

EVALUATING PRACTICAL PRUNING AND TRELLISING MEASURES TO IMPROVE
CROP YIELD AND SUSTAIN BALANCED CROP LOAD IN BUNCH WINE GRAPES

by

RACHAEL WHITE

(Under the Direction of Cain Hickey)

ABSTRACT

Grapevine canopies are managed in a variety of ways that can ultimately impact crop yield, canopy structure, and vegetative growth of the vine. Dormant pruning strategies can be altered throughout the lifetime of a vineyard and directly impact crop yield and vegetative growth of the grapevine. The trellis system, often considered to be permanent throughout the vineyard lifespan, can influence the source: sink relationships in the vine. The research presented herein evaluated practical pruning and trellising measures to improve crop yield while sustaining a balanced crop load in bunch wine grapes grown in North Georgia. A new trellis system, termed Athena, increased crop yield by 79% over the popular, spur pruned, vertically shoot positioned trellis system. Pruning to greater bud densities than currently recommended increased crop yield while rarely reducing sugar levels, and vine balance was maintained under high crop yields, particularly when canopy division was implemented.

INDEX WORDS: bud density, canopy management, Chambourcin, crop yield, leaf area, pruning, crop level, training systems, trellising systems, yield, Traminette, source: sink relationship

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RACHAEL WHITE

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RACHAEL WHITE

Major Professor: Cain Hickey
Committee: Tony Wolf
Marc van Iersel

Electronic Version Approved:

Ron Walcott
Interim Dean of the Graduate School
The University of Georgia
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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

European (*Vitis vinifera* L.) and hybrid bunch grapes are widely used for winemaking worldwide, with the goal of producing high quality wines in an economic fashion. The wine grape industry contributed \$219.9 billion to the United States (US) economy in 2017 (John Dunham & Associates 2017). In the state of Georgia, the wine industry contributed over 20,000 jobs, \$88 million in tourism, and \$4.1 billion in total economic activity in 2017 and the Georgia wine industry continues to grow (John Dunham & Associates 2017, Moss 2018). Maintaining production of economically sustainable, high quality grape crops will aid in the growth and success of domestic and international grape and wine industries.

Two practical methods to change the health, quantity, and composition of grapes is through dormant pruning measures and canopy training within a trellising system. Trellising and pruning manipulate the microclimate within the canopy that can impact disease prevalence, efficacy of pesticide applications, sunlight penetration to the fruit, and fruit composition at harvest (Gladstone and Dokoozlian 2003, Intrieri 1987, Smart 1988, Smart et al. 1985, Zyl and Huyssteen 1980). The standard trellising system used for wine grape production in the Eastern US is a series of wires attached to the trellis posts that guide shoot growth vertically; this system, commonly referred to as “VSP”, is a single canopy trellising system with vertical shoot positioned training (VSP). The VSP system is popular because it is cheaper and simpler to establish and maintain when compared to divided canopy trellising systems (Kliewer and Dokoozlian 2005, Reynolds et al. 1996, Zoenklein et al. 2008). However, the VSP system limits exposed leaf area and, by extension, photosynthetic capacity because the canopy is guided

between a series of closely spaced (10 to 12 cm) catch wires (Dokoozlian and Kliewer 1995a, Zoecklein et al. 2008).

Training systems affect yield, management efficiency, and the efficacy of a pest management program. Training systems are thus an important consideration for vineyard establishment as they impact management decisions and the crop yield potential throughout the productive lifespan of the vineyard (Miller et al. 1993, Reynolds and Vanden Heuvel 2009, Wolf 2008). As a function of increased exposed leaf area and thus sunlight interception, training systems with divided canopies produce higher yields compared to single canopy systems (Bates 2008, Carbonneau and Casteran 1987, Kliewer and Dokoozlian 2005, Reynolds and Vanden Heuvel 2009, Zoecklein et al. 2008). However, divided canopy systems require more labor to manage, can be difficult to manage using mechanized equipment, and typically limit vine planting density per unit land when compared to single canopy systems such as VSP (Gladstone and Dokoozlian 2003, Kliewer and Dokoozlian 2005, Reynolds et al. 1996).

Dormant pruning impacts crop yield, vineyard longevity, and perennial disease prevalence (Howell et al. 1987, Morris and Main 2010, Wessner and Kurtural 2013). The most common training/pruning methods for bunch grape production in the Eastern US is bilateral cordon training with spur pruning. The Lyre and Smart-Dyson training systems are variations of bilateral cordon training that use four cordons with spur pruning in order to increase crop yield (Carbonneau and Casteran 1987, Reynolds et al. 2004). A less common training and pruning practice is head training with cane pruning. Some regions in the Western US adopt the use of bilateral cane pruning over spur pruning, despite no perceived differences in fruit quality between the two pruning measures (Kasimatis et al. 1985, Skinkis and Gregory 2017, Wessner and Kurtural 2013). The Keuka high renewal and Scott-Henry systems are variations on bilateral

cane pruning that use four or more canes to increase crop yield (Reynolds and Vanden Heuvel 2009).

Vine training and pruning can influence the source-sink relationship between leaves (tissue sources of carbohydrates) and the fruit and other actively growing vine tissues (to which carbohydrates are transported). Increased sunlight interception by a grapevine canopy has been found to result in increased crop yield, vine size, and flower bud initiation (Dami et al. 2005, Edson et al. 1995, Gatti et al. 2011, Howell et al. 1987, Kliewer et al. 1967). Training and pruning strategies have been extensively researched due to their impact on the perennial production of fruit. Despite regionally ingrained training and pruning preferences, optimization of crop yield through management is cultivar-specific, and dependent on vine vigor, rootstock, and nutrient availability (Edson et al. 1995, Morris and Main 2010, Zoecklein et al. 2008). For example, dividing the canopy can increase yield in most cultivars (Kliewer and Dokoozlian 2005, Palliotti 2012, Zoecklein et al. 2008), but grafting the scion of many grape cultivars onto a 420-A rootstock will reduce the vigor and impact the crop yield (Wolf 2008). However, training and pruning practices warrant re-evaluation in field studies due to the regionally accepted, yet anecdotal, adoption and perceived value.

The aim of the research conducted as part of this thesis was to manipulate the source: sink relationships of grapevines, evaluate the quantity and quality of grapes produced, and quantify vegetative tissue production. A primary goal was to modify a tight, single canopy system (VSP) to a horizontally divided canopy system while precluding the need to remove vines and re-establish the vineyard. The retro-fitted trellis divided the canopy in an attempt to increase air movement through, and sunlight interception by, the canopy, despite retention of greater shoot densities compared to the standard VSP system. Pruning, training, and increasing physical

space in the canopy in order to retain greater bud densities are all practical ways to change the quantity and quality of grapes that can be produced from a vineyard. Though pruning, training, and modifying canopy management are all fundamental vineyard management practices, each can impact source-sink relationships of the grapevine.

A. Pruning Methods

Many grape growing regions adopt a particular pruning system over others. Many regions in the Western US use bilateral or unilateral cane pruning for premium, red wine production due to the perceived, superior wine quality when compared to spur pruning. Conversely, in the Eastern US, cane pruning has been perceived to reduce yield and cold hardiness compared to spur pruning. Despite these regional anecdotes, studies in California, Oregon, and Virginia found few grape quality differences between spur and cane pruning (Hatch et al. 2019, Kasimatis et al. 1985, Rosner and Cook 1983, Skinkis and Gregory 2017). Labor availability, ease of mechanization, and fruitful bud location for a given cultivar are all additional considerations for choosing one pruning method over another (Gatti et al. 2011, Hatch et al. 2019).

i. Cordon Training with Spur Pruning

Spur pruning is generally implemented with cordon training systems where the spurs are positioned upward in a single or divided canopy training system (mid-wire cordon with vertical shoot positioning and Lyre), downward in a high-wire (Hudson River Umbrella and standard high-wire), or a combination of upward and downward (Smart-Dyson) (Howell et al. 1987, Reynolds and Vanden Heuvel 2009). Cordons can either be unilateral, bilateral, or quadrilateral and retention of optimal cordon number per vine can depend on cultivar and site vigor, but also labor availability and finances.

In general, cordon training with spur pruning is easier to mechanize, has decreased labor costs in the dormant season, and allows for easier crop yield estimates when compared to other pruning methods (Hatch et al. 2019, Reynolds et al. 1996, Skinkis and Gregory 2017). However, success in spur pruning can be cultivar specific as some *V. vinifera* do not produce fruitful basal buds (Shaulis and May 1971). While variable across cultivars, spur pruning also tends to result in the production of greater amounts of unfruitful, non-count shoots when compared to other pruning methods. This is the result of unfruitful shoot proliferation that increases labor requirements for shoot thinning in the spring (Kurtural et al. 2006, Morris et al. 2004, Reynolds et al. 1996). While shoot thinning can be mechanized, it is not as precise as when performed by human labor and is thus generally implemented in high acreage, low value wine and juice grape vineyards (Geller and Kurtural 2013, Kurtural et al. 2012). Shoot thinning is also extremely time sensitive, which can constrain migrant vineyard labor resources between neighboring vineyards during the short timeframe that shoots are at an optimal height for thinning (Gatti et al. 2011, Reynolds et al. 1996).

ii. Head Training with Cane Pruning

Cane pruning is generally paired with head training and is the most common alternative to cordon training with spur pruning (Hatch et al. 2019, Reynolds and Vanden Heuvel 2009). Much like cordon training, canes can be fastened to the fruiting wire in different arrangements to result in the retention of one (unilateral), two (bilateral), or four (quadrilateral) canes in a given trellising system. Despite negative perceptions of cane pruning in the Eastern US, recent studies have shown that cane pruning can be a viable option even in regions where cold damage is of concern (Hatch et al. 2019). Cane pruning results in adventitious shoot growth that is confined to

the head region of the vine, typically resulting in reduced labor needs for shoot thinning (Howell et al. 1987, Rosner and Cook 1983).

Cane pruning is more difficult to mechanize and requires more skilled labor when compared to spur pruning (Hatch et al. 2019, Wessner and Kurtural 2013). While spur pruning retains only one to three basal buds on several spurs, cane pruning retains roughly eight to 12 buds on one cane. Apical cane buds tend to break first, resulting in the potential for cold damage to those buds. Thus, delayed pruning is not a viable frost mitigation practice with cane pruning as it is with spur pruning. Recent studies have shown that cane pruning slightly delays early season phenology compared to spur pruning (Hatch et al. 2019), but other studies that show cane pruned vines can decrease bud cold hardiness versus spur pruned vines (Howell et al. 1987, Rosner and Cook 1983). Thus, while cane pruning might mitigate spring frost damage, it may also increase bud cold damage.

B. Shoot Density

The use of dormant pruning or shoot thinning to change the shoot density can effectively change the canopy microclimate (Dokoozlian and Kliewer 1995a, Reynolds et al. 1994a, Shaulis and May 1971, Smart 1988, Smart and Robinson 1991, Wolf 2008). Optimum shoot densities of 15 to 30 shoots per meter of row have been reported, depending on the cultivar, site, and training system (Reynolds et al. 1994a, Smart 1988, Smart and Robinson 1991). In general, the training system chosen has a higher impact on the shoot density than other factors (Smart and Robinson 1991). Higher shoot densities can increase self-shading, reduce berry number per cluster, yet can increase crop yield (Reynolds et al. 1994a, 1994b, Shaulis and May 1971). Shoots trained to tightly spaced systems with higher shoot densities promote disease development by crowding

clusters, shading the fruit zone and limiting airflow through the canopy (Smart and Robinson 1991, Smithyman et al. 1998, Wolf 2008).

C. Grapevine Trellising Systems

Grapevine trellising systems have been developed to suit a variety of cultivar growth habits, climates, and production goals. Trellising systems can be separated into two general categories; divided and single canopy. Horizontally- or vertically-divided canopy systems generally increase leaf area compared to single canopy systems (Carbonneau and Casteran 1987, Gladstone and Dokoozlian 2003, Morris and Main 2010). Single canopy systems are adaptable to different site conditions and cultivars, are more easily mechanized, and are more economical to establish and maintain as compared to divided canopy systems (Gatti et al. 2011). The management efficiency and cost effectiveness of single canopy systems are attributes that have resulted in such systems to be the industry standard in many growing regions (Reynolds et al. 1994b, Wolf 2008, Zoecklein et al. 2008). However, on sites with excessive amounts of water and nutrients, single canopy systems can result in vines with overly vigorous vegetative growth. While growth can be remedially regulated throughout the season through manual shoot thinning, shoot positioning, and hedging, such cultural practices often require an overwhelming amount of time and labor inputs (Howell et al. 1987, Morris and Main 2010, Reynolds et al. 1996). Divided canopy systems help mitigate excessive vegetative growth by increasing the number of buds per vine, and thus crop yield, when compared to single canopy systems (Gladstone and Dokoozlian 2003, Kliewer and Dokoozlian 2005).

i. Single Canopy

Single canopy systems were developed for sites with average or reduced water and/or nutrient availability; however, with proper management, single canopy systems can perform well

on sites that confer excessive vegetative growth (Reynolds and Vanden Heuvel 2009, Reynolds et al. 2004). Excessive vegetative growth, paired with unconstrained resource availability, exacerbates the magnitude of canopy self-shading and creates an environment that is optimal for fungal disease (Jackson and Lombard 1993, Smart 1985, Smart et al. 1985, Smithyman et al. 1998). However, by reducing the amount of lateral space required for vine training, greater vine densities can be planted within single as compared to divided canopy systems. The most popular single canopy system employs vertical shoot positioning training (VSP) which directs the canopy upward through a series of tightly-spaced catch wires that are often directly fastened to vineyard posts (Reynolds and Vanden Heuvel 2009, Zoecklein et al. 2008, Zyl and Huyssteen 1980).

ii. Divided Canopy

Both horizontally and vertically divided canopy systems increase exposed leaf area and crop yield compared to single canopy systems (Carbonneau and Casteran 1987, Dokoozlian and Kliewer 1995a, Gladstone and Dokoozlian 2003, Kliewer and Dokoozlian 2005, Reynolds and Vanden Heuvel 2009). Dividing the canopy increases the exposed leaf area and thus augments vine carbon assimilation and the capability to mature the crop (Gladstone and Dokoozlian 2003, Kliewer and Dokoozlian 2005). Dividing the canopy corresponds with increasing cordon, spur, and/or cane number; all which effectively increase crop yield per vine compared to single canopy systems. Higher crop yield is a result of greater cluster number as well as increased berry weight found in divided canopy systems compared to the single canopy systems (Kliewer and Dokoozlian 2005, Palliotti 2012, Reynolds et al. 1996, Zoecklein et al. 2008). Due to the reduced amount of canopy self-shading, divided canopy systems need less leaf area (0.5 to 0.8 m² of leaf area per kg of fruit) to ripen a gram of fruit compared to single canopy systems (0.8 to 1.2 m² of leaf area per kg of fruit) in the high radiation conditions of the Central Valley of California

(Dokoozlian and Kliewer 1995a, Kliewer and Dokoozlian 2005). However, poorly managed divided canopy systems can have diminished or negative impacts on canopy structure and therefore less carbon is gained and less fruit is ripened (Kliewer and Dokoozlian 2005).

Divided canopy systems are separated horizontally, vertically, or via a combination of the two. Despite the greater land area required per vine, horizontally divided systems, such as Geneva Double Curtain (GDC) and Lyre systems, are more commonly employed than vertically divided systems. Divided canopies are more frequently used in juice grape production but also in the cultivation of Norton (Carbonneau and Casteran 1987, Reynolds et al. 1994b, Zoecklein et al. 2008). Vertically divided systems, such as the Scott Henry and Smart-Dyson, split the fruit zone into upward and downward sections. Vertically dividing the canopy requires more labor in shoot positioning to retain the canopy shape (Reynolds and Vanden Heuvel 2009, Zoecklein et al. 2008)

Cultivar selection and vineyard site can dictate the effectiveness of divided training systems at the time of implementation. Cultivars that exhibit a trailing habit are better suited to a system like GDC whereas upright growing cultivars are better suited to a Lyre (Carbonneau and Casteran 1987, Zoecklein et al. 2008). Divided canopy systems were created for sites with average to excessive soil nutrient and water availability such as those found in the Eastern US, therefore vineyard site has a large impact on their suitability. However, on sites that are deficient in mineral nutrients and water resources, dividing the canopy can result in over-cropping. Over-cropping can reduce the lifespan of the vineyard by reducing storage reserves within the vine and attenuating vegetative growth in successive growing seasons, leading to diminished fruit yield and under-ripe fruit (Jackson and Lombard 1993, Smart and Robinson 1991, Winkler 1954).

D. Source: Sink Relationship

Trellising, training, and pruning methods are methods utilized to manipulate the source: sink relationship of a grapevine. Sources are any plant tissue that manufactures or stores specific carbohydrates, like glucose, whereas sinks are the places of immediate or final use/storage of carbohydrates (Keller 2015a). Typically, the most productive sources are unshaded, mature leaves that produce more photosynthates than what is necessary for their own growth and maintenance. However, all green tissues of the vine are considered sources including the shoots and green grape berries (Keller 2015a). Sinks are typically not photosynthetic (trunks, roots, flowers, and ripening berries), or do not produce enough photosynthates to maintain or continue growth, so material needs to be translocated into these vine tissues (growing shoot tips and new leaves; ripening berries). Throughout the season, the sources and sinks change as the main sources, the leaves, mature and provide greater photosynthates to the woody growth and roots of the vine.

i. Source

Prior to bud break, storage reserves from the previous growing season are the main sources of photosynthates, as there are minimal photosynthetically active tissues on the vine. The woody portions of the vine will lose dry matter between bud break and when the leaves of the new shoots become photosynthetically active and initiate carbon fixation (Buttrose 1966, Holzapfel et al. 2010, Weyand and Schultz 2006). As the season progresses, any cell that performs photosynthesis is considered a source cell which includes mature leaves, unripe berries, and shoots. After the initial flush of growth, photosynthesis produces the main source of carbohydrates needed to drive plant growth. Through this process, the plant uses a concentration gradient for mass diffusion to take up carbon dioxide and release excess water through the leaf stomata. Chloroplasts, filled with the accessory pigment chlorophyll which is “excited” by

sunlight interception, assimilate the carbon dioxide and water into carbohydrates while releasing water and oxygen as byproducts (Keller 2015b).

