aurora Gold fescue							
RP	--	--	--	--	3.59	3.45	3.52
NRP	--	--	--	--	3.61	3.55	3.58
Mean[c]	--	--	--		3.60 ab	3.50 abc	
Perennial ryegrass							
RP	3.48	3.49	3.33	3.44	3.65	3.51	3.58
NRP	3.54	3.50	3.40	3.48	3.64	3.48	3.56
Mean[c]	3.52 a	3.49 a	3.37 b		3.64 a	3.49 bc	
Orchardgrass							
RP	3.57	3.54	3.37	3.49	3.59	3.50	3.54
NRP	3.56	3.55	3.37	3.49	3.58	3.53	3.55
Mean[c]	3.56 a	3.55 a	3.37 b		3.59 ab	3.51 abc	
Elite II fescue							
RP	--	--	--	--	3.60	3.46	3.53
NRP	--	--	--	--	3.60	3.49	3.55
Mean[c]	--	--	--		3.60 ab	3.48 bc	
Herbicide strip							
RP	3.50	3.45	3.27	3.41	3.59	3.46	3.53
NRP	3.58	3.51	3.50	3.48	3.56	3.44	3.50
Mean[c]	3.54 a	3.48 a	3.30 b		3.58 ab	3.45 c	

Significance[d]	2007-2009	2010-2011
CC	ns	ns
RP	<0.0001	ns
YEAR	<0.0001	<0.0001
CC x RP	0.0067	ns
CC x YEAR	ns	ns
RP x YEAR	ns	ns
CC x RP x YEAR	ns	ns

[a] Data for Aurora Gold fescue, Elite II fescue collected in 2010 and 2011 only.
[b] RP: root-pruning; NRP: non-root-pruning; CC: cover crop
[c] Means across and within years followed by the same letter are not different at ($P \leq 0.05$) level of significance.
[d] Significance of treatment effects and interactions ($p > F$; ns = not significant).
* Means within column and individual cover crop are different due to root pruning at ($P \leq 0.05$) level of significance when followed by an asterisk

Table 2.7 Berry weights as affected by treatment combination, 2007 to 2009, 2010 and 2011[a] .

	Berry wt (g)						
Cover Crop Root Pruning[b]	**2007**	**2008**	**2009**	**Mean[c]**	**2010**	**2011**	**Mean**
KY-31 fescue							
RP	1.34	1.16	1.45	1.31	1.59	1.57	1.58
NRP	1.38	1.45	1.45	1.43	1.71	1.50	1.60
Mean	1.36	1.31	1.45	1.37 b	1.65 a	1.54 a	
Aurora Gold fescue							
RP	--	--	--	--	1.60	1.58	1.59
NRP	--	--	--	--	1.66	1.61	1.61
Mean	--	--	--	--	1.63 a	1.57 a	
Perennial ryegrass							
RP	1.41	1.25	1.56	1.41	1.61	1.46	1.53
NRP	1.38	1.39	1.44	1.40	1.63	1.53	1.58
Mean	1.39	1.32	1.50	1.40 ab	1.62 a	1.49 b	
Orchardgrass							
RP	1.40	1.40	1.56	1.45	1.55	1.58	1.56
NRP	1.51	1.41	1.49	1.47	1.64	1.53	1.59
Mean	1.46	1.40	1.53	1.46 a	1.59 a	1.56 a	
Elite II fescue							
RP	--	--	--	--	1.60	1.53	1.57
NRP	--	--	--	--	1.58	1.57	1.58
Mean	--	--	--	--	1.59 a	1.55 a	
Herbicide strip							
RP	1.36	1.43	1.53	1.44	1.65	1.57	1.61
NRP	1.46	1.39	1.45	1.43	1.65	1.56	1.60
Mean	1.41	1.41	1.49	1.44 ab	1.65 a	1.56 a	

Significance[d]	**2007-2009**	**2010-2011**
CC	0.0515	ns
RP	ns	ns
YEAR	<0.0001	<0.0001
CC x RP	ns	ns
CC x YEAR	ns	ns
RP x YEAR	<0.0151	ns
CC x RP x YEAR	ns	ns

a Data for Aurora Gold fescue, Elite II fescue collected in 2010 and 2011 only.

b RP: root-pruning; NRP: non-root-pruning; CC: cover crop

c Means across and within years followed by the same letter are not different at ($P \leq 0.05$) level of significance.

d Significance of treatment effects and interactions ($p > F$; ns = not significant).

Table 2.8 Mean total leaf petiole nitrogen concentration (%) at bloom, in vines exposed to cover crops and root pruning in 2007, 2009 and 2010 (n=6).

Cover crop Root pruning[a]	2007	2009	2010
KY-31 fescue			
RP	0.83	0.94	1.10
NRP	0.95	0.99	1.29
Mean	0.89	0.96	1.19
Aurora Gold fescue			
RP	0.80	0.86	1.08
NRP	0.84	0.87	1.19
Mean	0.82	0.86	1.13
Perennial ryegrass			
RP	0.80	0.85	1.15
NRP	0.95	0.96	1.35
Mean	0.88	0.91	1.25
Orchardgrass			
RP	0.80	0.95	1.14
NRP	0.91	0.86	1.31
Mean	0.85	0.90	1.22
Elite II fescue			
RP	0.78	0.84	1.16
NRP	0.85	0.89	1.37
Mean	0.82	0.86	1.26
Herbicide strip			
RP	0.78	1.07	1.30
NRP	0.80	1.02	1.31
Mean	0.79	1.05	1.30

Year and RP			
Year[b]	0.84 c	0.92 b	1.23 a
RP	0.80 *	0.92	1.15 *
NRP	0.88 *	0.93	1.30 *

Significance[c]	
CC	ns
RP	<0.0001
YEAR	<0.0001
CC x RP	ns
CC x YEAR	0.0041
RP x YEAR	0.0025
CC x RP x YEAR	ns

[a] RP: root-pruning; NRP: non-root-pruning; CC: cover crop

[b] Yearly means followed by the same letter are not different at ($P \leq 0.05$) level of significance.

[c] Significance of treatment effects and interactions ($p > F$; ns = not significant)

* Mean values between RP and NRP treatment within years are different at ($P \leq 0.05$) level of significance when followed by an asterisk.

Table 2.9 YAN, NOPA, Arginine, Ammonium content of berries at harvest, 2009.

Cover crop Root pruning[a]	YAN (mg N/L)	NOPA (mg N/L)	Arginine (mg/L)	Ammonium (mg/L)
KY-31 fescue				
RP	149	89.67	158.17	41.17
NRP	176	106.00	215.83	43.17
Mean	163 b	97.83 b	187.00 b	42.18
Perennial ryegrass				
RP	171	104.33	188.67	44.00
NRP	204	120.00	262.00	51.50
Mean	188 ab	112.17 a	225.33 b	47.75
Orchardgrass				
RP	165	99.17	196.00	41.50
NRP	195	110.33	243.83	54.83
Mean	180 ab	104.75 ab	292.92 b	48.17
Herbicide strip				
RP	204	110.33	283.67	58.67
NRP	216	120.33	310.33	55.83
Mean	210 a	115.33 a	297.00 a	57.25
Mean				
RP	172	100.88	206.63	46.33
NRP	198	114.17	258.00	51.33
Significance[b]				
CC	0.0444	0.0061	0.0464	ns
RP	0.0316	0.0461	0.0258	ns
CC x RP	ns	ns	ns	ns

[a] RP: root-pruning; NRP: non-root-pruning; CC: cover crop
[b] Significance of treatment effects and interactions ($p > F$), ns = not significant.

Table 2.10 YAN, NOPA, Arginine, Ammonium content of berries at harvest, 2010.

Cover crop Root pruning[a]	YAN (mg N/L)	NOPA (mg N/L)	Arginine (mg/L)	Ammonium (mg/L)
KY-31 fescue				
RP	94	80.17	45.00 b	4.50 b
NRP	149	131.17	50.17 b	5.00 b
Mean	121 b	105.67 b	47.58	4.75
Herbicide strip				
RP	180	147.33	100.50 b	9.00 b
NRP	346	285.50	193.33 a	16.00 a
Mean	263 a	216.42 a	146.92	12.50
Mean				
RP	137 b	113.75 b	72.75	6.75
NRP	247 a	208.33 a	121.75	10.50
Significance[b]				
CC	0.0028	0.0122	0.0028	0.0005
RP	0.0034	0.0079	<0.0001	0.0004
CC x RP	ns	ns	<0.0001	0.0012

[a] RP: root-pruning; NRP: non-root-pruning; CC: cover crop
[b] Significance of treatment effects and interactions ($p > F$), ns = not significant.

Table 2.11 YAN, NOPA, Arginine, Ammonium content of berries at harvest, 2011.

Cover crop Root pruning[a]	YAN (mg N/L)	NOPA (mg N/L)	Arginine (mg/L)	Ammonium (mg/L)
KY-31 fescue				
RP	184	110.33	197.83	50.83
NRP	189	123.67	240.67	32.50
Mean	187	117.00	219.25	41.67
Aurora Gold fescue				
RP	182	119.33	218.67	33.83
NRP	195	124.17	260.17	35.50
Mean	189	121.75	239.42	34.67
Perennial ryegrass				
RP	203	128.17	249.83	42.33
NRP	193	121.67	245.00	40.33
Mean	199	124.92	247.42	41.33
Orchardgrass				
RP	182	122.83	221.67	28.67
NRP	208	126.50	264.67	47.33
Mean	195	124.67	243.17	38.00
Elite II fescue				
RP	164	110.33	164.67	26.50
NRP	171	115.33	185.17	37.33
Mean	167	112.83	174.92	31.92
Herbicide strip				
RP	173	113.17	181.50	37.50
NRP	182	113.33	209.83	42.17
Mean	178	113.25	195.67	39.83
Mean				
RP	181	118.19	205.69	36.61
NRP	190	119.94	234.25	39.19
Significance[b]				
CC	ns	ns	ns	ns
RP	ns	ns	ns	ns
CC x RP	ns	ns	ns	ns

[a] RP: root-pruning; NRP: non-root-pruning; CC: cover crop

[b] Significance of treatment effects and interactions ($p > F$), ns = not significant.

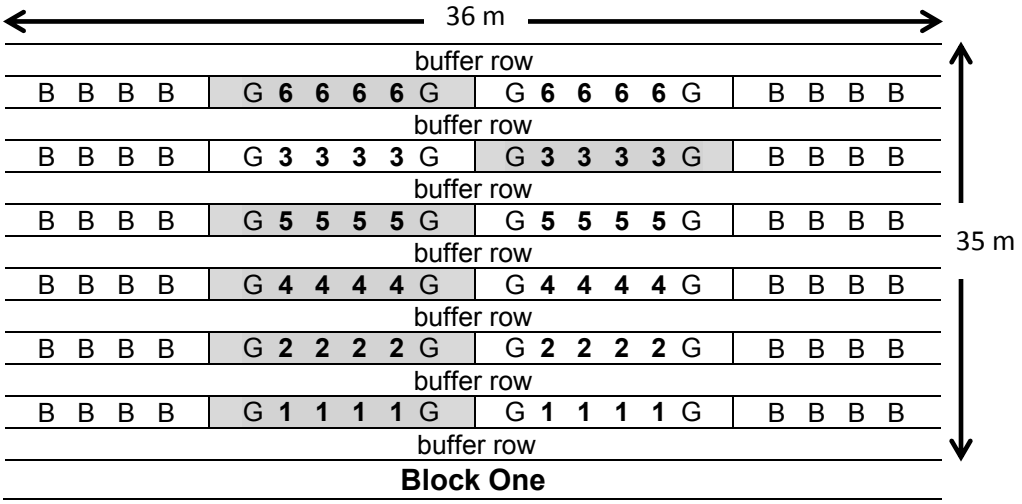
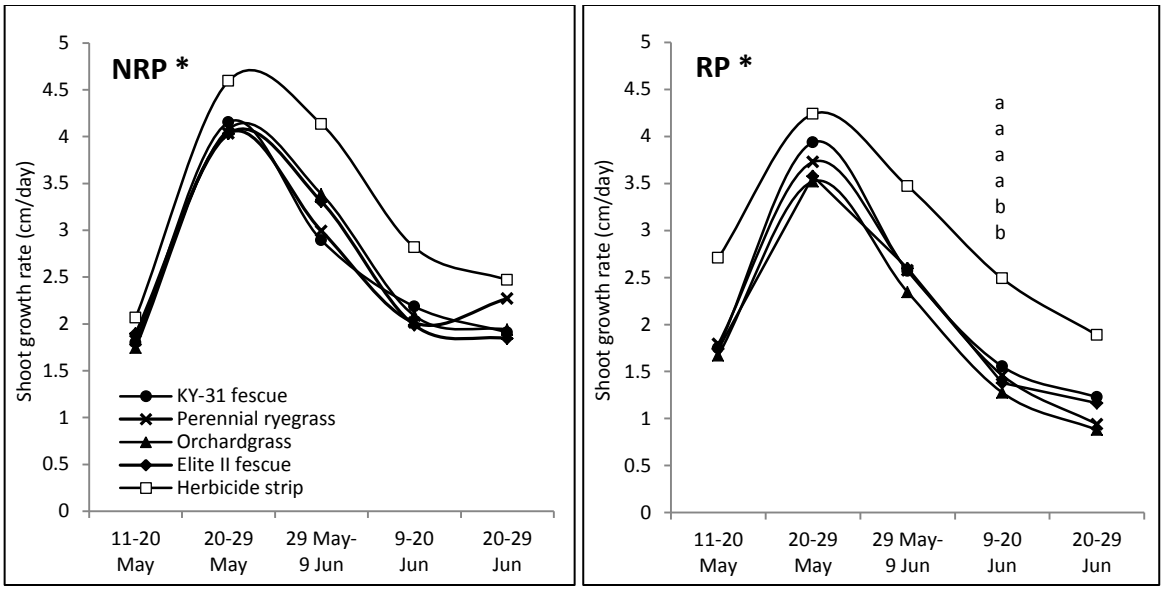
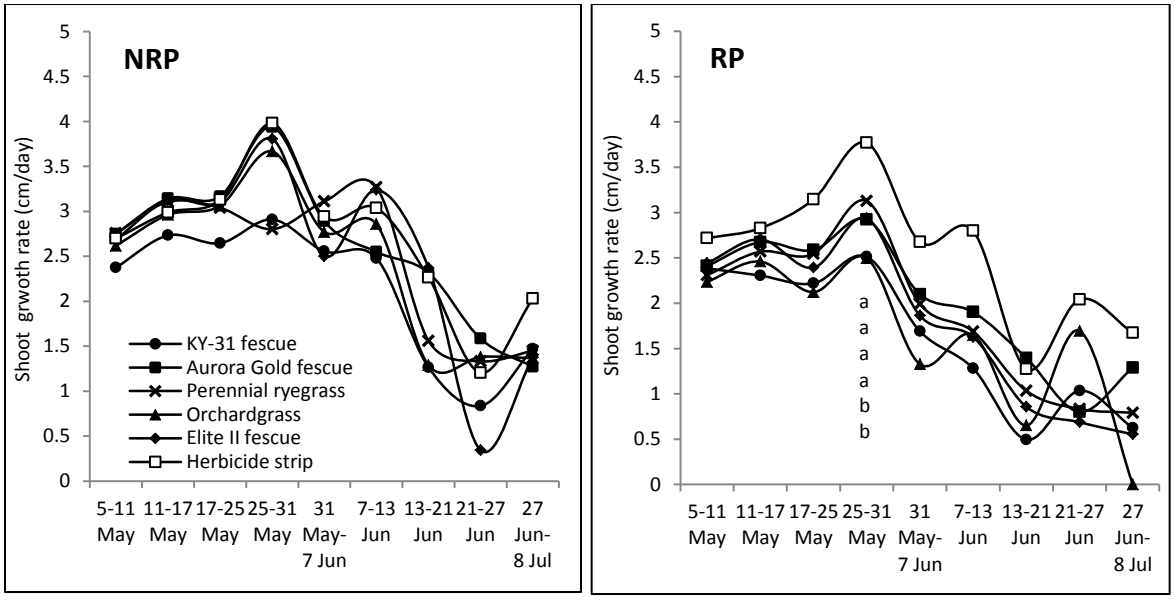


Figure 2.1 Split-plot design and layout for block one, the numbers represent a single vine and correspond to the following cover crops: 1 = tall fescue (*Festuca arundinacea* Shreb.) cv KY-31; 2 = hard fescue (*Festuca ovina* L.) cv Aurora Gold; 3 = perennial ryegrass (*Lolium perenne* L.); 4 = orchardgrass (*Dactylis glomerata* L.); 5 = turf-type, tall fescue (*Festuca arundinacea* Shreb.) cv Elite II; 6 = herbicide strip. Shaded split-plot = root-pruned; unshaded split-plots = non-root-pruned; G = guard vine, B = buffer panel vine. Five additional blocks contained the same, randomly applied treatments. Plot dimensions without buffer panels were 22 m long x 5.5 m wide (2 interrows of 2.74 m each). There was an elevation increase of ~20 m from block one to block six.



2006	11-20 May	20-29 May	29 May-9 Jun	9-20 Jun	20-29 Jun
CC	0.0383	ns	0.0046	0.0033	ns
RP	ns	0.0019	0.0004	<0.0001	<0.0001
CC x RP	ns	ns	ns	ns	ns



2007	5-11 May	11-17 May	17-25 May	25-31 May	31 May-7 Jun	7-13 Jun	13-21 Jun	21-27 Jun	27 Jun-8 Jul
CC	ns	ns	0.0168	ns	ns	ns	0.0092	ns	ns
RP	0.0002	< 0.0001	< 0.0001	0.0012	< 0.0001	0.0001	< 0.0001	ns	0.0010
CC x RP	ns	ns	ns	ns	ns	ns	ns	ns	ns

Figure 2.2 Shoot growth rates as a function of cover crop and herbicide strip (CC) with root-pruning (RP) or non-root-pruned (NRP) during 2006 and 2007. Corresponding tables provide ANOVA significance ($p > F$) for main effects and their interactions at each measurement interval within each year. * Vines grown with Aurora Gold fescue were not measured in 2006.

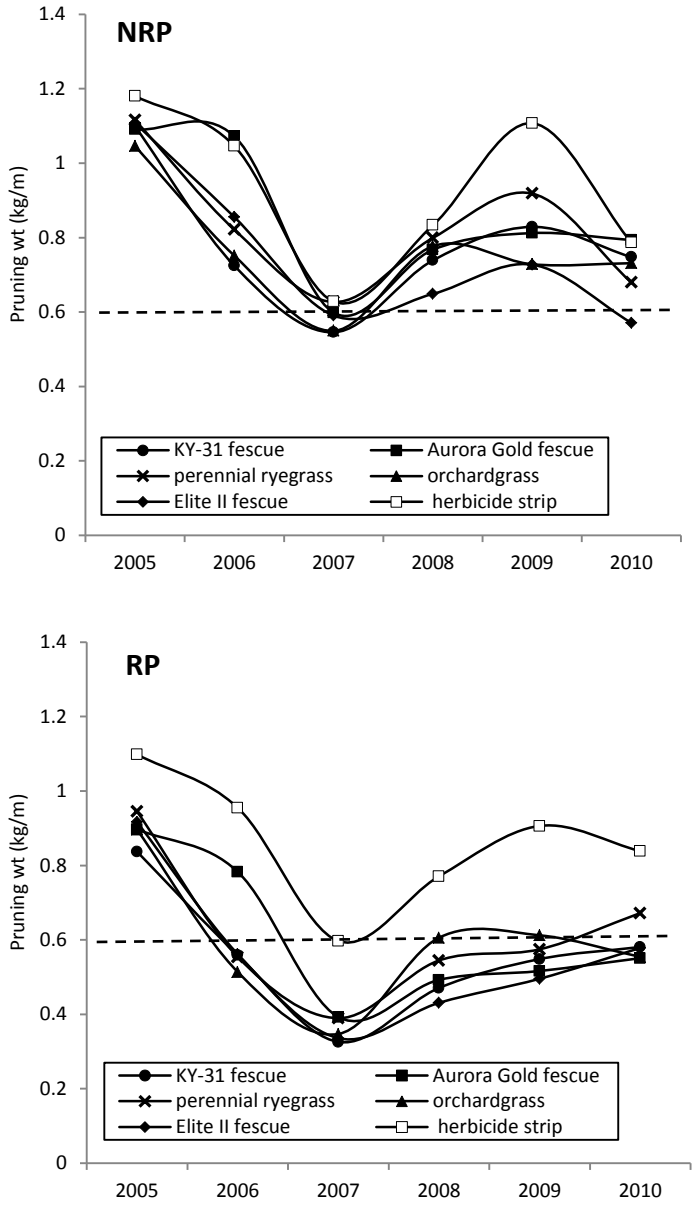
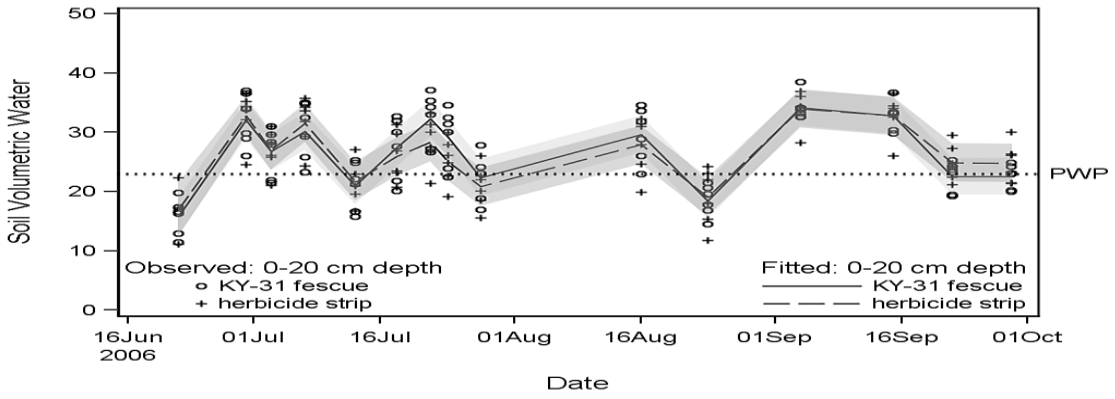
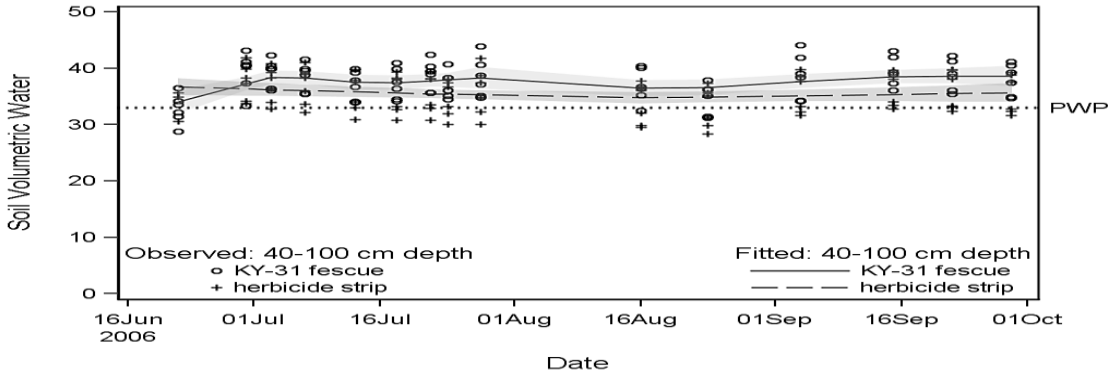
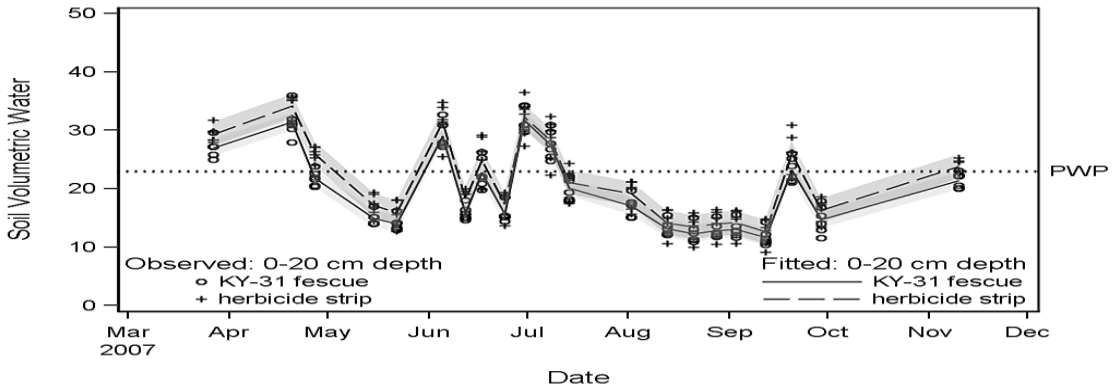
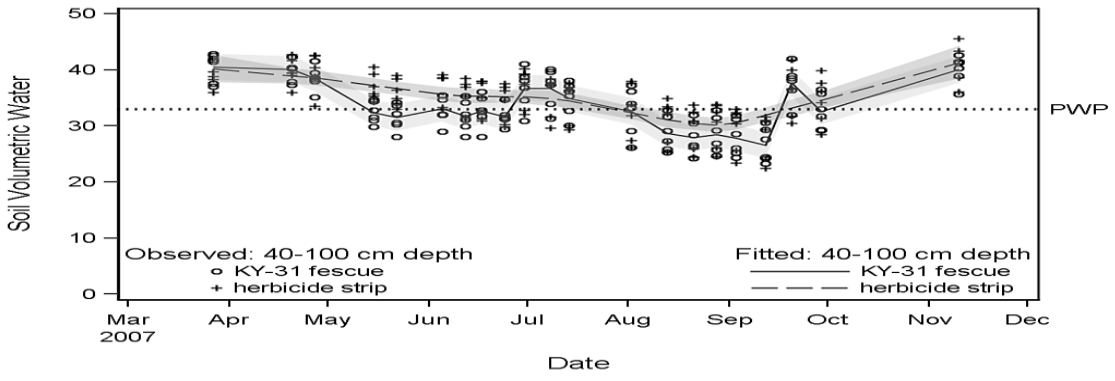


Figure 2.3 Dormant cane pruning weights by treatment combination, NRP = non-root-pruned, RP = root-pruned, 2005–2010. Dashed horizontal lines indicate upper limit of optimum pruning weight (0.60 kg/m) Smart and Robinson (1991).


Soil Volumetric Water
50
40
30
20
10
0
PWP
Observed: 0-20 cm depth
KY-31 fescue
herbicide strip
Fitted: 0-20 cm depth
KY-31 fescue
herbicide strip
16Jun
2006
01Jul
16Jul
01Aug
16Aug
01Sep
16Sep
01Oct
Date


Soil Volumetric Water
50
40
30
20
10
0
PWP
Observed: 40-100 cm depth
KY-31 fescue
herbicide strip
Fitted: 40-100 cm depth
KY-31 fescue
herbicide strip
16Jun
2006
01Jul
16Jul
01Aug
16Aug
01Sep
16Sep
01Oct
Date


Soil Volumetric Water
50
40
30
20
10
0
PWP
Observed: 0-20 cm depth
KY-31 fescue
herbicide strip
Fitted: 0-20 cm depth
KY-31 fescue
herbicide strip
Mar
2007
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Date


Soil Volumetric Water
50
40
30
20
10
0
PWP
Observed: 40-100 cm depth
KY-31 fescue
herbicide strip
Fitted: 40-100 cm depth
KY-31 fescue
herbicide strip
Mar
2007
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Date

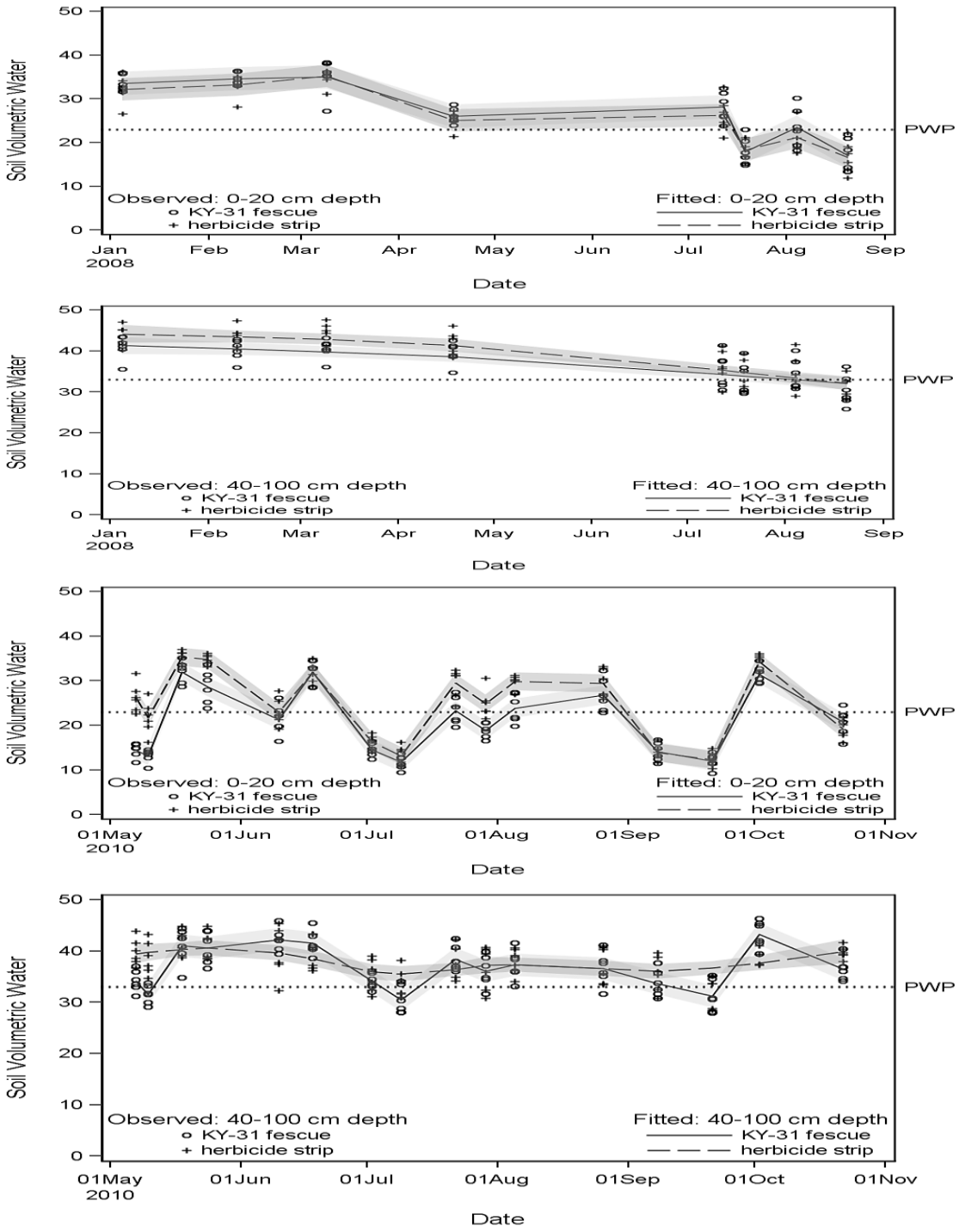


Figure 2.4 Soil volumetric water content (%) at 0-20 cm and 40-100 cm soil depth below the trellis in plots with either KY-31 fescue (trt 1, open circle, solid line) or hebicide strip (trt 6, cross, dashed line) in 2006-2008 and 2010. Shaded bands represent a 95% confidence interval computed for the fitted model in order to assess the significance of treatments within each date at each depth(n=6). Horizontal dotted lines indicate permanent wilting point (PWP) within each soil depth range.