Greater photosynthetic rates result in more carbon fixation and increased carbohydrate production. Once a leaf has fixed enough carbon for its own use in growth and maintenance, remaining photosynthates are stored as starch and/or translocated throughout the vine to other sinks. However, the rate of photosynthesis can impact where photosynthates are translocated throughout the vine. For example, in times of shorter day length and lower daily light integral early in the growing season, metabolites will be translocated mostly to the growing shoot tips rather than other sinks like the blooming flowers or setting fruit (Keller and Koblet 1995).

Canopy self-shading is the most common limiting factor to sunlight interception in fruit zones of single canopy systems, that receive less than 1% to 10% of the ambient light (Dokoozlian and Kliewer 1995a, Gladstone and Dokoozlian 2003). Exteriors of these canopies receive approximately 90% of the photosynthetically active radiation while the interior of the canopies receive only small “flecks” of sun that pass through gaps in the exterior canopy (Dokoozlian and Kliewer 1995b, 1995a, Smart 1988). In contrast, the fruit zones of divided canopy receive more than 30% of ambient light, indicating there are more photosynthetically active leaves exposed to direct sunlight compared to single canopy systems (Dokoozlian and Kliewer 1995b, Gladstone and Dokoozlian 2003, Kliewer and Dokoozlian 2005, Smart and Robinson 1991).

ii. Sink

Shoot apical meristems are primarily carbohydrate sinks until immediately preceding bloom. Fruit then become the main carbohydrate sinks from bloom until harvest. Later in the season, after harvest and before leaf drop, the permanent (woody) vine tissues become storage

sinks that aid in preparation for overwintering. The growing portion of the root system is also strong late- season sink, particularly when water and nutrients are limited.

The sinks receive metabolites from sources via translocation through the phloem. The most common compound found in the phloem, besides water, is sucrose that creates a mass flow, osmotic gradient where the sinks have a negative pressure compared to the sources (Candolfi- Vasconcelos et al. 1994, Keller 2015a, Wardlaw 1990). The osmotic gradient caused by high sucrose concentration within the phloem causes other metabolites and nutrients to flow directionally with sucrose. This phenomenon becomes especially important as grape berries assimilate potassium in the ripening process (Keller 2015a). Further, clusters are often thought of as one sink by themselves as they are supplied by the same strand of phloem. However, a study has shown that individual berries on a rachis ripen independently and can each accumulate varying amounts of sugar (Coombe 1992).

iii. Relationship

The source: sink relationship is commonly studied by way of changing crop yield and/or evaluating berry sugar accumulation and other important sensory impact compounds. Leaf removal, shoot topping, and cluster removal are all common methods that manipulate the source: sink relationships during the growing season. Basal shoot leaf removal removes sources around the fruit and, when an extreme amount of basal shoot leaves are removed before bloom, can limit berry number per cluster and crop yield (Frioni et al. 2019, Hickey et al. 2018). Removing shoot tips and clusters shifts metabolite accumulation from the removed portions to the remaining sinks. However, removing berries or clusters later in the season has a lesser impact on berry size when compared to when those sinks are removed before bloom, indicating the vine can self-adjust to sources and sinks present on the vine (Keller et al. 2008).

While in-season manipulation of sources and sinks effectively manipulates growth and development, a more permanent way to change the source: sink relationship is trellis selection. Dividing the canopy has been shown to improve sunlight interception and source tissue efficiency by increasing the amount of fruit that can be ripened per unit leaf area when compared to single canopies (Kliewer and Dokoozlian 2005). Single canopy trellising causes significant self-shading that can reduce the amount of fruit produced particularly in heavy cropping situations (Dokoozlian and Kliewer 1995b, Kliewer and Dokoozlian 2005, Zoecklein et al. 2008). Ultimately, increasing the source tissue exposed to sunlight will increase yield to the limit of photosynthetic and cultivar capacity (Keller 2015b, 2015a). Increasing the number of sinks by leaving more buds during dormant pruning has been shown to negatively impact fruit quality especially in single canopy systems (Howell et al. 1987, Reynolds et al. 1994a, Wolpert et al. 1983). However, with divided canopy systems, increasing the amount of buds or clusters retained does not have a significant impact on primary fruit chemistry (Bates 2008, Palliotti 2012, Reynolds et al. 1996).

E. Conclusion

Wine grape canopies can be managed in a variety of ways to manipulate the source: sink relationship. Dormant pruning strategies can increase or limit fruit production depending on the site, cultivar, and target crop production goals. Pruning is considered changeable throughout the lifetime of the vineyard and different regions tend to adopt pruning methods based on tradition or anecdote. Trellising system is considered permanent and more difficult to change throughout the lifetime of the vineyard. Trellis system structure can either help or hinder fruit production by changing the amount of leaf area exposed and subsequent sunlight interception or affecting the relative canopy density and subsequent self-shading of the leaves. The research presented herein

evaluated practical pruning and trellising measures and their impact on crop yield, primary fruit chemistry, vegetative growth, and crop load in several widely planted bunch wine grape cultivars planted in Northern Georgia.

CHAPTER 2

EVALUATION OF CANOPY DIVISION AND CANE PRUNING TO RETROFIT SPUR- PRUNED, VERTICAL SHOOT-POSITIONED PETIT MANSENG IN GEORGIA¹

¹ White, R., A. Vogel, J. Scaduto, and C. Hickey. Accepted by *Catalyst: Discovery into Practice*
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Abstract

The vertical shoot positioned training system (VSP) is a popular system used for wine grape production. VSP system dimensions can limit exposed leaf area, resulting in an imbalanced source: sink ratio. We investigated the effects of retrofitting single-canopy, VSP in a Petit Manseng vineyard by comparing two treatments levels: canopy training [a vertically divided system (DC-VSP) or a single, vertically-positioned canopy system (SC-VSP)] and pruning [bilateral cane pruning without shoot thinning (CP), quadrilateral cane pruning without shoot thinning (QCP), or spur pruning with shoot thinning to 13 shoots / m row (SP)]. DC-VSP decreased mid-canopy density by 56% when compared to SC-VSP. QCP increased crop yield by 42% compared to both SP and CP. DC-VSP increased crop yield by 31% relative to SC-VSP, but only in the second of two seasons. In 2018, the combination of DC-VSP with QCP increased crop yield by 79% when compared to the combination of SC-VSP with SP. QCP combined with SC-VSP produced a crop load of 13.9 while QCP combined with DC-VSP produced a crop load of 10.9. Our results indicate that canopy division is an important tool to increase source tissue efficiency to counterbalance higher crop levels. The novel combination of QCP with DC-VSP will be called “Athena”.

Summary.

Goals: Single canopy training with vertical shoot positioning is the predominant training and shoot positioning system in *V. vinifera* vineyards. We questioned if a single canopy with vertical shoot positioning was the most productive system on which to cultivate the modest-yielding cultivar Petit Manseng. We retrofitted low, bilateral cordon-trained, spur-pruned Petit Manseng vines trained to a single canopy by dividing the canopy with two cross arms in combination with bilateral cane pruning or dividing the fruit zone laterally with quadrilateral cane pruning. Our goals were to evaluate the effect of three different pruning techniques in combination with two training techniques on canopy architecture, crop yield and primary fruit composition over two years.

Key findings:

- Spur pruning increased pruning weight by 0.1 kg/m row compared to quadrilateral cane pruning.
- Divided, vertical shoot positioning increased pruning weights by 0.1 kg/m of row compared to single canopy, vertical shoot positioning.
- An average of 101% greater leaf exposure layer and 56% greater leaf layer number were present in mid-canopies of single canopy, vertical shoot positioned plots relative to divided, vertical shoot positioned plots.
- Quadrilateral cane pruning increased crop yield by an average of 45% (2017) and 34% (2018) when compared to bilateral cane pruning and spur pruning.
- Quadrilateral cane pruning combined with divided, vertical shoot positioning increased crop yield by 79% when compared to spur pruning combined with single canopy, vertical shoot positioning in 2018.

- Quadrilateral cane pruning produced an average crop load of 12.4, 126% greater than that produced by spur pruning over two seasons, while divided, vertical shoot positioning produced an average crop load of 7.2, 33% lower than produced by single canopy, vertical shoot positioning.

Impact and significance: Spur pruning produced a lower crop load than quadrilateral cane pruning. The relatively high crop load in quadrilateral cane pruning indicated over-cropping. That unbalanced source: sink relationship was alleviated through the use of canopy division, which decreased canopy self-shading and increased crop yield when compared to single canopy, vertical shoot positioned training in the second of two years. “Athena” is a novel training system that combines the divided, vertical shoot-positioned canopy with quadrilateral cane pruning to improve exposed canopy leaf area and crop production, respectively. The Athena system does require further testing over an extended time period, in various growing conditions, and in other cultivars.

Overview.

Training and pruning contribute to the perennial vineyard sustainability and maintenance of economical crop yields.^{1,2} Vineyards can be trained to single or divided canopy systems, each of which has pros and cons. The optimal use of a training system is case-specific and is partially determined by growing region, vineyard site, production goals, and cultivar choice. However, canopy division generally improves the canopy microclimate by maximizing canopy functional (exposed) leaf area especially in conditions of dense canopies caused by high vegetative vigor.^{3,4} Increased canopy functional leaf area enhances carbon assimilation, vine sustainability, and the amount of crop that can be ripened in cases of high site vigor.^{1,3}

Relative to a single canopy, a divided canopy has greater cropping potential and increased canopy leaf area *per vine*, as in the Lyre and Geneva double curtain (GDC) systems.^{1, 5, 6, 7, 8} However, some horizontally divided canopy training systems use trellis hardware that laterally extends into vineyard alleyways. As a consequence, divided systems often require vines to be planted at considerable between-row spacing to accommodate farm vehicle passage. Greater land area is often required to train the same number of vines on a horizontally divided system relative to a single canopy system.^{1, 2, 7, 8} Thus, assuming a greater vine density with the single canopy system, the crop yield *per unit land* may be similar between divided and single canopy systems. The most commonly used single canopy system involves a series of trellis catch wires that guide vertical shoot growth. Catch wires in the single canopy, vertical shoot positioning are closely spaced (10 to 15 cm) which often causes overcrowding of canopy vegetation and causes significant self-shading, limiting the amount of photosynthetically active leaf area.^{3, 5, 9} From a fiscal perspective, divided canopy systems initially incur greater costs than single canopy systems due to the extra wires and hardware needed for trellising infrastructure. While divided canopy systems can have greater labor requirements to install and manage than single canopy systems, those input costs could be offset due to a decreased planting density and therefore reduced plant material costs.¹⁰

Head training with cane pruning is a standard practice in some wine growing regions whereas cordon training with spur pruning is standard in other regions.^{11, 12, 13} Partiality to one pruning practice may be due to misjudged differences in wine quality and anecdotally observed difference in crop yield.^{11, 12} While spur pruning is more common in eastern US vineyards, spur pruning results in an increase in unfruitful shoots growing from adventitious buds on cordons when compared to bilateral cane pruning.¹⁴ Unfruitful shoots are particularly undesirable in

humid, US growing regions as the result is excessively dense canopies, limited spray penetration, and intensified fungal disease incidence.^{9, 15} High vegetative growth with spur pruning increases dormant cane pruning weight which depresses crop load (crop yield: pruning weight ratio)^{16, 17,}^{18, 19} resulting in vines with high source: sink ratios.²⁰ An excessively vegetative vine, as indicated by a low crop load, has the vegetative capacity to produce more crop; however, the *capacity* to produce more crop does not necessarily equate to greater crop yield in excessively vegetative vines.

Spur pruning may require shoot thinning to a targeted, optimal density.⁹ Along with being costly, shoot thinning labor can be scarce due to the narrow window of opportunity to effectively implement this practice and the simultaneous need for labor crews in several local vineyards.¹⁰

While mechanizing spur pruning can reduce labor cost during the dormant pruning season, shoot thinning can reduce the economic value of mechanical pruning.^{19, 21} Cane pruning, on the other hand, has greater labor demands due to cane tying during the dormant season, which is less time-sensitive than during the rapid flush of shoot growth in the spring when shoot thinning is required.^{10, 12} For example, in the dormant season, pruning and brush pulling cannot be fully mechanized in cane pruned vineyard and canes must be tied to the fruiting wire. However, cane pruned vines have less adventitious shoots, most of which are borne in the head region of the vine, requiring less time-sensitive shoot thinning labor compared to spur pruning.

Cane pruning reduces the amount of perennial wood retained on the vine, which may reduce the incidence of wood-borne diseases and the production of adventitious, unfruitful buds.^{1, 12}

However, cane pruning has been shown to slightly reduce crop yield compared to cordon training with spur pruning in some cultivars.^{19, 22} Thus, retaining more than two canes may offset crop yield deficits while sustaining the practical, labor-related benefits of cane pruning

mentioned above. Retaining more than two canes could increase short-term crop yield. However, we suspect retaining several canes may result in vine over-cropping^{17, 22, 23, 24, 25} and a potential shift in carbohydrates toward fruit production, ultimately reducing vine size, crop yield over time, and fruit quality.^{22, 23, 25} Canopy division increases functional leaf area and carbon gain.^{1, 5, 10, 23, 26} Canopy division may improve vine carbon balance and aid in fruit maturation and vine size maintenance over time if more than two canes are retained to bear more crop.^{16, 19, 22} Along with site and cultivar selection, training system choice is an important consideration for optimizing between-row spacing when designing and establishing a vineyard.⁹ Relative to training system choice, pruning method choice may not be viewed as immediately important when establishing a vineyard, as it can be a flexible, annual decision.^{11, 12} Training system choice, which is often single canopy with vertical shoot positioning for *V. vinifera* production in the eastern US, may be viewed as a permanent choice after vineyard establishment. Since there are several benefits to canopy division^{1, 5, 6, 7, 10}, we were interested in evaluating if a single canopy, vertical shoot positioned training system could be horizontally divided without the need to re-establish the vineyard at a greater between-row spacing. We retrofitted cordon-trained, spur-pruned, single canopy, vertical shoot positioned Petit Manseng through canopy division with either bilateral or quadrilateral cane pruning. We evaluated changes in vine size (pruning weight), vegetative growth and canopy structure, crop yield, and fruit composition that resulted from the pruning-training combinations.

Major observations and interpretations.

Brief description of experimental setting and treatments. A split plot design was replicated in four blocks in a vertically-shoot positioned, commercial Petit Manseng vineyard planted in 2010 located in Rabun County, Georgia. The vineyard was seven-years-old at the start of the project

and the same vines were used over two seasons. The main plot evaluated two canopy training effects and the sub-plot examined three pruning effects. One trellising treatment was a single canopy, vertical shoot positioned training system (SC-VSP) that trained the canopy between two sets of catch wires, each set 12 cm apart in width, and placed 45 cm and 85 cm above the fruiting wire. The other training treatment horizontally divided the single canopy into a “V-shape” (DC-VSP) using trellis catch wires positioned the same distance above the fruiting wire as the SC-VSP but using a 61 cm-wide cross arm at 45 cm above the fruiting wire and a 92 cm-wide cross arm at 85 cm above the fruiting wire. The three pruning treatments in sub-plots were: spur pruning in tandem with shoot thinning to the industry standard⁹ of 13 shoots per m of cordon (SP), bilateral cane pruning with canes between 8 to 12 buds long (mean = 11, data not shown) without shoot thinning (CP), and quadrilateral cane pruning with canes between 8 to 12 buds long (mean = 11, data not shown) without shoot thinning (QCP). The quadrilateral cane system needed an extra set of fruiting wires, which were horizontally separated to a width of 36 cm using a cross arm that was placed at approximately 100 cm above the ground. This decreased the angle of the “V-shape” of the DC-VSP in the QCP plots versus the other two pruning techniques and this is the newly termed “Athena” system (Figure 1). The QCP combined with SC-VSP plots used an identical method to divide the fruit zone, but the canopy was then forced between the SC-VSP catch wires.

Meteorology. Considerably more rain fell in 2018 relative to 2017, and more growing degree days (GDD) were accumulated in 2018 than in 2017 (Figure 1). In 2017, 2010 GDD accumulated and 1393 mm of rain fell between 1 Apr to 31 Oct. In 2017, the greatest monthly GDD accumulation was between June and August. The greatest monthly rainfall occurred in May, July, and October in 2017. In 2018, 2133 GDD accumulated and 1517 mm of rain fell

between 1 Apr to 31 Oct. GDD steadily accumulated in 2018, with the warmest months occurring between June and September.