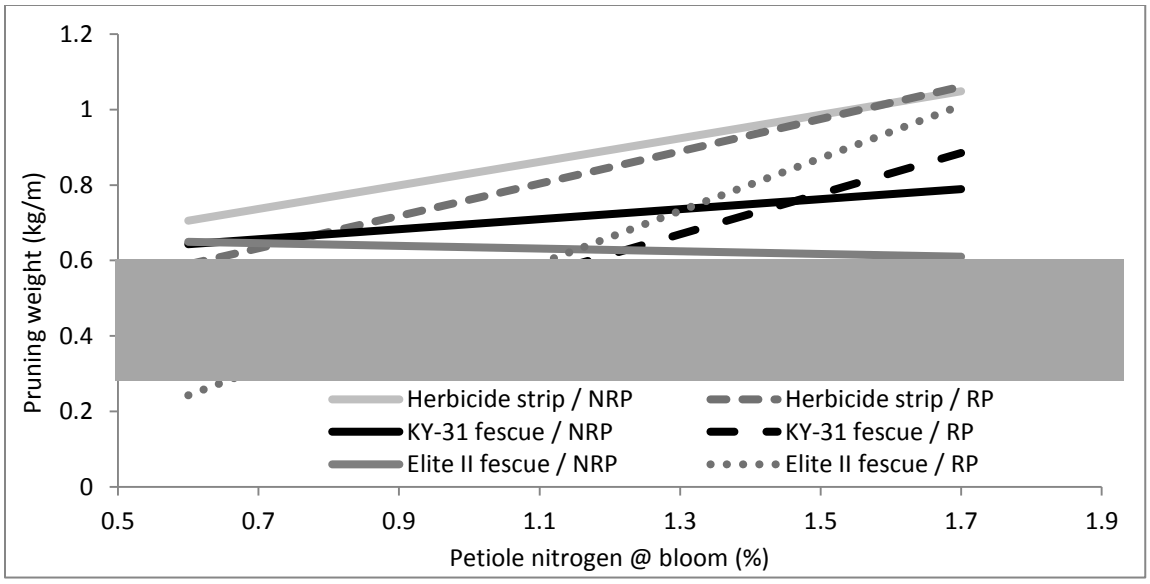


Figure 2.5 Analysis of covariance of petiole nitrogen @ bloom (%) to pruning weights (kg/m) of grapevines exposed to cover crops and/or root pruning and *P*-values for slope and intercept comparisons of petiole nitrogen and pruning weights 2007, 2009 and 2010, data combined. Area within shaded box represents suggested range of pruning weights (0.30 to 0.60 kg/m) indicative of vine balance (Smart and Robinson 1991). P-values in bold indicate differences at the at ($P \leq 0.05$) level of significance.

Table 2.12 *P*-values for slope and intercept comparisons of bloom N (%) and pruning weights 2007, 2009 and 2010 as shown in Figure 2.5.

		P values for intercept comparisons					
Cover crop Root pruning		KY-31 fescue NRP	KY-31 fescue RP	Elite II fescue NRP	Elite II fescue RP	Herbicide strip NRP	Herbicide strip RP
KY-31 fescue	NRP	---	**0.0296**	0.6573	**0.0061**	0.8581	0.3590
KY-31 fescue	RP		---	**0.0053**	0.5934	**0.0349**	0.1595
Elite II fescue	NRP			---	**0.0006**	0.5036	0.1372
Elite II fescue	RP				---	**0.0068**	**0.0454**
Herbicide strip	NRP					---	0.4350
Herbicide strip	RP						---

		P values for slope comparisons					
		KY-31 fescue NRP	KY-31 fescue RP	Elite II fescue NRP	Elite II fescue RP	Herbicide strip NRP	Herbicide strip RP
KY-31 fescue	NRP	---	0.1246	0.4497	**0.0329**	0.4405	0.2011
KY-31 fescue	RP		---	**0.0206**	0.5739	0.3746	0.6636
Elite II fescue	NRP			---	**0.0033**	0.1032	**0.0289**
Elite II fescue	RP				---	0.1311	0.2880
Herbicide strip	NRP					---	0.5988
Herbicide strip	RP						---

Literature Cited

Battany, M.C., and M.E. Grismer. 2000. Rainfall runoff and erosion in Napa Valley vineyards: Effects of slope, cover and surface roughness. Hydrol. Process. 14:1289-1304.

Celette, F., J. Wery, E. Chantelot, J. Celette, and C. Gary. 2005. Below ground interactions in a vine (*Vitis vinifera* L.) tall fescue (*Festuca arundinacea* Shreb.) intercropping system: water relations and growth. Plant Soil 276:205-217.

Celette, F., A. Findeling, and C. Gary. 2009. Competition for nitrogen in an unfertilized intercropping system: The case of an association of grapevine and grass cover in a Mediterranean climate. Eur. J. Agron. 30:41-51.

Coombe, B.G. 1995. Grapevine phenology. *In* Viticulture volume I– Resources. Coombe, B.G., and P. Dry (eds), pp 150-166. Winetitles, Adelaide.

Dokoozlian, N.K., and W.M. Kliewer. 1995. The light environment with grapevine canopies II. Influence of leaf area density on fruit zone light environment and some canopy assessment parameters. Am. J. Enol. Vitic. 46: 219-226.

Dry, P.R., and B.R. Loveys. 1998. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. Aust. J. Grape Wine Res. 4:140-148.

Dry, P.R., B.R. Loveys, A. Johnstone, and L. Sadler. 1998. Grapevine response to root pruning. Aust. Grapegrower Winemaker. Annual Technical Issue 73-78.

During, H. 1987. Stomatal response to alteration of soil and air humidity in grapevines. Vitis 26:9-18.

Ferree, D.C., D.M. Scurlock, G.R. Johns, and R. Riesen. 2000. Root pruning has little effect on Seyval, Catawba or Concord grapevines. Sm. Fruit Rev. 1:19-27.

Giese, G., and T.K. Wolf. 2009. Root pruning and groundcover to optimize vine vigor and berry composition in Cabernet Sauvignon grapevines. Abstr. Am. J. Enol. Vitic. 60:551A.

Giese, G., C. Velasco-Cruz, L. Roberts, J. Heitman, and T.K. Wolf. 2014. Complete Vineyard Floor Cover Crops Beneficially Limit Grapevine Vegetative Growth. Sci. Hortic. 170:256-266.

Grechi, I., Ph. Vivin, G. Hilbert, S. Milin, T. Robert, and J.P. Gaudillere. 2007. Effect of light and nitrogen supply on internal C:N balance and control of root-to-shoot biomass allocation in grapevine. Env. Exp. Bot. 59:139-149.

Hatch, T.A., C.C. Hickey, and T.K. Wolf. 2011. Cover crop, rootstock and root restriction regulate vegetative growth of Cabernet Sauvignon in a humid environment. Am. J. Enol. Vitic. 62:298-311.

Hochberg, U., A. Degu, and A. Fait. 2013. Near isohydric grapevine cultivar displays higher photosynthetic efficiency and photorespiration rates under drought stress as compared with near anisohydric grapevine cultivar. Physiol. Plant. 147: 443-452.

Holland, S., A. Howard, J.L. Heitman, T.J. Sauer, W. Giese, T.B. Sutton, N. Agam, A. Ben-Gal, and J.L. Havlin. 2014. Implications of an interrow fescue cover crop for below-canopy water dynamics in a North Carolina vineyard. Agron. J. (in press).

Ingels, C.A., K.M. Scow, D.A. Whisson, and R.E. Drenovsky. 2005. Effects of cover crops on grapevines, yield, juice composition, soil microbial ecology, and gopher activity. Am. J. Enol. Vitic. 56:19–29.

Keller, M. 2005. Deficit irrigation and vine mineral nutrition. *In* Proceedings of the Soil Environment and Vine Mineral Nutrition Symposium. P. Christensen and D.R. Smart (eds), pp 91-107. American Society for Enology and Viticulture, Davis, CA.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O.Schabenberger. 2006. Multi-factor Treatment Designs with Multiple Error Terms. *In* SAS for Mixed Models. pp. 124-139.

Lopes, C.M., A. Monteiro, F.E. Rückert, B. Gruber, B. Steinberg, and H.R. Schultz. 2004. Transpiration of grapevines and co-habitating cover crop and weed species in a vineyard. A ‘‘snapshot’’ at diurnal trends. Vitis 43:111–117.

Matthews, M. A., M.M. Anderson, and H.R. Schultz. 1987. Phenological and growth responses to early and late season water deficits in Cabernet franc. Vitis 26:147–160.

McArtney, S.J., and D.C. Ferree. 1999. Root and cane pruning affect vegetative development, fruiting and dry-matter accumulation of grapevines. HortScience 34: 617-621.

McClymont, L., I. Goodwin, M.G. O'Connell, and A.D. Wheaton. 2006. Effects of available soil volume on growth, bud fertility and water relations of young Shiraz grapevines. Aust. Jour. Grape and Wine Res. 2:30-38.

McCutchan, H. and K. Shackel. 1992. Stem water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). J. Am. Soc. Hortic. Sci., 117: 607-611.

Monteiro, A., and C.M. Lopes. 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agric. Eco. Environ. 121:336–342.

Morlat, R., and A. Jacquet. 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. Am. J. Enol. Vitic. 54:1–7.

NRCS (Natural Resource Conservation Service), United States Department of Agriculture. Web Soil Survey, Surry County, North Carolina, Available online at http://websoilsurvey.nrcs.usda.gov/, Accessed [9/16/2011].

Patakas, A., B. Noitsakis, and A. Chouzouri. 2005. Optimization of irrigation water use in grapevines using the relationship between transpiration and plant water status. Agric. Eco. Environ. 106: 253-259.

Pellegrino, A., E. Lebon, T. Simonneau, and J. Wery. 2005. Towards a simple indicator of water stress in grapevine (*Vitis vinifera* L.) based on the differential sensitivities of vegetative growth components. Aust. J. Grape Wine Res. 11: 306-315.

Pickering, A.H., I.J. Warrington, and D.J. Woolley. 2005. Root pruning of Cabernet Sauvignon (*Vitis vinifera* L.) decreases bunch stem necrosis. Limiting factors for primary production, June, 2005, Lincoln, New Zealand. (Conference Presentation)

Ripoche, A., A. Metay, F. Celette, and C. Gary. 2011. Changing the soil surface management in vineyards: immediate and delayed effects on the growth and yield of grapevine. Plant and Soil 339: 259-271.

Ruppert, D., M.P. Wand, and R.J. Carroll. 2003. Scatterplot smoothing. *In* Semiparametric Regression. pp. 57-89. Cambridge University Press, NY.

Saayman, D., and L. Van Huyssteen. 1983. Preliminary studies on the effect of a permanent cover crop and root pruning on an irrigated Colombar vineyard. S. Afr. J. Enol. Vitic. 4:7-12.

Schultz, H. R., and M. A. Matthews. 1988. Vegetative growth distribution during water deficits in *Vitis vinifera* L. Aust. J. Plant Phys. 15:641–656.

Smart, D., A. Breazeale, and V. Zufferey. 2006. Physiological changes in plant hydraulics induced by partial root removal of irrigated grapevine (Vitis vinifera cv. Syrah). Am. J. Enol. Vitic. 57: 201-209.

Smart, R.E., and M.D. Robinson. 1991. Sunlight into Wine: A Handbook for Wine Grape Canopy Management. Winetitles, Adelaide

Smith, M.W., M.E. Wolf, B.S. Cheary, and B.L. Carroll. 2001. Allelopathy of bermudagrass, tall fescue, redroot pigweed, and cutleaf evening primrose on pecan. HortScience 36:1047-1048.

Sweet, R., and R.P. Schreiner. 2010. Alleyway cover crops have little influence on Pinot noir grapevines (*Vitis vinifera* L) in two western Oregon vineyards. Am. J. Enol. Vitic. 61:240-252.

Steenwerth, K.L., A.J McElrone, A. Calderón-Orellana, R.C. Hanifin, C. Storm, W. Collatz and C. Manuck. 2013. Cover crops and tillage in a mature merlot vineyard show few effects on grapevines. Am. J. Enol. Vitic. 64: 515-521.

Tan, S., and G.D. Crabtree. 1990. Competition between perennial ryegrass sod and Chardonnay wine grapes for mineral nutrition. HortScience 25:533-535.

Tesic, T., M. Keller, and R.J. Hutton. 2007. Influence of vineyard floor management practices on grapevine vegetative growth, yield and fruit composition. Am. J. Enol. Vitic. 58:1-11.

Van Leeuwen, C., O. Tregoat, X. Choné, B. Bois, D. Pernet, and J.P. Gaudillére. 2009. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? J. Int. Sci. Vigne Vin 43:121-134.

Wolpert, J.A., P. Phillips, R.K. Striegler, M.V. McHenry and J.H. Foott. 1993. Berber orchardgrass tested as a cover crop in commercial vineyard. Calif. Agri. Vol. 47: 23-25.

Zoecklein, B.W., K.C. Fugelsang, B.H. Gump, and F.S. Nury. 1999. Wine Analysis and Production. Kluwer Academic, New York.

Zufferey, V., and D.R. Smart. 2012. Stomatal behaviour of irrigated Vitis vinifera cv. Syrah following partial root removal. Functional Plant Biology 39: 1019–1027.

CHAPTER III

COMPLETE VINEYARD FLOOR COVER CROPS FAVORABLY LIMIT GRAPEVINE VEGETATIVE GROWTH

Abstract: Complete vineyard floor cover crops were evaluated in a long-term study for their ability to regulate excessive vegetative growth of the grapevine (*Vitis vinifera* L.) variety 'Cabernet Sauvignon'. Treatments were: tall fescue (*Festuca arundinacea* Shreb.) 'KY-31_and 'Elite II', hard fescue (*Festuca ovina* L.) 'AuroraGold', perennial ryegrass (*Lolium perenne* L.), orchardgrass (*Dactylis glomerata* L.), and an under-trellis herbicide strip combined with KY-31 fescue interrows. Compared to herbicide-treated soil strip, Elite II fescue reduced vine pruning weights (kg/vine) 28%, individual cane weight (g) 20%, and canopy leaf layer number 25%. KY-31 fescue produced the greatest biomass and stand density, while perennial ryegrass produced the least biomass and Aurora Gold hard fescue produced the lowest stand density. Elite II fescue produced less biomass but equivalent stand density compared to KY-31 fescue. Treatments minimally impacted vine water potential (Ψ_{md}, Ψ_{stem}), indicating that the grasses were not overly competitive with grapevines for soil moisture. All grass treatments tended to depress grapevine nitrogen levels relative to the under-trellis herbicide strip treatment, but no treatment resulted in vine nitrogen levels below the acceptable sufficiency range. Because of its establishment and growth characteristics, desired suppression of vine vegetative growth, and its low impact on crop yield, we considered Elite II fescue the optimal cover crop evaluated.

Introduction

Deep, fertile soils, long growing seasons, and abundant growing season rainfall, which are common to the mid-Atlantic US and other humid regions worldwide, contribute to excessive

vine vigor and vine size (Hatch et al. 2011). Excessive vine growth includes dense, shaded canopies that foster disease, negatively impact fruit and wine quality potential, and necessitate increased canopy management expense to correct (Smart and Robinson 1991). Even in more arid regions, wine grape producers invest considerable effort and expense in vine canopy management measures such as shoot and leaf thinning, shoot hedging, and shoot positioning to remedy poor canopy architecture caused by vigorous shoot growth. Proactive measures to achieve optimal vine size and canopy architecture, such as more extensive use of vineyard floor cover crops, would be desirable to reduce the annual canopy management costs.

Cover crops are utilized in vineyards throughout the world for a variety of reasons (Ingels et al. 2005, Van Huyssteen et al. 1984, Volaire and Lelièvre 2010). Aside from their primary role in soil stabilization, cover crops regulate vine vegetative growth and vigor with varied success (Hatch et al. 2011, Tesic et al. 2005). Cover crop competition that improves vine canopy characteristics and berry environment can indirectly improve berry composition (Giese and Wolf 2009, Lopes et al. 2008, Montiero and Lopes 2007, Tesic et al. 2007). Cover cropped interrows are widely used in US and temperate European vineyards and are being evaluated in new grape growing regions such as China (Hua et al. 2005, Ingels and Klonski 1998, Volaire and Lelièvre, 2010). An interrow cover crop combined with a variable width herbicide strip under the trellis is the conventional practice in the mid-Atlantic region (Derr 2008). But some vineyardists have utilized complete vineyard cover crops, establishing cover crops between rows (interrow) and under the trellis (intrarow). The long-term sustainability and consequences of complete floor cover crops on grapevine performance have not been explored in the humid mid-Atlantic region. Complete vineyard cover crops were evaluated as a means to regulate the extent and duration of vine growth in the mid-Atlantic.

Considerations for choice of vineyard cover crops include their degree of competition with vines for water and nutrients, their growth cycle (perennial vs. annual), their adaptation and persistence in the vineyard environment, and their propensity to harbor organisms that could impact grapevines. Cover crops have a variable impact on soil water content and grapevine nutrient uptake (Costello 2010, Smith et al. 2008, Sweet and Schreiner 2010, Tesic et al. 2007), the variance owing at least in part to the climate aridity and to edaphic conditions (Monteiro and Lopes 2007). An example of this variable response to the same cover crops was reported by Tesic et al. (2007) who found large treatment differences in vegetative growth, canopy structure, yield components, berry weight and composition when the same complete, partial and no cover crop treatments were compared at two Australian sites that differed in the water-holding characteristics of their respective soils, and in seasonal precipitation. They reaffirmed that competition for water and nutrients at bloom or berry set can lead to decreased yields and vine capacity, especially under warm, arid conditions.

Perennial and annual cover crops (Celette et al. 2008, Hatch et al. 2011) or resident vegetation (Lopes et al. 2008) can suppress vine vigor and vegetative growth by competing with vines for water and nitrogen. Because of their shorter growth cycle and less root development relative to perennial cover crops, annual plants are less competitive for soil nitrogen (Celette et al. 2009). Perennial cover crop species produce more root biomass relative to annual species in the autumn-winter period and consequently have greater nitrogen sequestering potential than do annual plants (Stork and Jerie 2003). Leguminous cover crops often lack persistence but may also supply more nitrogen than desired in an already high vigor vineyard (Patrick-King and Berry 2005). Persistent perennial cover crops may not be practical as complete floor management systems in vineyards where winter protection of grapevines requires hilling and de-

hilling of soil with grafted grapevines. Such winter injury protection is not used in the Yadkin Valley of North Carolina and thus perennial grasses would be favored over annual cover crops to minimize establishment costs.

Much of the mid-Atlantic region is considered a "transitional" area for turf grass selection. Cool or warm season grasses may perform well in this area, but the choice of which to use would depend on specific needs. Grapevines have indeterminate shoot growth but exhibit their most vigorous growth between budbreak and veraison, which occurs approximately 100 days after bud break. Soil moisture reserves supplemented by seasonal rains contribute to the often excessive growth of grapevines during this period (Montiero and Lopes 2007). Cool season grasses therefore exhibit a growth pattern that parallels the vigorous spring growth of grapevines, a period when the imposition of competition for moisture and nutrients is most logical.

The objective was to evaluate five cool-season, perennial grasses as complete vineyard floor cover crops, and to compare their performance with the conventional floor management scheme of an under-trellis herbicide strip combined with sod interrows. It is hypothesized that the grasses would compete with vines for water and nutrients to favorably limit vine vegetative growth and that the cover crops would be persistent. The performance of these grasses with respect to stand development and biomass production, their impact on soil moisture, and the primary growth response of grapevines are the subjects of this report.

Materials and Methods

Experimental Description and Design: The study was conducted from 2005 to 2011 in a Yadkin Valley vineyard in western North Carolina (36^{o} 21'N, 80^{o} 46' W). The grape cv. 'Cabernet Sauvignon', clone 8 (*Vitis vinifera*), grafted on rootstock cv. SO4 (*Vitis riparia* x *Vitis*

berlandieri) was planted in 1999. Vines were spaced 1.83 x 2.74 m (1993 vines/ha) in rows oriented approximately north/south on a south-facing slope of 1-4%. The predominate soil type is the Fairview series (very deep: 0.75 – 1.50 m rooting depth, well drained, kaolinitic, mesic, Typic Kanhapludult, (NRCS Web Soil Survey) with a sandy clay loam surface texture. Hourly air temperatures and daily rainfall were recorded on a meteorological station located ~ 50 m from the vineyard block. Long-term (1971-2000) weather data from Mt Airy, NC (36° 46' N; 80° 55'W), approximately 17 km from the vineyard (NC State Climate Office), were used for comparison. Vines were cordon-trained and spur-pruned, with upright shoots vertically shoot-positioned on the trellis with the aid of trellis catch wires.

Five, cool-season perennial grasses were tested as complete vineyard floor cover crops: (1) *Festuca arundinacea* Schreb., cv. KY-31, a forage-type tall fescue and (2) cv. Elite II, a turf-type tall fescue; (3) *Festuca ovina,* cv. Aurora Gold hard fescue; (4) *Lolium perenne,* perennial ryegrass; and (5) *Dactylis glomerata,* orchardgrass. A sixth treatment comprised a 90-cm wide, under-trellis, herbicide treated strip, combined with tall fescue cv. KY-31 maintained in adjacent interrows. Cover crops were established in August 2005 under the trellis and in adjacent interrows on either side of each study row in a randomized complete block design. A single border row was used between experimental rows. Blocks were imposed across rows with all cover crop treatments randomly assigned within each block. Each block comprised 13 adjacent rows in the vineyard (6 study rows and 7 border rows) and was replicated six times. Experimental units were 8-vine plots. Plot dimensions were 22 m long x 5.5 m wide (2 interrows of 2.74 m each). Resident ground vegetation within the experimental vineyard area was treated with glufosinate (Rely®, 3% concentration) herbicide prior to cover crop establishment. The under-trellis portion of each cover crop plot was subsequently seeded and raked in by hand.

Interrows were planted with a Truax Inc. (New Hope, MN) sod seeder. Seeding rates used to ensure a dense, uniform stand were: 56 kg/ha (fescues), 45 kg/ha (orchardgrass) and 68 kg/ha (perennial ryegrass). The under-trellis portion of the herbicide strip treatments was treated with flumioxazin (Chateau®, WDG) at 0.70 kg/ha in 420 L of water applied at grapevine budbreak. Glufosinate (Rely®, 3% concentration) was applied as needed to maintain a weed-free strip. In 2009, calcium nitrate was applied in two applications of 17 kg/ha actual N each, the first at one week prior to grape bloom and the second immediately post-bloom. In 2010, a single application of calcium nitrate at a rate of 17 kg/ha N was applied pre-bloom. At each application, the fertilizer was distributed in a circle ~ 45 cm from the base of each vine in all treatments. Interrows were mowed several times per season with a flail mower and the cut material left in place. The under-trellis cover crop plots were cut twice a year with hand-held line trimmers.

Cover Crop Measurements: To assess cover crop performance, stand density -- the percentage of grass-covered soil -- was visually assessed by two people at under-trellis (UT) and interrow (IR) locations on three aimlessly distributed 0.33 m^2 quadrats per plot replicate in December 2007; April and October 2008; June 2009; March, May, June and October 2010; August and October 2011. A turf-grass stand density scale (Morris, 2000) was adapted and used to assign a numerical ranking for stand density as follows: 6 = complete stand, 0% invasive plants/bare ground; 5 = < 10% invasive species/bare ground; 4 = 10-25% invasive species/bare ground; 3 = 26-50% invasive species/bare ground; 2 = 51-75% invasive species/bare ground; 1 = 76-100% invasive species/bare ground.

Aboveground cover crop biomass was collected from one to four times each growing season from 2007 to 2011. Biomass samples were harvested at 7.5 cm above the soil surface from two aimlessly placed circular quadrats (707 cm^2 each) within each under-trellis plot

replicate, per collection date. The quadrats were the same cross-sectional area as that occupied by mini-lysimeters (MLs) described below. Harvested grass samples were placed in paper bags, oven dried (50^{o} C for 48 h) and weighed.

Grapevine Measurements: To determine how the treatments affected grapevine water status, vine water potential was measured as mid-day, stem water potential (Ψ_{stem}) with a pressure chamber (Model 670, PMS Instrument Co; Corvallis, OR, USA) between 1100 and 1500 h on the following dates: 6 July, 7 August, 9 and15 September 2009 and 25 May, 2, 9, 22, 30 July, 5 August and 5 September 2010. Well-exposed mid-shoot leaves were enclosed in aluminum foil covered plastic bags 1 h before beginning Ψ_{stem} measurements. The enclosed leaves were then excised and, within 15 s, placed in the chamber and the chamber pressurized at a rate of approximately 0.3 MPa/s. Thus, water potential readings were taken on four leaves per replicate plot at each date.

Nitrogen concentration was measured in leaf petioles at bloom in 2007, 2009 and 2010. Twenty five petioles per plot replicate were collected from leaves opposite an inflorescence. Laboratory analyses for petiole nitrogen content were conducted by the Agronomic Division of the North Carolina Department of Agriculture and Consumer Services, Raleigh, NC. Point quadrat analysis (PQA) of canopy density was performed each season from 2006 to 2011 (Smart and Robinson, 1991). One hundred probe insertions were made 2.5 to 5.0 cm apart within the vine's fruit zone (20 to 40 cm above the cordon wire) per plot replicate. Pruning weights (kg/vine) were collected each winter from 2005 to 2010 and used to calculate average cane weights (g).

Grape crop yield was regulated by adjusting shoot density to 18 shoots per vine two weeks after budbreak, and then thinning to 36 clusters per vine (2 clusters per shoot) when

berries reached approximately 7 mm in diameter.