Dormant cane pruning weight, length, presence, shoot number per meter of row, and post-fruit set lateral growth. Dormant cane pruning weight was greater in SP relative to CP and QCP and was increased in DC-VSP relative to SC-VSP (Table 1). QCP and CP had an average of 70% and 25% lower pruning weight, respectively, when compared to SP over two years. DC-VSP produced an average pruning weight of 0.4 kg/m row, which was 64% greater than the average pruning weight observed in SC-VSP over two years. Both DC-VSP and SP produced pruning weights that fell between 0.3 and 0.6 kg/m row, which is slightly below the ideal range.²⁷

Treatment effects on pruning weight were a function of their effect on shoot number and vigor, as indicated by measurements of dormant cane length and shoot numbers (Table 1). Quadrilateral cane pruning (QCP) reduced dormant cane length by an average of 26% when compared to SP, whereas CP reduced average dormant cane length by only 6% relative to SP, over two years.

Quadrilateral cane pruning (QCP) produced shorter dormant canes at *each* node relative to SP (26% in 2017 and 35% in 2018) (data not shown). CP produced shorter dormant canes across *most* nodes when compared to SP (6% in 2017 and 10% in 2018), but dormant canes in the mid-fruiting region in CP were substantially shorter than those produced from the mid-cordon region in SP (24% in 2017 and 48% in 2018, data not shown). As previously reported, dormant cane length was differentially affected by pruning treatment and suggests that shoot growth is limited by bilateral cane pruning, at least in vineyards planted at 1.5 m or 1.8 m between vines¹⁴, as was the case herein. In addition to producing longer dormant canes, SP increased pruning weight relative to QCP and CP as a function of greater numbers of dormant canes across all bud positions. Cane pruning (CP) produced greater than, or equal, pruning weights compared to

QCP, which may have been a function of the increase in lateral shoot length observed in CP relative to other pruning treatments during the growing season (an average of 55% longer lateral shoots in 2017 and 90% longer lateral shoots in 2018). Thus, while there were fewer dormant canes present in CP, those fewer dormant canes weighed more due to lateral shoot production during the growing season. There was a higher pruning weight in DC-VSP relative to SC-VSP in both years.

Early-season phenology. Spur pruning (SP) accelerated bud break (modified EL stage four²⁸) and early season growth relative to CP and QCP (Figure 2) while training treatment had no impact on phenology (data not shown). On 21 April 2018, the average EL stage in SP was considered at bud break, 2.9 in CP, and 3.1 in QCP. A week later, the average EL stage was greater than 4 in all treatments, but the EL stage of SP was advanced relative to QCP and CP. Those trends continued through 4 and 10 May 2018, the final dates that phenology was assessed. In North Georgia, delayed spur pruning is a common tool used to slow bud break in an attempt to mitigate frost injury. However, delayed pruning can diminish crop yield relative to dormant spur pruning.²⁹ In line with previous reports¹⁴, our data suggests that cane pruning can modestly delay early season phenology when compared to spur pruning. Cane pruning may thus limit the percent of tissues damaged by spring frost compared to spur pruning. The efficacy of a cultural practice at frost injury avoidance is highly dependent on when the frost actually occurs. For example, cane pruning would have no advantage at mitigating tissue damage relative to spur pruning if a frost occurred after 27 Apr 2018 at our experimental site. Further, delayed pruning (leaving long spurs to be pruned after the period of greatest frost threat) cannot be practiced with cane pruning.

Veraison fruit zone and mid-canopy Point Quadrat Analyses. Pruning treatment generally impacted fruit zone architecture more consistently and to a greater magnitude than training

treatment (Table 2). Divided canopy with vertical shoot positioning (DC-VSP) and QCP produced greater amounts of foliage surrounding the fruit zone relative to other treatments. There were 9% and 32% more leaf contacts (LLN) in QCP when compared to SP in 2017 and 2018, respectively, and a subsequent 40% and 57% increase in shade layers around the clusters (CEL) in QCP relative to SP in 2017 and 2018, respectively. There was an interaction between pruning and training in both 2017 and 2018. The combination of QCP with training treatments produced the greatest CEL compared to all other pruning and training treatment combinations (data not shown). In summary, QCP produced a shaded fruit zone which could increase acidity in grapes and limit fruit character in wine.²⁷ Thus, it may be worthwhile to selectively remove leaves surrounding clusters if practicing QCP pruning, particularly in cultivars with greater rot susceptibility than Petit Manseng.

Mid-canopy architecture was evaluated to estimate photosynthetically active leaf area (Table 2), some of which is shaded in single canopy, vertical shoot positioned systems^{5, 7, 10}, particularly in high vigor vineyards. In general, DC-VSP decreased mid canopy density relative to SC-VSP while pruning treatment had a lesser impact on mid-canopy architecture (Table 2). The mid canopies of SC-VSP had 52% and 60% greater LLN relative to DC-VSP in 2017 and 2018, respectively. Consequently, there was 96% and 105% greater LEL in the mid-canopy of the SC-VSP relative to DC-VSP in 2017 and 2018, respectively. Canopy division can improve the wine quality potential compared to single canopy training systems.^{6, 10, 26} In a Chambourcin vineyard in Georgia, a training system fitted to the exact specs of the DC-VSP treatment produced 60% greater leaf area index (the green leaf area per unit ground area) and a 116% greater *effective* leaf area index (leaf area index that is not shaded by other leaves in the canopy) relative to a standard single canopy training system combined with vertical shoot positioning (data not shown). Thus,

the greater pruning weight observed in DC-VSP relative to SC-VSP (Table 1) may have been a result of greater photosynthetically active leaf area in DC-VSP, which has been documented to promote vine growth.^{3, 4} The reduction in pruning weight and cane length observed in QCP were indicative of a shift in metabolite partitioning from vegetative growth to fruit production and ripening^{17, 23, 24} and may be reflective of over-cropping in that treatment.^{16, 22} Thus, dividing the training system (e.g. DC-VSP) with QCP may augment vine growth in the presence of the increased bud numbers when retaining four canes for fruit production.

Crop yield components. When compared to CP and SP, QCP increased crop yield by an average of 44% in 2017 and by an average of 34% in 2018 (Table 3). Those crop yield increases were primarily attributed to greater cluster numbers observed in QCP relative to CP and SP. CP pruning had greater berry numbers per cluster and subsequently greater cluster weight when compared to both QCP and SP. Thus, despite having fewer clusters per vine, CP had comparable crop yield to SP in 2017. While pruning treatment proved to have greater and more consistent effect on crop yield than training treatment, DC-VSP produced a 31% greater crop yield than SC-VSP in 2018 alone. A statistical interaction revealed that QCP with DC-VSP produced greater crop than any other pruning x training treatment combination in 2018 (data not shown). Quadrilateral cane pruning (QCP) combined with DC-VSP (mean= 5.83 kg/vine) resulted in 45% greater crop yield relative to SP grown with DC-VSP (mean= 4.03 kg/vine) in 2018. Perhaps the most industry-relevant finding was QCP combined with DC-VSP (mean= 5.83 kg/vine) increased crop yield by 79% relative to the most common pruning and training combination in commercial vineyards in the eastern US, SP with SC-VSP (mean = 3.25 kg/vine). Crop load, the ratio between crop yield and dormant cane pruning weight, is optimal when between 4 to 10 in single canopy systems and 5 to 10 in divided canopy systems with a threshold

of 12 for both canopy systems.^{26, 27} Due to low pruning weight (Table 1) and high crop yield (Table 3), QCP crop load was 13.2 in 2017 (Table 3). In 2018, the crop load in QCP plots was 11.6 and fell slightly above the documented “balanced” range.²⁷ Thus, our observations suggest that retaining greater bud numbers per vine, as with QCP, may help alleviate the often observed, “unbalanced”, low, crop loads due to excessive vegetative growth in humid regions and particularly on sites that confer high vine vigor. Crop load in CP and SP pruning fell below the optimal, balanced range. In 2017, DC-VSP produced a lower crop load than that of SC-VSP (Table 3). Despite having a greater crop yield, DC-VSP produced a similar crop load to that of SC-VSP in 2018. While a treatment interaction was not observed, DC-VSP combined with QCP produced a mean crop load of 10.1, which was lower than that of the 16.3 mean crop load produced by SC-VSP combined with QCP in 2017 (data not shown). Further, despite DC-VSP producing greater crop yield than SC-VSP in 2018, similar crop loads were observed between DC-VSP combined with QCP (mean = 11.6) and SC-VSP combined with QCP (mean = 11.5) (data not shown). Thus, DC-VSP supported greater vine growth (as evidenced by greater pruning weight in Table 1) relative to SC-VSP, suggesting that canopy division can aid in greater crop production while sustaining balanced, vegetative growth relative to single, undivided canopies.^{1,}

5, 10, 26

In 2017 and 2018, QCP had the lowest berry weight throughout the entire post-veraison period (Figure 3). Spur pruning (SP) maintained the highest berry weight in 2018 but CP had the highest harvest berry weight in 2017 throughout the entire post-veraison period (Figure 3). In 2018, DC-VSP produced heavier berries than SC-VSP and DC-VSP tended to produce heavier berries throughout both post-veraison periods (Figure 3). Heavier berries were previously observed with canopy division.¹⁰ The increase in berry weight with divided canopies could be a

function of increased light interception, leading to greater carbon assimilation and increased water uptake, thus greater berry size.^{10,27}

Primary fruit composition. Treatments had modest effects on primary juice chemistry, but some statistically significant responses were observed (Table 4). Quadrilateral cane pruning (QCP) increased titratable acidity (TA) by 0.5 g/L in 2017 relative to SP, a response of questionable practical importance for a cultivar with highly acidic juice like Petit Manseng. DC-VSP plots increased TA by 0.5 g/L in 2017 and by 0.3 g/L in 2018 relative to SC-VSP. Acidity is typically higher in grapes produced in shaded fruit zones³⁰ as temperature-driven malic acid respiration is increased in exposed relative to shaded grapes. The larger amount of leaves and clusters observed in DC-VSP and QCP fruit zones (Table 2) likely increased shading and resulted in elevated acidity relative to SC-VSP and single-fruit zone-treatments (CP and SP). Unlike in standard divided canopy systems, the DC-VSP converged from the widest point at the top of the trellis on a single fruiting wire (CP and SP) or a tightly spaced set of wires (QCP) which increased the amount of leaves and clusters present in the fruit zone of the vine.

Pruning treatment affected soluble solids content development only in Aug, which is well before commercial harvest would commence (Figure 4). The SC-VSP plots had greater soluble solids than DC-VSP on all pre-harvest dates in 2018 (Figure 4). While the higher exposed leaf area and decreased shading layers in the mid canopy of the DC-VSP plots (Table 2) were anticipated to enhance soluble solid development in that treatment, SC-VSP had 0.6 greater soluble solid content at harvest than DC-VSP in 2018 (Table 4). A 0.6 increase in soluble solids translates to approximately 0.33% difference in alcohol concentration (volume/volume) after fermentation into wine, an alcohol amount of perhaps little practical relevance. The reduction in soluble solid *content* observed in DC-VSP versus SC-VSP may have been a function of the greater crop yield

and greater berry weight in DC-VSP (Table 4). Therefore, *absolute* carbon gain was equal to or greater in DC-VSP compared to SC-VSP plots, but the greater number and size of sink tissues in DC-VSP may have attenuated grape sugar *content* relative to SC-VSP.

Broader impact.

Pruning and training are important considerations when designing a vineyard. It is atypical to change training systems without the need to remove and replant vines, a costly undertaking due to labor and material costs as well as lost production years. While flexible, the pruning methods also tend to remain constant throughout the lifespan of the vineyard. Our results show that a spur pruned, SC-VSP training system can be retrofitted by cane pruning and canopy division. While the modified training system did not impact crop in the first season, the divided canopy system increased crop yield by 31% relative to a single canopy system in the second year. The fact that QCP with DC-VSP produced 79% greater crop yield without differentially affecting crop load relative to SP with SC-VSP indicates that increased crop production with QCP can be healthily sustained when canopy division is used to accentuate canopy leaf exposure. A very general economic assessment shows that a 79% increase in crop yield translates to an estimated increase of \$7,180 per ha (assuming if the increase in yield was sold as crop at \$2,000/ton), or \$34,140 per ha if sold as wine at a \$20 per bottle price point not including other production costs. The combination of the DC-VSP and QCP has been named “Athena”. Athena should be formally evaluated in field studies conducted over longer time periods and in other cultivars and growing regions.

Experimental design.

The experiment was conducted in a commercial Petit Manseng vineyard, which was grafted to 3309 C rootstock and planted in 2010 in Rabun County, Georgia. Vines were 1.5 m apart and

rows were 2.7 m apart, running north to south. The soil was a combination of Bradson fine sandy loam and Transylvania-Troxaway complex which are sandy-clay loams and silty loams, respectively.³¹ Vines were trained to low, bilateral cordons at approximately 100 cm above the ground and shoots were positioned vertically with the aid of two sets of trellis catch wires positioned at 45 cm and 85 cm above the fruiting wire and approximately 12 cm apart. A randomly assigned split-plot design was implemented in four blocks. Experimental units consisted of four vines. The main plot evaluated canopy training effects and the sub plot examined pruning effects within each of the main plots, as described below. Vines were hedged to 0.61 meters above the top catch wire to prevent draping and canopy shading. Fruit zone leaf removal was implemented between EL stages 29 to 31 by removing two leaves and laterals from the two cluster bearing nodes. The pest management program was standard for the region and was effective at managing insects and diseases.

Canopy trellising and training treatments were either a standard single canopy with vertical shoot positioning (SC-VSP) that were trained between the two sets of catch wires already present in the vineyard, or a divided canopy with vertical shoot positioning (DC-VSP) where the canopy was separated into a “V-shape” using two cross arms at the two catch wire positions. The dimensions of the standard SC-VSP system mimicked that of the already-established single canopy training with vertical shoot positioning (described above). The divided canopy training system with vertical shoot positioning (DC-VSP) trained the shoots up and outward in a V-shaped trellising. This was done by using two sets of cross arms, one 61 cm-long cross arm fastened 45 cm above the fruiting wire, and another 92 cm-long cross arm fastened 85 cm above the fruiting wire. The existing wires of the original trellis were then moved to the outside notch in the cross arms, spacing the wires 58 cm apart for the first cross arm and 89 cm apart for the

second cross arm. The shoots were periodically hedged 0.2 m above the top catch wire in all treatments and were positioned throughout the growing season to ensure that the canopy was trained to the intended treatment system.

Pruning treatments consisted of three training/pruning combinations: Bilateral cordon training with spur pruning and shoot thinning to 13 shoots per m of cordon (SP); head training with bilateral cane pruning and shoot thinning of adventitious shoots in the head region (CP); and head training with quadrilateral cane pruning and shoot thinning of adventitious shoots in the head region (QCP). The quadrilateral cane system needed an extra set of fruiting wires, which were horizontally separated to a width of 36 cm using a cross arm that was placed at approximately 100 cm above the ground.

Meteorology. Growing degree days and rainfall were calculated using a weather station five miles away from the vineyard. Growing degree days were calculated using the formula:

$$[(\text{minimum daily temperature} - \text{maximum daily temperature})/2] - 10 = \text{GDD}_{10}.$$

Dormant cane pruning weight, length, presence, shoot number per meter of row, and post-fruit set lateral shoot growth. Cane pruning weights were measured by vine with a field scale during the dormant season. In order to characterize pruning treatment effect on shoot growth and investigate previously observed variability in shoot production along the length of a cane, individual dormant cane length and presence was taken by rating the lengths of the dormant canes using a numerical scale. “Zero” was a cane that was not present, “one” was a cane that fell below the first catch wire, “two” was a cane that was between the first and second catch wire, and “three” was a cane that was above the second (top) catch wire. A cane that was not present at the retained bud position was not accounted for when averaging dormant cane length but was used to objectively quantify how treatment affected the percent of dormant canes present.

Shoot number per meter of row was taken around bloom (EL stages 19 to 25) to establish differences in shoot numbers between the different pruning treatments. In order to characterize shoot vigor and the potential for fruit zone shading, lengths of lateral shoots were measured at modified EL stage 29²⁸, one week after the first primary shoot hedging occurred. Lateral shoots were measured between the primary shoot nodes 3 to 7 on the middle two vines of an experimental unit as these are the primary laterals causing shade in the fruit zone.

Early-season phenology. The modified Eichhorn-Lorenz (EL) stage²⁸ was used to evaluate bud phenology during the bud break period of April and May in 2018. The EL stage was evaluated on all of the buds (including those not growing) of the middle two vines in each experimental unit. The modified EL stage was assessed weekly over four consecutive weeks.

Veraison fruit zone and mid-canopy Point Quadrat Analysis. Point Quadrat Analysis (PQA) was completed at veraison (modified Eichhorn-Lorenz stage 35).^{27, 28} A thin, metal probe was inserted every 30 cm through the fruit zone and mid-canopy (equidistant between the second and top catch wires) in a parallel fashion to the vineyard floor. The tissue contacts (leaf, cluster, or gap - if there was nothing present) were recorded in the order in which they were contacted as the probe transected the fruit zone or mid-canopy.²⁷ The probe insertion results were used to produce the following PQA metrics: occlusion layer number (total number of contacts), cluster exposure layer (number of contacts between the cluster and the canopy boundary), and leaf exposure layer (number of contacts between the leaves and the canopy boundary).³² The mid-canopy of the DC-VSP was transected twice, on either side of the canopy.

Components of crop yield. Harvest occurred on 23 Sep 2017 and 29 Sep 2018. Vines were harvested into single lugs on a per vine basis and cluster counts were taken at the same time. Lugs were then weighed using a field scale and the cluster counts were recorded. Cluster weight

was determined by dividing the total crop yield per vine divided by the cluster number from that same vine. Berry number per cluster was determined by taking the cluster weight divided by the individual berry weight calculated from the composite berry sample taken immediately before harvest (as per the primary chemistry data methods, below). Crop load was determined on a per vine basis by dividing the kg of crop yield by the kg of cane pruning weight produced within the same growing season.

Primary fruit composition. Bi-weekly, composite berry samples were taken from veraison through harvest for soluble solids (Brix) analysis; juice pH and titratable acidity were only measured on the composite berry sample taken immediately before harvest. Equal amounts of berries were randomly sampled from both canopy sides of each vine, creating composite samples of 120 berries from each experimental unit in 2017 and 80 berries from each experimental unit in 2018. Berries were hand-pressed in a plastic bag to express juice. Soluble solids (Brix) were measured using an Atago PAL-1 Digital Refractometer. The TA and pH were measured with a Titrino 848 Plus auto titrator (Metrohm, USA, Riverview, FL). Juice TA was measured by titrating a solution of 5 mL of grape juice and 40 mL of distilled water to an endpoint pH of 8.2 with a 0.1 M NaOH base following previously described protocols.³³ The pH probe of the Titrino 848 Plus was used to measure pH on undiluted grape juice.

Statistical analysis. JMP Pro v. 13 was used for statistical analysis of the data. Mixed models were used to evaluate the random effect of block, the fixed effects of training and pruning, and the interaction between training and pruning. Significant mean separation ($\alpha \leq 0.05$) was determined with Tukey's honest significant difference (HSD) in the pruning experiment. Student's t-test was used to determine mean separation ($\alpha \leq 0.05$) for the training experiment.

Pruning and training effects on EL stage progression and berry weight and soluble solid development were analyzed within each date using Tukey's HSD (pruning experiment) and Student's t-test (training experiment).

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Treatment effects	Pruning Weight (kg/m row)		Cane Length Rating ^a		Dormant Cane Presence (%) ^b		Lateral Shoot Length (cm) ^c		Shoot Numbers (per m) ^d	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Trellising^e										
DC-VSP	0.4 a	0.3 a	2.4 a	2.5	73.7	84.3	6.3	8.3	11	14 a
SC-VSP	0.2 b	0.2 b	2.2 b	2.3	74.9	80.4	5.5	8.5	11	13 b
Pruning^f										
QCP	0.2 c	0.2 b	2.0 c	2.0 c	61.1 b	70.8 c	4.9 b	6.0 b	14 a	17 a
SP	0.4 a	0.4 a	2.5 a	2.7 a	98.0 a	94.7 a	5.1 b	7.9 b	13 b	13 b
CP	0.3 b	0.3 b	2.3 b	2.5 b	63.7 b	81.7 b	7.6 a	11.4 a	7 c	9 c
Significance^g										
Trellising (TR)	<0.0001	<0.0001	<0.0001	ns	ns	ns	ns	ns	ns	0.0280
Pruning (PR)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0094	0.0012	<0.0001	<0.0001
TR*PR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

^a Cane length was taken as a rating based on the metric provided in the methods. A “1” rated cane did not reach the first catch wire; a “2” rated cane was between the first and second catch wire; and a “3” rated cane was taller than the second catch wire

^b Percentage based on cane presence per bud position retained.

^c Measured at EL stage 29, one week post primary shoot hedging in 2017 and 2018

^d Shoot numbers were taken between EL stages 19 to 25 (bloom) and were taken on both sides of the QCP.

^e DC-VSP=divided canopy with vertical shoot positioning and SC-VSP=single canopy with vertical shoot positioning.

^f QCP = head training with quadrilateral cane pruning and adventitious shoots thinned from the head region; SP = bilateral cordon training with spur pruning and shoots thinned to 13 shoots / linear m of row; CP = head training with bilateral cane pruning and adventitious shoots thinned from the head region.

^g Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Student’s T-test (Trellising experiment) and Tukey’s honest significant difference (Pruning experiment)

Table 2.2 Trellising and pruning effect on select *fruit zone* and *mid - canopy* enhanced point quadrat analyses, as measured at veraison in Petit Manseng in 2017 and 2018.

Treatment effects	Fruit Zone Leaf Layer Number (LLN)		Fruit Zone Leaf Exposure Layer (LEL)		Cluster Exposure Layer (CEL)		Mid-Canopy Leaf Layer Number		Mid-Canopy Leaf Exposure Layer	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Trellising ^a										
DC-VSP	2.0	1.7 a	0.5 a	0.4 a	0.7	0.6	2.3 b	2.1 b	0.2 b	0.2 b
SC-VSP	2.0	1.4 b	0.4 b	0.2 b	0.8	0.5	3.5 a	3.4 a	0.5 a	0.5 a
Pruning ^b										
QCP	2.2 a	1.9 a	0.8 a	0.6 a	0.9 a	0.9 a	2.9 ab	2.7 ab	0.4	0.4
SP	2.0 ab	1.4 b	0.3 b	0.2 b	0.7 b	0.4 b	3.1 a	3.0 a	0.4	0.4
CP	1.8 b	1.3 b	0.2 c	0.2 b	0.6 b	0.4 b	2.7 b	2.6 b	0.3	0.3
Significance ^c										
Trellising (TR)	ns	0.0085	0.0123	0.0116	ns	ns	<0.0001	<0.0001	<0.0001	<0.0001
Pruning (PR)	0.0139	<0.0001	<0.0001	<0.0001	0.0003	<0.0001	0.0419	0.0404	ns	ns
TR*PR	ns	ns	ns	ns	0.0295	0.0171	ns	ns	ns	ns

^a DC-VSP=divided canopy with vertical shoot positioning and SC-VSP=single canopy with vertical shoot positioning.

^b QCP = head training with quadrilateral cane pruning and adventitious shoots thinned from the head region; SP = bilateral cordon training with spur pruning and shoots thinned to 13 shoots / linear m of row; CP = head training with bilateral cane pruning and adventitious shoots thinned from the head region.

^c Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Student's T-test (Trellising experiment) and Tukey's honest significant difference (Pruning experiment).

Table 2.3 Trellising and pruning effect on components of crop yield and crop load in Petit Manseng in 2017 and 2018.

Treatment effects	Crop yield (kg/vine)		Cluster number		Cluster Weight (g)		Berry # / Cluster		Berry Weight (g)		Crop Load	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Trellising^a												
DC-VSP	4.0	4.5 a	39	51 a	110.7	93.7 a	99	73	1.1	1.3 a	4.4 b	7.5
SC-VSP	4.1	3.5 b	39	42 b	110.6	85.8 b	101	72	1.1	1.2 b	7.3 a	8.3
Pruning^b												
QCP	5.1 a	4.9 a	55 a	62 a	93.4 b	78.2 b	88 b	67 b	1.1 b	1.2 c	9.7 a	10.6 a
SP	3.5 b	3.6 b	35 b	42 b	100.0 b	85.0 b	89 b	66 b	1.1 a	1.3 a	3.4 b	5.5 c
CP	3.6 b	3.5 b	26 c	35 c	138.9 a	106.1 a	123 a	85 a	1.1 a	1.2 b	4.4 b	7.5 b
Significance^c												
Trellising (TR)	ns	<0.0001	ns	0.0001	ns	0.0117	ns	ns	ns	<0.0001	0.0003	ns
Pruning (PR)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0005	<0.0001	0.0012	<0.0001	<0.0001	<0.0001
TR*PR	ns	0.0040	ns	0.0135	ns	ns	ns	ns	ns	ns	ns	ns

^a DC-VSP=divided canopy with vertical shoot positioning and SC-VSP=single canopy with vertical shoot positioning.

^b QCP = head training with quadrilateral cane pruning and adventitious shoots thinned from the head region; SP = bilateral cordon training with spur pruning and shoots thinned to 13 shoots / linear m of row; CP = head training with bilateral cane pruning and adventitious shoots thinned from the head region.

^c Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Student's T-test (Trellising experiment) and Tukey's honest significant difference (Pruning experiment).

Table 2.4 Trellising and pruning effect on primary juice composition in Petit Manseng at harvest in 2017 and 2018.						
Treatment effects	Soluble solid content (°Brix)		pH		TA (g/L)	
	2017	2018	2017	2018	2017	2018
Trellising ^a						
DC-VSP	24.1	22.3 b	2.8 b	3.1	10.5 a	6.7 a
SC-VSP	24.1	22.9 a	2.9 a	3.1	9.9 b	6.4 b
Pruning ^b						
QCP	24.1	22.6	2.8	3.1	10.4 a	6.6
SP	24.2	22.7	2.8	3.1	9.9 b	6.8
CP	24.1	22.5	2.9	3.2	10.2 ab	6.5
Significance ^c						
Trellising (TR)	ns	0.0018	0.0034	ns	0.0005	0.0450
Pruning (PR)	ns	ns	ns	ns	0.0117	ns
TR*PR	ns	ns	ns	ns	ns	ns

^a DC-VSP=divided canopy with vertical shoot positioning and SC-VSP=single canopy with vertical shoot positioning.

^b QCP = head training with quadrilateral cane pruning and adventitious shoots thinned from the head region; SP = bilateral cordon training with spur pruning and shoots thinned to 13 shoots / linear m of row; CP = head training with bilateral cane pruning and adventitious shoots thinned from the head region.

^c Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Student's T-test (Trellising experiment) and Tukey's honest significant difference (Pruning experiment).

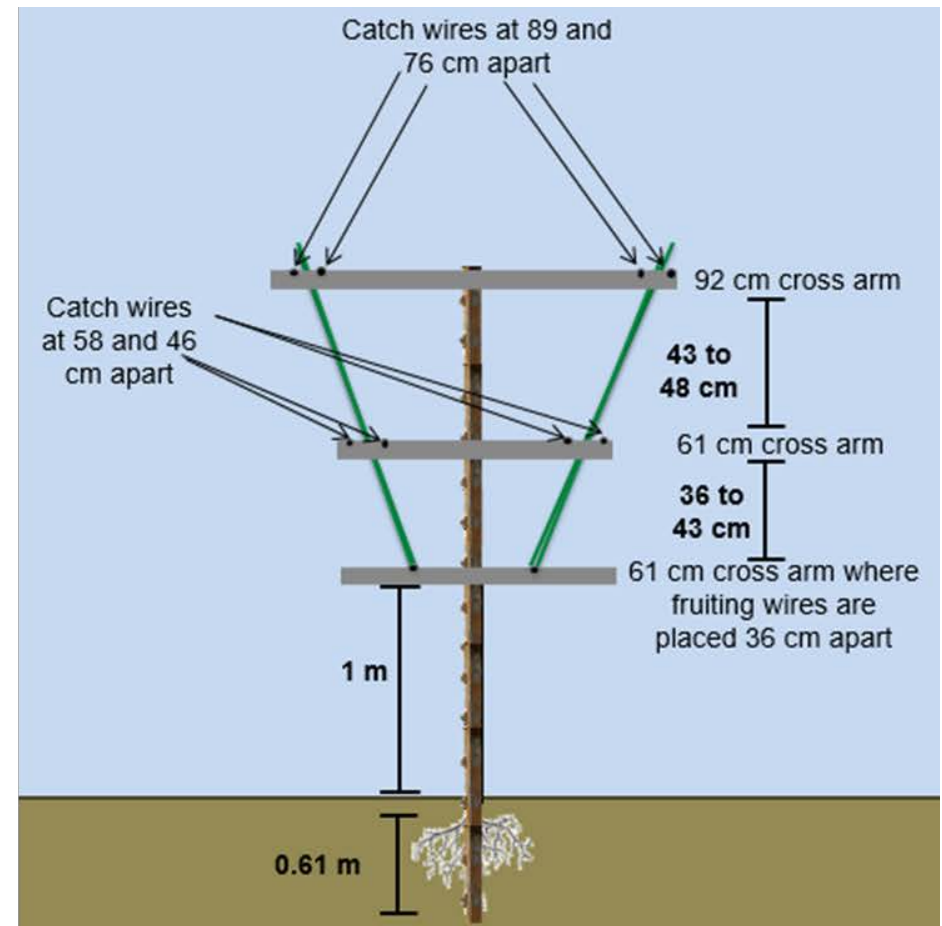
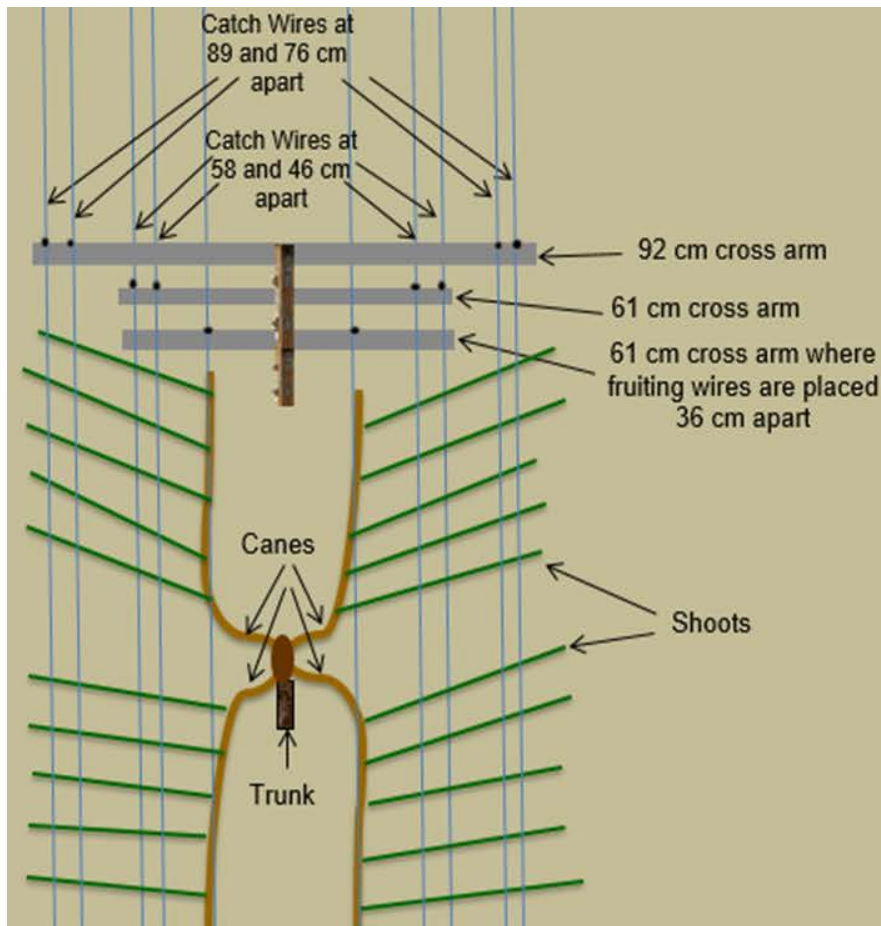


Figure 2.1 Diagram outline of the trellising and training system

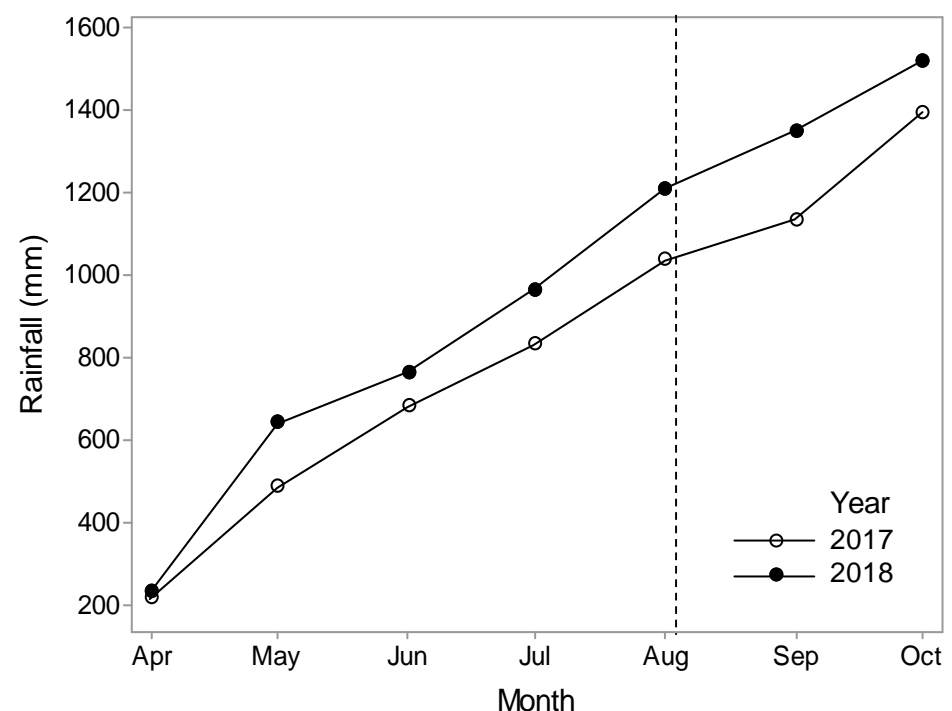
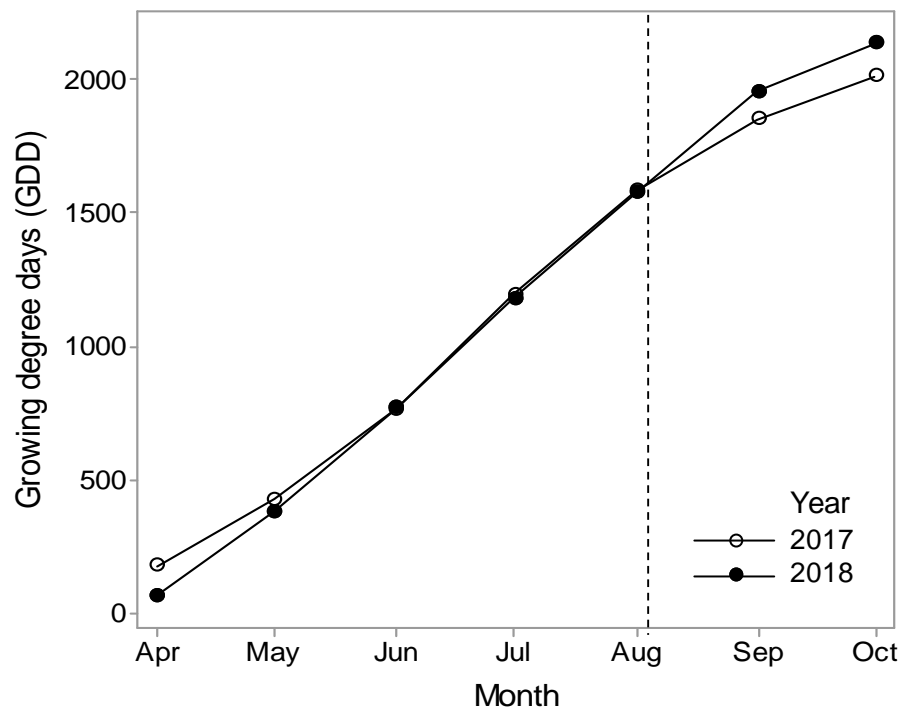


Figure 2.2 Growing degree day and rainfall accumulation for 2017 and 2018. Growing degree days were calculated using a base line of 10°C. The dashed vertical line is when veraison started.