Soil Water Measurements: To determine how treatments affected soil moisture content, volumetric soil water content (θ_v) was measured with a capacitance probe (model PR-2, Delta-T Devices Inc.; Cambridge, UK) at depths of 10, 20, 30, 40, 60 and 100 cm in all KY-31 fescue and herbicide strip treatment replicates. We chose to limit volumetric soil water content (θ_v) measures to the KY-31 fescue and the herbicide strip plots because of the amount of effort, material and time required to install the probe access tubes and to monitor soil moisture. The capacitance probe access tubes were installed between 11 and 13 April 2006 as per the manufacturer's instructions. There were two under-trellis and two interrow probe sampling tube locations per plot. One under-trellis tube was located mid-way between vines two and three; the other between vines six and seven. Interrow sampling tubes were located perpendicular to the under-trellis sampling tube locations approximately 1.37 m into the interrow. Each measurement was an average of three readings per date, sample tube location and soil depth, with the capacitance probe rotated 120^o between readings. Estimated soil net water use (mm/1000 mm) was derived from the PR-2 capacitance probe measurements of volumetric soil water measurements in the field which were then interpreted with soil water retention curves as follows: on 28 January 2009, three soil cores (7.6 cm diameter × 7.6 cm height) centered at depths of 15, 30 and 45 cm were excavated from positions within a 20 cm radius of each capacitance probe access tube. The 144 intact soil cores were transported to the Environmental Soil Physics lab, Department of Soil Science, North Carolina State University, Raleigh, NC and both low and high pressure water retention curves were generated from the soil cores using a desorption procedure that uses pressure as described by Klute (1986). Field capacity and permanent wilting point moisture levels were calculated at each of the three soil depths (15, 30

and 45 cm). Field capacity (FC) values, defined as the amount of soil moisture retained at 33.33 kPA (SSSA, 1997) were 0.35, 0.39, 0.40 cm^3/cm^3; permanent wilting point (PWP) values, defined as the amount of soil moisture retained at 1500 kPA (SSSA, 1997) were 0.23, 0.29 and 0.33 cm^3/cm^3 (Table 3.1). Volumetric water content values measured with the PR-2 capacitance probe at the same time as soil core collection were aligned and interpreted with the water retention curve values. For example, when the volumetric soil water content was determined to be 0.35 with the PR-2 capacitance probe at the 15 cm depth, that soil depth was considered to be at FC (Table 3.1).

Cover Crop Water Use Estimation: Mini-lysimeters (MLs) were used to gravimetrically measure and compare daily under-trellis evapotranspiration of cover crops (E_{cc}) and evaporation from soil in the herbicide strip treatment (E_s). Thirty-six plastic buckets (37 cm deep, 29 cm internal diameter), with drainage holes at the bottom and handles for ease in lifting and weighing, were used as MLs. In December 2005, cylindrical holes were excavated under the trellis, midway between vines 4 and 5 in each plot, to accommodate the MLs. The ML holes were lined with fiberglass screen to facilitate extraction and insertion of the MLs for weighing. Soil from each ML excavation was placed into its respective ML bucket in reverse order of its extraction to mimic the existing soil profile of the site. MLs were moved to a greenhouse and each cover crop species was established in 6 MLs. MLs with established grasses were re-installed in their respective vineyard plot locations in March 2006. Unplanted MLs were similarly established in the herbicide strip plots. The top of each ML was positioned evenly with surrounding terrain at each location. A dry-down weighing interval was initiated following a rain event or ML watering as follows: MLs were withdrawn from their holes, placed across the interrow from their respective excavation sites, watered to saturation and allowed to drain for 24 h. At field capacity

(FC) the MLs were weighed with a digital scale with a resolution of 20 g (CS200, Intercomp, Medina, MN, USA) and reinstalled in their under-trellis locations. MLs were then weighed every 24 h until occurrence of a rain event or ML weights stabilized. Upon ML weight stabilization, in the absence of a rain event, MLs were watered as described above. Daily E_{cc} (mm/day) was calculated as the change in bucket weight per day (kg/day) per m^2 of ML surface area (ML surface area = 0.07 m^2) and converted to mm/d ($kg/m^2 = l/m^2 = mm$) (Centinari et al., 2009).

Statistical Analysis: A randomized complete block design (RCBD) was used in this study. The statistical model associated with the RCBD had block effects (random), fixed effects (treatments/ cover crops) and in cases where repeated observations were taken from the experimental units, there were additional treatment factors of date, year, or sampling interval. When date, year or interval was included as a treatment factor, the layout was a split plot design (nested design) with cover crop as the whole plot factor and date, year or interval as the split plot factor. Data was analyzed with SAS GLIMMIX (SAS 9.3, 2002-2010, SAS Institute Inc., Cary, NC), an appropriate procedure to analyze data from designs such as RCBD or split plot designs, among other more complicated designs (Littell et al. 2006). Treatment means were considered different at 5% level of significance ($p\text{-value} < 0.05$). The significance of mean differences was adjusted for multiple comparisons by Tukey's post-hoc test. Separate analyses were performed on soil moisture data from two locations within the plots: one with the data collected under-trellis, and the other with data collected at the interrow. Seasonal changes in soil moisture content that occurred at under-trellis locations were computed from pooled data for each of the instrumented treatments: herbicide strip and KY-31 fescue. No significant differences in interrow soil moisture were observed between the herbicide strip and KY-31 fescue treatments which both used KY-31 fescue as interrow cover crop. Therefore, interrow soil moisture data is not reported. Grape crop

yield, pruning weights, cane weight and grapevine canopy density data were analyzed with the same procedure as explained above (i.e. using cover crop and year as factors). Additionally, letter ranking of significant treatment differences was accomplished with a macro within GLIMMIX (Piepho 2012).

Results

Mean annual precipitation and air temperature representative of the Yadkin Valley, NC were 1191 mm and 13^{o}C, respectively, from 1971 to 2000 (NC State Climate Office). Annual rainfall measured at the vineyard in 2007 was less than average while annual precipitation in 2005, 2006 and 2009 to 2011 was slightly greater than the study period annual average of 1000 mm (Table 3.2). Rainfall averaged > 75 mm per month from April to October every year of the study and was > 100 mm per month, April to October in 2006, 2008 and 2010. In 2007, the driest year of the study, approximately 64% (491 mm) of rainfall occurred during the growing season of April – October.

KY-31 fescue had the greatest, and Aurora Gold hard fescue the least, interrow (IR) stand density, compared to the other grasses (Fig. 3.1). Elite II fescue, orchardgrass and perennial ryegrass had IR stand densities similar to one another and equivalent to KY-31 fescue at the first three sampling dates. Orchardgrass IR stand density was equivalent to that of KY-31 fescue and greater than that of Aurora Gold, perennial ryegrass or Elite II fescue by final sampling date: 5 June 2010. As expected, IR stand density of the herbicide strip treatment was equivalent to that of KY-31 fescue at all sampling dates (Fig. 3.1).

The UT stand densities of Elite II and KY-31 fescue were equivalent and greater than that of orchardgrass, perennial ryegrass or Aurora Gold hard fescue, which did not differ from

each other, regardless of sampling date (Fig.3.1). Overall, KY-31 fescue maintained the most consistent stand density at both locations over all sampling dates (Fig. 3.1). The essentially bare soil of the herbicide strip was intentionally excluded from the UT assessment.

Biomass of KY-31 fescue averaged 2.22 Mg ha^{-1} dry matter (DM) (Table 3.3). KY-31 fescue was the most productive cover crop and perennial ryegrass the least productive at all measurement periods except for June 2009, when perennial ryegrass and Elite II fescue were the least productive and did not differ from each other. Perennial ryegrass produced significantly less biomass compared to KY-31 fescue across all years and was less than Aurora Gold hard fescue biomass at all but two dates (Table 3.2). A significant cover crop by time interaction was evidenced by generally greater amounts of biomass of any given cover crop species measured in October compared to biomass measurements in July 2008 or in March or July of 2010. This interaction was also evident in the absolute lower amount of cover crop biomass collected in 2011 relative to the biomass each cover crop produced in 2007, except for Elite II fescue and perennial ryegrass. Biomass measured in July 2010 did not differ between cover crops.

Cover crops increased canopy gaps and depressed leaf layer number, percent shaded leaves and shaded clusters relative to the herbicide strip (Table 3.3). Elite II fescue improved all canopy density attributes relative to the herbicide strip. Aurora Gold hard fescue improved all canopy density attributes relative to the herbicide strip except percentage of shaded leaves. There was a significant interaction between cover crop and year on leaf layer number (Fig. 3.2). For example, in 2007, the driest year of the study, there were no differences between treatments for leaf layer number. However, in 2008, leaf layers were reduced in vines exposed to any cover crop. Except for 2007, vines in Elite II fescue plots had significantly fewer leaf layers every season compared to leaf layers of vines grown with the herbicide strip. From 2006 to 2011, vines

in Elite II fescue plots had the absolute fewest leaf layers but did not differ from perennial ryegrass plots in this regard. Leaf layer number of vines grown with KY-31 fescue, did not differ from leaf layers of vines in the herbicide strip, except in 2008. Although vines in the herbicide plots had significantly greater leaf layers than did vines grown with cover crops, with the exception of 2008, no treatments exceeded 1.5 leaf layers (Table 3.3).

Cover crop by year interaction on pruning weights was significant ($P \leq 0.0001$) each year (Table 3.4). Pruning weights of all treatments decreased from 2005 to 2007, the driest year of the study, and subsequently increased for all treatments except orchardgrass from 2007 to 2009 (Table 3.4). There were, however, treatment differences in the percentage of change and amount of reduction in pruning weights during those periods. For instance, pruning weights of vines with the herbicide strips declined approximately 46% from 2005 to 2007 and increased 64% from 2007 to 2009. Pruning weights of all cover-cropped vines combined, except Aurora Gold fescue, declined 51% from 2005 to 2007 but increased only 47% from 2007 to 2009 (Fig. 3.3). Pruning weights of KY-31 and Elite II fescue vines declined annually from 2005 to 2010 compared to pruning weights of vines in herbicide strips (Table 3.4). Vines in orchardgrass plots had lower pruning weights relative to those of herbicide-treated vines in five of six years; except 2008, which had the most growing season rainfall during the study. Pruning weights declined for all treatments between 2005 and 2011. Pruning weights of cover cropped vines were 12.5% less than pruning weights of vines grown with an herbicide strip in 2005. By 2010, a 22.5% pruning weight reduction due to cover crops was evident relative to herbicide strip grown vines over the same period.

KY-31 fescue reduced individual cane weights relative to the herbicide strip except in 2007 and 2010. Similarly, cane weights of vines grown with Elite II fescue were less than cane

weights of the herbicide strip vines in every year except 2005 and 2007 (Table 3.4). In 2007, cane weights did not differ among treatments and were the lowest within each treatment relative to all other years. From 2008 to 2010, Elite II fescue vines' pruning weights and average cane weights were significantly less than those of the herbicide strip (Table 3.4). By 2010, cane weights of vines in Elite II fescue were 23% less than those of vines grown with an herbicide strip.

Crop yields were unaffected by cover crops except in 2006 (Table 3.4). In 2006, crop yield of vines exposed to KY-31 fescue was significantly less than yield of vines in the herbicide strip, but did not differ from vines grown with perennial ryegrass, orchardgrass or Elite II fescue. Crop yields of vines in Aurora Gold hard fescue were the absolute highest of all treatment vines in 2006 and significantly greater than yields of vines grown in KY-31 fescue or orchardgrass plots.

Petiole N levels measured at bloom generally increased vine growth in all treatments following application of fertilizer N in 2009 and 2010 (Fig. 3.4). Excluding the herbicide strip treated vines, petiole N levels of all vines grown with cover crops did not differ in 2007 and 2009. A significant interaction between year and cover crop treatment on petiole N measured at bloom was observed as petiole N levels increased in herbicide strip exposed vines from 2007 to 2010. Petiole N also increased in vines exposed to cover crops during this same time period but significantly less so compared to vines in the herbicide strip (Fig. 3.4).

Net soil water use was similar between the KY-31 fescue and the herbicide strip plots over three seasons when averaged over the 0-20 cm or the 0-100 cm soil depths (Fig. 3.5). The net water use in both treatments generally reflected the amount of rainfall that occurred in the measurement interval. KY-31 plots often exhibited increased soil moisture over the entire 0-100

cm profile compared to the herbicide plots. Measured soil water contents were within the plant available water range for both treatments throughout the experiment (data not shown).

Estimated water use of cover crops measured by ML weight loss, was significantly greater compared to the estimated water loss of the herbicide treated soil from 13-22 June and 1-5 July 2006 (Fig. 3.6). No differences in estimated water use were measured between treatments from 18 to 24 July 2006. ML water use measured in 2007, was similar to the 2006 pattern, with cover crops using slightly more water compared to water loss in the herbicide treated soil early in the growing season (Fig. 3.6). Water use, as determined by ML over the course of the study, ranged from 3.28 mm/d for KY-31 fescue to 1.52 mm/d of water loss for the herbicide-treated plots. Cover crops did not significantly affect vine water status. Vine stem water potentials did not fall below -0.6 MPa on any measured date over the course of the experiment (data not shown).

Discussion

All evaluated cover crops were adapted to the regional climate and soil conditions, but some performed better than others in terms of growth, persistence, and their desired impacts on grapevine performance. Cover crop growth and persistence was assessed by both stand density and biomass production. Stand density is probably more important than the absolute amount of biomass produced where the goal is to reduce run-off and increase infiltration of rainfall (Glenn and Welker 1989). KY-31 fescue's stand density was superior to that of the other cover crops we evaluated. Although perennial ryegrass, orchardgrass and Aurora Gold hard fescue reduced grapevine growth in some years, their inferior stand density allowed weeds to become established.

In contrast to stand density, cover crop biomass production has been positively associated with effective competition with vines and other perennial crops (Sweet and Schreiner 2010; Tworkoski and Glenn 2001, Volaire and Lelièvre 2010); the more biomass, the greater the competition. In the relatively wet growing seasons of 2009 and 2010, Elite II fescue and KY-31 fescue had substantially increased cover crop biomass. March 2009 biomass of KY-31 and Elite II fescues were respectively 30% and 60% greater, respectively, compared to the biomass of each measured in April 2008, following the dry growing season of 2007 (Table 3). KY-31 fescue and orchardgrass produced the greatest biomass among grasses, with amounts typically surpassing the biomass production in vineyard studies in more arid regions. The average biomass of all grasses in this study was about 25% greater than the average biomass of all grasses or clover/grass mixtures measured in a similar fashion in an Oregon study (Sweet and Schreiner 2010). Differences in biomass between the two studies could be attributed to regional differences in growing season rainfall. The Oregon site's average seasonal rainfall was approximately 43% less than Dobson, NC (330 mm versus 584 mm). The tall fescues, KY-31 and Elite II, and orchardgrass, each produced about 40% more biomass in our study than did those same species (different cultivars) in a similar study in southern France (Volaire and Lelièvre 2010).

KY-31 fescue produced approximately 30% more under-trellis biomass than orchardgrass did in this study. By contrast, orchardgrass had greater persistence and biomass than KY-31 fescue when the two were compared as alleyway cover crops in a shaded environment of an Arkansas loblolly pine plantation experiment (Burner 2003). The loblolly pine canopy provided 52% more alleyway shade compared to an un-shaded control in that study. Interestingly, KY-31 fescue produced more biomass and persisted better than the orchardgrass did in the *un-shaded* control in that same loblolly pine study. Although not quantified, the incident radiation of the

under-trellis environment of our study was probably more similar to the un-shaded versus the shaded alleyways of the aforementioned loblolly pine study. If so, this would partially explain the relative performance of the KY-31 fescue and orchardgrass in our study.

Fertilizer application and available nitrogen obviously impact the amount of cover crop biomass. Cover crop biomass collected in December 2007 was 30% less than that collected in October 2010, following the application of fertilizer N in 2009 and 2010. There was an expected increase in cover crop growth as the grasses became more established and took up more nutrients. However, this explanation cannot be verified because we did not test nutrient levels in cover crops themselves before and after fertilizer application.

Cover crop biomass production differences may also depend partially on the degree of cover crop summer dormancy. There are broad cultivar differences in this regard and these differences impact each cultivar's consequent use of water and nutrients during the growing season (Volaire and Lelièvre 2010). Some cultivars of tall fescue, including KY-31, are actually considered to be summer-active (Malinowski et al. 2009), and would likely use more water and nutrients compared to summer-dormant species/cultivars during the midsummer.

Timing or season of cover crop defoliation also impacts the amount of biomass collected; similar to when the same species are cultivated and repeatedly harvested as forage crops. For example, cuttings of orchardgrass were greatest in spring, intermediate in summer and least in fall, in a Canadian study and there were seasonal differences in cover crop response to applied N (Bittman et al. 2004). Similarly, in a New York comparison of N uptake and N use efficiency of orchardgrass and tall fescue exposed to different levels and types of fertilizer N, orchardgrass had greater amounts of spring harvested biomass but tall fescue had greater overall amounts of biomass produced from subsequent harvests of the grasses' regrowth during the season (Cherney

et al. 2002). It was found that orchardgrass biomass production peaked in summer and was less productive than KY-31 in late-winter/early spring (March) or fall (October). This seasonal dynamic harmonizes well with the strategy to impose competitive stress on vines during the rapid phase of shoot growth that occurs from bud-break through veraison.

Grapevines with thin (< 1.5 leaf layers) open canopies have been positively associated with improved grape and wine composition. All treatment vines in the current study, inclusive of vines in the herbicide plots, produced canopies within the benchmark ranges of desirable canopy winegrape ideotype (Smart and Robinson 1991). Further, to a practical point of this study, all cover crops reduced the percentage of shaded clusters and number of canopy leaf layers relative to vines in the herbicide strip treatment. However, Elite II fescue more consistently and positively impacted canopy architecture in all canopy assessment categories relative to other treatments.

Pruning weights between 0.30 and 0.60 kg/m of canopy are an accepted benchmark range for wine grapes, and considered indicative of balanced vine vegetative growth (Smart and Robinson, 1991). Pruning weights of all vines grown with cover crops were within that desired benchmark range following the dry 2007 growing season. Conversely, pruning weight of vines grown with herbicide strips exceeded the upper threshold of the benchmark range every year of the study. Both KY-31and Elite II fescues reduced in pruning and average cane weights the most. Aurora Gold fescue reduced pruning weights and individual cane weights in four of six years relative to the herbicide strip. The positive association of increased cover crop biomass and reduced vegetative vine growth as measured by pruning weights is similar to that of other studies as mentioned above.

All cover crops in the current study exerted some positive suppression of vine vegetative growth with minimal impact on crop development. KY-31 fescue reduced yields by 12% relative to the yield of vines in the herbicide strip in 2006. This was the only yield reduction attributed to a cover crop in this study. Although Elite II fescue vines had pruning weights and average cane weights equivalent to those vines exposed to KY-31 fescue, crop yield of vines in Elite II plots was not reduced in any year. Cover crop impact on grape crop yield appears to be dependent on regional climate. For instance, similar to our results, only a minimal yield reduction was measured after complete vineyard cover crops had been in place for two or three years in a humid Australian vineyard (Tesic et al. 2007). Furthermore, there was no grape crop yield reduction due to the use of interrow cover crops in a cool, and seasonally humid Oregon climate (Sweet and Schreiner, 2010), or in an arid Portuguese cover-cropped vineyard (Montiero and Lopes 2007). Conversely, grape crop yields are typically reduced when perennial cover crops are used in warm, arid climates. For example, orchardgrass (*Dactylis glomerata* L.) cv. 'Berber' interrows reduced Cabernet Sauvignon dormant pruning weights by 58% and crop yield by 53%, relative to a clean-cultivated control (Wolpert et al. 1993). In climates described as 'Mediterranean' (average annual rainfall of $\leq$ 650 mm) forage type cultivars of tall fescue and orchardgrass, used as interrow cover crops, reduced grape crop yield relative to clean cultivated or bare soil controls (Volaire and Lelièvre 2010). The authors did not test turf-type cultivars such as Elite II tall fescue due to their limited heat and drought resistance.

In 2007, the driest year of the current study, petiole N of vines in the herbicide strip was not significantly less than that of vines exposed to KY-31 fescue. However, the lack of applied fertilizer N prior to 2009 likely contributed to the muted differences in petiole N levels between treatments and overall lower levels of petiole N in 2007 compared to N levels measured in 2009

and 2010. Despite a significant cover crop by year interaction, levels of petiole N across all treatments in all years were considered adequate for normal production (Bates and Wolf 2008). The reduction in total petiole N of vines exposed to some cover crops likely contributed to the depression of vegetative vine growth in those vines compared to vines in the herbicide plots. For instance, Aurora Gold hard fescue had petiole N levels of 0.86% and 1.13% in 2009 and 2010 respectively, relative to petiole N levels of 1.05% and 1.30% of vines in the herbicide plots in those respective years.

Estimated water use of KY-31 fescue at both 0-20 cm and 0-100 cm depths did not differ substantially from that of the herbicide strip in 2006, 2007 and 2010. Water use differences that did occur were most evident early in the season at the 0-20 cm depth when growth of KY-31 fescue was most active. This early spring cover crop growth and concomitant water use was desired as part of the strategy to suppress vine growth, and is consistent with what others have demonstrated (Centinari et al. 2011, Lopes et al. 2011).

Greater water use by grass covered soil versus bare soil has been well established by benchmark lysimeter studies as discussed by Geiger et al. (2009) and, more recently, in a vineyard environment similar to ours where MLs were used (Centinari et al. 2011, 2013). Greater evapotranspiration of KY-31 fescue as measured with ML relative to the herbicide treated soil was similar to differences determined by others (Centinari et al. 2013, Volaire and Lelièvre 2008). However, at midday, under-trellis MLs were shaded and grape canopies and grass interrows were illuminated. Therefore, ML readings and evapotranspiration calculations were not indicative of ET_{cc} from the entire cover crop area. There is a scarcity of data for under trellis evapotranspiration, but our ML estimates of ET_{cc} that ranged between 1.36 and 5.81 mm/d, were greater than that of herbicide treated soil with one exception (noted below), and

generally agree with those determined by others (Bremer 2003, Centinari et al. 2009, 2011). Bare soil, however, may lose more soil moisture than sodded soil in some situations due to the mulching effect of the cover crop (Lopes et al. 2011). The essentially bare soil in the herbicide strip treatment had a significantly greater rate of water loss as determined by ML during a single period of data collection: 10-12 June 2007 (Fig. 6). Regardless of this apparent conflict in the ML data, other perennial crops besides grapes also display depressed vegetative growth when exposed to permanent sod cover, despite the greater infiltration of rainfall that occurs with sod versus bare soil (Celette et al. 2008, Glenn and Welker 1989, Gulick et al.1994). KY-31 fescue had a relatively greater degree of estimated evapotranspiration compared to the herbicide treated soil, based on ML measurements and soil capacitance measurements. Despite this fact and KY-31 fescue's greater biomass and stand density relative to other cover crops, KY-31 fescue did not substantially alter estimated grapevine water use in this test.

Other factors besides competition for water and nitrogen likely contributed to the variable vegetative growth suppression we observed. Possibilities include: seasonal differences in climate (previously discussed), grapevine rooting patterns, vine age, time of cover crop establishment, rootstock and allelopathic effects of cover crops.

Cover crops can alter grapevine rooting patterns which may impact the vine's uptake of water and nutrients, especially in vineyards with deep soils with a high water holding capacity (Celette et al. 2008). Grapevine roots will explore deeper soil horizons when grass roots dry the horizons near the soil surface (Celette et al. 2008, Morlat and Jacquet 2003). For example, over 69% of grapevine roots were located under the vine row when interrow cover crops were present (Morlat and Jacquet 2003). Grapevine roots in these deeper soil horizons that hold substantial moisture could mitigate the effects of all but the most extreme droughts.

Vine age (6 years at study initiation) that provided vines a deep rooting capability and ample carbohydrate storage in perennial wood, possibly damped the magnitude of treatment effects relative to younger, smaller vines (e.g., Hatch et al. 2011). Allelopathic effects on perennial crops have also been associated with some cover crop species; KY-31 fescue was shown to reduce growth of seedling pecan trees (Smith et al. 2001). Keller et al. (2001) found that soil-N and rootstock each independently and significantly affected growth and gas exchange of Müller-Thurgau vines. In that study, SO4 (the rootstock used in our study) had the strongest vegetative response to N supply compared to vines grafted on other rootstocks. Lateral shoot growth of vines grafted to SO4 increased as soil-N levels increased and SO4 was the only rootstock that displayed nitrogen by rootstock interaction (Keller et al. 2001). Had a different rootstock been used in our study, a more dramatic vine reaction to the cover crops might have been realized as was shown in a similar regional study (Hatch et al. 2011).

Conclusions

Cool season, perennial grasses used as complete vineyard floor cover crops effectively reduced excessive vegetative growth of Cabernet Sauvignon grapevines in a high rainfall environment. Elite II and KY-31 fescue had the greatest stand density and biomass production and reduced vine pruning weights and cane weights the most with minimal impact on yield. Pruning weights of Elite II treated vines were within the desired benchmark range of 0.30 to 0.60 kg/m, indicative of balanced vine growth, in 2007, 2008 and 2010. Furthermore, Elite II fescue improved *all* point quadrat canopy metrics relative to the conventional herbicide strip treatment in all years. This improvement suggests that less canopy management would be required in vines grown with this complete vineyard floor cover crop compared to vines with the conventional

under-trellis herbicide strip. Complete cover crop establishment and a growing season with average to below average rainfall is required before consistent effects on vine vegetative growth to the desired degree can be realized the mid-Atlantic. Although occasional soil moisture depletion differences were measured between cover crop treatments, there were no measurable treatment effects on vine water potential. Nevertheless, intrarow cover crops provide one strategy for reducing vine size and promoting more desirable grapevine canopy architecture under humid grape growing conditions.

Table 3.1 Mean soil volumetric water content (cm^3 / cm^3) as determined by capacitance probe and associated pressure determined during generation of water retention curve for experimental site soil. Plant available water (PAW): water (cm^3 / cm^3) at each of three depths: 15, 30 and 45 cm.

	Pressure (kPa)							
	0.03	0.3	0.5	10	33.3	50	500	1500
Depth cm	**Soil Volumetric Water Content (cm^3 / cm^3)**							
15	0.44	0.39	0.37	0.37	0.35	0.34	0.28	0.23
30	0.44	0.42	0.41	0.40	0.39	0.38	0.35	0.29
45	0.45	0.43	0.42	0.42	0.40	0.40	0.35	0.33

Plant available water parameters			
	Soil Volumetric Water Content (cm^3 / cm^3)		
Depth cm	**Field Capacity (33.33 kPa)**	**Permanent Wilting Point (1500 kPa)**	**Plant Available Water**
15	0.35	0.23	0.12
30	0.39	0.29	0.10
45	0.40	0.33	0.07

Table 3.2 Biomass of five cover crops measured under-trellis in different months, 2007-2011: KY-31 tall fescue (KY), Aurora Gold fescue (AG), perennial ryegrass (PG), orchardgrass (OG) and Elite II tall fescue (EF).

	Biomass										
	2007	2008		2009	2010			2011			
Cover Crop	Dec	Apr	Oct	June	March	May	July	Oct	Aug	Oct	Mean
	Mg DM ha $^{-1}$ †										
KY	3.10 a	0.86 a	2.21 a	1.23 ab	1.54 a	2.84 a	1.69	3.40 ab	2.97 a	2.44 a	2.22 a
AG	2.90 a	0.54 ab	2.65 a	1.22 ab	1.57 a	1.46 b	1.86	3.56 ab	1.80 ab	2.03 ab	1.97 ab
PG	0.69 c	0.22 b	0.76 b	0.86 b	0.55 b	1.12 b	1.31	1.97 b	1.02 b	0.93 c	0.95 d
OG	2.23 ab	0.35 b	1.09 b	1.33 a	0.69 b	3.04 a	1.68	2.49 ab	1.87 ab	1.17 bc	1.59 c
EF	1.72 b	0.42 ab	1.44 b	0.86 b	1.06 ab	1.96 ab	1.52	3.75 a	2.70 a	2.08 ab	1.75 bc
Main effects and interactions											
Cover crop			*<0.0001*								
Year_month			*<0.0001*								
Cover crop x Year_month			*<0.0001*								

† Means within a column followed by different letters differ at $P \leq 0.0001$.

Values not followed by letters are not significantly different from other values in that column.

Table 3.3 Canopy point quadrat metrics of vines exposed to five complete vineyard floor cover crops: KY-31 tall fescue (KY), Aurora Gold fescue (AG), perennial ryegrass (PG), orchardgrass (OG) and Elite II tall fescue (EF) or herbicide strip (HS), 2006 to 2011.

Cover crop	Gaps (%)[†]	Leaf layer number[†]	Shaded leaves (%)[†]	Shaded clusters (%)[†]
KY	14.12 ab	1.18 b	12.32 ab	22.78 b
AG	13.81 ab	1.16 b	13.49 ab	22.48 bc
PG	12.00 bc	1.09 bc	10.59 b	20.73 bc
OG	11.50 bc	1.17 b	13.33 ab	20.13 bc
EF	15.66 a	0.99 c	10.38 b	16.66 c
HS	9.45 c	1.33 a	15.05 a	29.12 a
Main effects and interactions				
Cover crop	0.0094	0.0022	0.0017	<0.0166
Year	<0.0001	0.0002	<0.0001	<0.0001
Cover crop x Year	NS	0.0176	NS	NS

[†]Means within a column followed by different letters are significantly different ($P < 0.05$), NS = not significant.

Table 3.4 Pruning weights, cane weights and crop yield of vines exposed to five complete vineyard floor cover crops: KY-31 fescue tall fescue (KY), Aurora Gold fescue (AG), perennial ryegrass (PG), orchardgrass (OG), Elite II tall fescue (EF) or herbicide strip (HS), 2005 to 2010.

Cover crop	Pruning weight (kg/vine) †					
	2005	**2006**	**2007**	**2008**	**2009**	**2010**
KY	1.77 b	1.17 b	0.80 b	1.11 bc	1.26 bc	1.22 bc
AG	1.82 b	1.70 a	0.91 ab	1.15 bc	1.22 bc	1.30 ab
PG	1.89 ab	1.26 b	0.93 ab	1.23 b	1.37 b	1.33 ab
OG	1.78 b	1.16 b	0.82 b	1.27 ab	1.23 bc	1.15 bc
EF	1.85 b	1.30 b	0.85 b	0.99 c	1.12 c	1.04 c
HS	2.08 a	1.83 a	1.12 a	1.47 a	1.85 a	1.46 a
Main effects and interactions						
Cover crop			<0.0001			
Year			<0.0001			
Cover crop x Year			<0.0001			
Cover crop	**Cane weight (g) †**					
	2005	**2006**	**2007**	**2008**	**2009**	**2010**
KY	81 b	54 b	48	63 bc	73 bc	62 ab
AG	85 ab	76 a	52	66 bc	65 bc	53 bc
PG	89 ab	59 b	55	69 bc	76 b	67 a
OG	82 b	53 b	50	73 ab	70 bc	55 bc
EF	85 ab	58 b	49	53 c	63 c	50 c
HS	96 a	82 a	64	81 a	99 a	64 ab
Main effects and interactions						
Cover crop			0.0001			
Year			<0.0001			
Cover crop x Year			<0.0001			
Cover crop	**Crop yield (kg/vine) †**					
	2005	**2006**	**2007**	**2008**	**2009**	**2010**
KY	4.38	7.31 c	3.63	3.77	4.34	3.88
AG	4.89	8.44 a	4.41	4.45	4.82	4.54
PG	4.85	7.79 abc	3.86	4.21	4.92	4.46
OG	4.64	7.54 bc	3.71	4.08	4.31	4.03
EF	4.80	7.78 abc	4.16	4.56	4.21	3.89
HS	4.69	8.32 ab	4.32	3.87	4.45	4.55
Main effects and interactions						
Cover crop			NS			
Year			<0.0001			
Cover crop x Year			NS			

† Means within a parameter and column followed by different letters are significantly different at $P \leq 0.05$ (NS = not significant).

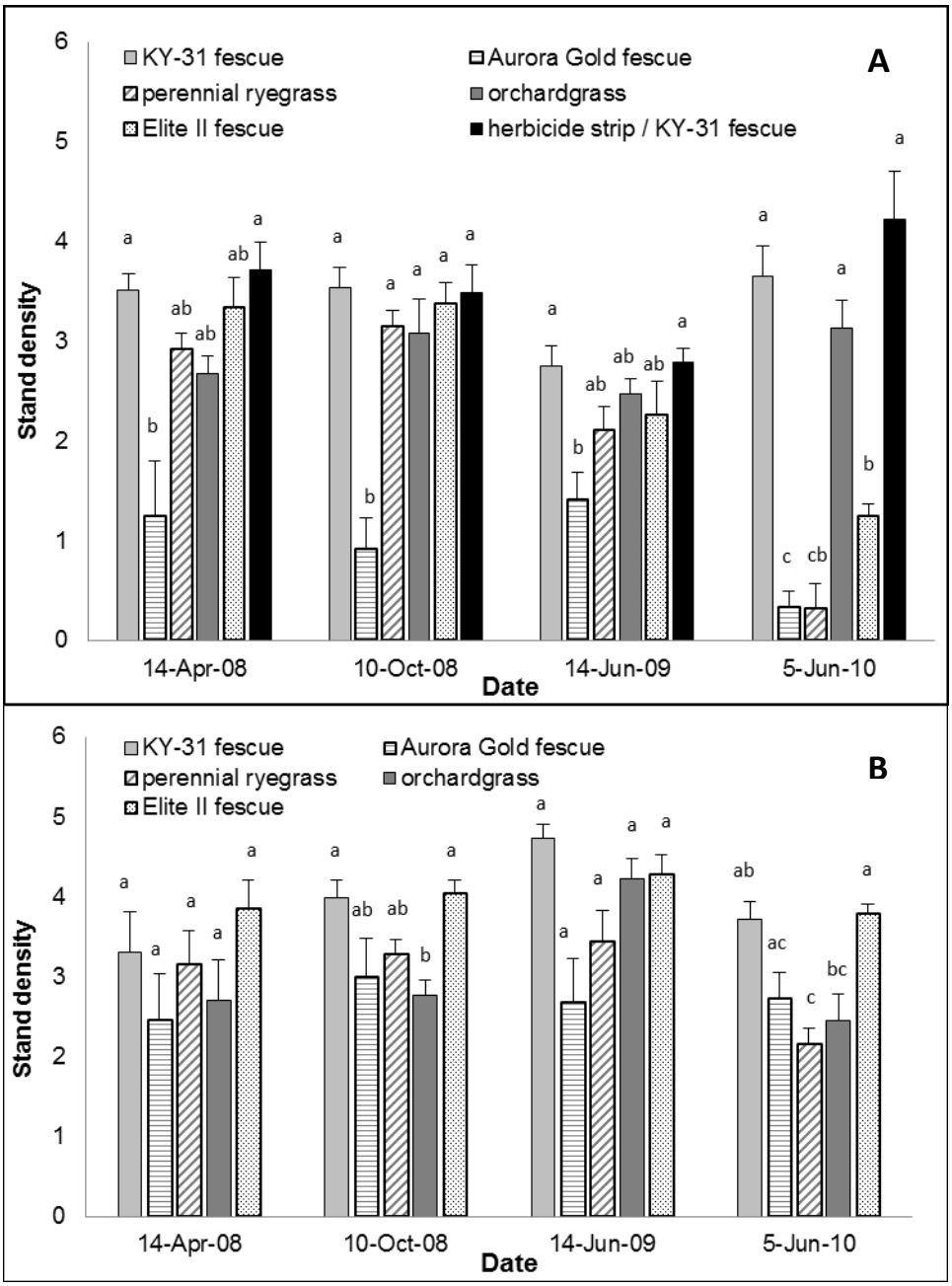


Figure 3.1 Average cover crop stand density ranking (±SE) at interrow (A) and under-trellis (B) locations, measured in April and October 2008, June 2009 and June 2010. Stand density scale adapted from Morris (2000), as follows: 6 = complete stand, 0% invasive plants/bare ground; 5 = < 10% invasive species/bare ground; 4 = 10-25% invasive species/bare ground; 3 = 26-50% invasive species/bare ground; 2 = 51-75% invasive species/bare ground; 1 = 76-100% invasive species/bare ground.

† Herbicide strip treatment excluded; essentially bare soil was not evaluated at the under-trellis location.

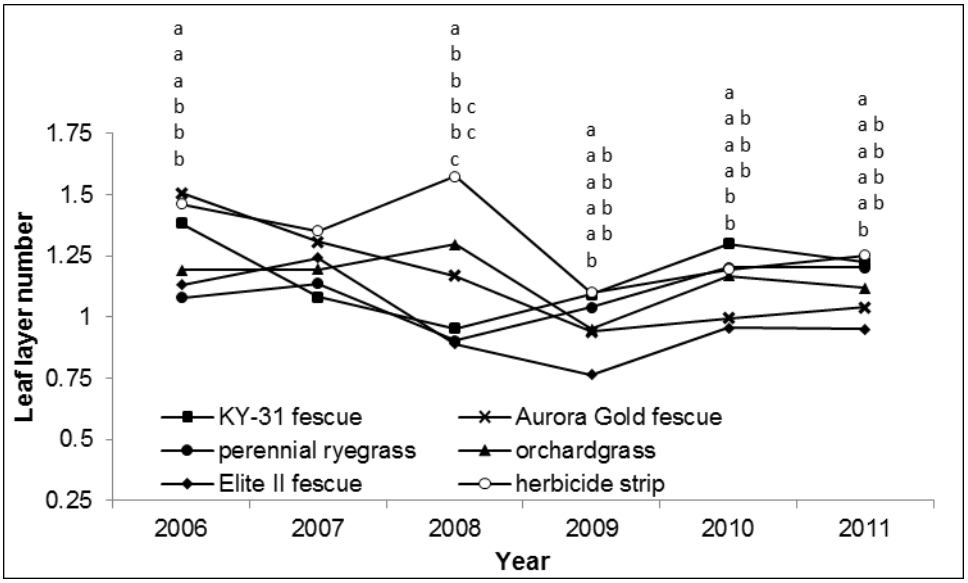


Figure 3.2 Leaf layer number in vines grown with complete vineyard floor cover crop or herbicide strip treatments, 2006 to 2011. Treatment means within each year with same letter do not differ at $P \leq 0.05$.

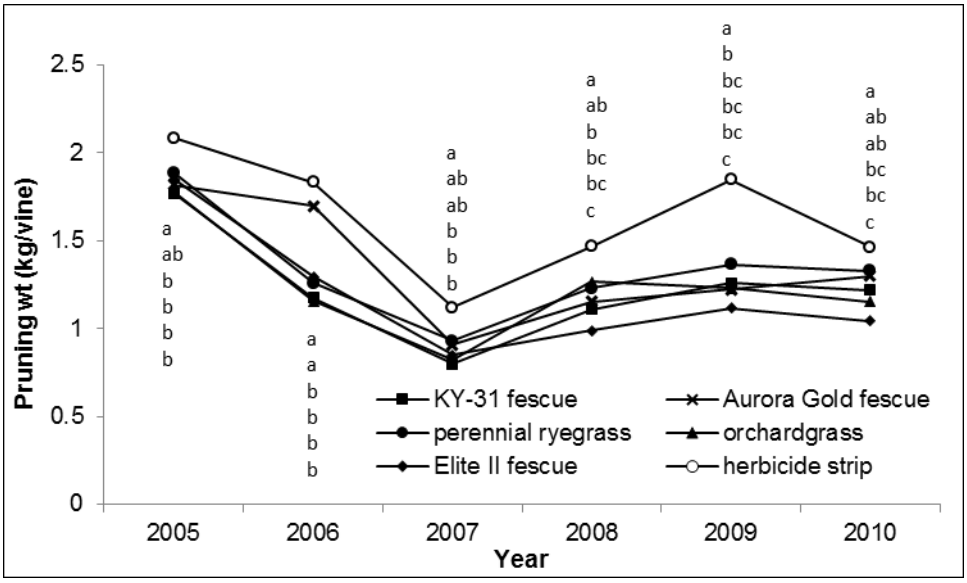


Figure 3.3 Pruning weights of vines grown with complete vineyard floor cover crop or herbicide strip treatments 2005 to 2010. Treatment means within each year with same letter do not differ at $P \leq 0.05$.

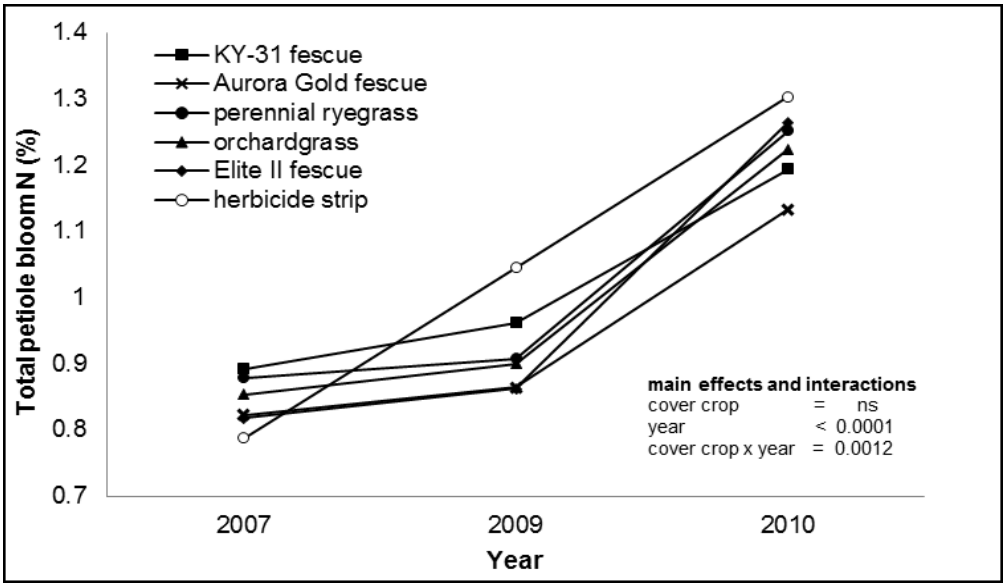


Figure 3.4 Total petiole nitrogen (%) at bloom of vines exposed to complete vineyard floor cover crop or herbicide strip treatments in 2007, 2009 and 2010.

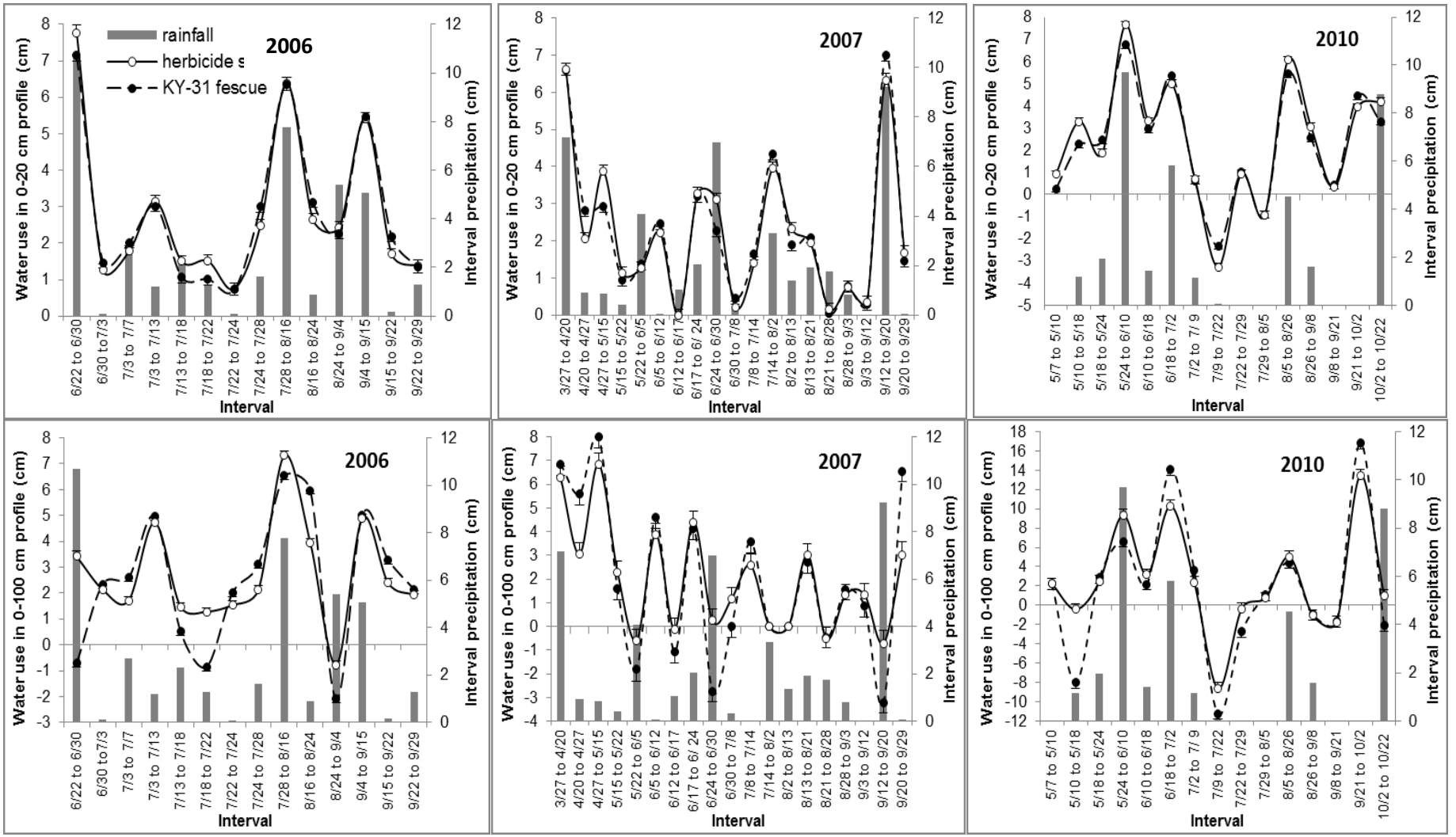


Figure 3.5 Mean (± SE) estimated water use† (cm) as measured with capacitance probe in 0-20 and 0-100 cm depths of the soil profile, under-trellis in KY-31 fescue and herbicide strip in 2006, 2007 and 2010. †Data calculated from the sum of rainfall with soil water depletion (use) determined by difference in readings by capacitance probe at the beginning and end of each period. Negative values indicate an increase in soil water due to rainfall and lack of water use by either the cover crop or grapevine. Run-off, deep percolation beyond 1 m and rise of capillary water were not accounted for.

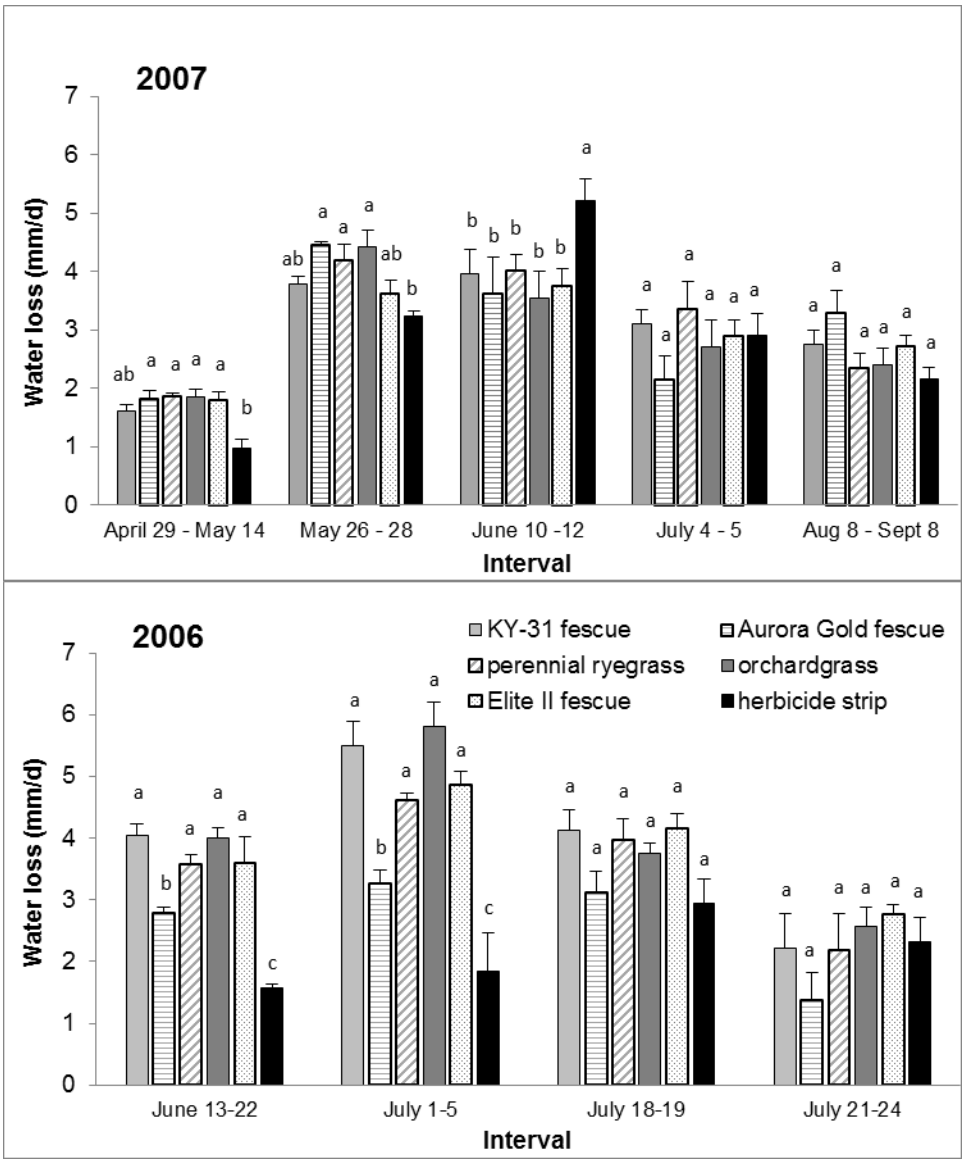


Figure 3.6 Daily water loss (mm/d) for cover crop or herbicide treated soil, measured with mini-lysimeters (MLs) during intervals in 2006 and 2007. Columns within an interval with different letters are significantly different at $P \leq 0.05$. Data are mean values $\pm$ 1 SE (n=6).

Literature Cited

Bates, T.R., and T.K., Wolf 2008. Nutrient Management. In: T.K.Wolf, editor, Wine Grape Production Guide for Eastern North America. NRAES, Cooperative Extension, Ithaca, NY. 141-168.

Bittman, S., B. J. Zebarth, C.G.Kowalenko, and D.E. Hunt. 2004. Season of year effect on response of orchardgrass to N fertilizer in a maritime climate. Can. J. Plant Sci. 84:129-142.

Bremer, D.J., 2003. Evaluation of microlysimeters used in turfgrass evapotranspiration studies using the dual-probe heat-pulse technique. Agron. J. 95:1625-1632.

Burner, D.M., 2003. Influence of Alley Crop Environment on Orchardgrass and Tall Fescue Herbage. Agron. J. 95:1163–1171.

Celette, F., A. Findeling, and C. Gary C. 2009. Competition for nitrogen in an unfertilized intercropping system: The case of an association of grapevine and grass cover in a Mediterranean climate. Eur. J. Agron. 30:41-51.

Celette, F., R.Gaudin, and C. Gary. 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. Eur. J. Agron. 29:153-162.

Centinari, M., S.Poni, I. Filippetti, E. Magnanini, and C. Intrieri. 2009. Evaluation of an open

portable chamber system for measuring cover crop water use in a vineyard and comparison with a mini-lysimeter approach. Agric. For. Meteorol. 149:1975-1982.

Centinari, M., S. Poni, D.S. Intrigliolo, D. Dragoni, and A.N. Lasko. 2011. Cover crop evapotranspiration in a northeastern US Concord (Vitis labruscana) vineyard. Aust. J. Grape Wine Res. 18:73-79.

Centinari, M., I. Filippetti, T. Bauerle, G. Allegro, G. Valentini and S. Poni, 2013. Cover crop water use in relation to vineyard floor management practices. Am. J. Enol. Vitic. 64:522-526.

Cherney, D.J.R., J.H.Cherney and E. A. Mikhailova. 2002. Orchardgrass and tall fescue utilization of nitrogen from dairy manure and commercial fertilizer. Agron. J. 94:405–412.

Costello, M.J., 2010. Grapevine and soil water relations with nodding needlegrass (Nassella cernua), a California native grass, as a cover crop. HortScience 45(4):621-627.

Derr, J.F., 2008. Vineyard Weed Management. In: T.K.Wolf, editor, Wine Grape Production Guide for Eastern North America. NRAES, Cooperative Extension, Ithaca, NY. 262-271.

Geiger, R., R.H.Aron and P. Todhunter. 2009. The Climate near the Ground. 7th ed., Rowman and Littlefield, Lantham, MD. US.

Giese, G., and T. K. Wolf. 2009. Root pruning and groundcover to optimize vine vigor and berry composition in Cabernet Sauvignon grapevines. Abstr. Am. J. Enol. Vitic. 60:551A.

Glenn, D.M., and W.V. Welker. 1989. Orchard soil management systems influence rainfall infiltration. J. Amer. Soc. Hortic. Sci. 114(1):10-14.

Gulick, S.H., D.W. Grimes, D.S. Munk and D. A. Goldhamer. 994. Cover crop enhanced water infiltration of a slowly permeable fine sandy loam. Soil Sci. Soc. Am. J. 58:1539-1546.

Hatch, T.A., C.C.Hickey and T.K.Wolf. 2011. Cover crop, rootstock and root restriction regulate vegetative growth of Cabernet Sauvignon in a humid environment. Am. J. Enol.Vitic. 62:298-311.

Hua Li, Zhu-mei Xi, Yu-lin Fang, and Zhang Zhen-wen. 2005. Effects of grass cover in vineyard on the vine growth and wine quality. Jour. Fruit Sci. 22: 697-701.

Ingels, C.A., K.M Scow., D.A. Whisson and R.E. Drenovsky. 2005. Effects of cover crops on grapevines, yield, juice composition, soil microbial ecology, and gopher activity. Am. J. Enol. Vitic. 56:19-29.

Ingels, C, and K. Klonski. 1998. Historical and current uses. p. 3-8. *In* Ingels, C , R. Bugg, G. McGourty, and P. Christensen (eds.) Cover cropping in vineyards: a grower's handbook. Publication 3338. University of California, Division of Agriculture and Natural

Resources, Davis, California, USA.

Keller, M., M. Kummus, and M. C Vasconcelos. 2001. Soil nitrogen utilisation for growth and gas exchange by grapevines in response to nitrogen supply and rootstock. Aust. J. Grape Wine Res. 7:2-11.

Klute, A., 1986. Water retention laboratory results, *In* Methods of soil analysis. 635-662. Part 1, 2nd ed Agron Monogr 9 ASA and SSSA, Madison, WI.

Littell, R C., G. A.Milliken, W.W. Stroup, R D. Wolfinger, and O. Schabenberger. 2006. SAS® for Mixed Models, Second Edition. Cary, NC: SAS Institute Inc.

Lopes, C.M., A. Monteiro, J.P. Machado, N. Fernandes and A. Araujo. 2008. Cover cropping in a sloping non-irrigated vineyard: II - Effects on vegetative growth, yield, berry and wine quality of 'Cabernet Sauvignon' grapevines. Ciencia Tec. Vitiv. 23:37-43.

Lopes, C.M., T.P.Santos, A.Monteiro, M.L Rodrigues, J.M.Costa and M.M. Chaves. 2011. Combining cover cropping with deficit irrigation in a Mediterranean low vigor vineyard. Scientia Horticulturae 129:603-612.

Malinowski, D.P., J. Kigel and W.K. Pinchak. 2009. Water deficit, heat tolerance, and persistence of summer-dormant grasses in the U.S. southern plains. Crop Sci. 49:2363-2370.

Monteiro, A., and C.M. Lopes. 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agric. Ecosyst. Environ. 121:336-342.

Morlat, R., and A. Jacquet. 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. Am. J. Enol. Vitic. 54:1-7.

Morris, K.N., 2001. A guide to the NTEP turfgrass ratings, http://www.ntep.org/reports/ratings.htm., Accessed [2/10/2013].

NRCS (Natural Resource Conservation Service), United States Department of Agriculture. Web Soil Survey, Surry County, North Carolina, Available online at http://websoilsurvey.nrcs.usda.gov/, Accessed [9/16/2011].

North Carolina Environment and Climate Observing Network (NC ECONet), State Climate Office of North Carolina, North Carolina State University. Available online at http://www.nc-climate.ncsu.edu/econet. Accessed [6/29/2013].

Patrick-King, A.P., and A.M. Berry. 2005. Vineyard d^{15}N, nitrogen and water status in perennial clover and bunch grass cover crop systems of California's central valley. Agric. Ecosyst. Environ. 109:262-272.

Piepho, H.P., 2012. A SAS macro for generating letter displays of pairwise mean comparisons. Communications in Biometry and Crop Science 7: 4-13.

Smart, R.E., and M. Robinson. 1991. Sunlight into Wine: A Handbook for Wine Grape Canopy Management. Winetitles, Pty. Ltd., Adelaide, Australia.

Smith, M.W., M.E. Wolf, B.S. Cheary and B.L. Carroll. 2001. Allelopathy of bermudagrass, tall fescue, redroot pigweed, and cutleaf evening primrose on pecan. HortScience 36:1047-1048.

Smith, R.L., M. Bettiga, M. Cahn, K. Baumgartner, L.E. Jackson and T. Bensen. 2008. Vineyard floor management affects soil, plant nutrition, and grape yield and quality. Calif. Agric. 62(4):184-190.

Soil Science Society of America, 1997. Glossary of soil science terms. SSSA, Madison, WI.

Stork, P.R., and P.H. Jerie. 2003. Initial studies of the growth, nitrogen sequestering, and de-watering potential of perennial grass selections for use as nitrogen catch crops in orchards. Aust J. Agric. Res. 54:27-37.

Sweet, R., and R.P. Schreiner. 2010. Alleyway cover crops have little influence on Pinot noir grapevines (*Vitis vinifera* L) in two western Oregon vineyards. Am. J. Enol. Vitic. 61:240-252.

Tesic, T., M. Keller, and R.J. Hutton. 2007. Influence of vineyard floor management practices on grapevine vegetative growth, yield and fruit composition. Am. J. Enol. Vitic. 58:1-11.

Tworkoski, T.J., and D.M. Glenn. 2001. Yield, shoot and root growth, and physiological responses of mature peach trees to grass competition. Hortscience 36:1214-1218.

Van Huyssteen, L., J.L. Van Syl, and A.P. Koen. 1984. The effect of cover crop management on soil conditions and weed control in a Columbar vineyard in Oudtshoon. S. Afr. J. Enol.Vitic. 5(1):7-16.

Volaire, F., and F. Lelièvre. 2010. Role of summer dormant perennial grasses as intercrops in rainfed Mediterranean Vineyards. Crop Sci. 50:2046-2054.