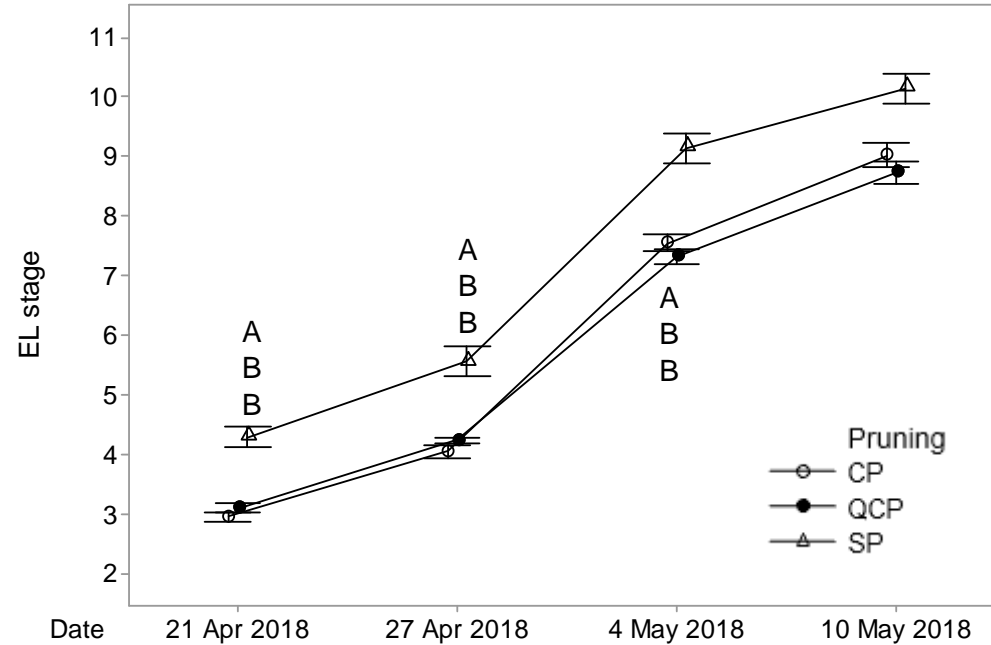


Figure 2.3 The effect of pruning treatment on bud phenology in spring 2018. QCP is head training with quadrilateral cane pruning and adventitious shoots thinned from the head region, SP is bilateral cordon training with spur pruning and shoots thinned to 13 shoots / linear m of row, and CP is head training with bilateral cane pruning and adventitious shoots thinned from the head region. Means within the same date not sharing the same letter were significantly different and means in same date without letters were not statistically significantly different ($\alpha = 0.05$), Tukey's honest significant difference. Error bars indicate the standard error; n=4.

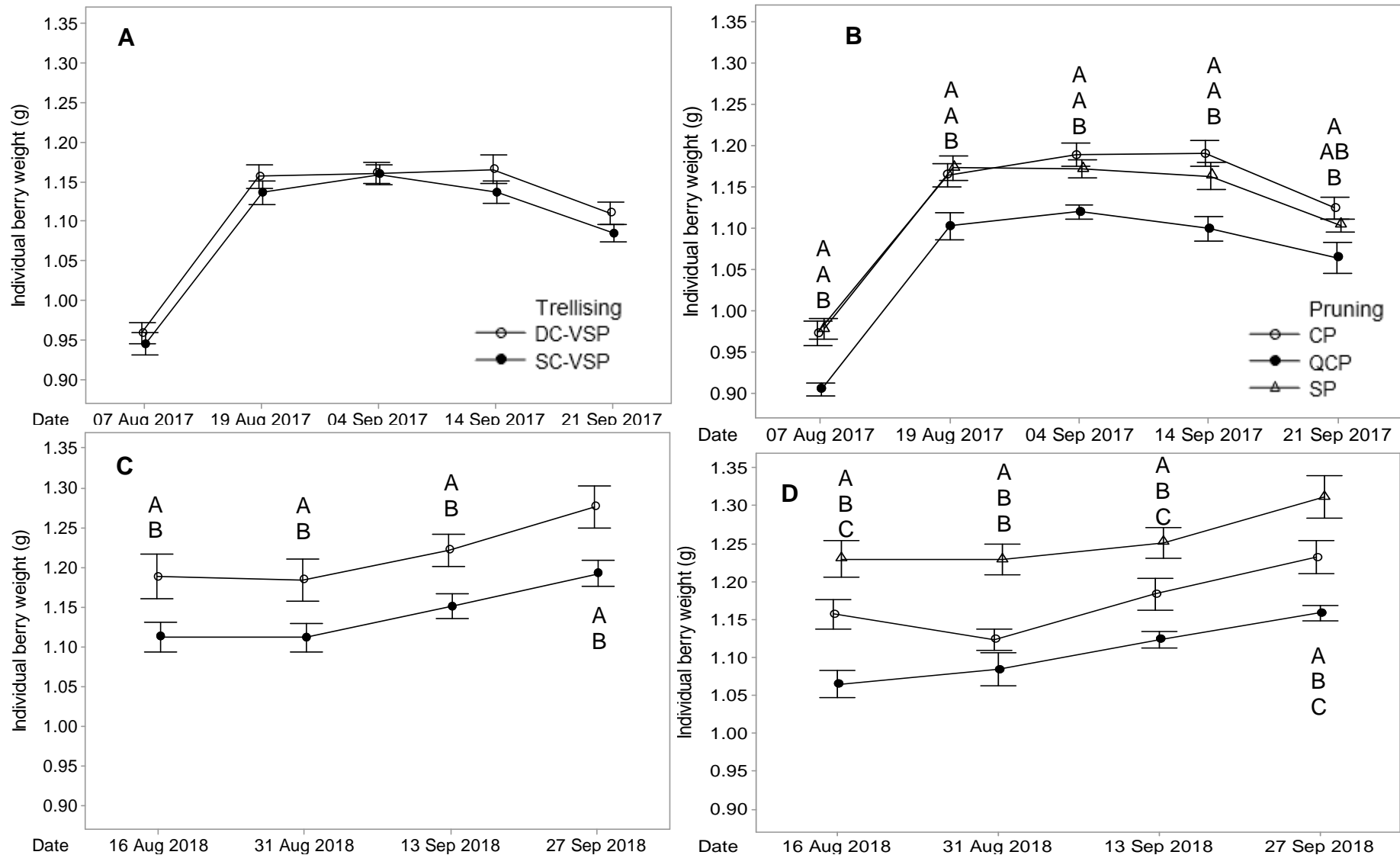


Figure 2.4 Effect of trellising (A, C) and pruning (B, D) treatments on berry weight accumulation over 2017 (A, B) and 2018 (C, D). DC-VSP (divided canopy with vertical shoot positioning) and SC-VSP (single canopy with vertical shoot positioning) trellising (A and C) over post veraison periods in 2017 and 2018. QCP is head training with quadrilateral cane pruning and adventitious shoots thinned from the head region, SP is bilateral cordon training with spur pruning and shoots thinned to 13 shoots / linear m of row, and CP is head training with bilateral cane pruning and adventitious shoots thinned from the head region (B and D). Means within the same date not sharing the same letter were significantly different and means in same date without letters were not statistically significantly different ($\alpha = 0.05$), Student's T-test (Trellising experiment) and Tukey's honest significant difference (Pruning experiment). Error bars indicate the standard error; $n=4$.

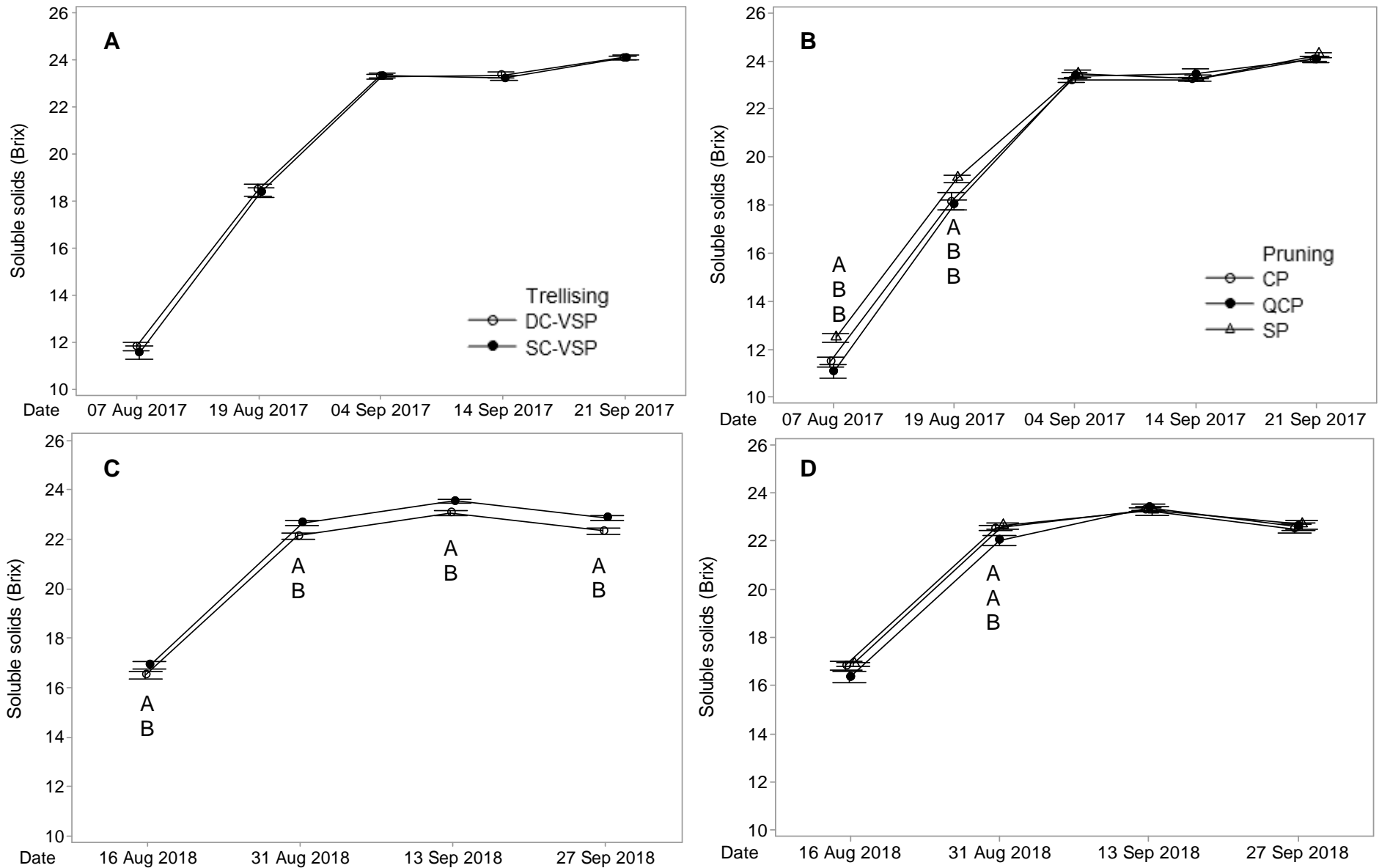


Figure 2.5 Effects of trellising (**A, C**) and pruning (**B, D**) treatments on soluble solids accumulation in 2017 (**A and B**) and 2018 (**C and D**). DC-VSP (divided canopy with vertical shoot positioning) and SC-VSP (single canopy with vertical shoot positioning) trellising (**A and C**) over post veraison periods in 2017 and 2018. QCP is head training with quadrilateral cane pruning and adventitious shoots thinned from the head region, SP is bilateral cordon training with spur pruning and shoots thinned to 13 shoots / linear m of row, and CP is head training with bilateral cane pruning and adventitious shoots thinned from the head region (**B and D**). Means within the same date not sharing the same letter were significantly different and means in same date without letters were not statistically significantly different ($\alpha = 0.05$), Student's T-test (Trellising experiment) and Tukey's honest significant difference (Pruning experiment). Error bars indicate the standard error; n=4.

CHAPTER 3

CANOPY DIVISION MAINTAINS VINE BALANCE UNDER HIGH CROP YIELD IN CHAMBOURCIN²

² White, R., N. Eason, and C. Hickey. To be submitted to *Catalyst: Discovery into Practice*

Abstract

Pruning and training systems in wine grape vineyards can impact source: sink relationships and crop yield and fruit composition. Vertical shoot positioned training (VSP) is one of the most popular training systems in the eastern US. However, the VSP system limits exposed leaf area when compared to a divided canopy system. We explored the impact of increasing canopy leaf area exposure and its effect on crop yield and fruit composition of the French-American hybrid Chambourcin. We compared the effects of pruning to differential bud densities, within a retrofitted, divided, vertical shoot positioned system and the standard vertical shoot positioned system, on canopy structure, crop yield components, and primary and secondary fruit chemistry. Treatments were 26 buds per m of cordon, 20 buds per m of cordon, and an industry standard of 13 buds per m of cordon all replicated within either the retrofitted divided canopy training system or the single canopy training system. Dividing the canopy increased crop yield in both seasons while enhancing fruit maturity in the second season compared to the single canopy system. Bud density treatments had no impact in the first year, but greater bud number per m of cordon increased crop yield in the second year to the detriment of primary fruit chemistry. Dividing a single canopy vertical shoot positioned system increased crop yield consistently over two years and enhanced fruit maturity indicating a better source: sink relationship.

Summary.

Goals: Pruning and canopy management are tools used to achieve healthy, perennial vine growth and commercially acceptable yields of quality grape crops. We investigated if the currently recommended pruning densities are justified in high-yielding hybrid cultivars such as Chambourcin and if canopy division would increase crop yield or hasten fruit ripening. The goals of this project were to retrofit a single-canopy, Chambourcin vineyard by using canopy division while also implementing spur pruning to various bud densities. We evaluated the effect of bud density and trellising treatment on canopy architecture, crop yield, primary fruit composition, and total berry phenolics and anthocyanins of Chambourcin.

Key Findings:

- Dividing the canopy increased pruning weight by 52% when compared to single canopy plots in 2018.
- Canopy division reduced mid-canopy leaf layer number and increased effective leaf area index by an average of 38% relative to the single canopy in both years
- Canopy division increased cluster weight by an average of 15% when compared to single canopy over two years.
- Canopy division increased crop yield by an average of 25% over two years compared to single canopy. In the second season, pruning to 26 buds per m of cordon increased crop yield by 37% compared to 13 buds per m of cordon.
- In the second season, 26 buds per m of cordon decreased soluble solid content by 9%, decreased pH, and increased titratable acidity compared to 13 buds per m of cordon.

Impact and Significance: Pruning to higher bud densities has a positive impact on crop yield in the year that had favorable bloom-time weather. Regardless of weather, there was a negative

relationship between increasing bud density and berry number per cluster. Dividing the canopy decreased canopy-self shading, increased the effective leaf area of the canopy, and increased crop yield by increasing berry number per cluster in both years. Dividing the canopy also aided in fruit ripeness in the high bud density plots. Canopy division thus allows for spur pruning to a higher dormant bud density while mitigating negative impacts on vine health, crop yield and fruit composition.

Overview.