Wolpert, J.A., P. Phillips, R.K. Striegler, M.V. McHenry and J.H. Foott. 1993. Berber orchardgrass tested as a cover crop in commercial vineyard. Calif. Agric. 47(5):23-25.

CHAPTER IV

EFFECT OF COVER CROP AND ROOT PRUNING TREATMENTS ON SENSORY ANALYSIS OF CABERNET SAUVIGNON

Abstract: Wine aroma and flavor profiles of Cabernet Sauvignon wines associated with complete vineyard floor cover cropping and root pruning vineyard treatments were evaluated using descriptive sensory analysis, hedonic preference tests and solid-phase microextraction (SPME) with gas chromatography-mass spectrometry (GC-MS). Treatments were arranged in a split-plot, randomized, complete block experimental design with vineyard floor management (cover crop schemes) as main plots and annual vine root pruning (RP), or not (NRP), as splitting factors. Cover cropping included: tall fescue (*Festuca arundinacea* Shreb.) 'KY-31', and an under-trellis herbicide strip combined with 'KY-31'fescue interrows, as a conventional floor management scheme. Eleven trained panelists described wine aroma, flavor, texture/mouthfeel and aftertaste attributes. Analysis of variance (ANOVA) revealed wine was not a significant source of variation for any of the 22 attributes used. Wine principal component analysis (PCA) of factor 1 and 2 explained 56% of the total variation. A hedonic preference test revealed no treatment difference in the test wines**.** No treatment differences were perceived by hedonic tests for aroma or consumption. Limited treatment differences detected in chemical compounds by gas chromatography–mass spectrometry (GC-MS) analysis in treatment wines were correlated to descriptive terms developed by sensory analysis.

Introduction

Cabernet Sauvignon (*Vitis vinifera* L.) is a widely recognized commercial wine grape cultivar with a high degree of consumer acceptance and strong winery demand. The variety is planted in a substantial number of vineyards in the mid-Atlantic region of the United States, is relatively resistant to fruit cracking and rot and has an average yield > 3.9 tons per acre (Wolf 1999). However, Cabernet Sauvignon produces excessive vegetative vigor that contributes to increased disease incidence and is associated with reduced berry compositional quality (Smart and Robinson 1991). Growing season water deficits have been connected to red wine grape quality and improvement of sensory attributes of resultant wines (Chapman et al. 2005, Matthews et al. 1990). Therefore, there is interest in aggressive use of cover crops and root pruning to temper vine vigor and optimize berry composition via competition with vines for water and nutrients (Giese et al. 2014).

The commonly measured fruit composition components (Brix, pH and TA) have limited value in the prediction of sensory attributes. The characterization of useful sensory attributes and descriptors and connecting them to measured chemical compounds present or found in a finished wine is logical but largely unexplored. Therefore, making and analyzing wine from vineyard experiments is a requisite step in order to make progress toward the goal of manipulation of sensory attributes via vineyard management (Chapman et al. 2005).

Numerous studies involving sensory profiling and lexicon development of wines exist (Gutierrez Afonso et al. 1998, Mirarefi et al. 2004, Stone et al. 1974). One form of sensory evaluation; descriptive sensory analysis, has been used in viticulture and enology research to determine the impact of various treatments on sensorial features of finished wines (Reynolds et al. 1996) and to develop descriptive terms (Mirarefi et al. 2004). Several studies have examined

the effect of viticultural management and treatments on berry composition of white wine grapes (Peyrot des Gachons et al. 2002). Kelly et al. (2013) used sensory consensus training followed by SPME GC/MS analysis to evaluate wines made from Petit Manseng (*Vitis vinifera* L.) vines that had been subjected to various levels of vineyard applied foliar nitrogen. In that study, sensory data demonstrated treatment differences in intensities of five attributes including: honey aroma and flavor, lemon aroma, and grapefruit and pear flavor. Honey aroma and flavor, and pear flavor were highly influenced by judge. Lemon aroma was influenced by both replicate and judge while grapefruit flavor was highly influenced by both treatment and treatment by judge interactions. In an Indiana study, Skinkis (2006) associated vineyard trellis system effects on monoterpene levels and sensory perception of corresponding Traminette wines. The author determined that trellis systems with a more open and sunlit fruiting zone increased monoterpene levels in the fruit, which in turn, improved the wines made from that fruit. Chapman et al. (2005) used a trained sensory panel to develop different sensory attributes of Cabernet Sauvignon wines made from vines grown with different water status and connected those attributes to different levels of compounds in the wines measured with chemical analysis.

Although the impact of various vineyard cover crops on wine quality has been investigated, there has been minimal examination of wine taste and aroma that is correlated to measured chemical compounds in wines associated with various vineyard manipulations, including cover cropping, in the mid-Atlantic growing region. The study objective was to determine whether root pruning and complete vineyard floor cover crops would differentiate and improve aroma and flavor in wines made from Cabernet Sauvignon under humid growing conditions relative to those wines associated with conventional floor management. A secondary

objective of this study was to identify and quantify chemical compounds associated with articulated sensory attributes.

Materials and Methods

General description and experimental design: The study was conducted using Cabernet Sauvignon (*Vitis vinifera* L.) grapes grown in a commercial North Carolina vineyard (lat. 36°23'3.90"N; long. 80°43'12.20"W). Vines were planted in 1999 on rootstock SO4 (*Vitis riparia* x *Vitis berlandieri*) with 1.83 m intra-row and 2.74 m inter-row spacing. Vines were spur-pruned and cordon-trained, with upright shoots vertically shoot-positioned. The soil at the site is described as a well-drained clay-loam with moderate water–holding capacity and high ability to transmit water (NRCS 2007). The experiment was set up as a split-plot randomized complete block design with six replications of four treatments. Two panels of four vines each made up each main plot replication. Treatments consisted of six replicates of cover crop x root-pruning treatments including (1) KY-31 fescue planted over the entire vineyard floor including under-trellis and (2) 90 cm wide herbicide strip in the under-trellis vine row combined with KY-31 fescue interrows. The floor management main plots were split and root-pruning (RP) or no root-pruning (NRP) applied as subplots.

Harvest and fermentation: After treatment differences in vegetative vigor were measured for several years (Giese et al. 2014), it was decided to make wine from four selected vineyard treatments in the last year of the study (2010) in order to determine if treatment differences would be evident in the resultant wines. Grapes were hand harvested from all six replicates of treatment combinations of KY-31 fescue RP/NRP and herbicide strip RP/NRP on 6 October 2010 at 20 ±1 Brix. Fruit from replicates one and two, three and four, and five and six were

combined to create fermentation replicates: one, two and three, respectively within each of the treatment combinations. Grapes were crushed and de-stemmed separately (Bucher Vaslin E-2 crusher/destemmer, Bucher Vaslin, North America) and each lot distributed into a separate 60 L Nalgene food grade plastic container to create three replicates per treatment for fermentation. All must lots were adjusted to 3.4 pH with tartaric acid and chaptalized with sucrose to ~ 24 to 26^{o} Brix to obtain equal sugar levels in all lots and achieve ~ 12.5 percent alcohol in the finished wines.

Musts were fermented with VIN 13 wine yeast (Scott Laboratories, Petaluma, CA) at a rate of 25 g/100 L, following hydration, as per supplier recommendations and Superfood® (Lesaffre Yeast Co., Milwaukee, WI) was added at a rate of 1 g/3.78 L. Fermentation took place at ~12°C in the plastic containers and was monitored daily by hydrometry. At dryness, on 18 October 2010, the must lots were pressed with a bladder press (BP-80 S/S press, St. Patrick's of Texas) to a pressure of two bars and held for two minutes. Both free run and press fraction wine was racked into 18.9 L gallon glass carboys (Carolina Wine Supply, Yadkinville, NC) and 20 mg/L sulfur dioxide added. After approximately three months, SO_2 levels were adjusted to 0.80 ppm molecular sulfur dioxide and wines were filtered using 0.45 µm pads (Buon Vino® Super Jet Filter, Cambridge, ON, Canada), then bottled into 750 ml glass bottles with natural cork closures (Twin Top® 1+1 corks, Portocork, Napa, CA). Each replication yielded at least 24 bottles each.

Wine chemistries: Samples from each of the 3 carboys per treatment were tested prior to bottling. Residual sugar measured was using AOAC method 920.57. Titratable acidity was measured by titration with 0.1 *N* NaOH, to 8.20 pH endpoint (Accumet® model 15 pH meter, Fisher Scientific, Pittsburgh, PA). Total sulfur dioxide was measured using the aeration/oxidation TTB

official method (SSD:TM:500, revision 3) with revisions for free sulfur dioxide (Zoecklein et al. 1995). Ethanol was measured using AOAC method 920.57 (Cunniff 1995). Samples of the bottled test wines were tested prior to use in sensory analysis (Table 4.1).

Sensory analysis: Lexicon development with subsequent intensity training used a combination of the Spectrum™ Descriptive Analysis method (Meilgaard et al. 2007) and Quantitative Descriptive Analysis method™ (Stone and Sidel 1992). A 15 cm unstructured line scale was used for intensity rating. Eleven panelists were recruited based on interest and availability. Panelists were commercial winemakers, vineyard managers and viticulture and enology students (9 men and 2 women, age range 21 to 56 yrs) all of whom consumed wine on a regular basis. Three four hour training sessions were conducted in July 2011; during the first session terms were generated, using four different commercial 2010 North Carolina Cabernet Sauvignon wines. This provided diversity in aroma, flavor and texture profiles. The last two sessions were devoted to intensity ratings of the terms generated by the panelists.

Panelists completed three sessions and in the first session discussed their impressions of the intensity of the various standards. During the initial training session, panelists generated 52 descriptive terms in the following classes: aroma, flavor-by-mouth, texture/mouthfeel and aftertaste. Aroma was defined as the odor of the wine perceived by the olfactory system (Meilgaard et al. 2007). Flavor-by-mouth was defined as the aromatics perceived by the posterior nares when the wine was held in the mouth (Mirarefi et al. 2004). Texture/mouthfeel was defined as the characteristic identified by tactile senses resulting from expectorating the wine. Mouthfeel was defined as in-mouth sensations (e.g., coating), as opposed to texture in which the perceived sensations are related to the food itself (e.g., firmness) (Mirarefi et al. 2004). Aftertaste was defined as the final flavor or texture impressions immediately after expectorating the wine.

Finish was described in terms of length; a short finish was as one lasting < 10 sec ("low" on line scale), a medium finish 10 to 30 sec (middle of line scale), and a long finish > 30 sec ("strong" on line scale). Panelists defined the descriptors generated, agreed upon and identified possible references for the terms. Panelists used an open discussion to eliminate terms that were either present in low concentrations or those that were present in most wines at uniform levels of intensity (Mirarefi et al. 2004). Finally, the panelists reached consensus for 22 descriptive attributes; eleven aroma attributes, ten flavor-by-mouth attributes, two texture attributes, and aftertaste attributes were used in the assessment (Table 4.2).

During the final two sessions, results were not discussed. A neutral base wine (Paul Masson Cabernet), presented in 60-ml plastic cups with lids at room temperature, was used to produce aroma, flavor-by-mouth, texture/mouthfeel and aftertaste references for the terms generated. Reference standards were prepared for each of the 22 attributes in varying intensities (low, medium and high). The rinsing protocol recommended by Mirarefi et al. (2004) was utilized as follows: chewing unsalted oyster crackers (The Kroger Company, Cincinnati, OH), followed by rinsing with warm spring water (40°C) and room temperature spring water (22°C). All samples were expectorated.

The panelists used a 15-cm line scale to rate the intensity of attributes by marking the line in relation to the perceived intensity of that term. The scale had the end-word anchor of "low" at the left end of the scale and the word "strong" at the right end of the scale, 1.0 cm from the terminus (Anderson 1970, Meilgaard et al. 2007, Stone and Sidel 1992). Reference standards were available for panelists to utilize if needed. Samples were presented as described above. An unstructured scale of 0 to 15 was used with 1 being "low" and 14 being "strong." These panelist-generated lines were later individually measured and values entered for analysis.

Following sensory analysis, the four test wines were subjected to a hedonic preference test for aroma and flavor. Over two consecutive days in April 2012, 120 students from Wines and Vines class (Virginia Tech, Blacksburg, VA) evaluated the experimental Cabernet Sauvignon wines in individual booths with white lighting in the Food Science Sensory Lab (Virginia Tech, Blacksburg, VA). The gender of each panelist was recorded and each was served the four treatment wines in duplicate. The four treatment wines were served at two separate seatings, with a 30 min rest in between. A portion (333 ml) of each of the three replicate wines of each treatment was combined to obtain the test wine for that treatment. This preserved the amount of experimental wine for further sessions. Wines were served in ISO glasses covered with plastic lids. Each glass received 60 ml of wine, coded with a three-digit random number, and served at room temperature (22°C). The rinse protocol detailed above was used for all sessions. All samples were expectorated. In these two sessions, four experimental wines, three replications each, were evaluated on a scale of 1 to 9, with 1 indicating 'extremely dislike' to 9 indicating 'exremely like' and experimental data was collected.

GC-MS: GC-MS analysis was performed in 2014 on triplicate wine samples collected from finished 2010 treatment wines that had been stored at 18^{o} C. Wine samples (4 ml) for GC-MS were prepared with 1.0 g NaCl in 10 ml glass vials sealed with a septa top (MicroLiter® Analytical Supplies, Inc., Suwanee, GA). Pre-incubation time was 30 seconds at 30°C with vials agitated at 250 rpm. A CAR/DVB/PDMS grey SPME fiber (Supelco Sigma-Aldrich, St. Louis, MO) penetrated the vial at a 32 mm depth into the headspace and was equilibrated for 30 min. The SPME fiber was injected into a 6890N Network GC System, 5975B inert MSD GC-MS (Agilent Technologies, Santa Clara, CA). The fiber was desorbed for 90 seconds with an inlet temperature of 250°C into a DB-Wax column (30 m x 2 mm). Helium carrier gas flow rate was 1

mL/min. Initial oven temperature was 40°C, ramped at 6°C/min to 230°C. To assess the influence of the isolated compounds on aroma, odor activity values (OAVs) were determined by dividing the concentration of each compound by its sensory perception threshold. Those compounds with OAVs greater than one may contribute to the aroma (Guth 1997). GC-MS analysis was provided by Department of Food Science and Technology, Enology Group, Molly Kelly PhD, Enology Extension Specialist, Duck Pond Drive, Virginia Tech, Blacksburg, VA 24061.

*Statistical analysis***:** The four treatment wines were analyzed using ANOVA with SAS (version 9.3, SAS Institute, Cary, NC). Attributes that differed were further analyzed using least significant difference (LSD) and Student's t-test procedures (α=0.05). Multivariate analyses, correlation analysis, and principal component analysis (PCA) were conducted using SAS (version 9.3, SAS Inst.).

Results and Discussion

Initially over 50 terms were generated by the panel to describe the treatment wines. These attributes were reduced to 22 and reference standards developed by the panel were provided for each, after discussion and consensus by the panel (Table 4.2). The frequency (%) and intensity (%) of generated aroma attributes did not differ when applied for all four treatment wines (Figure 4.1 and Figure 4.2). The ANOVA results of the 22 sensory attributes rated for the experimental Cabernet Sauvignon wines indicate that judges were a significant source of variation for only seven of 22 attributes: wood chip, strawberry, alcohol, black pepper, black cherry, cherry and sour (Table 4.3). With the exception of wood chip and raisin there was no significant source of variation in the replication of the samples. Wine was not a significant

source of variation for any of the 22 attributes, thus vineyard floor management and root pruning were inconsequential to the sensory attributes.

The hedonic preference test did not reveal treatment differences for flavor and aroma, possibly indicating that vintage effects masked any potential differences in the wines or that the experience level of panelists used for this test did not allow for perception of differences in the test wines (Figure 4.3). However, the lack of treatment differences in frequency (%) and intensity (%) of aroma attributes substantiated the lack of hedonic preference differences.

Despite the lack of significant differences in sensory attributes or in hedonic preference due to wine treatments, PCA analysis was performed to determine any clustering or association between attributes (Figure 4.4) and to visualize relationships of the attributes to the component chemical compounds measured in the wine with GC-MS procedures. PC I explained 33.6% of the variance, whereas PC II explained 22.8% of the variance, for a total of 56.4% of the variation of the data represented in the biplot. Examination of the loading factors (Table 4.4) reveals how the attributes group together. PC I contrasted wines perceived to have cherry, black cherry, rose petals, cocoa/chocolate, black currants, anise, clove, butterscotch and walnut with wines that indicated bell pepper, green grass, green bean and asparagus. PC II separated wines perceived high in bell pepper, green grass, green bean, asparagus and wood chip with those perceived to be high in raisin, alcohol, black pepper, cocoa/chocolate, black currants and butterscotch attributes. It is apparent from the PCA plot (Figure 4.4) that PC I may explain a substantial amount of the variability because the largest cluster of attributes were found on this factor. Further illustration of the various sensory attributes' occurrence in the treatment wines is provided (Figure 4.5 and Figure 4.6).

The GCMS data (Table 4.5) suggested significant treatment differences in some wine aroma and flavor volatiles. Significant differences were observed in a number of alcohol compounds. For example, phenethyl alcohol in herbicide strip was different from wines made from vines exposed to KY-31 fescue. Although all treatments had odor activity values (OAVs) >1, KY-31 fescue demonstrated the highest amount. Compounds with OAVs greater than one may contribute to the overall aroma of the wine samples analyzed in this study. Phenethyl alcohol contributes rose, lilac, spice and honey notes. Because vines subjected to root pruning had relatively lower levels of petiole N (Giese et al. 2014), it is reasonable that those vines may have had less nitrogen to dedicate to the formation of the amino acid derived compounds (Francis and Newton 2005). Significant differences were evident between herbicide strip/RP and KY-31 fescue/RP for the compound n-hexanol. All values exceeded the OAV of 1, with wine associated with the herbicide strip/RP wine having the highest amount of the compound. This alcohol contributes resin and green aromas/flavors to wine (Villamor and Ross 2013). Green aromas/flavors are generally associated with perceived lower quality. The final difference in alcohol compounds was observed in 1-octanol. KY-31 fescue/RP was different from the other treatments and again as it contained the highest value. Pleasant and sweet are descriptors used for 1-octanol and likely contributed to the perception of strawberry aroma that was proximal to this alcohol in the corresponding PCA biplot (Figure 4.4). It is interesting that both strawberry and alcohol aroma descriptors were significantly greater for wines associated with KY-31fescue/RP relative to other treatments especially that of the herbicide strip/NRP (Figure 4.5). However, there were no treatment differences for taste by mouth of these descriptors of any others articulated in the study (Figure 4.6).

It appears that KY-31 fescue/RP also had an effect on higher alcohols in this variety. In grape must with relatively low nitrogen, surplus alpha-keto acids (made mostly from sugars) form higher alcohols, due to the shortage of alpha-nitrogen levels needed for amino acid synthesis (Vilanova et al. 2007). This is supported by YAN levels observed in must made from vines exposed to KY-31 fescue/RP that were 31% lower than those YAN levels in musts of from vines grown with the herbicide strip/NRP (Giese et al. 2014).

One terpene showed significant differences among treatments; terpinene-4-ol levels were similar in both KY-31 fescue/RP and NRP, but were highest in herbicide strip/NRP wines. No other differences were observed in terpene content among treatments. This compound is the active ingredient in tea tree oil and is the compound of highest concentration in essential oil of nutmeg; it has peppery and mildly earthy tones (Leffingwell.com).

Esters showed the most treatment differences. For instance, ethyl decanoate levels were lowest in KY-31 fescue/RP compared to other treatments. This compound lends aromas/flavors of flowers to wine (Genovese et al. 2007). Ethyl nonanoate was also lowest in KY-31 fescue/RP; however, no treatment values were above the OAV. Hexyl acetate was lowest in KY-31 fescue/RP compared to other treatments, but all had OAVs >1. Hexyl acetate contributes fruity, green apple and herb notes (www. flavornet.com). The only remaining esters that showed differences among treatments and were lowest in KY-31 fescue/RP wines were isoamyl octanoate and ethyl dodecanoate. However, levels across treatments did not exceed OAVs of >1. Perhaps when assimilable nitrogen is not limited, amino acids may be utilized for alternative processes that do not involve formation of these compounds.

In contrast, the ester isoamyl acetate was higher in KY-31 fescue/RP than other treatments. All values had OAVs>1. Isoamyl acetate has banana aroma/flavor (Palomo et al.

2007). Due to generally lower levels of tissue nitrogen levels when root pruning is imposed, it is unclear how these vines could harbor increased levels of amino acids in this instance. These differences may be due to soil or climatic conditions that influenced vine nitrogen levels at critical compound accumulation times such as veraison and post-veraison. Diethyl succinate was also increased in KY-31 fescue/RP; however, all OAV values were less than one. The same was true for ethyl myrsitate and ethyl palmitate values. Phenethyl acetate showed differences among treatments with KY-31 fescue/RP having increased levels relative to levels in other treatments. All treatments had OAVs greater than one. Phenethyl acetate has rose and fruity notes that it contributes to wine (Genovese et al. 2007).

Fatty acid compounds that showed differences among treatments included decanoic acid (highest in KY-31 fescue/RP) but OAVs were less than one. The same was true for nanoic acid. Hexanoic acid and octanoic acid both showed differences among treatments. Again KY-31 fescue/RP had increased values compared to other treatments. All treatment values were above an OAV of one. Both of these compounds have fatty and cheese-like attributes (Lopez et al. 2004) possibly indicative of a treatment difference.

Some differences were observed in the aldehyde/ketone compounds. Trans-2-cis-6-nonadienal, octanal and decanal all showed differences, with KY-31 fescue/RP having consistently higher values. All treatment values were, however less than one for the OAV. The OAVs for nonyl aldehyde were all greater than one. The highest value was found in KY-31 fescue/NRP, followed by similar values for KY-31 fescue/RP and herbicide strip/RP. This result may indicate that nitrogen is not the only factor in determining aroma and flavor content and that vine water status, although not indicative of accepted stress levels, played a role in compound synthesis. Nonyl aldehyde has a fruity, floral, waxy odor (flavornet.com).

No differences were observed in beta-damascenone although all treatment values had OAVs above one. On the other hand, gamma butyrolactone showed differences among treatments with the highest value observed in KY-31 fescue/RP. Gamma-butyrolactone has caramel, buttery notes associated with it (Toci et al. 2012).

Wine and juice aromas and flavors result from many interactions among a large number of compounds. Compounds interact and combine, displaying synergistic (one compound enhances the perception of another) and antagonistic (one compound suppresses perception of another) interactions (Gustav et al. 2011) or masking effects. Interactions of individual compounds influence and can determine the overall aroma and flavor of wine without being recognized at their individual OAV (Etievant 1991). Aroma and flavor compounds in mixtures almost always show reciprocal suppression in which each compound decreases the perceived intensity of the others (Laing et al. 1984). Some aroma and flavor increases may be due to volatiles binding to proteins, resulting in a decrease in their suppressive effect on other free volatiles (Jones et al. 2008).

Conclusions

Wine aroma and flavor profiles of Cabernet Sauvignon made from vines associated with the cover crop KY-31 fescue (*Festuca arundinacea* Shreb) or herbicide strip both with and without root pruning vineyard treatments were evaluated using descriptive sensory analysis, hedonic preference test and solid-phase microextraction (SPME) with gas chromatography-mass spectrometry (GC-MS). Twenty-two sensory attributes were generated and did not differ in frequency or intensity between wines as applied by the panel. Hedonic preference testing for flavor and aroma did not differ by treatment. Wine sensory attributes were not affected by

treatment, yet, some treatment differences in chemical compounds were detected with GC-MS analysis and some correlation back to articulated sensory attributes via these chemical compounds was accomplished. Although wines were made from a single vintage, the results suggests an initial, portfolio of compounds to compare to other similar vineyard studies that may affect wine sensory attributes and quality perception of Cabernet Sauvignon.

Table 4.1 Analysis of 2010 Cabernet Sauvignon wines associated with KY-3 fescue/RP, NRP or Herbicide strip/RP, NRP, 2010[a].

Cover crop Root pruning[a]	Residual sugar (%)	pH	Alcohol (%)	Free SO_2 (ppm)
KY-31 fescue				
RP	0.3	3.71	13.9	46
NRP	1.0	3.55	13.6	35
Herbicide strip				
RP	0.3	3.52	13.6	40
NRP	0.6	3.47	13.3	31

[a] analysis results represent average of 3 replications of each wine tested on 18 July 2011

Table 4.2 Attributes, definitions, and references of Cabernet Sauvignon test wines associated with KY-31 fescue/RP, NRP or Herbicide strip/RP, NRP, 2010:

Aroma/flavor	Black pepper[a]	Black pepper aroma associated with fresh ground pepper. 1 teaspoon fresh ground pepper.
	Black cherry[a]	Black cherry aroma associated with associated with commercial black cherry jam
	Blackberry[a]	Blackberry flavor/aroma associated with commercial blackberry jam
	Canned cherry[a]	Cherry flavor/aroma associated with canned bing cherries
	Canned Asparagus[a]	Flavor/aroma with canned asparagus.
	Canned green bean[a]	Flavor/aroma with canned green bean
	Canned black currant[a]	Flavor/aroma with canned black currants
	Walnut[a]	Flavor/Aroma associated with English walnuts
	Spice[a]	Aroma associated with allspice.
Flavor by Mouth	Tobacco	Aroma elicited by fresh flue cured tobacco, leaves obtained from local grower.
	Sour	Fundamental taste sensation No reference.
	Butterscotch	Flavor/aroma associated with butterscotch candy.
	Bell pepper[a]	Flavor/aroma associated with green bell peppers. Portion freshly squeezed and diluted in base wine.
	Wood chips[a]	Flavor associated with fresh oak chips soaked in 750 ml of base wine
	Rose[a]	Flavor associated with fresh rose petals. 2-6 petals of rose (0.25 mL linalool + 0.5 mL geraniol in 100 mL diH_2O - spike one ml of solution into base wine.
	Raisin/prune[a]	Flavor/aroma associated with prune juice diluted in base wine.
	strawberry[a]	Flavor/aroma associated with 2-6 fresh strawberries crushed and diluted in base wine.
	Anise[a]	Flavor/aroma associated with commercial anise flavored candy diluted into base wine
	Green grass[a]	Aroma associated with cut and partially dried turf grass
	Cloves	Flavor/aroma associated with cloves soaked in base wine
	Cocoa powder	Flavor/aroma associated with cocoa powder mixed into base wine
	Alcohol	Flavor/Aroma associated with Everclear® diluted into base wine

[a]Reference was prepared in base wine: Cabernet Sauvignon (Paul Masson, Madera, CA).

Table 4.3 Significance levels (*P*-values) from analysis of variance for descriptive ratings of attributes of Cabernet Sauvignon wines made from grapevines exposed to KY-31 fescue/RP, NRP or Herbicide strip/RP, NRP, 2010.

Attribute	Judge	Wine	Rep	J x W	J x R	W x R
butterscotch	0.2556	0.2462	0.0667	0.4071	0.2961	0.3673
bell pepper	0.2083	0.8011	0.9857	0.9777	0.6859	0.7793
wood chip	**0.0452**	0.5912	**0.0462**	0.4994	**0.0445**	0.7131
rose petals	0.7894	0.709	0.7846	0.7629	0.6148	0.8264
raisins	0.2341	0.1467	**0.0285**	0.9421	0.1393	0.1072
strawberry	**0.0230**	0.9553	0.6055	0.6616	0.8649	0.8117
anise	0.1251	0.9457	0.5787	0.876	0.5845	0.6662
green grass	0.4208	0.5427	0.534	0.5136	0.4239	0.5701
cloves	0.1938	0.7658	0.9033	0.7134	0.8867	0.6574
cocoa/chocolate	0.0673	0.3411	0.2461	0.0628	0.1619	0.1442
alcohol	**0.0417**	0.6732	0.2407	0.9367	0.2672	0.5909
black pepper	**0.0312**	0.4846	0.4042	0.3629	0.876	0.5918
black cherry	**0.0340**	0.1213	0.0929	0.0617	0.4713	0.164
blackberry	0.1891	0.9952	0.8869	0.6433	0.8281	0.9355
cherry	**0.0134**	0.5382	0.6449	0.2198	0.5383	0.7641
asparagus	0.1551	0.8132	0.8644	0.7956	0.8536	0.6509
green beans	0.1172	0.5401	0.8326	0.643	0.7474	0.526
black current	0.5272	0.7481	0.1433	0.7146	0.2757	0.7187
walnut	0.529	0.6327	0.6698	0.6905	0.5573	0.684
spice	0.2599	0.6901	0.3794	0.6591	0.6075	0.8044
sour	**0.0161**	0.4982	0.177	0.2424	0.3122	0.1393
tobacco	0.5858	0.7119	0.5599	0.4393	0.3175	0.4393

F ratios are shown for sources of variation. Values in boldface indicate significance at $P < 0.05$ Replications denoted as Rep. J x W, J x R, W x R indicate judge by wine interaction, judge by replication interaction, and wine by replication interaction respectively.

Table 4.4 Factor loadings of the aroma attributes on PCs I and II for Cabernet Sauvignon wine data.

Attribute	**PC I**	**PC II**
cherry	0.28	0.20
strawberry	0.06	0.17
raisins	0.16	-0.28
black cherry	0.26	0.09
alcohol	0.10	-0.21
black pepper	0.10	-0.21
bell pepper	-0.08	0.30
rose petals	0.36	0.06
cocoa chocolate	0.28	-0.13
blackberry	0.11	0.04
spice	0.25	0.10
tobacco	0.09	0.04
green grass	-0.15	0.25
butterscotch	0.29	-0.17
anise	0.28	0.19
cloves	0.27	0.19
black currants	0.30	-0.17
wood chips	0.20	0.28
asparagus	-0.13	0.32
green bean	-0.14	0.33
walnut	0.29	0.19
sour	-0.03	-0.33

Table 4.5 Effect of cover cropping scheme and root pruning (RP) or non-root pruning (NRP) on free aroma compounds ug/L in 2010 Cabernet Sauvignon wine (n = 3).

Compound	Odor threshold (ug/L)	Vineyard treatment				*P*-value
		Herbicide strip RP	Herbicide strip NRP	KY-31 fescue NRP	KY-31 fescue RP	
Alcohols						
1-octen-3-ol	NA[e]	13.74±0.16 a[a]	11.78±0.09 a	14.93±0.32 a	11.18±0.58 a	0.5849
1-propanol	9000[f]	3560.00±0.17 a	4893.33±0.09 a	6043.33±0.24 a	4883.33±0.31 a	0.5694
2-ethyl-1-hexanol	270000[f]	1178.48±0.003 a	1174.95±0.00 a	1172.48±0.01 ab	1144.55±0.02 b	0.0813
benzyl alcohol	200,000[g]	697.72±0.17 a	859.60±0.18 a	878.19±0.18 a	1048.34±0.19 a	0.2192
n-butanol	500[d]	5296.67±0.06 a*	5496.67±0.02 a*	5723.33±0.11 a*	5556.67±0.05 a*	0.7103
phenethyl alcohol	750[g]	288816.67±0.08 c*	347143.33±0.13 bc*	417710.00±0.15 ab*	491866.67±0.18 a*	0.027
2-methyl propanol	40000[c]	2703.33±0.26 b	3836.67±0.16 b	4173.33±0.47 b	18040.00±0.50 a	0.0177
3-methyl butanol	30000[c]	345380.00±0.15 a*	515110.00±0.14 a*	594073.33±0.53 a*	577416.67±0.21 a*	0.415
n-hexanol	8000[c]	10496.67±0.05 b*	14143.33±0.12 ab*	17350.00±0.55 ab*	26693.33±0.25 a*	0.0984
1-octanol	110-130[b]	680.16±0.15 b*	875.13±0.17 b*	885.04±0.32 b*	1899.25±0.28 a*	0.0038
Terpenes						
citronellol	100[c]	39.77±0.93 a	40.60±0.03 a	56.10±0.37 a	52.69±0.24 a	0.6924
linalool oxide isomer 2	NA[e]	0.06±0.17 a	12.53±1.72 a	0.07±0.13 a	0.07±0.86 a	0.4556
linalool	15[c]	1.59±0.87 a	2.92±0.20 a	4.37±0.45 a	4.37±0.22 a	0.1814
p-cymene	NA[e]	20.28±0.00 a	20.28±0.00 a	20.27±0.001 a	20.27±0.001 a	0.73

terpinene-4-ol	110-400[i]	83.58±0.10 b	197.53±0.48 a*	150.35±0.22 ab*	148.13±0.26 ab*	0.1609
a-terpineol	350[g]	52.74±0.55 a	58.75±1.08 a	103.58±0.68 a	114.71±1.09 a	0.4249
Esters						
ethyl decanoate	200[f]	412.68±0.15 a*	376.13±0.00 a*	537.69±0.38 a*	129.71±0.53 b	0.0084
ethyl lactate	>1000[i]	8.62±0.19 a	11.41±0.13 a	24.95±0.98 a	13.32±0.11 a	0.4508
ethyl nonanoate	850[g]	8.26±0.67 a	5.75±0.17 a	6.81±0.07a	2.39±0.33 b	0.0166
hexyl acetate	2[b]	174.60±0.39 a*	117.67±0.00 a*	188.40±0.27 a*	2.30±0.11 b*	0.0055
methyl salicylate	40[h]	10.91±0.02 a	10.51±0.09 a	10.20±0.05 a	10.29±0.13 a	0.6413
iosamyl acetate	30[c]	292.38±0.30 b*	966.29±0.34 b*	760.95±0.17 b*	1803.77±0.50 a*	0.0193
ethyl heptanoate	2.2[d]	1102.84±0.001 a*	1103.47±0.00 a*	1098.55±0.01 a*	1095.57±0.01 a*	0.5157
ethyl octanoate	2[g]	4346.69±0.15 a*	3699.71±0.08 a*	4816.50±0.33 a*	3423.90±0.58 a*	0.4665
iosoamyl octanoate	125[f]	18.29±0.03 ab	14.37±0.34 bc	18.49±0.24 a	12.73±0.09 c	0.0288
diethyl succinate	200,000[g]	1410.75±0.02 b	1424.05±0.00 b	1360.45±0.06 b	1517.38±0.02 a	0.0084
phenethyl acetate	250[c]	2201.38±0.35 b*	2818.81±0.27 b*	2983.23±0.24 ab*	4319.73±0.16 a*	0.0595
ethyl dodecanoate	5900[h]	36.14±0.07 a	32.27±0.03 ab	29.79±0.16 b	1.51±0.68 c	<0.0001
ethyl myristate	2000[i]	11.50±1.73 b	0.00 b	0.00 b	51.82±0.55 a	0.0509
ethyl palmitate	>2000[b]	8.85±1.73 b	0.00 b	0.00 b	495.93±0.08 a	<0.0001
Fatty acids						

2-ethylhexanoic acid	NA[e]	0.41±0.07 a	0.43±0.02 a	0.32±0.63 a	0.27±0.11 a	0.2367
benzoic acid	NA[e]	0.00 a	0.02±1.50 a	0.00 a	0.2±0.04 a	0.3636
decanoic acid	10,000[h]	1383.33±0.07 b	1333.33±0.04 b	1266.67±0.17 b	2666.67±0.19 a	0.0042
dodecanoic acid	10000[h]	0.013±1.54 a	0.00 a	0.013±1.54 a	1526.71±1.73 a	0.4547
hexanoic acid	3000[h]	5626.67±0.08 b*	4960.00±0.11 b*	7356.67±0.17 b*	12320.00±0.24 a*	0.0078
isovaleric acid	120-700[f]	14383.33±0.06 a*	15383.33±0.07 a*	14160.00±0.15 a*	13896.67±0.02 a*	0.6218
myristic acid	NA[e]	0.24±0.38 a	0.23±0.26 a	0.25±0.12 a	0.30±0.40 a	0.6767
nonanoic acid	3000[b]	0.00 b	0.00 b	0.00 b	1.20±0.35 a	0.001
trans-2-hexenoic acid	NA[e]	0.41±0.07 a	0.43±0.02 a	0.32±0.63 a	0.27±0.11 a	0.2367
octanoic acid	3000[b]	61056.67±0.23 b*	84216.67±0.21 b*	94570.00±0.34 b*	151556.67±0.22 a*	0.009
Aldehydes /ketones						
2-acetylfuran	10,000[d]	0.03±0.10 a	0.03±0.33 a	0.05±1.20 a	0.05±0.20 a	0.6631
benzaldehyde	350[f]	2.56±0.14 a	1.23±0.10 b	2.58±0.33 a	1.71±0.39 ab	0.0299
decanal	NA[e]	0.06±0.17 b	0.07±0.14 b	0.07±0.43 ab	0.16±0.44 a	0.0813
furfural	NA[e]	1.03±0.12 a	1.10±0.06 a	1.42±0.25 a	1.31±0.32 a	0.3442
hexanal	NA[e]	0.00 a	0.06±1.83 a	0.00 a	0.03±1.00 a	0.5173
nonyl aldehyde	1[h]	38.41±0.75 ab*	11.86±0.87 b*	69.21±0.63 a*	35.74±0.19 ab*	0.1037
octanal	NA[e]	0.00 b	0.00 b	0.05±1.20 ab	0.08±0.13 a	0.0284
trans-2-cis-6-nonadienal	NA[e]	2.05±0.15 b	1.83±0.01 b	1.51±0.76 b	3.59±0.20 a	0.0259

trans-2-nonenal	NA[e]	0.09±0.33 a	0.06±0.17 a	0.12±0.67 a	0.09±0.22 a	0.4529
C-13 norisoprenoids						
beta-damascenone	0.05[c]	188.04±0.11 a*	119.49±0.38 a*	189.87±0.44 a*	134.92±0.09 a*	0.3573
Lactones						
gamma-butyrolactone	500[h]	0.38±0.05 b	0.33±0.03 b	0.48±0.23 b	33666.67±0.40 a*	0.0018

[a] Different letters within rows indicate significant differences at $p<0.05$ (t-test, LSD)
[b] Odor detection threshold determined in water from Leffingwell & Associates Database
[c] Odor detection threshold determined in water (Ohloff 1978)
[d] Odor recognition threshold determined in 90% water and 10% ethanol (Guth1997)
[e] NA indicates threshold level is not available
[f] Odor detection threshold determined in water from Chemadvisor website (http://chemadvisor.com)
[g] Odor detection threshold determined in water from Good Scents Company website (http://thegoodscentscompany.com)
[h] Odor thresholds calculated in a 11% water/ethanol solution (Ferreira et al. 2000)
[i] Thresholds calculated in wine solution (Etievant 1991)
* = odor activity value (OAV) >1

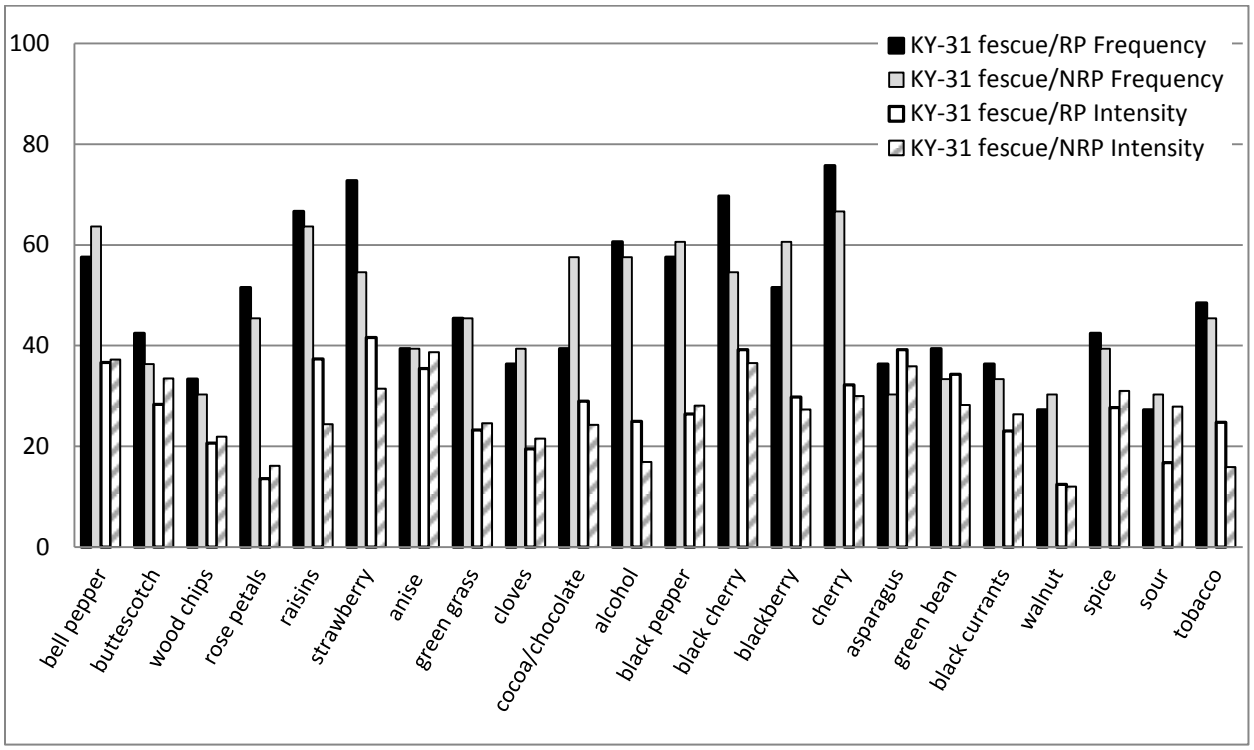


Figure 4.1 Intensity (%) and frequency (%) of aroma descriptors for wines from vines exposed to KY-31fescue/RP (n=3), KY-31fescue/NRP (n=3), 2010.

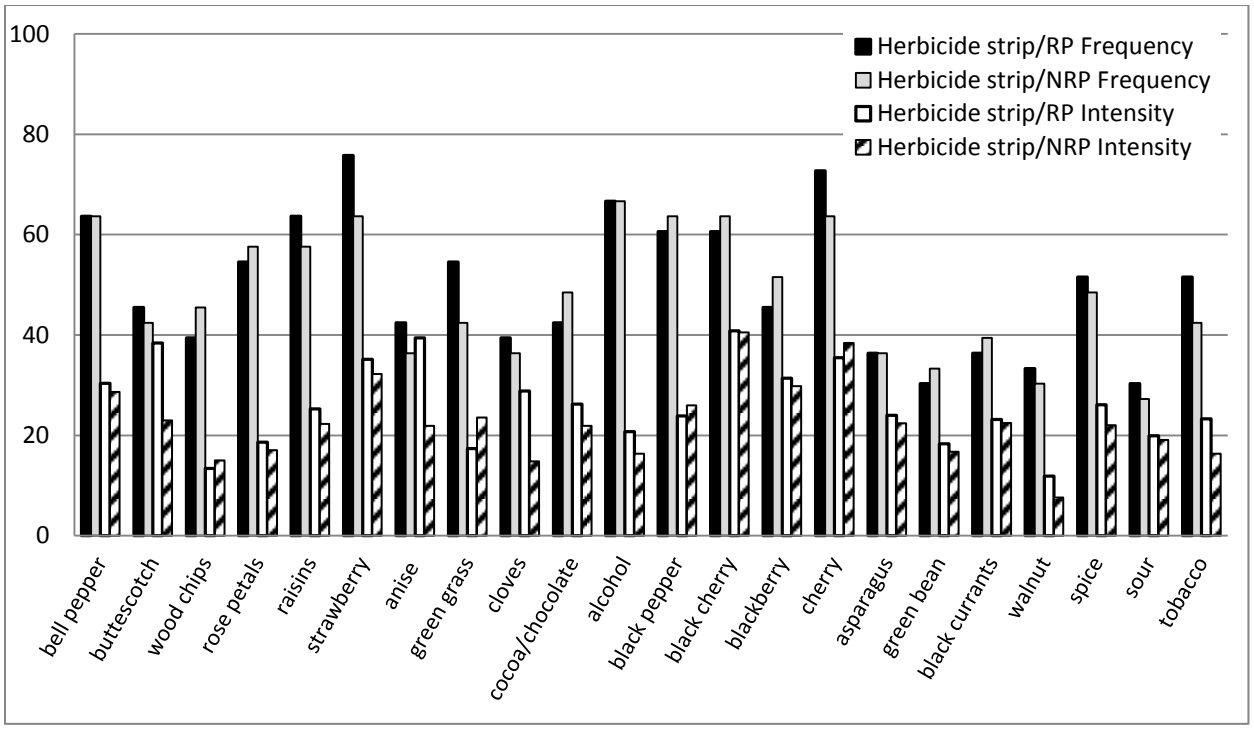


Figure 4.2 Intensity (%) and frequency (%) of aroma descriptors for wines from vines exposed to Herbicide strip/RP (n=3), Herbicide strip/NRP (n=3), 2010

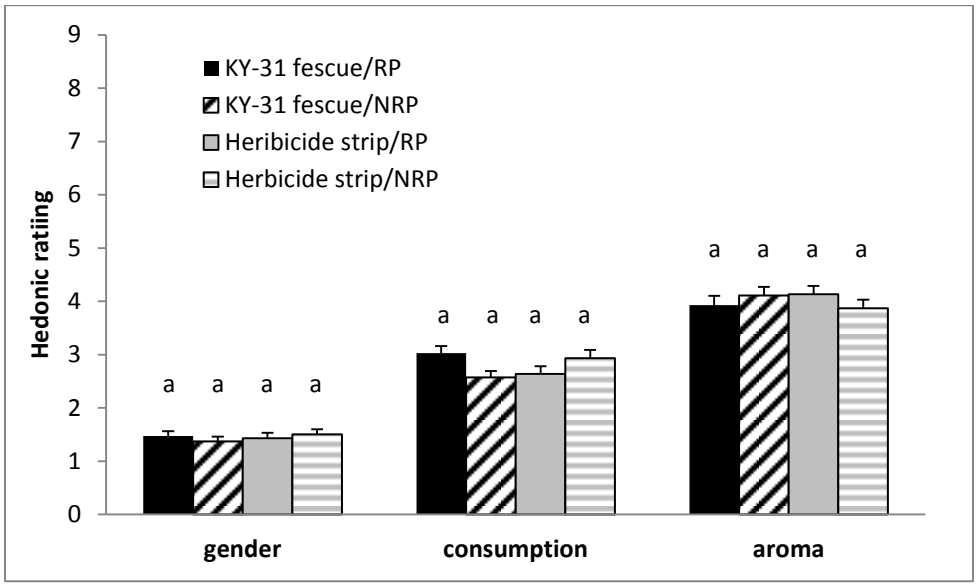


Figure 4.3 Hedonic preference tests of Cabernet Sauvignon test wines associated with KY-31 fescue/RP, NRP or Herbicide strip/RP, NRP, 2010. Columns within a category (gender, consumption or aroma) with different letters are significantly different at $P \leq 0.05$. Data are mean values $\pm$ 1 SE (n=2).

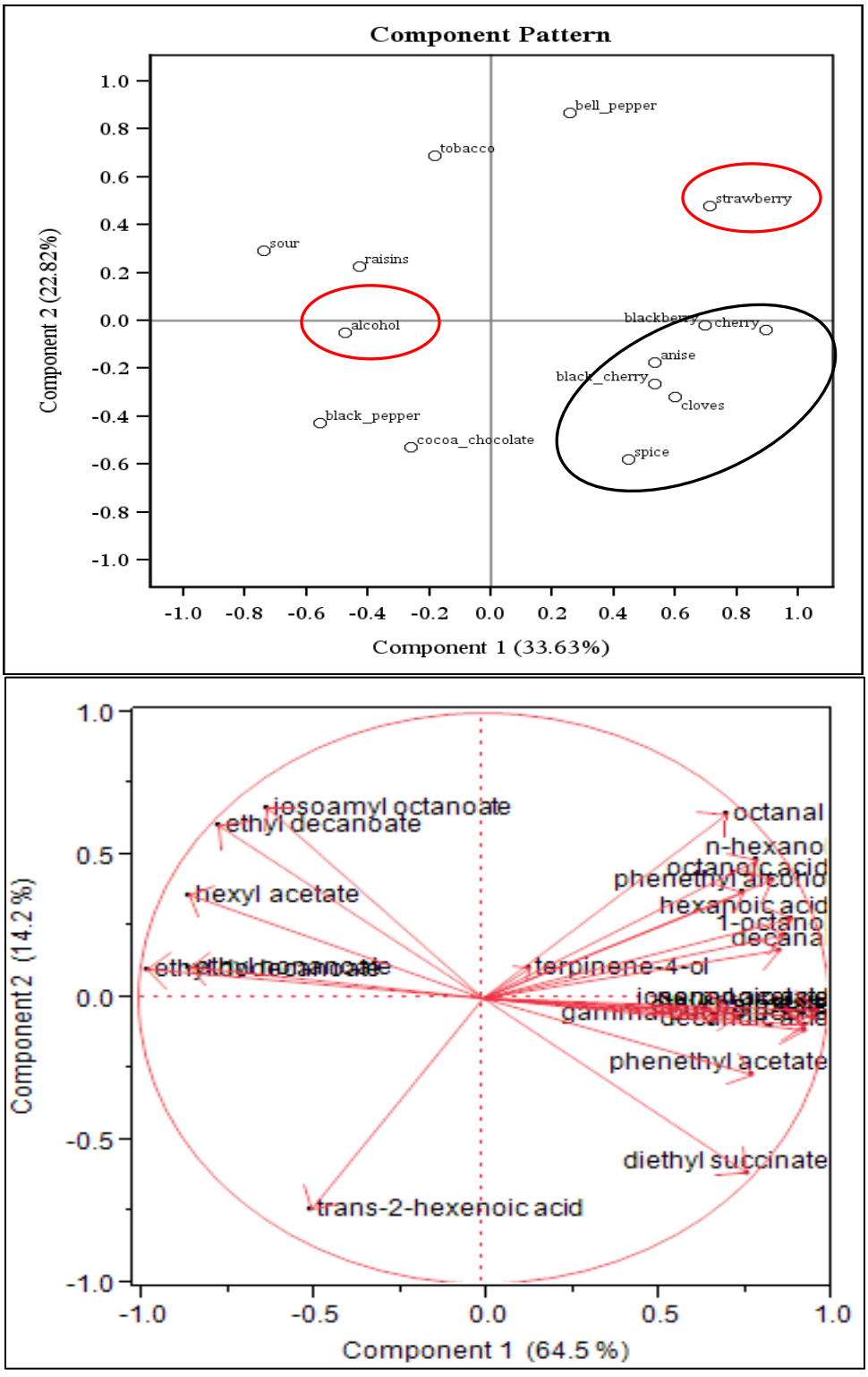


Figure 4.4 Principle component analysis (PCA) of aroma descriptors and free aroma compounds from wines made from vines exposed to KY-31 fescue/RP, NRP or Herbicide strip/RP, NRP, 2010.

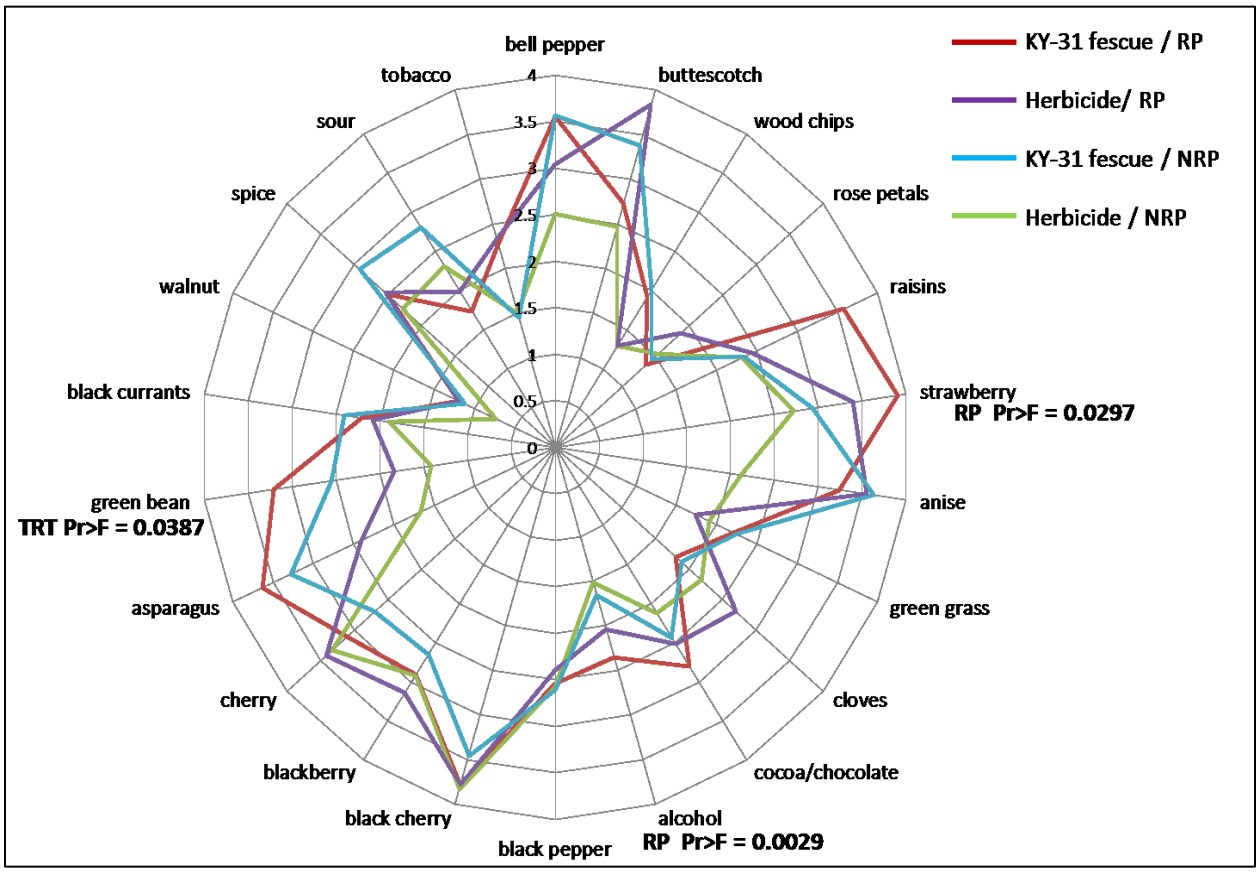


Figure 4.5 Aroma descriptors of wines from vines exposed to KY-31 Fescue/RP, NRP or Herbicide strip/RP, NRP, 2010.

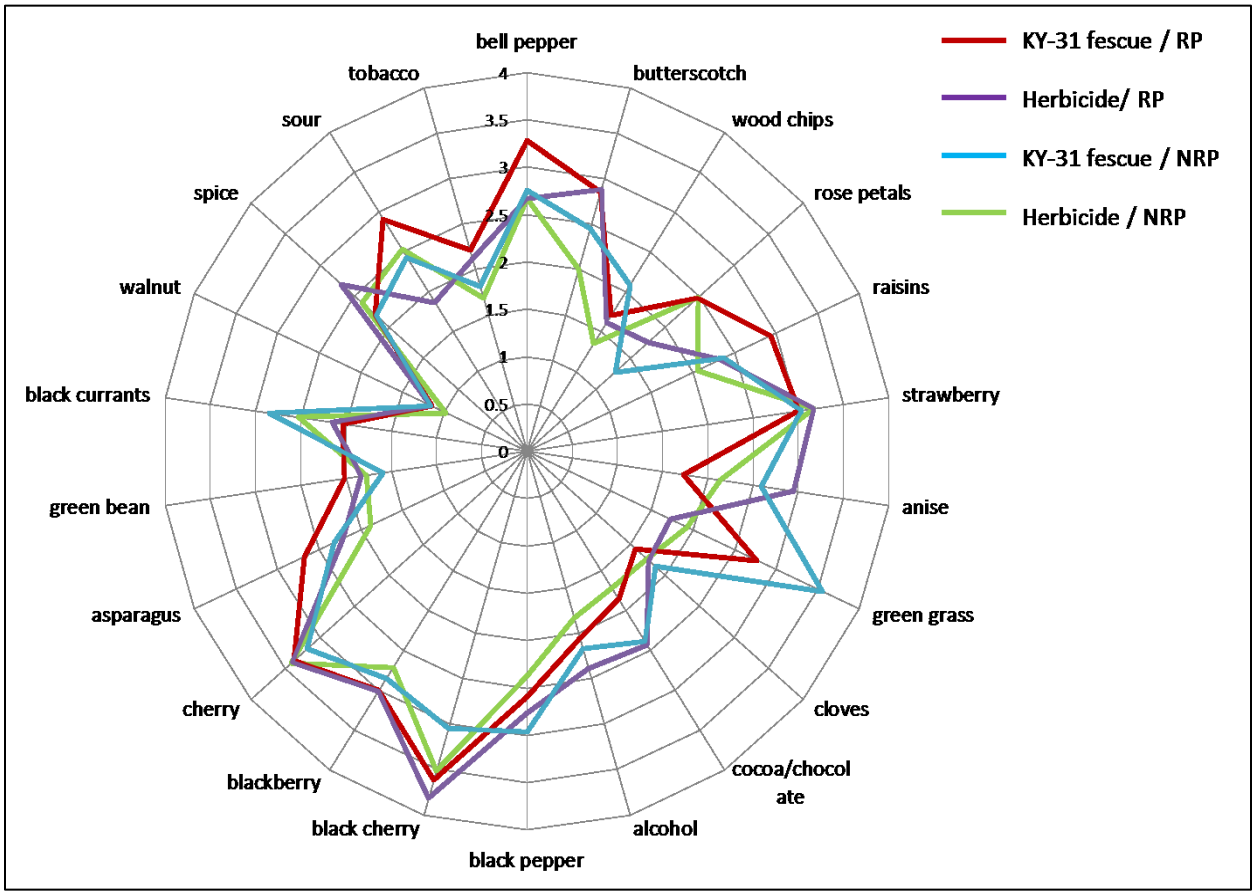


Figure 4.6 Taste by mouth descriptors of wines from vines exposed to KY-31 Fescue/RP, NRP or Herbicide strip/RP, NRP, 2010.

Literature Cited

Anderson, N.H. 1970. Functional measurement and psychological judgment. Psychol. Rev. 77:153-170.