Over-cropping leads to the costly, imprecise practice of remedial cluster thinning, which reduces crop yield without a guarantee of improved quality of the retained crop. Crop load calculations and balanced pruning can be used to assess and achieve a balance between vegetative and reproductive growth and therefore improve vineyard health, sustainability and crop yield and quality.¹⁻⁴ The relationship between vegetative and reproductive growth is normally indexed using crop load (the quotient of crop yield weight and dormant cane pruning weight).⁵ “Balanced pruning” uses the weight of dormant pruned canes to determine an appropriate bud number to retain and crop yield to achieve. For example, bud number retention goes up when the weight of dormant pruned canes goes up. A 30+10 pruning formula (30 buds left for the first 0.45 kg of dormant cane prunings plus a subsequent 10 nodes left for every 0.45 kg of prunings) is a common balanced pruning formula.^{6,7} While the optimal crop load for specific cultivars is not well documented, balanced pruning formulas can vary between *Vitis vinifera* and hybrid cultivars and also between different trellising methods.^{5,8,9} For example, implementing the recommended balanced pruning formula for *V. vinifera* often results in under-cropping of hybrid bunch grape cultivars.¹⁰⁻¹² Additionally, optimal crop load varies across training systems and, while not established, will likely vary among cultivars and growing regions. However,

calculating crop load and implementing balanced pruning are time consuming and are therefore rarely implemented in commercial settings.^{2,13,14}

Instead of calculating crop load or using balanced pruning, many growers have adopted the practice of retaining 13 to 20 buds per linear m of cordon across cultivars.^{13,15 12,13,16} Dormant pruning sets the bud density and impacts the overall shoot density, potential cluster number, crop yield, and crop load.^{12,17,18} Thus, the targeted shoot density is normally set during the dormant season by pruning to a targeted bud density; shoot number is subsequently adjusted during the spring (generally before EL stage 12).¹⁶

Trellising methods can have a large impact on vegetative vigor, crop yield, and dormant cane pruning weight.^{10,14,19,20} In general, divided canopy systems, such as the Geneva Double Curtain (GDC), Smart-Dyson, and Lyre, tend to have higher dormant cane pruning weights compared to single canopy systems. The increase in dormant cane pruning weights and crop yield in divided systems has been linked to an increase in exposed leaf area resulting in relatively greater carbon assimilation relative to single canopy systems.^{3,14} While divided canopies also require more labor inputs to maintain the canopy middles compared to single canopy systems, those input costs could be offset with the greater crop yield.²¹

Single canopy systems, like the popular VSP system, involve a series of closely spaced (13-15 cm) trellis catch wires that guide vertical shoot growth.²² The close shoot spacing causes self-shading of the leaves which reduces the effective leaf area and shades the fruit zone.^{23,24} The crowded fruit zone reduces air flow which can increase fungal disease incidence and can abate spray penetration through the canopy.²⁴ Thus, while recommended shoot densities of 12 to 15 shoots per m may be an attempt to moderate crop yield, those densities may be necessary to limit fruit zone and canopy congestion in tight, single canopy systems.^{1,25} In well managed divided

canopy systems, fruit zone and canopy crowding are not as prevalent which can positively influence the amount of fruit produced compared to single canopy systems.^{14,26,27}

Chambourcin is a French-American hybrid cultivar known for producing ample vegetative growth but also large clusters and high crop yields. The common balanced pruning formula (30 nodes retained for the first 0.45 kg of prunings plus 10 nodes for each additional 0.45 kg of prunings) could be considered inaccurate for Chambourcin, resulting in under-cropping.^{5,8,15}

According to research on the high crop yielding, hybrid cultivars Seyval blanc and Chancellor, excessive crop loads (beyond “12”, or 12 kg of fruit per 1 kg of pruning weights) in a divided canopy system did not impact primary fruit chemistry nor the crop yield over time.^{15,28} Further, in a balanced pruning experiment in Chambourcin, pruning level to various bud densities did not have an impact crop yield, primary chemistry, and cold hardiness, and the vines continued to produce high amounts of cane pruning weights.⁵ We questioned if canopy division would limit canopy crowding and maintain leaf area exposure for fruit maturation under greater bud densities than would produce the lowest, currently recommended shoot density of 13 buds per m cordon.^{15,25,28} We, thus, sought to evaluate the effects of various bud densities in both divided and non-divided canopies on canopy architecture, leaf area index, crop yield, and primary and secondary fruit composition in Chambourcin, a widely-planted hybrid, red bunch wine grape cultivar in the eastern US.

Major observations and interpretations.

Brief description of experimental settings and treatments. A randomized, split plot design was replicated in four blocks within a commercial, own-rooted Chambourcin vineyard. The vineyard was trained to bilateral cordons with vertical shoot positioning and planted in White County, Georgia in 2014. The main plot evaluated two different trellising types; a retrofitted, divided

canopy, vertical shoot positioned system (DC-VSP) and the single canopy, vertical shoot positioned system (SC-VSP), the latter of which the vines were already trained to. The SC-VSP system used a series of eight wires spaced 21 cm apart ascending the post with 18 cm between the two catch wires to position the canopy. The DC-VSP system used a series of four cross arms and 12 wires to train the divided canopy into a “V-shape”. For further detail on the trellis design of the divided system, please see the “Experimental design” section. The sub plot, which was randomly assigned within each main plot, was comprised of three different density treatments to retain the following bud densities during dormant pruning: 13 buds per m cordon (LOW), 20 buds per m cordon (MED), and 26 buds per m cordon (HIGH)

Meteorology. Substantially more rain fell in 2018 compared to 2019; however, growing degree day (GDD) accumulation did not vary greatly between the two seasons (Figure 1). In 2018, 2395 GDD accumulated and 1208 mm of rain fell between 1 Apr and 31 Oct. GDD were accumulated steadily through the 2018 season, but the greatest amount of rainfall occurred in May. In 2019, 2486 GDD accumulated and 915 mm of rain fell between 1 Apr and 31 Oct. The fastest rate of GDD accumulation was observed from Jun through Aug and the most rain fell in Oct during the 2019 season. In 2018, 293 mm more rain fell than in 2019. Most of the rain in 2018 fell during bloom (EL stages 23 to 26) and most rain fell after harvest in 2019.¹⁶ Average total daily solar radiation was, on average, 2 MJ/m² greater during the month that bloom occurred in 2019 relative to bloom in 2018. Radiation trends were thus in parallel with rainfall trends, together showcasing the poor weather conditions during bloom of 2018 relative to 2019.

Dormant cane pruning weight and shoot counts. Dormant cane pruning weights were increased through canopy division. In 2018, DC-VSP increased pruning weights by 52% compared to SC-VSP due to an 46% increase in individual cane weight (Table 1). Vines were pruned to targeted

bud densities and were not shoot thinned. However, not all buds broke and grew into shoots during the season, as evidenced by the shoot count data (Table 1). The 2018 season had 75%, 86%, and 95% of the buds retained produce shoots in HIGH, MED, and LOW, respectively. In 2019, 83%, 89%, and 95% of buds retained produce shoots in HIGH, MED, and LOW, respectively. As anticipated, there were no significant differences in shoot counts between the trellising treatments. While different bud densities did not have an impact on pruning weight, different bud densities did impact the individual cane weight. The HIGH plots had 33% lower cane weight compared to LOW. Individual cane weights of MED fell between those observed in HIGH and LOW; MED density produced canes that weighed 17% more than the HIGH plots, but still 22% lower weights than LOW.

Dividing the canopy increased cane pruning weight and overall vine size. This could be attributed to increased carbon gain due to increased exposed leaf area, ultimately equating to greater vegetative growth.^{26,27} Other studies have shown that increasing the exposed leaf area by dividing the canopy increases dormant cane pruning weights despite retaining similar amounts of buds in dormant pruning.^{29,30} This could be attributed to increases in lateral shoot growth development; however, the vines in the DC-VSP were managed to maintain canopies free of laterals. The different bud densities did not impact pruning weights possibly due to a shift in carbon gain from the vegetative portions of the vine to the reproductive fractions of the vine which reduced the amount of weight produced per cane.

Veraison fruit zone and mid-canopy Point Quadrat Analyses, and post-harvest leaf area index.

In the *fruit zone*, DC-VSP increased leaf exposure layer (LEL) by an average of 121% when compared to SC-VSP over two years. Fruit zone LLN maintained consistently between the recommended levels of 1 to 2 leaf layers in the fruit zone in both years. This could have been due

to fruit zone leaf removal prior to taking PQA. On average, the DC-VSP decreased *mid-canopy* leaf layer number (LLN) by 43% when compared to SC-VSP over two years (Table 2). That decrease in LLN equated to an average of 81% lower mid-canopy LEL in DC-VSP compared to SC-VSP over two years.

Canopy division (DC-VSP) increased leaf area index (LAI) and effective leaf area index (LAIe) compared to SC-VSP. Canopy division (DC-VSP) increased LAI by 60% and 81% and LAIe by 116% and 156% compared to SC-VSP in 2018 and 2019 respectively. Other research has shown reduced LLN, and increased cluster exposure layer and leaf area in divided canopy systems when compared to single canopy systems.^{14,31,32} Increasing exposed leaf area has been correlated with increased crop yield in other divided canopy systems.²⁶ A more open canopy also increases airflow through the canopy, reducing disease in some cultivars.²³ The decreased LLN and LEL in the DC-VSP mid-canopy indicates less radiation occlusion from mid-canopy leaves when compared to SC-VSP, as evidenced by greater effective leaf area index (LAIe). Density treatments did not impact canopy metrics with the consistency or magnitude as canopy division did (Table 2). There was an interaction between trellising and density treatments in 2019 with the biggest differences between SC-VSP/HIGH and DC-VSP/LOW. However, in LLN, SC-VSP/HIGH and SC-VSP/LOW separated from SC-VSP/VSP and all of the SC-VSP treatments separated from the DC-VSP. In LEL, SC-VSP/HIGH separated from SC-VSP/MED with SC-VSP/LOW falling between. SC-VSP/MED was similar to DC-VSP/HIGH and DC-VSP/MED but significantly different from DC-VSP/LOW. The combination of SC-VSP/HIGH increased mid-canopy LLN by 86% (mean= 3.5) and mid-canopy LEL (mean= 0.5) by 182% compared to DC-VSP/LOW (mean= 1.9, mean= 0.2, respectively) (data not shown). This interaction showed that the increased shoot number in the SC-VSP/HIGH plots produced a greater leaf area that was

self-shaded relative to the leaf area that was relatively exposed in the DC-VSP/LOW plots (Tables 1 and 2).

Crop yield components. In 2018, DC-VSP increased berry number per cluster by 14%, cluster weight by 17%, and ultimately crop yield by 21% when compared to SC-VSP (Table 3). In 2019, DC-VSP had a similar increase in yield compared to SC-VSP (29%), and this was a consequence of greater berry number per cluster (14%), cluster weight (13%), but also cluster number per vine (8%). Harvest berry weights were not impacted by trellising. However, berry weight accumulation showed that DC-VSP had higher berry weights on the third sample date in both 2018 and 2019 compared to SC-VSP (Figure 2). In 2019, berry weight decreased over the last two weeks, potentially due to dehydration in the relatively dry, post-veraison period of 2019. Pruning to different bud densities impacted crop yield in 2019, but not in 2018 (Table 3). HIGH produced 14% greater crop yield than MED, and 37% greater crop yield compared to LOW in 2019. Crop load was not significantly impacted by pruning density in 2018. However, DC-VSP decreased crop load by 24% compared to SC-VSP. SC-VSP had a crop load that was slightly higher than the accepted normal for single canopy systems.¹ While density treatment affected crop yield only in 2019, other yield components were affected in both 2018 and 2019. We speculate that differences in weather during the bloom periods of 2018 and 2019 differentially impacted berry number per cluster as well as cluster number. HIGH, MED, and LOW in the first year produced 50%, 44%, and 39% lower crop yield compared to the respective treatments in 2019. Likewise, the trellising treatments produced an average of 47% lower crop yield in 2018 compared to 2019. The lower crop yield observed in 2018 relative to 2019 was likely due to rainy bloom time weather in 2018 which reduced fruit set and ultimately berry number per cluster.

Canopy division and different bud densities had an impact on yield in both years. There was a negative relationship between increasing shoot number and berry number per cluster that was stronger in the second year, possibly due to overall better fruit set (Figure 3). For example, LOW produced the fewest clusters per vine with an average of 41 average clusters per vine over two years, but also had the greatest average berry number per cluster (91 berries per cluster). Inversely, HIGH produced the most clusters per vine with an average of 65 clusters per vine over two years, but also produced the lowest average berry number per cluster (74 berries per cluster) and thus lowest average cluster weights over two years. Dividing the canopy, however, seemingly mitigated the effect of increasing bud density on berry number per cluster as most of the DC-VSP data points fell above the regression line in both years (Figure 3, panels A and C). Thus, lower berry number per cluster and lower cluster weights may be a consequence of retaining greater bud densities but dividing the canopy might mitigate the effect of increasing dormant bud number.

Our observations suggest that shoot number is not the lone determinant of berry number per cluster weight, but that leaf area per shoot was also an important determinant (Figure 4). Increasing the effective leaf area per shoot has a stronger relationship with berry number per cluster than just increasing shoot number especially in the first year of the project that had poor fruit set. This could be because increasing the whole vine source: sink ratio can impact the overall fruit set of a vine.³³ However, trends observed in Figures 3 and 4 suggest that dividing the canopy, increasing the exposed leaf area, could mitigate the effects of increased shoot number on crop yield by facilitating fruit set, increasing the berry number per cluster, thus increasing overall carbon gain.³⁴

Primary fruit composition and secondary metabolites. Density treatment had no impact on primary fruit composition in 2018 but had a significant impact on all primary fruit composition components in 2019 (Table 4). In 2019, primary fruit chemistry responses were indicative of over-cropping in the HIGH and MED treatments. There were reduced soluble solids in the HIGH (9% decrease) and the MED (5% decrease) compared to the LOW treatment in 2019. Soluble solids were lower in HIGH and MED beginning slightly after veraison, a trend maintained through harvest (Figure 5). HIGH and MED also had decreased pH (4% and 2%, respectively) and higher titratable acidity (TA) (6% and 4%, respectively) compared to the LOW treatment. A study involving cluster thinning in Ohio had a similar trend where reducing cluster number per vine increased soluble solid content and fruit ripeness at harvest.³⁵

Canopy trellising method affected juice TA and pH in both years, but results were inconsistent between treatments and were of questionable practical importance given marginal absolute magnitudes of differences in those components. However, despite increasing crop yield by 29% in 2019, DC-VSP also had consistently higher soluble solid concentration ending in 7% higher soluble solids than SC-VSP at harvest in that year (Figure 5).

Much like trellising and density treatments did not impact the rate of soluble solids accumulation, or harvest soluble solids concentration in 2018, LAIe: crop yield ratio also had no significant relationship on harvest soluble solids (Figure 6). However, there was a stronger, and positive relationship between the LAIe: crop yield ratio and soluble solids at harvest in 2019. In a favorable season, dividing the canopy can increase carbon gain to sustain and ripen high crops. These trends are supported by the data separation within the canopy division treatments (Figure 6, panel C) but not the density treatments (Figure 6, panel D) when looking at the relationship between LAIe: crop yield and soluble solids at harvest. Sustaining a high LAIe: crop yield ratios,

as through canopy division, aids in fruit maturation (Figure 6) despite greater crop yield in (Table 3). Previous studies found that divided canopy systems reduce the amount of leaf area needed to ripen a gram of fruit and increasing sources at bloom increases fruit set.^{26,33} Due to the increased crop yield and higher soluble solid content, along with the increased LAI found in DC-VSP, this study corroborates the previous studies asserting that increased exposed leaf area helps to ripen a greater amount of fruit.

Trellising did not impact total berry anthocyanins, but SC-VSP had higher total berry phenolics by 5% compared to DC-VSP in 2018 (Table 4). While density treatment did not affect total phenolics, LOW had greater anthocyanin content than MED in 2018. Previous studies have shown that reducing crop yield through cluster thinning increases anthocyanin and total phenolic content of the fruit.³⁶

Broader impact.

Dormant pruning and trellising grapevines are important tools that can manipulate the source:sink relationship and impact the amount and quality of crop produced. Canopy division has been shown to aid in fruit ripening and increase fruit set even in years of difficult bloom time weather. While increasing bud density by retaining more buds per linear foot of row would logically increase crop yield by increasing clusters per vine, it appears that bud density has a poorer relationship to crop yield when bloom-time weather is rainy. However, in years with dry bloom-time weather and favorable fruit set, dividing the canopy along with a higher bud density (26 buds per m row) increased yield by 70% compared to the industry standard single canopy trellising with VSP and pruning to 13 buds per m row. However, there was a trade off in primary chemistry where leaving higher bud densities decreased overall fruit ripeness (lower soluble solids, higher TA, and lower pH at harvest) compared to those left with the industry standard 13

buds per m row. Canopy division helped to mitigate those fruit chemistry responses by increasing soluble solids at harvest when compared to the single canopy system. If it is desirable to increase crop yield in Chambourcin, then retaining greater bud densities (20 to 26 buds per m cordon) in divided canopies would aid in maintaining vine balance and fruit maturation relative to retaining greater bud densities in single canopies. Future work could involve replicating a similar project in other cultivars including *V. vinifera* and replicating the project in cooler regions where fruit ripening might be attenuated.

Experimental design.

The experiment was conducted in a commercial, non-grafted Chambourcin vineyard planted in 2014 in White County, Georgia. Vines were planted 1.83 m apart in rows that were 2.75 m apart in rows running east to west. The soil was Hayesville sandy clay loam on 10% to 25% slopes.³⁷ Vines were trained to low, bilateral cordons at approximately 80 cm above the ground and shoots were positioned vertically with the aid of four sets of trellis catch wires positioned at 25 cm, 46 cm, 69 cm, and 89 cm above the fruiting wire and approximately 21 cm apart. A randomly replicated split-plot design was implemented in four blocks. Experimental units consisted of four vines. The main plot evaluated canopy trellising and the sub plot examined bud density effects within each of the main plots. Main plot and sub-plot treatments are described in greater detail, below.