Chapman, D.M., G.Roby, S.E. Ebeler, J. Guinard, and M. Matthews. 2005. Sensory attributes of Cabernet Sauvignon wines made from vines with different water status. Aust. J. Grape Wine Res. 11:339-347.

Cunniff, P. 2005. Official methods of analysis of AOAC International. AOAC International. Arlington, VA.

Etievant, P. 1991.Wine. In Volatile compounds in foods and beverages. H. Maarse, (Ed) TNO-CIVO Food Analysis Institute. Zeist, the Netherlands. Marcel Dekker, Inc., New York. pp 483-546.

Ferreira, V., N. Ortin, A. Escudero, R. Lopez, and J. Cacho. 2002. Chemical characterization of the aroma of Grenache rosé wines: aroma extract dilution analysis, quantitative determination, and sensory reconstitution studies. J. Agric. Food Chem. 50:4048-4054.

Francis, I.L. and J.L. Newton. 2005. Determining wine aroma from compositional data. Aus. J. Grape Wine Res. 11:114-126.

Genovese, A., A. Gambuti, P. Piombino. and L. Moio. 2007. Sensory properties and aroma compounds of sweet Fiano wine. Food Chem. 103: 1228-1236.

Giese, G., T. Wolf, M. Kelly, L. Roberts, and C. Velasco-Cruz. 2014. Root pruning and under-trellis cover crop impacts on Cabernet Sauvignon vegetative growth, crop yield components, and berry chemistry. *In progress* (Chapter 2, PhD thesis, Virginia Polytechnic Institute and State University).

Gustav, S., B. Prior, and F.F. Bauer. 2011. Wine flavor and aroma. J Ind Microbiol. Biotechnol. 38:1145-1159.

Guth, H., 1997. Identification of character impact odorants of different white wine varieties. J. Agric. Food Chem. 45: 3022-3026.

Gutierrez Afonso, V.L., J. Darias, R. Armas, M.R. Medina, and M.E. Diaz. 1998. Descriptive analysis of three white wine varieties cultivated in the Canary Islands. Am J. Enol. Vitic. 49:440-444.

Jones, P.R., R. Fawel, I.L. Francis, and E.J. Waters. 2008. The influence of interactions between major white wine components on the aroma, flavour and texture of model white wine. Food Quality and Preference. 19:596-607.

Kelly, M. 2013. Effect of Foliar Nitrogen and Sulfur Applications on Aroma Profile of Petit Manseng (*Vitis vinifera* L.) using Descriptive Analysis. PhD thesis. Virginia Polytechnic Institute and State University.

Lacroux, F., O. Tregoat, C. Van Leeuwen, A. Pons, T. Tominaga, V. Lavigne-Creuge, and D. Dubourdieu. 2008. Effect of foliar nitrogen and sulfur application on aromatic expression of *Vitis vinifera* L. cv. Sauvignon blanc. J. Int. Sci. Vigne Vin 42:125-132.

Laing, D.G., H. Panhuber, M. Wilcox, and E.A. Pittman. 1984. Quality and intensity of binary odor mixtures. Physiology and Behavior. 33:309-319.

Lawless, H.T., and H. Heymann. 1998. Sensory Evaluation of Food: Principles and Practices. Kluwer Academic Publishers, New York.

Meilgaard, M.C., G.V. Civille, and B.T. Carr. 2007. Sensory Evaluation Techniques, 4th ed. CRC Press, New York.

Mirarefi, S., S.D. Menke, and S.Y. Lee. 2004. Sensory profiling of Chardonel wine by descriptive analysis. J. Food Sci. 69: S211-S217.

Muñoz, A.M., and G.V. Civille. 1992. The Spectrum descriptive analysis method, *In* ASTM Manual Series. MNL 13. Manual on Descriptive Analysis Testing. RC Hootman (ed.), pp. 22-34. ASTM International, West Conshohocken, PA.

NRCS (Natural Resource Conservation Service), United States Department of Agriculture. Web Soil Survey, Surry County, North Carolina, Available online at http://websoilsurvey.nrcs.usda.gov/, Accessed [9/16/2011].

Ough, C.S., and A.A. Bell. 1980. Effect of vineyard nitrogen fertilization level on the formation of some fermentation esters. Am. J. Enol. Vitic. 32:125-127.

Palomo, E.S., M.C. Diaz-Maroto, M.A. Gonzalez Vinas, A. Soriano-Perez, and M.S. Perez-Coello. 2007. Aroma profile of wines from Albillo and Muscat grape varieties at different stages of ripening. Food Control. 18:398-403.

Perestrelo, R., A. Fernandes, F.F. Albuquerque, J.C. Marques and J.S. Camara. 2006. Analytical characterization of the aroma of Tinta Negra Mole red wine: identification of the main odorants compounds. Anal. Chimica Acta. 563:154-164.

Peyrot des Gachons, C., C. Van Leeuwen, T. Tominaga, J.P. Soyer, J. Gaudillere, and D. Dubourdieu. 2002. Influence of water and nitrogen deficit on fruit ripening and aroma potential of *Vitis vinifera* L. cv. Sauvignon blanc in field conditions. J. Sci. Food Agric 85:73-85.

Pino, J A, and O. Queris 2011. Characterization of Odor-Active Compounds in Guava Wine. J Ag Food Chem. 59(9):4885-4890.

Skinkis, P. 2006. The effects of shading on monoterpene accumulation in 'Traminette' grape berries and the identification and quantitative analysis of monoterpene constituents. PhD thesis, Purdue University.

Stone, H., and J.L. Sidel. 1992. Sensory Evaluation Practices, 2nd ed. Academic Press, Orlando, FL.

Stone, J., S. Oliver, A. Woolsey, and R.C. Singleton. 1974. Sensory evaluation by quantitative descriptive analysis. Food Tech. 28(11):24-34.

Tao, Y. and L. Zhang. 2010.Intensity prediction of typical aroma characters of cabernet sauvignon wine in Changli County (China). Food Sci and Tech. 43:1550-1556.

Toci, A.T., P. Crupi, G. Gambacorta, T. Dipalmo, D. Antonacci and A. Coletta. 2012. Free and bound aroma compounds characterization by GC-MS of Negroamaro wine as affected by soil management. J. Mass Spectrom. 47:1104-1112.

Vilanova, M., M. Ugliano, C. Varela, T. Siebert, I.S. Pretorius. and PA. Henxchke. 2007. Assimilable nitrogen utilization and production of volatile and non-volatile compounds in chemically defined medium by Saccharomyces cerevisiae wine yeasts. Appl. Microbiol. Biotechnol. 77:145-157.

Villamor R.R. and C.F. Ross. 2013. Wine matrix compounds affect perception of wine aromas. Annu. Rev. Food Sci. Technol. 4:1-20.

Zoecklein, B.W., K.C. Fugelsang, B.H. Gump, and F.S. Nury. 1995. Wine Analysis and Production. Chapman and Hall, New York.

CHAPTER V

ROOT PRUNING AND UNDER-TRELLIS COVER CROP INFLUENCES ROOT FREQUENCY AND DISTRIBUTION OF CABERNET SAUVIGNON

Abstract: Grapevine root density and distribution of Cabernet Sauvignon vines (*Vitis vinifera* L., clone FPS 8; SO4 rootstock, *Vitis berlandieri x Vitis riparia*) associated with complete vineyard floor cover cropping and root pruning vineyard treatments were evaluated using soil pit root excavations and soil trench wall profiles in 2008 and 2010. Root distributions were fitted to the asymptotic equation of Y = (1- ßd), where d = soil depth (cm) and Y = the cumulative root fraction from the soil surface to depth d, and ß was considered a measure of vertical root distribution used as a response variable to test for differences between cover cropping/root-pruning treatments. Treatments were arranged in a split-plot, randomized, complete block experimental design with vineyard floor management (cover crop schemes) as main plots and annual vine root pruning (RP), or not (NRP), as splitting factors. Cover crop treatments included: tall fescue (*Festuca arundinacea* Shreb.) 'KY-31', and an under-trellis herbicide strip combined with 'KY-31'fescue interrows, as a conventional floor management scheme. The greatest root biomass occurred at the 40-60 cm soil depth across all treatments although treatments did not differ. In 2008, vines in KY-31 fescue/RP plots produced the greater root biomass and density at soil depths > 60cm relative to KY-31 fescue/NRP vines. The cumulative fraction of roots of all treatment vines did not differ and generally occurred at soil depths < 80 cm and all root distributions had fitted values of ß generally < 0.9370, indicating shallower rooting distributions relative to other published and similarly analyzed grapevine root distributions.

Introduction

Grapevine root system density and distribution dictate or influence a vine's ability to intercept and absorb soil water and nutrients. This observation follows a generally accepted tenet in plant biology that lateral root spread and maximum rooting depth are correlated and reflect above ground plant biomass and/or volume (Schenk and Jackson 2002). Thus, differences in root density and distribution should confer differences in aerial vine vegetative growth and yield, regardless of whether vines are grafted or own-rooted. Most reports of grapevine root patterns have documented differences among rootstock genotypes or management practices in the context of the soil environment (Morano and Kliewer 1994, Smart et al. 2005). In a comprehensive review of grapevine rooting patterns, Smart et al. (2006) emphasized and illustrated that many reports were hindered by exclusive and limited use of the profile wall method (Bohm 1979) as an investigative technique. The lack of repetition, common to many root system studies involving excavation, especially in light of the fact of extreme heterogeneity of individual vines under field conditions, precluded statistical separation of means.

A most basic issue in repeatable, root quantification is the definition of the root itself and fine roots in particular (Pierret et al 2005). The determination of frequency and mass of fine roots in particular is most difficult and is typically underestimated across all studies of woody or herbaceous species (Pierret et al. 2005). As further explained by (Pierret et al. 2005), "It is well documented that all these techniques (extractive techniques, whereby soil is sampled and washed away in order to quantify root biomass and length) yield highly variable results, (e.g. CV > 100% for minirhizotron and washing techniques), and that results obtained using two different techniques are, more often than not, difficult to compare".

It is a commonly held conception that a rootstock's genetics influences a grapevine's rooting pattern and that root emergence angle (geotropism) dictates the angle of root penetration into the soil and ultimate rooting depth of a given rootstock. However, Smart et al. (2005) documented that root emergence angle from rootstock cuttings was not a good predictor of rooting depth in field settings. Grapevines are very deeply rooted plants relative to other woody species (Bouard 1971, Guillion 1905, Seguin 1972). The most widely referenced article on grapevine rooting depth (> 6 m) is based on a single observation from the Bordeaux region of France (Seguin 1972). However, evidence of cultural practices on grapevine rooting depth and distribution are more reliable and local information can be more usefully applied in order to best match rootstock choice and management to desired scion cultivar and production goals. For example, N. Shaulis (unpublished maps, 1963 as cited by Smart et al. 2006) extensively detailed differences in grape root distribution based on soil type in New York. More recently, Bates et al. (2002) excavated, entire, 3-year-old 'Concord' vines inclusive of their root systems and documented that roots house 84% of the starch and 75% of the nitrogen stored in vines at the beginning of the season. Vineyard floor management, including permanent sward, cultivation, straw mulch and herbicide application has each been shown to impact grapevine rooting pattern (Van Huyssteen and Weber 1980). In a study of soil nutritional status of Yadkin Valley AVA vineyards in North Carolina, it was observed that most sites had rooting depths of < 1 m (J. Havlin, soil science NCSU, personal communication). Studies of interrow and complete vineyard floor cover crops have provided insight into initial effects on depth and pattern of grapevine rooting and its consequent support of vegetative and reproductive growth. Extended field studies of cover crop effect on grapevine growth that included inspection of roots have shown that grapevine roots move into deeper soil profiles and grow preferentially into the vine row when

interrow are occupied with cover crops (Morlat and Jacquet 2003, Sweet and Schreiner 2010, Tesic et al. 2007).

The intent of this study was to determine if grapevine root distribution and density were measurably affected by multi-season application of under-trellis cover crops and root pruning. Insight into how vine rooting patterns differ upon exposure to these practices could inform management decisions on vineyard site selection, rootstock choice, and irrigation and fertilization practices as well as cover cropping schemes at sites with similar climatic and edaphic conditions.

Materials and Methods

Vineyard description and experimental design: The study used Cabernet Sauvignon vines (*Vitis vinifera* L., clone FPS 8; SO4 rootstock, *Vitis berlandieri x Vitis riparia*) in a mature, commercial vineyard (7.3 ha, 2.74 m x 1.83 m spacing) planted in 1999 within the Yadkin Valley American Viticultural Area, Surry County, North Carolina (36^{o} 21'N; 80^{o} 46' W). The experiment was a split-plot field study to determine the effects of under trellis cover crop and root pruning with design and management described elsewhere (Giese et al. 2014b). The vineyard soil was a Fairview complex clay loam with a rooting depth that ranged from 0.75 to 1.50 m [well drained, kaolinitic, mesic, Typic Kanhapludults (NRCS http://soils.usda.gov 2007)].

Vine root assessment: In May 2008, a mechanical excavator was used to dig twelve pits 1.2 m deep, 1.5 m wide and 3.7 m long with lengths of each pit oriented parallel to and ~ 40 cm away from the line of vine trunks in each selected treatment row. The 1.5 m width of each soil pit was oriented perpendicular to a vine trunk within the plot and extended into the row middle

ending ~1.35 m from the adjacent buffer row. A variation of the profile wall method was used to quantify root intercepts on both the perpendicular and parallel pit face corresponding to each sample vine (Bohm 1979, Van Zyl 1988). Visibility was improved by painting the pit face white and teasing the soil away to expose the roots (Figure 5.1). A portable grid of tautly situated twine that delineated 20 cm x 20 cm 'subquadrats' (Smart et al. 2006b) was centered on a selected sample vine and placed on the pit face (Figure 5.2). Root intercepts within each subquadrat were visually separated into three diameter classes: < 2 mm, 2 to10 mm, and > 10 mm and each diameter class was counted separately and entered into its corresponding subquadrat (Tables 5.2 to 5.5) for comparison.

Following root intercept quantification, a 5 x 5 grid of 20 cm x 20 cm squares was delineated on the perpendicular pit face and twenty-five 20 cm x 20 cm x 20 cm (8000 cm^3) soil monoliths corresponding to each of the twenty-five grid locations, and containing ~8-10 kg (fresh mass) of soil was extracted with a site built, 20 cm x 20 cm x 20 cm, open ended, steel box used as a soil probe (Figure 5.3). A 5 cm diameter steel rod, ~1.20 m long was attached to the top of the described "soil probe" and used to accommodate a pneumatic impact hammer which was used to sequentially drive the probe assembly into the soil to capture each 8000 cm^3 monolith subsample (Figure 5.4). Each pit sample of twenty-five soil block subsamples, represented approximately four percent of the total soil volume allotted to each sampled vine, based on the vine spacing of 1.83 m x 2.74 m and rooting depth of ~1 m. Each of the soil subsamples (25 monoliths per treatment replicate, 300 soil monoliths each in 2008 and 2010) were labeled according to depth and distance from the vine trunk, placed in a plastic bag and transported out of the field. Soil monolith subsamples not immediately processed were stored at 5°C.

Each soil monolith was subsequently sieved by hand through a 6 mm steel mesh screen to separate and determine the number, diameter and mass of grapevine roots therein. All fibrous, white roots were determined to be grass roots and discarded. Extracted roots were washed with tap water, blotted dry and separated into three categories based on their diameter: < 2 mm, 2 to10 mm, and > 10 mm. Washed root samples were dried at 75°C for 120 hours and weighed. Excavation, vine intercept quantification and vine root collection/biomass determination was limited to three vines, representative of three replications each that had been exposed to one of the following treatment combinations: KY-31 fescue RP/NRP and herbicide strip RP/NRP treatments.

The cumulative fraction of roots with increasing depth was calculated using a model equation previously used to describe vertical root distributions of northern forest species (Gale and Grigal 1987). Over 200 grape root distributions were also fitted to this model in a review of previous published root distributions (Smart et al. 2006b). The model expresses the cumulative fraction of roots as a function of soil depth by testing its fit to the model $Y = (1 - ßd)$, where Y is the cumulative fraction of roots with depth and d is the soil depth in centimeters. The calculated coefficient ß can be used as a numerical index of depth distribution, where higher values for ß correspond with greater proportions of roots with depth (Smart et al. 2006b). The calculated ß values, as indicative of cumulative fraction of roots with increasing depth, allowed examination of the data according to cover crop/RP treatment within the soil type and climatic region. Calculation of ß values in this manner also allowed comparison of study data to characterizations of grapevine rooting distributions in previous studies.

Root intercept and biomass determinations and calculation of ß values were repeated in October 2010 using the three replications that were not disturbed in 2008. These treatment combinations were also used for soil moisture data collection as previously described.

Statistical analysis: Treatment main effects and their interactions were analyzed according to a split-plot experimental design using a mixed model with repeated measures (SAS 9.2, 2002-2008, SAS Institute Inc., Cary, NC). Analysis of variance (ANOVA) was performed between treatment combinations within years and treatment combinations' interaction with soil depth and distance from vine trunk was included as a model factor as root occurrence at one depth is contingent of roots present at the previous depth or distance. The fixed effects in this model were cover crop or herbicide strip, root pruning and cover crop x root pruning interaction term. Block, and block interaction with main effects were treated as random variables. When interaction was evident, the SLICE option was used to isolate each independent variable effect at a fixed level of other variables. Differences of cover crop and root pruning treatments, their interactions and interactions with depth and distance were compared with least squares means with adjustments for multiple comparisons using the Tukey-Holm adjustment with ($P \leq 0.05$) as the critical value to declare significant differences.

Results

Grapevine root dry weights of all treatment vines were generally greatest at soil depths < 60 cm and generally decreased with soil depth > 60cm, regardless of treatment or year of assessment (Table 5.1, Figures 5.5 and 5.6). KY-31 fescue/RP vines had greater root weight at the 60 to 80 cm and 80 to 100 cm soil depths than did the KY-31 fescue/NRP vines in 2008 (Table 5.1). There was a significant cover crop by root-pruning interaction at 60 to 80 cm and the

80 to 100 cm soil depths in 2008, reflected in a ~87% increase in root weight below the 60 cm soil depth when KY-31 fescue/RP was present versus KY-31 fescue/NRP, and ~22% increase in root weight in herbicide strip/RP treated vines compared to the herbicide strip/NRP vines below 60 cm soil depth (Table 5.1 and Figure 5.5). The herbicide strip/NRP vine root biomass at depths of 40 to 100 cm trended greater than that of the herbicide strip/RP vines in 2010 although the difference was not statistically separated (Figure 5.6).

Average ß value across all treatments in the study was < 0.9370. However, ~32% of the cumulative root fraction of vines exposed to KY-31 fescue/RP or herbicide strip/RP occurred > 40 cm soil depth compared to ~ 4% and ~16% respectively, at that same depth in 2008 (Table 5.2). This result was not repeated in 2010, as root distributions were more similar across all treatments that year.

Root intercept counts of RP vines, regardless of cover cropping, indicated that more roots with diameters < 2mm were present at depths of 60-120 cm in 2008, in both the perpendicular and parallel planes compared to vines that were not root-pruned (Tables 5.3 and 5.4). This trend was also evident in 2010, as intercept counts of vines associated with KY-31 fescue/RP were slightly more numerous than those of KY-31 fescue/NRP vines at soil depths of 60 cm to 100 cm (Tables 5.5 and 5.6). However, the trend was reversed in intercept counts of vines exposed to herbicide strip/NRP, as they closely approximated or exceeded the counts of herbicide strip/RP vines in both planes at depths > 60 cm in 2010 (Tables 5.5 and 5.6).

Discussion

KY-31 fescue/RP at a consistent depth stimulated growth of vine root systems in deeper soil compartments relative to vines exposed KY-31 fescue/NRP in 2008. This acclimation was

evident in a significant cover crop by RP interaction effect on root dry weights at the 40 to 60 and 80 to 100 cm depth in 2008. The interaction also appeared in conjunction with a reduction in pruning weights due to root pruning across all years except 2010, regardless of vineyard floor treatment (Giese et al. 2014). This vine reaction suggests resource reallocation to the roots at the expense of the shoots that is sometimes exacerbated when cover crops are present (Celette 2005). Interestingly, this defined shift in root growth per cover crop by root-pruning interaction was not evident in the 2010 excavation, possibly reflective of the lack of root-pruning effect on pruning weights in that year.

Root pruned vines in this study had rooting compartments that were temporarily and spatially limited relative to vines that were not root-pruned. Severing roots at 45 cm on both sides of the vine trunks to a depth of approximately 45-60 cm, physically limited the soil compartment available to grapevines' root systems. This degree of root pruning resulted in a volume of soil approximately 33% of the volume available to vines in the herbicide strip/NRP plots.

Although root dry weights of various treatments in this study were inconsistently associated with treatments, substantially more roots occurred at the 40 to 60 cm depth relative to more shallow soil depths across all treatments and in both years. This is similar to other studies that showed that the upper soil horizon with cover crop grass roots present will contain fewer grapevine roots when those soil layers are occupied by grass roots (Celette et al. 2009, Morlat and Jacquet, 2003, Saayman and Van Huyssteen 1983). Soil horizons closer to the soil surface with cover crops in place will have less soil moisture compared to those same soil layers with no cover crop present (Celette et al. 2009). Although there were no measured differences in soil moisture per treatment and soil depth in this study, when a lack of soil moisture or competition

with a grass cover crop does occur, a vine's root system will grow deeper to obtain water, if soil conditions allow (Morlat and Jacquet 2003, Smart et al. 2006a). As the N mineralization zone near the surface is less populated by vine roots (Celette et al. 2009), less N is taken up by the vine, and consequently, shoot growth is limited as more resources are allocated to new root production in a deeper soil compartment.

A significant cover crop by root pruning interaction associated with an increased amount of root dry weight at 40 to 100 cm soil depth in KY-31 fescue/RP vines in 2008, indicated possible reallocation of vine resources to support increased root growth over shoot growth when root pruning and/or cover crop treatments were applied. With an increase in root growth, roots become stronger sinks for nitrogenous reserves and carbohydrates, and consequently, shoot growth will be reduced (Keller 2005). When cover crops are in place, they likely compete for water and nutrients with the newly formed grapevine roots each season. However, differences in root responses to soil moisture independent of nutrient supply cannot be practically separated under field conditions (Bauerle et al. 2008).

Nonetheless, there were no significant treatment differences on root growth evident in the 2010 excavation. This suggests that seasonal rainfall at our site was adequate for continued vine growth despite any reduction in near-surface soil water availability due to root pruning and/or cover crops. Additionally, petiole nitrogen levels measured in treatment vines (Giese et al. 2014) seldom fell below the accepted sufficiency range. Despite the number and volume of soil samples evaluated for grape roots, the ability to accurately characterize root distribution as a function of treatment is constrained by the heterogeneous nature of grapevine root occurrence and frequency that can be affected by resource availability, mechanical resistance due soil bulk density and vine density (Smart et al. 2006b).

Despite the heterogenous nature of root occurrence in general, we found similar root frequencies and distributions at corresponding soil depths < 60 cm indicated by intercept counts in both the parallel and perpendicular planes (Tables 5.2, 5.3, 5.4 and 5.5). This is in agreement with three other investigations that used profiles and root intercept counts in both directions (Williams and Smith 1991, Padgett-Johnson 1999, Morlat and Jacquet 2003). Some of the finer grapevine roots might have been lost through a 6-mm sieve, although we would believe that is a possible systemic error with all soil samples, and not treatment specific. Additionally, one might argue that it is difficult to distinguish grapevine roots from fescue roots. However, the more fibrous and lighter colored fescue roots were, with practice and tracing back to the sod, satisfactorily distinguished from grapevine roots, particularly at the deeper levels. One improvement that could be made would be to kill the sod well in advance of the root extraction to limit the volume of sod roots in the soil samples. As admitted by others, there is no widely accepted method to measure root length and biomass.

Despite these methodological limitations and shortcomings, the presence of under trellis cover crop roots in the soil horizon within 20 cm of the soil surface, limited the rooting volume available to grapevines. Cover crop treatments can enforce a soil volume that is ~80% of that available to vines with no cover crop or root pruning (Celette et al. 2005). Vines quite likely redistribute themselves in the presence of cover cropping. Consequently, vine roots grown with a cover crop, especially tall fescue (*Festuca arundinacea* Shreb.) *and* with root pruning simultaneously applied, could be limited to a soil volume as little as ~26% (~1.32 m^3 compared to ~5.0 m^3) of that available to vines grown with an herbicide strip/NRP. When grapevine roots were restricted to 0.015 m^3 soil volume, greater depressive effects on stem water potential and growth were observed than were measured in this study (Hatch et al. 2011). The soil volume of

treatment vines in this study was not limited to a degree that would exert the more obvious depressive effects evident in the Hatch et al. study (2011).

The soil at depth may contain adequate moisture but typically has fewer nutrients, a lower pH and higher bulk density. Overall, deeper soil horizons at the study site are less conducive to root foraging and growth (J Havlin, personal communication, 2014). Other studies have acknowledged that bulk density at depth is a primary limiting factor in downward root penetration. (Saayman and Van Huyssteen 1983, Van Huyssteen, 1988). However, as articulated by Morano (1995) and explained by Smart et al. (2006b) grapevines likely evolved to develop deep root systems in order to better compete with their host trees and understory plants in the wild. In such a scenario, deeply placed grapevine roots have the ability to reach water sources relatively distant to roots in dryer patches of soil and via axial flow, hydraulically redistribute that water to sustain the vine and provide for evapotranspiration (Smart et al. 2005).

Conclusions

A larger cumulative fraction of grapevine roots associated with KY-31 fescue/RP occurred at soil depths > 60 cm compared to other KY-31 fescue/NRP in one year. Although not statistically separated, root pruned vines regardless of cover cropping imposed, had substantially larger cumulative fraction of roots at the 40-60 cm soil depth relative to non-root-pruned vines in both years. The calculated ß values indicated that root distributions of all vines in this study were shallower in comparison to other studies. Greatest root biomass and intercept occurrence was generally at the 40-60 cm depth and most if not all roots occupied soil layers within ~ 80 cm of the soil surface regardless of treatment. This result was supported by intercept counts accomplished in two different planes. Although results indicated a significant relationship

between cover cropping and root pruning and their combined effects on root growth and distribution in one year, the study does not attempt to explain the inconsistent root density and depth of distribution based solely on treatment effects. Despite the challenges of its measurement and investigation, more information of vineyard site and management effects on root growth and its correlation to above ground growth is needed to improve grapevine performance.

Figure 5.1 Painted perpendicular pit face prior to partial soil removal to increase visibility of grapevine roots.

Figure 5.2 Perpendicular and parallel soil pit faces, painted with roots exposed and subquadrat grid in place on perpendicular face prior to counting root intercepts within each subquadrat.

Figure 5.3 Soil probe (8000 cm^3) used for extraction of soil sample blocks and determination of root number and weight in three diameter classes, 2008 (n=300) and 2010 (n=300).

Figure 5.4 Perpendicular soil pit face after sequential removal of twenty-five soil block samples for root count and biomass determination.

Table 5.1 Root dry weights per soil profile depth of vines exposed to cover crop and root pruning, 2008 and 2010.

May 2008					
	Root weight (g)				
Cover crop Root pruning[a]	**0-20 cm**	**20-40 cm**	**40-60 cm**	**60-80 cm**	**80-100 cm**
KY-31 fescue					
NRP	3.80	3.34	7.10	0.61 b	0.00 b
RP	3.33	3.50	20.80	2.55 a	2.24 a
Herbicide strip					
NRP	3.51	3.57	12.18	2.03 ab	1.76 a
RP	2.89	3.11	10.62	2.54 ab	2.34 a
Significance[b]					
RP	ns	ns	ns	ns	ns
CC	ns	ns	ns	0.0091	0.0062
CC x RP	ns	ns	ns	0.0505	0.0285
October 2010					
	Root weight (g)				
Cover crop Root pruning[a]	**0-20 cm**	**20-40 cm**	**40-60 cm**	**60-80 cm**	**80-100 cm**
KY-31 fescue					
NRP	2.55	3.09	17.32	2.20	2.48
RP	2.58	2.96	11.68	1.77	1.91
Herbicide strip					
NRP	2.95	2.49	5.79	1.81	1.64
RP	2.87	3.57	22.02	3.04	2.60
Significance[b]					
RP	ns	ns	ns	ns	ns
CC	ns	ns	ns	ns	ns
CC x RP	ns	ns	ns	ns	ns

[a] RP, root pruned; NRP non-root pruned.
[b] Significance of treatment effects and interactions ($p > F$; ns – not significant)
[x] Mean root weight values within a year and soil depth followed by the same letter are not different at ($P \leq 0.05$) level of significance

Table 5.2 Cumulative root distributions (cumulative fraction of the total) as a function of soil depth for four cover crop / root pruning combinations. The ß values are derived by the model of Gale and Grigal (1987) where Y = (1 - ßd); where Y is cumulative fraction of roots with depth and d is the soil depth (cm). 2008 and 2010.

May 2008						
	Cumulative fraction of the total root biomass (%) @ various soil depths					
Cover crop Root pruning[a]	**0-20 cm**	**20-40 cm**	**40-60 cm**	**60-80 cm**	**80-100 cm**	ß[b]
KY-31 fescue						
NRP	53.5	87.4	95.9	99.1	100	0.9206 a
RP	23.2	46.5	68.2	90.4	100	0.9367 a
Herbicide strip						
NRP	34.6	71.5	84.2	93.7	100	0.9323 a
RP	24.1	54.1	68.4	85.4	100	0.9379 a
October 2010						
	Cumulative fraction of the total root biomass (%) @ various soil depths					
Cover crop Root pruning[a]	**0-20 cm**	**20-40 cm**	**40-60 cm**	**60-80 cm**	**80-100 cm**	ß[b]
KY-31 fescue						
NRP	21.7	60.1	76.2	86.7	100	0.9366 a
RP	17.7	53.6	74.1	88.3	100	0.9367 a
Herbicide strip						
NRP	20.0	50.1	68.8	87.2	100	0.9375 a
RP	35.1	56.4	74.4	85.4	100	0.9370 a

[a] RP, root pruned; NRP non-root pruned.

[b] Calculated ß values within a year for each treatment combination followed by the same letter are not different at ($P \leq 0.05$) level of significance

Table 5.3 Grapevine root intercepts < 2mm, 2-10mm, >10mm in diameter listed from top to bottom within each grid subquadrat at each soil depth (0 to 120 cm) and distance (0 to 100 cm) from each sample vine trunk in the interrow soil profile, perpendicular to the vine row and associated with vines exposed to either KY-31 fescue RP/NRP or Herbicide strip RP/NRP, 2008

soil depth	KY-31 Fescue / NRP 2008					KY-31 Fescue / RP 2008				
0 - 20 cm	41	59	55	42	43	83	115	119	82	100
	0	0	1	2	1	3	1	1	1	1
	0	0	0	0	0	1	0	0	0	0
20 - 40 cm	43	46	38	46	39	52	86	72	66	54
	0	1	0	0	1	2	2	1	1	2
	0	0	0	0	0	0	0	0	0	0
40 - 60 cm	25	15	30	20	14	52	46	53	53	41
	0	0	0	0	0	1	1	0	0	2
	0	0	0	0	0	0	0	0	0	0
60 - 80 cm	6	5	4	6	5	33	34	31	35	29
	0	1	0	0	1	1	0	1	0	1
	0	0	0	0	0	0	0	0	0	0
80 - 100 cm	3	2	4	4	3	18	15	19	22	18
	0	0	0	0	0	1	0	0	0	1
	0	0	0	0	0	0	0	0	0	0
100 - 120 cm	2	0	0	0	0	12	14	7	14	10
	0	0	0	0	0	0	0	1	2	1
	0	0	0	0	0	0	0	0	1	0
	0 - 20 cm	20 - 40 cm	40 - 60 cm	60 - 80 cm	80 - 100 cm	0 - 20 cm	20 - 40 cm	40 - 60 cm	60 - 80 cm	80 - 100 cm

soil depth	Herbicide Strip / NRP 2008					Herbicide Strip / RP 2008				
0 - 20 cm	52	56	56	47	39	32	65	72	59	48
	1	1	0	0	1	1	0	0	1	1
	0	0	0	0	0	0	0	0	0	0
20 - 40 cm	48	50	52	42	39	35	54	66	47	31
	1	0	1	2	0	1	1	0	1	1
	0	0	0	0	0	0	0	0	0	0
40 - 60 cm	26	34	29	18	18	37	56	37	31	26
	0	0	0	0	0	0	0	1	1	1
	0	0	0	0	0	0	0	0	0	0
60 - 80 cm	11	18	17	15	14	13	18	29	19	20
	0	0	0	0	1	0	0	0	1	0
	0	0	0	0	0	0	0	0	0	0
80 - 100 cm	8	9	5	3	5	13	13	14	8	9
	0	0	0	0	0	1	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
100 - 120 cm	0	0	0	0	2	2	20	13	9	5
	0	0	0	0	0	2	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
	0 - 20 cm	20 - 40 cm	40 - 60 cm	60 - 80 cm	80 - 100 cm	0 - 20 cm	20 - 40 cm	40 - 60 cm	60 - 80 cm	80 - 100 cm

.

Table 5.4 Grapevine root intercepts < 2mm, 2-10mm, >10mm in diameter listed from top to bottom within each grid subquadrat at each soil depth (0 to 120 cm) and distance (0 to 70 cm from each sample vine trunk in the intrarow soil profile, parallel to the vine row and associated with vines exposed to either KY-31 fescue RP/NRP or Herbicide strip RP/NRP, 2008.

soil depth	KY-31 Fescue / NRP 2008							KY-31 Fescue / RP 2008						
0 - 20 cm	39	47	47	40	38	50	44	36	37	40	36	35	51	36
	1	1	1	1	3	2	1	1	1	1	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20 - 40 cm	34	44	40	32	65	48	40	44	39	47	41	37	48	51
	1	3	3	0	0	2	1	1	0	2	0	0	2	1
	0	1	1	0	0	0	0	0	0	0	0	0	0	0
40 - 60 cm	21	18	18	19	26	34	29	21	21	16	35	31	35	20
	0	0	0	0	0	0	0	1	0	0	0	1	0	1
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60 - 80 cm	6	10	12	13	6	20	4	10	17	14	19	26	23	11
	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80 - 100 cm	4	3	6	8	3	3	1	4	6	9	7	8	12	10
	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100 -120 cm	2	2	1	2	0	1	1	2	4	1	1	1	1	1
	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	50 - 70 cm	30 - 50 cm	10 - 30 cm	**0**	10 - 30 cm	30 - 50 cm	50 - 70 cm	50 - 70 cm	30 - 50 cm	10 - 30 cm	**0**	10 - 30 cm	30 - 50 cm	50 - 70 cm

soil depth	Herbicide Strip / NRP 2008							Herbicide Strip / RP 2008						
0 - 20 cm	15	24	19	32	23	18	12	37	42	48	53	45	45	37
	1	0	2	2	2	3	1	1	1	1	2	1	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20 - 40 cm	19	18	17	15	18	15	11	24	22	28	19	31	29	31
	0	0	1	0	0	0	0	1	3	1	1	2	0	0
	0	0	1	0	0	0	0	0	0	0	0	0	0	0
40 - 60 cm	21	21	16	35	31	35	20	21	11	10	11	13	17	24
	1	0	0	0	1	0	1	0	0	0	0	0	0	1
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60 - 80 cm	10	17	14	19	26	23	11	12	9	5	6	8	5	7
	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80 - 100 cm	4	6	9	7	8	12	10	2	3	3	6	4	3	2
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100 -120 cm	2	4	1	1	1	1	1	2	1	5	2	3	3	2
	0	0	0	0	0	1	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	50 - 70 cm	30 - 50 cm	10 - 30 cm	**0**	10 - 30 cm	30 - 50 cm	50 - 70 cm	50 - 70 cm	30 - 50 cm	10 - 30 cm	**0**	10 - 30 cm	30 - 50 cm	50 - 70 cm

Table 5.5 Grapevine root intercepts < 2mm, 2-10mm, >10mm in diameter listed from top to bottom within each grid subquadrat at each soil depth (0 to 100 cm) and distance (0 to 100 cm) from each sample vine trunk in the interrow soil profile, perpendicular to the vine row and associated with vines exposed to either KY-31 fescue RP/NRP or Herbicide strip RP/NRP, 2010.

soil depth	KY-31 Fescue / NRP 2010					KY-31 Fescue / RP 2010				
0 - 20 cm	9	20	8	15	10	22	31	22	13	12
	3	2	3	1	2	1	1	2	1	2
	0	0	0	0	0	0	0	0	0	0
20 - 40 cm	24	20	13	18	14	19	30	32	15	14
	5	4	2	1	1	2	3	4	0	0
	0	0	0	0	0	0	0	0	0	0
40 - 60 cm	18	9	10	18	10	11	11	27	16	13
	3	1	1	0	3	2	1	1	0	0
	0	0	0	0	0	0	0	0	0	0
60 - 80 cm	5	7	6	5	11	8	11	13	13	17
	0	0	0	0	1	1	0	1	0	0
	0	0	0	0	0	1	0	0	0	0
80 - 100 cm	5	4	5	2	3	21	16	44	11	8
	0	0	0	1	1	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
	0 - 20 cm	20 - 40 cm	40 - 60 cm	60 - 80 cm	80 - 100 cm	0 - 20 cm	20 - 40 cm	40 - 60 cm	60 - 80 cm	80 - 100 cm

soil depth	Herbicide Strip / NRP 2010					Herbicide Strip Root Pruned 2010				
0 - 20 cm	18	15	28	23	13	27	11	23	17	19
	3	1	3	2	3	5	1	2	0	2
	1	0	0	0	0	1	0	0	0	0
20 - 40 cm	9	14	20	12	20	10	7	24	17	26
	1	1	2	1	2	2	1	3	1	1
	0	0	0	0	0	0	0	0	0	0
40 - 60 cm	11	15	22	21	15	8	10	15	28	24
	0	1	0	2	0	1	1	0	0	0
	0	0	0	0	0	0	0	0	0	0
60 - 80 cm	16	15	49	19	12	10	11	10	15	10
	1	0	0	2	1	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
80 - 100 cm	8	13	22	24	13	11	7	4	4	1
	0	0	3	1	1	1	0	0	1	0
	0	0	0	0	0	0	0	0	0	0
	0 - 20 cm	20 - 40 cm	40 - 60 cm	60 - 80 cm	80 - 100 cm	0 - 20 cm	20 - 40 cm	40 - 60 cm	60 - 80 cm	80 - 100 cm

Table 5.6 Grapevine root intercepts < 2mm, 2-10mm, >10mm in diameter listed from top to bottom within each grid subquadrat at each soil depth (0 to 100 cm) and distance (0 to 70 cm from each sample vine trunk in the intrarow soil profile, parallel to the vine row and associated with vines exposed to either KY-31 fescue RP/NRP or Herbicide strip RP/NRP, 2010.

soil depth	KY-31 Fescue / NRP 2010						
0 - 20 cm	5	12	12	8	14	10	7
	2	1	1	2	1	0	1
	0	0	0	0	0	0	0
20 - 40 cm	17	27	26	27	27	31	13
	5	1	2	2	0	1	1
	1	0	0	0	0	0	0
40 - 60 cm	9	21	19	17	22	16	13
	0	1	0	0	1	1	1
	0	0	0	0	0	0	0
60 - 80 cm	5	11	12	6	9	13	12
	0	0	0	1	0	1	1
	0	0	0	0	0	0	0
80 - 100 cm	4	3	3	3	8	10	3
	1	0	0	0	0	0	0
	0	0	0	0	0	0	0
	50 - 70 cm	30 - 50 cm	10 - 30 cm	**10 - 0 - 10 cm**	10 - 30 cm	30 - 50 cm	50 - 70 cm

soil depth	KY-31 Fescue / RP 2010						
0 - 20 cm	14	19	35	20	31	22	13
	2	2	6	8	9	5	1
	0	0	0	0	0	0	0
20 - 40 cm	28	20	24	27	35	17	10
	5	2	3	2	6	0	1
	0	0	0	0	0	0	0
40 - 60 cm	14	19	23	15	20	22	12
	2	0	3	0	2	1	1
	0	0	0	0	0	0	0
60 - 80 cm	13	18	16	11	12	13	13
	0	0	1	0	1	0	1
	0	0	0	0	0	0	0
80 - 100 cm	12	10	12	12	11	16	14
	0	0	0	0	1	2	1
	0	0	0	0	0	0	0
	50 - 70 cm	30 - 50 cm	10 - 30 cm	**10 - 0 - 10 cm**	10 - 30 cm	30 - 50 cm	50 - 70 cm

soil depth	Herbicide Strip / NRP 2010						
0 - 20 cm	21	15	14	18	17	12	17
	2	0	1	3	1	2	3
	0	0	0	1	0	0	0
20 - 40 cm	10	11	10	11	15	15	10
	1	2	1	2	0	2	1
	0	0	0	1	0	0	0
40 - 60 cm	14	9	6	7	7	11	10
	1	0	1	0	1	1	1
	0	0	0	0	0	0	0
60 - 80 cm	7	7	8	7	14	11	15
	1	1	0	1	1	2	1
	0	0	0	0	0	0	0
80 - 100 cm	14	11	9	8	10	15	19
	1	0	0	0	1	1	2
	0	0	0	0	0	0	0
	50 - 70 cm	30 - 50 cm	10 - 30 cm	**10 - 0 - 10 cm**	10 - 30 cm	30 - 50 cm	50 - 70 cm

soil depth	Herbicide Strip / RP 2010						
0 - 20 cm	14	21	45	38	30	14	21
	3	3	6	6	2	2	3
	0	0	1	0	0	0	0
20 - 40 cm	16	13	13	12	29	14	17
	2	0	1	3	2	1	0
	0	0	0	0	1	0	0
40 - 60 cm	11	9	9	8	12	5	8
	0	1	2	1	3	1	0
	0	0	0	0	0	0	0
60 - 80 cm	10	5	3	1	5	6	3
	2	0	0	0	1	1	0
	0	0	0	0	0	0	0
80 - 100 cm	6	4	5	9	7	3	15
	0	1	2	1	0	0	1
	0	0	0	0	0	0	0
	50 - 70 cm	30 - 50 cm	10 - 30 cm	**10 - 0 - 10 cm**	10 - 30 cm	30 - 50 cm	50 - 70 cm

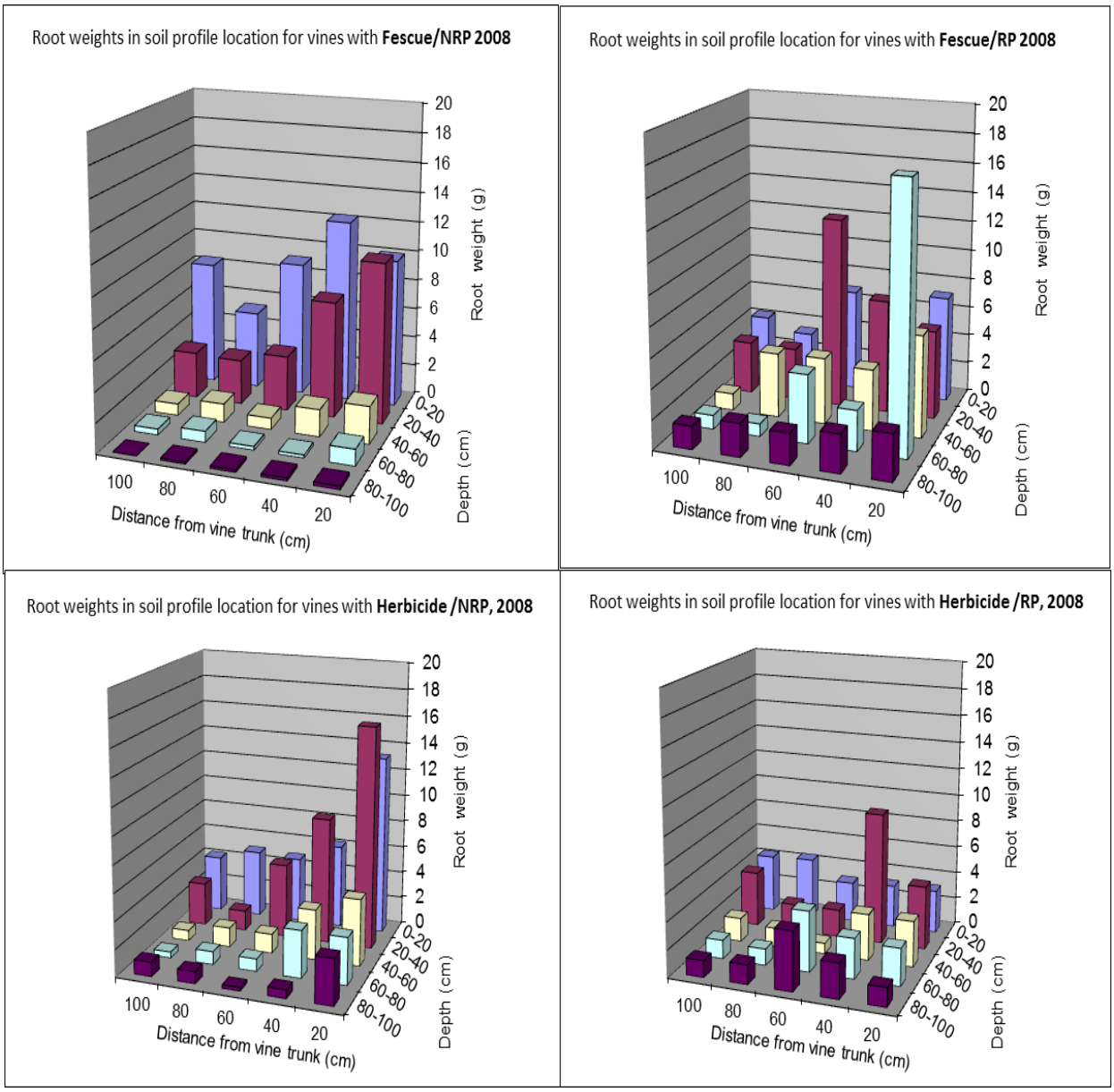


Figure 5.5 Mean dry root weight (g) collected at the specified depth and distance from vines exposed to KY-31 fescue RP/NRP or herbicide strip RP/NRP (n = 3), 2008.

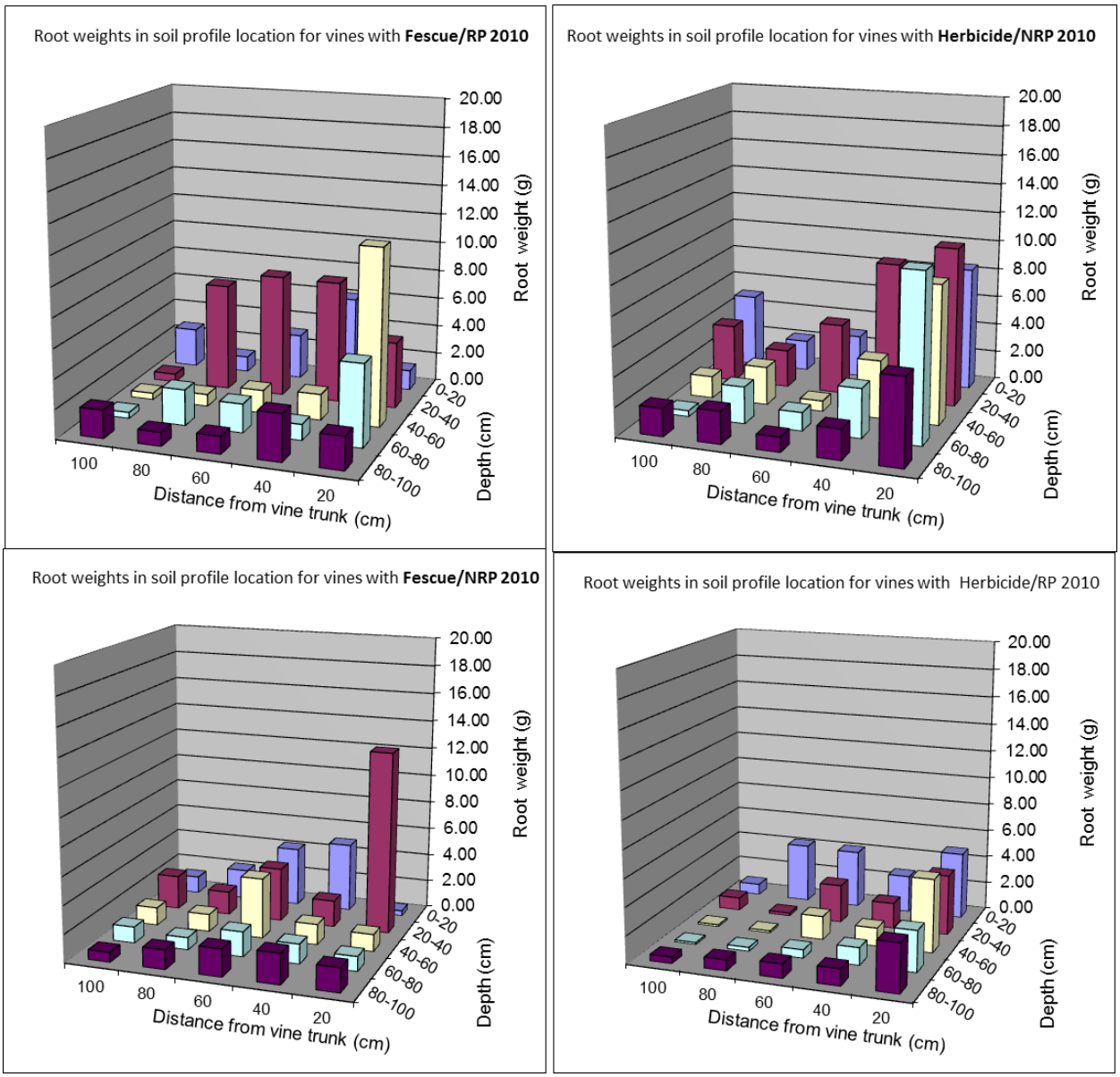


Figure 5.6 Mean dry root weight (g) collected at the specified depth and distance from vines exposed to KY-31 fescue RP/NRP or herbicide strip RP/NRP (n = 3), 2010.

Literature Cited

Bauerle, T.L., D. Smart, W.L. Bauerle, C. Stockert, and D.M. Eissenstat. 2008. Root foraging in response to heterogeneous soil moisture in two grapevines that differ in potential growth rate. New Phytologist 179: 857-866.

Bohm, W. 1979. Methods of Studying Root Systems. Springer Verlag, Berlin.

Bouard, J. 1971. Tissus et organes de la vigne. In: Sciences et Techniques de la Vigne. J. Ribereau-Gayon and E. Peynaud (Eds.). pp 3-130. Dunod, Paris.

Comas L.H., L.J. Andersen, R.M. Dunst, A. Lakso, and D. M. Eissenstat. 2005. Canopy and environmental control of root dynamics in a long-term study of Concord grape. New Phytologist 167: 829–840.

Gale, M.R., and D.F. Grigal. 1987. Vertical root distributions of northern tree species in in relation to successional status. Can. J. For. Res. 17:829-834.

Giese, G., T. Wolf, M. Kelly, L. Roberts, and C. Velasco-Cruz. 2014. Root pruning and under-trellis cover crop impacts on Cabernet Sauvignon vegetative growth, crop yield components, and berry chemistry. *In progress.* Chapter 2, PhD thesis, Virginia Polytechnic Institute and State University.

Guillon, J.M. 1905. Étude générale de la vigne: Historique les vignobles et les crus anatomie et physiologie, sol et climat. Masson, Paris.

Keller, M., Kummus M., and M. C. Vasconcelos 2001. Soil nitrogen utilisation for growth and gas exchange by grapevines in response to nitrogen supply and rootstock. Aust. J. Grape Wine Res. 7:2-11.

Morano, L., and W.M. Kliewer. 1994. Root distribution of three grapevine rootstocks grafted to Cabernet Sauvignon grown on a very gravelly clay loam soil in Oakville, California. Am. J. Enol. Vitic. 45:345-348.

Morlat, R., and A. Jacquet. 1993. The soil effects on the grapevine root system in several vineyards of the Loire valley (France). Vitis 32:35-42.

Morlat, R., and A. Jacquet. 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. Am. J. Enol. Vitic. 54:1-7.

NRCS (Natural Resource Conservation Service), United States Department of Agriculture. Web Soil Survey, Surry County, North Carolina, Available online at http://websoilsurvey.nrcs.usda.gov/, Accessed [9/16/2011].

Padgett-Johnson, M. 1999. Vine water relations, growth and root distribution of several *Vitis* species under irrigated and non-irrigated conditions. Thesis, Plant Biology, University of California, Davis.

Pierret, A., C.J. Moran, and C.Doussan. 2005. Conventional detection methodology is limiting our ability to understand the roles and functions of fine roots. New Phytologist 166: 967-980.

Saayman, D., and L. Van Huyssteen. 1983. Preliminary studies on the effect of a permanent cover crop and root pruning on an irrigated Colombar vineyard. S. Afr. J. Enol. Vitic. 4:7-12.

Schenk, H.J., and R.B. Jackson. 2002. Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. J. Ecol. 90(3):480-494.

Seguin, M.G. 1972. Repartition dans l'espace du systeme rediculaire de la vigne. Comptes rendus des seances de l'academie des sciences 274(D):2178-2180.

Smart, D., A. Breazeale, and V. Zufferey. 2006a. Physiological changes in plant hydraulics induced by partial root removal of irrigated grapevine (*Vitis vinifera* cv. Syrah). Am. J. Enol. Vitic. 57: 201-209.

Smart, D., E. Schwass, A. Lasko, and L. Morano. 2006b. Grapevine rooting patterns: a comprehensive analysis and review. Am. J. Enol. Vitic. 57: 89-104.

Smart, D., E. Carlisle, M. Goebel, and B.A. Nunez. 2005. Transverse hydraulic redistribution by a grapevine. Plant, Cell and Envir. 28:158-166.

Van Huyssteen, L. 1988. Soil preparation and grapevine root distribution: A qualitative and quantitative assessment. *In* The Grapevine Root and Its Environment. J.L. Van Zyl (Ed.), pp. 1-15. Technical comm. no. 215. Department of Agriculture and Water Supply, Pretoria.

Van Huyssteen, L., and H.W. Weber. 1980. The effect of selected minimum and conventional tillage practices in vineyard cultivation on vine performance. S. Afr. J. Enol. Vitic. 1(2):77-83.

Van Zyl, J.L. (Ed.). 1988. The Grapevine Root and Its Environment. Technical comm. no. 215. Department of Agriculture and Water Supply, Pretoria.

SUMMARY

This long-term, field study of aerial, root, and reproductive responses of vines exposed to root pruning and cover crops, independently and in combination, showed that some treatments limited vine vigor and size of excessively vigorous, field grown Cabernet Sauvignon vines. Root pruning reduced crop yields, but cover crops did not. Overall, vines grown with Elite II fescue had the greatest and most consistent reduction in pruning weights and canopy density, compared to other vines exposed to other cover crop/RP combinations. However, the practical effects on canopy architecture and berry composition were modest under the high vigor conditions of the experimental site. The interactive effect of root pruning and cover crops on vine growth suppression was likely due to the limited soil volume that results when both cover crops and root pruning are applied. This reduced soil volume likely intensified the competition for water and nitrogen. Based on its modest effect and considerable expense to apply, root pruning is not justified with the deep soils at this study site. Complete cover cropping, especially with Elite II fescue, is an effective and potentially cost-saving management tool to limit excessive grapevine vigor in high moisture viticulture regions.

All evaluated cool-season perennial grasses reduced vine size and vigor to some degree, but differed in their ability to reduce the vegetative growth of the excessively vigorous study vines. For example, orchardgrass and KY-31 fescue diminished vine shoot growth rate and shoot length more than did other cover crops, but Elite II and KY-31 fescue had the greatest stand density and biomass production. Elite II fescue reduced vine pruning weights 28% and individual cane weights 20% with a minimal impact on yield. Pruning weights of Elite II vines were within the desired benchmark range of 0.30 to 0.60 kg/m, indicative of balanced vine growth, in 2007, 2008 and 2010. Furthermore, Elite II fescue also improved all point quadrat canopy metrics

relative to the conventional herbicide strip treatment in all years, suggesting that less canopy management might be required in vines grown with this complete vineyard floor cover crop compared to vines with the conventional under-trellis herbicide strip. However, complete cover crop establishment and a growing season with average to below average rainfall is required before consistent effects on vine vegetative growth to the desired degree can be realized in humid growing regions such as the eastern US. Although occasional soil moisture depletion differences were measured between cover crop treatments, there were no measurable treatment effects on vine water potential. Nevertheless, aggressive use of suitable species and cultivars of cool season perennial grasses as intrarow cover crops provide one strategy for reducing vine size and promoting more desirable grapevine canopy architecture under humid grape growing conditions.

Wine aroma and flavor profiles of Cabernet Sauvignon made from vines associated with cover crop KY-31 fescue (*Festuca arundinacea* Shreb) x root pruning vineyard treatments were evaluated using descriptive sensory analysis and solid-phase microextraction (SPME) with gas chromatography-mass spectrometry (GC-MS). Although root pruning and under trellis cover cropping significantly and positively altered vine size and vigor, this positive impact did not translate into measureable differences in wine sensory attributes of the resultant wines. However, some treatment differences in chemical compounds were detected with GC-MS analysis and some correlation of these chemical compounds back to described sensory terms was accomplished. This result provides an initial, portfolio of compounds that may be compared to similar vineyard studies that may affect wine sensory attributes and quality perception of Cabernet Sauvignon.

A root-pruning by depth interaction that increased roots deeper in the soil profile relative to NRP vines was evident and substantiated by calculated cumulative root fraction of root biomass at different soil depths and root intercept counts. Although inconsistent between the two excavations, conservative mean separation tests suggest that root pruning induced a slightly higher density of roots and a deeper root distribution in 2008. This redistribution of roots likely contributes to the dampening of vegetative growth measured in RP vines. Additional studies should be conducted to determine the effects of specific soil conditions on root growth in order to further discern and separate genotypic interaction with variable environmental factors and vineyard manipulations that affect below ground conditions and consequent vine response.

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