Canopy trellising treatments were either (1) a standard VSP (SC-VSP) that were trained between the four sets of catch wires already present in the vineyard, or (2) a divided VSP canopy (DC-VSP) where the canopy was divided into a “V-shape” using four cross arms at the four catch wire positions. The standard SC-VSP trellising system had four sets of catch wires all spaced 18 cm apart laterally and 21 cm apart horizontally ascending the trellis post. The divided VSP trellising

system (DC-VSP) trained the shoots up and outward in a “V-shape”. Canopy division was implemented as a retrofit to the existing SC-VSP trellis. The DC-VSP system used a series of four cross arms and 12 wires to train the divided canopy into a “V-shape”. The cross arms were approximately 24 cm apart ascending the trellis post. The first cross arm was 30 cm long and spaced wires 28 cm apart to which the shoots were trained on the outside of. The second cross arm was 61 cm long with wires 36 and 58 cm apart to continue training the shoots in the desired shape. The third cross arm was 91 cm long and had wires 69 cm apart to which the shoots were trained outside. The fourth and last cross arm was also 91 cm long and had wires spaced 69 and 89 cm apart to complete the “V-shape” of the trellis. The shoots were periodically hedged before falling over the top catch wire and were positioned throughout the growing season to ensure that the canopy was trained to the intended trellising system as dictated by treatment. Laterals were trimmed from the middle of the DC-VSP to maintain canopy shape and prevent excessive shading in the middle of the canopy.

Density treatments. There were three density treatments Density treatments were implemented in the dormant season to the following densities: 13 buds per m of cordon (LOW); 20 buds per m of cordon (MED); 26 buds per m of cordon (HIGH). Density treatments consisted of two- and three-bud spurs to reach desired bud densities in both years.

Dormant cane pruning weight and shoot counts. Cane pruning weights were measured by vine with a field scale during the dormant season. Shoot numbers were counted per vine in Jul, between EL stages 31 to 33.¹⁶

Veraison fruit zone and mid-canopy Point Quadrat Analysis and post-harvest leaf area index. Point Quadrat Analysis (PQA) was completed at veraison (modified Eichorn-Lorenz stage 35).

^{1,16} A thin, metal probe was inserted every 30 cm through the fruit zone and mid-canopy in a

parallel fashion to the vineyard floor; the latter set of insertions were taken by resting the probe on the third catch wire during canopy insertion. The tissue contacts (leaf, cluster, or gap - if there no contact was made as the probe passed) were recorded in the order in which they were contacted as the probe transected the fruit zone or mid-canopy.¹ The probe insertion results were used to produce the following PQA metrics: leaf layer number (number of leaves per transection), and leaf exposure layer (number of shading layers between leaves and the nearest boundary).³⁸ The mid-canopy of the DC-VSP was transected twice, on either side of the canopy and averaged to produce one number.

The University of Adelaide's VitiCanopy app (2016) was used to measure leaf area index (LAI) and effective leaf area index (LAIe) after harvest in 2018 and 2019, which is the amount of leaf area per unit of ground area and amount of leaf area per unit of ground area exposed to sunlight, respectively.³⁹ This was done following the method described by the app developers that use pictures taken between 70 to 80 cm below the cordon to apply gap size assessment algorithms.³⁹

Components of crop yield. Harvest occurred on 24 Sep 2018 and 16 Sep 2019. Vines were harvested and cluster counts recorded on a per vine basis. The crop weight of each vine was measured with a field scale. Average cluster weight was determined by dividing the total crop yield per vine by the cluster number from that same vine. Berry number per cluster was determined by taking the average cluster weight divided by the individual berry weight (as calculated from the composite berry sample taken from each experimental unit immediately before harvest - per the primary chemistry data methods, below). Crop load was determined on a per vine basis by dividing the weight of crop yield by the weight of dormant cane prunings produced within the same growing season.

Primary fruit composition. Bi-weekly, composite berry samples were taken from veraison through harvest for Brix analysis; juice pH and titratable acidity were only measured on the composite berry sample taken immediately before harvest. Equal amounts of berries (40 berries) were randomly sampled from both canopy sides of each vine, creating composite samples of 80 berries from each experimental unit. Berries were hand-pressed in a plastic bag to express juice, which was collected in a 50 mL tube and centrifuged at 4000 RPM for five minutes before analyzing for sugars, acidity, and pH, as follows. Soluble solids (Brix) were measured using an Atago PAL-1 Digital Refractometer. The TA and pH were measured with a Titrino 848 Plus auto titrator (Metrohm, USA, Riverview, FL). Juice TA was measured by titrating a solution of 5 mL of grape juice and 40 mL of distilled water to an endpoint pH of 8.2 with a 0.1 M NaOH base following previously described protocols.²³ The pH probe of the Titrino 848 Plus was used to measure pH on undiluted grape juice.

Estimated total berry phenolics and anthocyanins

Composite samples of 80 berries were sampled from every experimental unit prior to harvest. Absorption spectroscopy was done using a Genesys 10S UV-Vis spectrophotometer to estimate total grape phenolics and anthocyanin content from those samples using exact methods from a previous study⁴⁰ which were adapted from phenolic quantification studies.^{41,42} Berry samples were frozen at -20 °C until testing could be started, at which time they were thawed, homogenized with a blender (Ninja Auto IQ, Ninja), and 30 mL of 0.025 M KCl buffer (pH 1.0) was added to 1.0 g of berry homogenate and 0.4 M sodium acetate buffer (pH 4.5) was added to 1.0 g of berry homogenate to separate anthocyanins at different wavelengths. The homogenate-buffer samples were shaken for 20 min using a wrist action shaker and then centrifuged for 5 min at ~4000 rpm. To quantify anthocyanins, the supernatant was pipetted into a 10 mm path length

methacrylate cuvettes (Thermo Fisher Scientific Inc.), and its absorbance at 520 and 700 nm was measured in duplicate with a Genesys 10S UV-Vis spectrophotometer.

Total phenolics were quantified by taking 0.5 g of berry homogenate with 30 mL of 0.025 M KCl buffer (creating a two parts sample to one part buffer solution) and shaking then centrifuging as with the other samples. The absorbance of the solution was measured in duplicate at 280 nm. The measurements of the different wavelengths were recorded and a spreadsheet was used to estimate phenolics on an absorbance unit/g berry-basis, and anthocyanins on a mg/g berry basis.

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Table 3.1 Trellising and density effects on Chambourcin pruning weights, shoot counts, and individual dormant cane weights in 2018 and 2019

Treatment effects	Pruning Weight (kg/ m of row)	Shoot Counts (#/ vine) ^c		Dormant cane weight (g/ shoot)
	2018	2018	2019	2018
Trellising ^a				
DC-VSP	0.7 a	30	32	42.3 a
SC-VSP	0.4 b	29	31	28.9 b
Density ^b				
HIGH	0.6	36 a	40 a	29.1 c
MED	0.6	31 b	32 b	34.0 b
LOW	0.5	23 c	23 c	43.6 a
Significance ^d				
Trellising (TR)	<0.0001	ns	ns	<0.0001
Density (PR)	ns	<0.0001	<0.0001	<0.0001
TR*PR	ns	ns	ns	ns

^a DC-VSP = divided VSP and SC-VSP =vertical shoot positioned trellising.

^b HIGH = 26 buds per m of row; MED = 20 buds per m of row; LOW = 13 buds per m of cordon

^c Shoot counts calculated on a per vine basis

^d Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were significantly different at $\alpha = 0.05$ based on adjusted p values using Student's T-test (Trellising experiment) and Tukey's honest significant difference (Density experiment)

Table 3.2 Trellising and density effect on select *fruit zone* and *mid - canopy* enhanced point quadrat analyses completed during veraison, leaf area index, and effective leaf area index, as measured in Chambourcin in 2018 and 2019.

Treatment effects	Fruit Zone Leaf Layer Number (LLN)		Fruit Zone Leaf exposure layer (LEL)		Leaf Area Index (LAI) ^a		Effective Leaf Area Index (LAle) ^b		Mid-Canopy Leaf Layer Number		Mid-Canopy Leaf Exposure Layer	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Trellising ^c												
DC-VSP	1.3	1.3	0.3 a	0.4 a	2.1 a	2.6 a	1.9 a	2.6 a	2.0 b	2.1 b	0.19 b	0.20 b
SC-VSP	1.3	1.3	0.1 b	0.2 b	1.3 b	1.4 b	0.9 b	1.0 b	2.8 a	3.1 a	0.32 a	0.39 a
Density ^d												
HIGH	1.3	1.4	0.2	0.3	2.6 a	2.1	1.4	1.8	2.6 a	2.8 a	0.30 a	0.35 a
MED	1.2	1.3	0.2	0.4	2.4 b	2.0	1.4	1.8	2.4 b	2.4 b	0.25 ab	0.27 b
LOW	1.2	1.2	0.2	0.3	2.2 c	2.0	1.3	1.8	2.2 c	2.4 b	0.21 b	0.28 b
Significance ^e												
Trellising (TR)	ns	ns	0.0003	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Density (PR)	ns	ns	ns	ns	<0.0001	ns	ns	ns	<0.0001	0.0021	0.0028	0.0142
TR*PR	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.0316	ns	0.0245

^a LAI = Total one-sided area of leaf tissue per unit of ground area as measured post-harvest. Calculated using VitiCanopy iPhone application.

^b LAle = LAI corrected using the clumping index to show how much of the total leaf area is effective as measured post-harvest. Calculated using VitiCanopy iPhone application.

^c DC-VSP = divided VSP and SC-VSP =vertical shoot positioned trellising.

^d HIGH = 26 buds per m of row; MED = 20 buds per 1 m of row; LOW = 13 buds per m of cordon.

^e Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Student's T-test (Trellising experiment) and Tukey's honest significant difference (Density experiment).

Table 3.3 Trellising and density effect on components of crop yield in Chambourcin 2018 and 2019.

Treatment effects ^a	Crop yield (kg/ vine)		Cluster number		Cluster Weight (g)		Berry #/ Cluster		Berry Weight (g)		Crop Load
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	
Trellising ^b											
DC-VSP	9.4 a	17.5 a	48	63 a	196.7 a	283.7 a	75 a	100 a	2.6	2.8	7.8 b
SC-VSP	7.7 b	13.9 b	46	58 b	167.9 b	241.4 b	66 b	87 b	2.5	2.8	10.3 a
Density ^c											
HIGH	8.9	17.9 a	52 a	79 a	170.7 b	227.8 c	66 b	83 b	2.6	2.7 b	10.0
MED	8.7	16.0 b	50 a	61 b	175.6 b	256.6 b	68 b	91 b	2.6	2.8 ab	8.7
LOW	7.9	13.1 c	40 b	43 c	200.5 a	303.2 a	78 a	105 a	2.6	2.9 a	8.5
Significance ^d											
Trellising	0.0002	<0.0001	ns	0.0040	0.0001	<0.0001	0.0019	0.0002	ns	ns	0.0007
Density	ns	<0.0001	<0.0001	<0.0001	0.0012	<0.0001	0.0052	<0.0001	ns	0.0114	ns
TR*PR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

^a DC-VSP = divided VSP and SC-VSP =vertical shoot positioned trellising.

^b HIGH = 26 buds per m of row; MED = 20 buds per 1 m of row; LOW = 13 buds per m of cordon.

^c Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Student's T-test (Trellising experiment) and Tukey's honest significant difference (Density experiment).

Table 3.4 Trellising and density effect on primary juice composition and total berry phenolics and anthocyanins in Chambourcin at harvest in 2018 and 2019.

Treatment effects	Soluble Solids Content (°Brix)		pH		Titratable Acidity (g/L)		Anthocyanin Content (mg/ g berry)		Total Phenolic Content (au/ g berry)	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Trellising^a										
DC-VSP	20.2	20.0 a	3.71 b	3.53 a	4.9 a	5.5 b	0.97	0.52 a	105.7 b	77.3 a
SC-VSP	20.3	18.7 b	3.76 a	3.44 b	4.7 b	5.8 a	1.00	0.27 b	111.4 a	58.7 b
Density^b										
HIGH	20.2	18.6 c	3.75	3.42 c	4.9	5.8 a	1.00 ab	0.27 c	110.5	58.0 c
MED	20.1	19.2 b	3.72	3.49 b	5.0	5.7 ab	0.94 b	0.38 b	106.2	66.5 b
LOW	20.4	20.2 a	3.73	3.55 a	4.7	5.4 b	1.02 a	0.53 a	109.1	79.3 a
Significance^c										
Trellising (TR)	ns	<0.0001	0.0028	<0.0001	0.0242	0.0085	ns	<0.0001	0.0223	<0.0001
Density (PR)	ns	<0.0001	ns	<0.0001	ns	0.0110	0.0389	<0.0001	ns	<0.0001
TR*PR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

^a DC-VSP = divided VSP and SC-VSP =vertical shoot positioned trellising.

^b HIGH = 26 buds per m of row; MED = 20 buds per 1 m of row; LOW = 13 buds per m of cordon.

^c Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Student's T-test (Trellising experiment) and Tukey's honest significant difference (Density experiment).

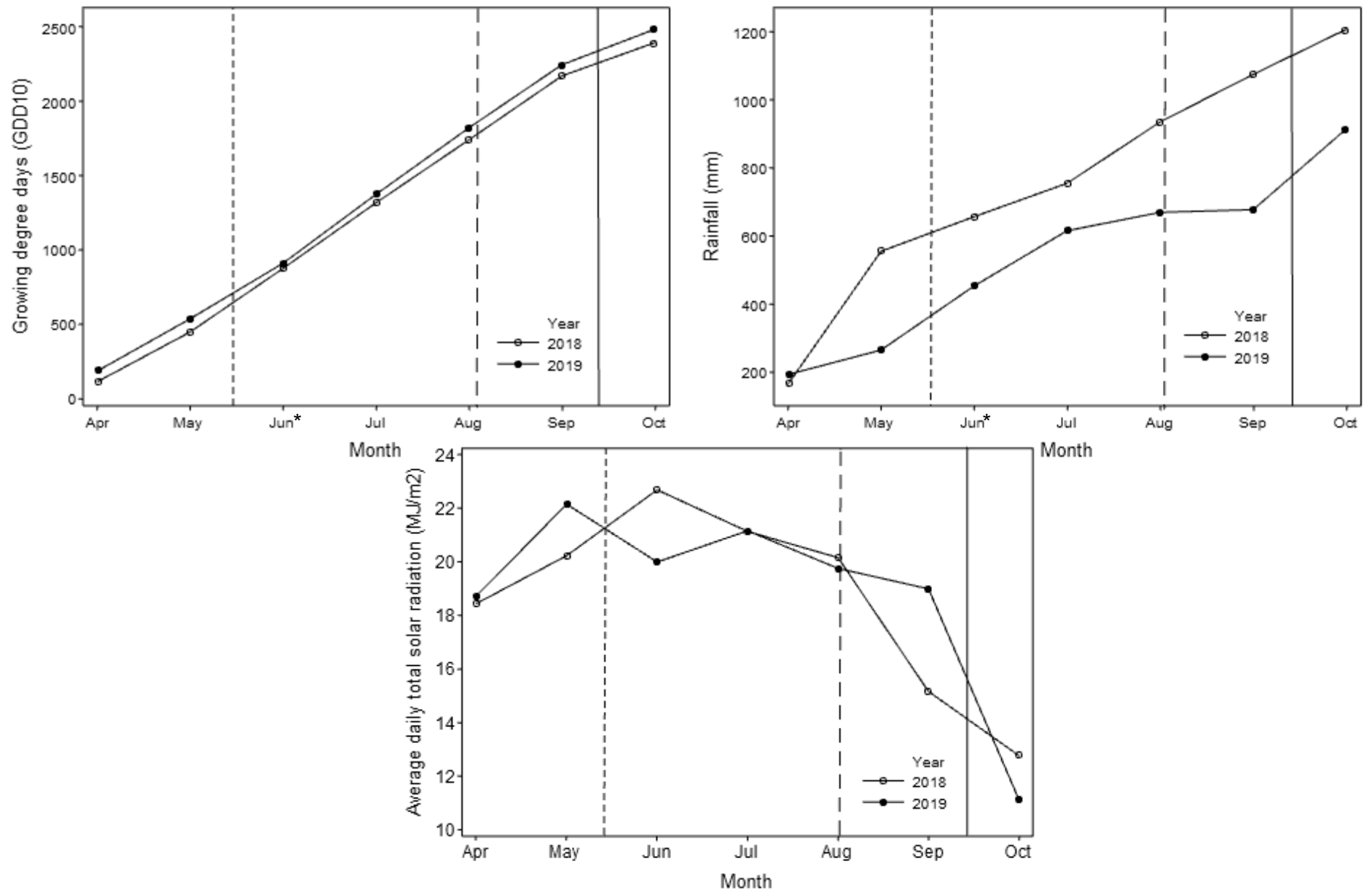


Figure 3.1 Growing Degree Day, Rain accumulation, and Average total solar radiation for 2018 and 2019. Growing degree days were calculated using a base line of 10°C. The first dashed vertical line indicates when the vineyard was at 50% bloom. The second dashed vertical line indicates the start of veraison. The solid vertical line indicates approximately when harvest occurred. The asterisk (*) indicates that weather from 15 through 30 Jun was recorded approximately 15 km away from the vineyard due to a lapse of data logger failure at the vineyard site. The average total solar radiation was taken from a data logger 15 km away to classify general trends.

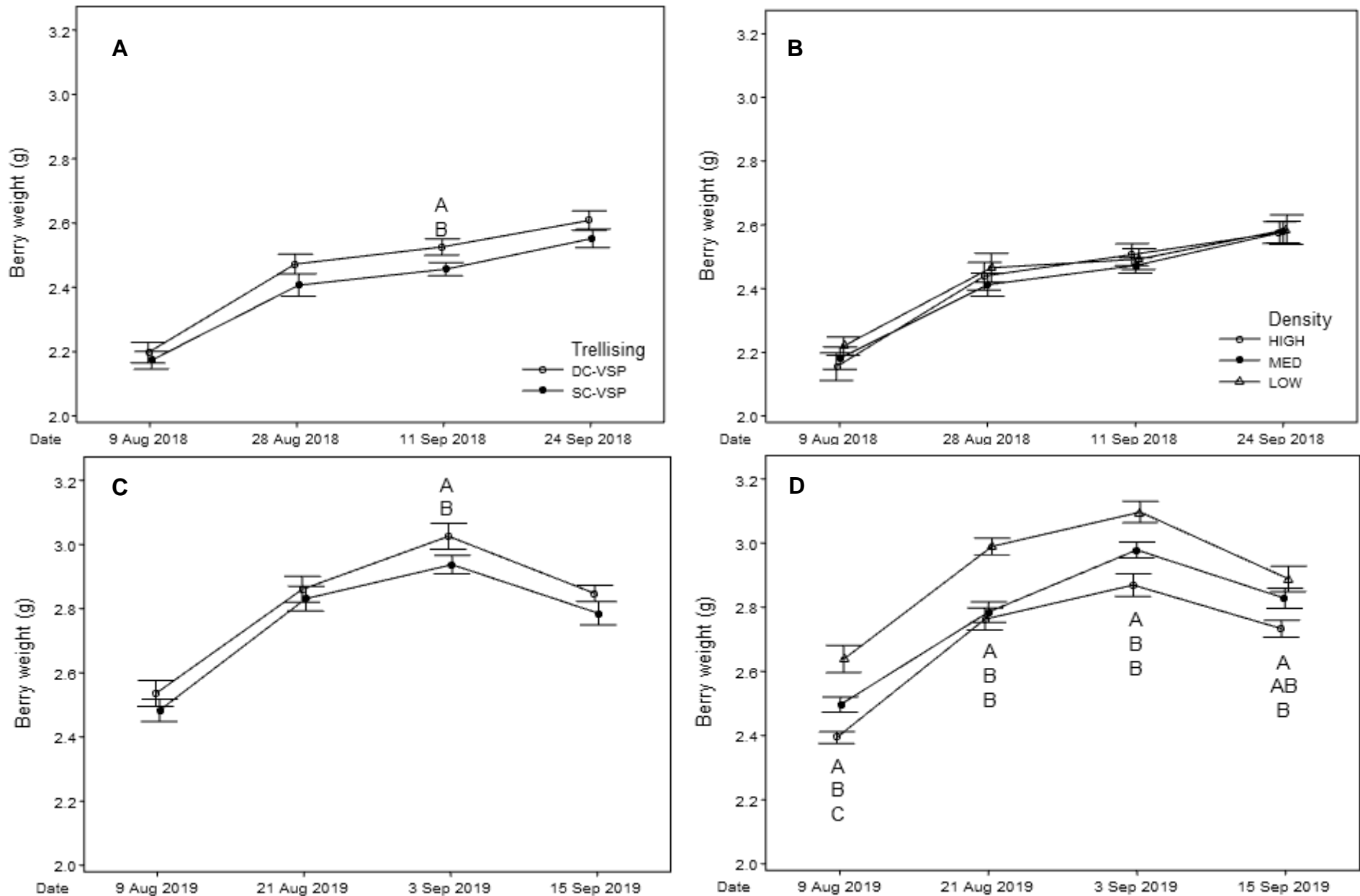


Figure 3.2 Effect of trellising and density treatments on berry weight accumulation over 2018 (**A** and **B**) and 2019 (**C** and **D**). DVSP (divided VSP) and VSP (vertical shoot positioning) trellising (**A** and **C**) over post veraison periods in 2018 and 2019. HIGH = 26 buds per m of row; MED = 20 buds per 1 m of row; LOW = 13 buds per m of row. The bud densities were set through dormant pruning. (**B** and **D**). Means within the same date not sharing the same letter were statistically significantly different, and means within the same date without letters were not statistically significantly different ($\alpha = 0.05$, Student's T-test (Trellising experiment) and Tukey's honest significant difference (Density experiment)). Error bars indicate the standard error; $n=4$.

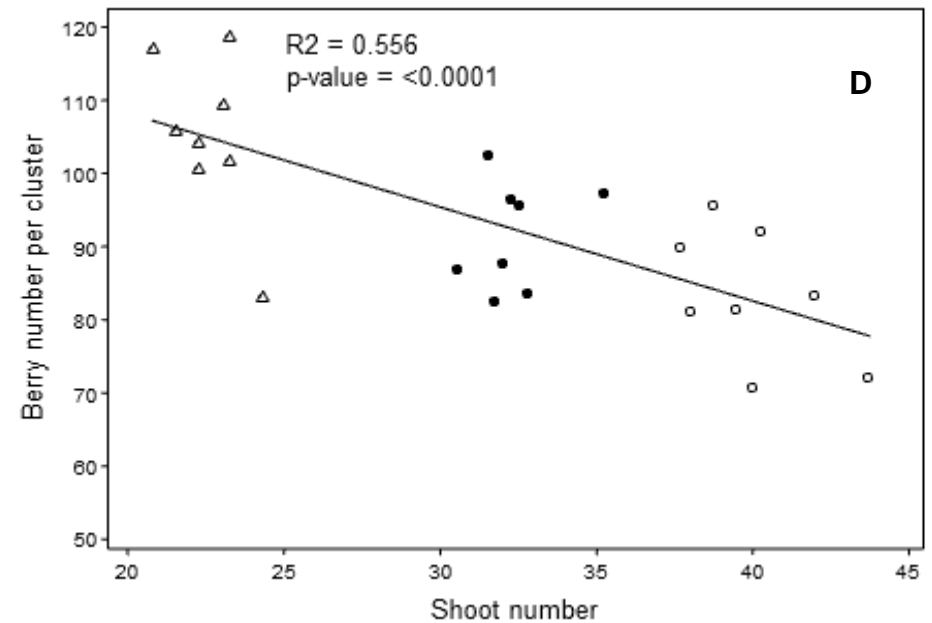
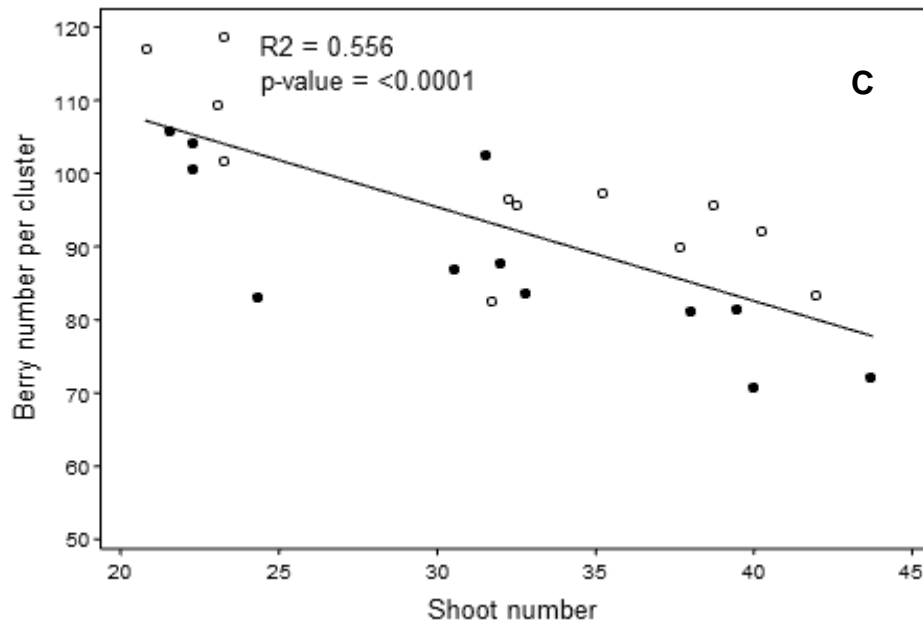
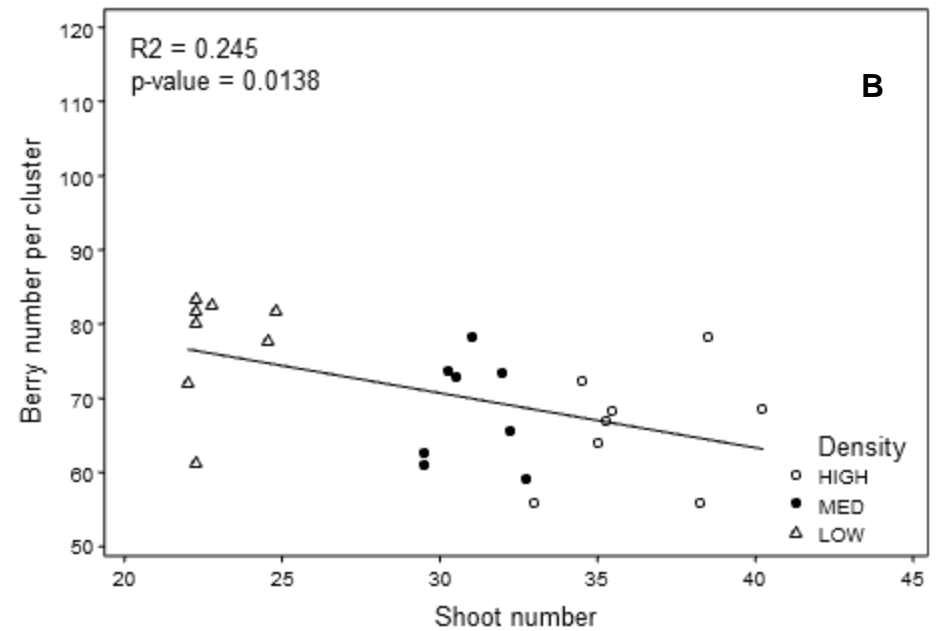
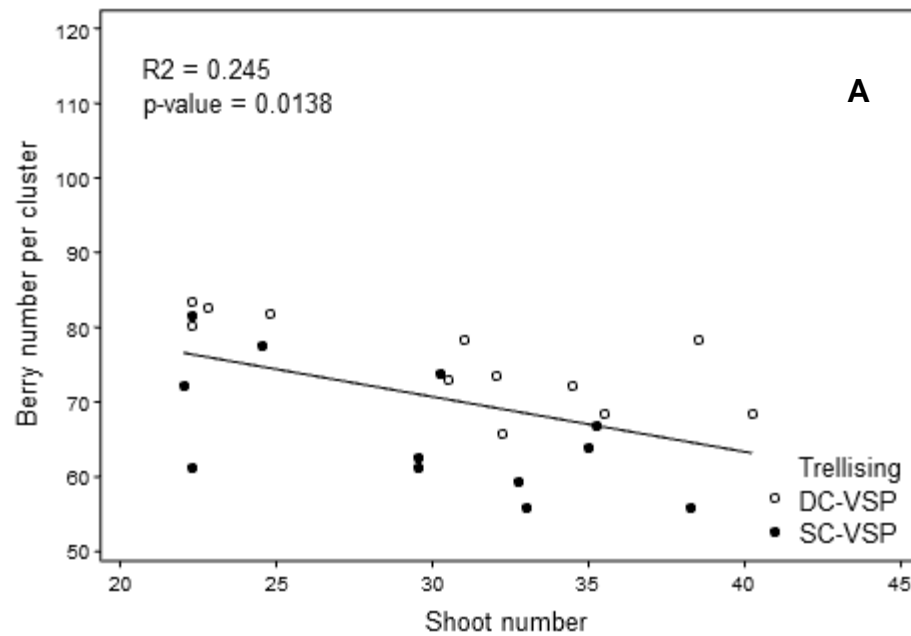


Figure 3.3 Effects of shoot number per vine on berry number per cluster in 2018 (**A** and **B**) and 2019 (**C** and **D**). DC-VSP (divided VSP) and SC-VSP (vertical shoot positioning) (**A** and **C**). HIGH = 26 buds per m of row; MED = 20 buds per 1 m of row; LOW = 13 buds per m of row. The bud densities were set through dormant pruning. (**B** and **D**). Regression lines from both years are linear.

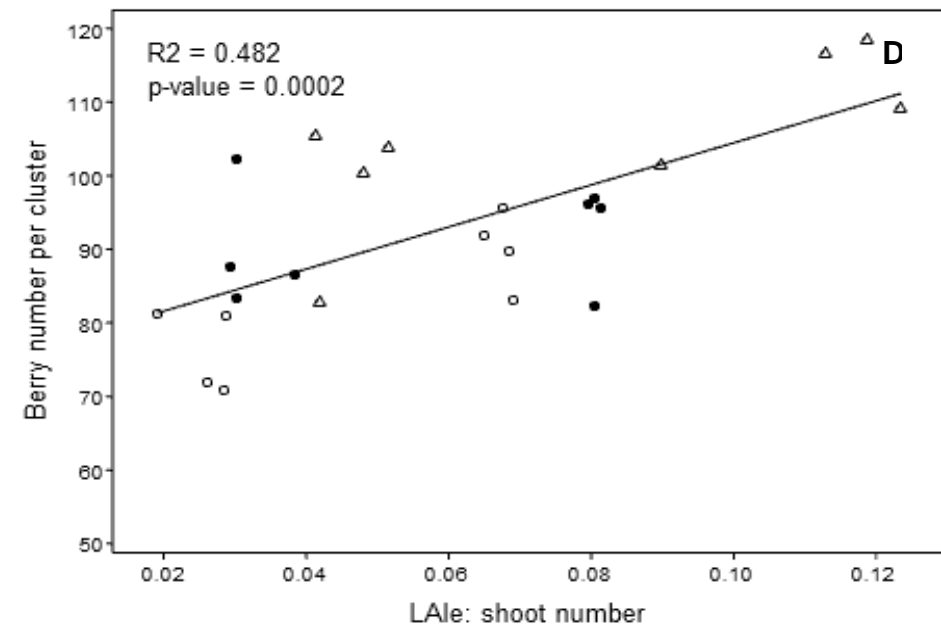
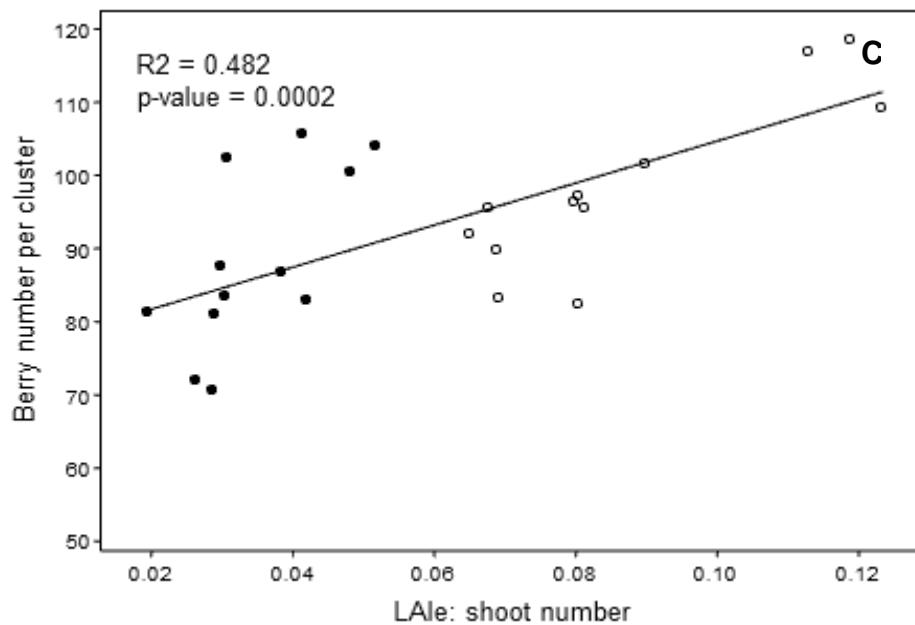
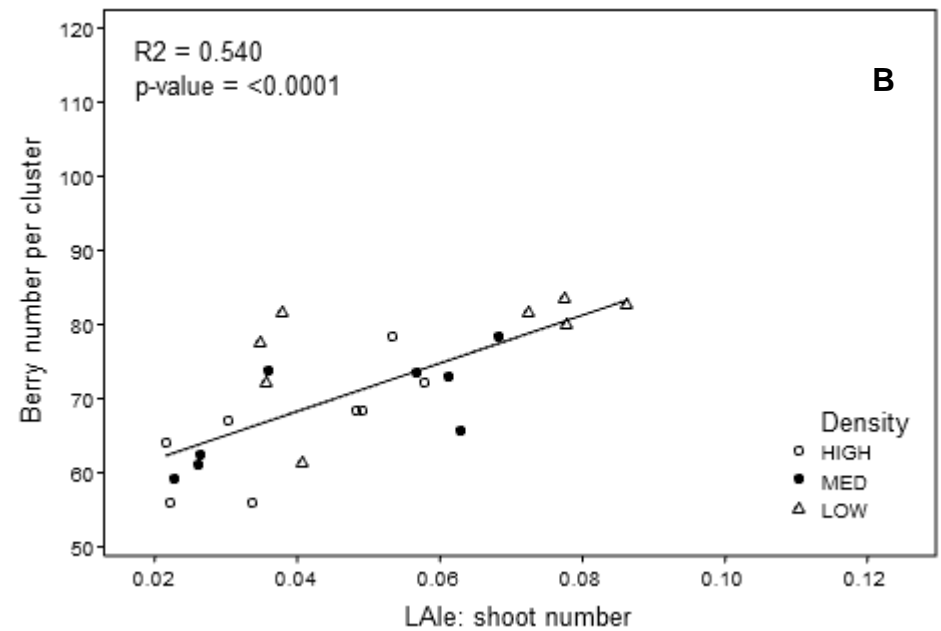
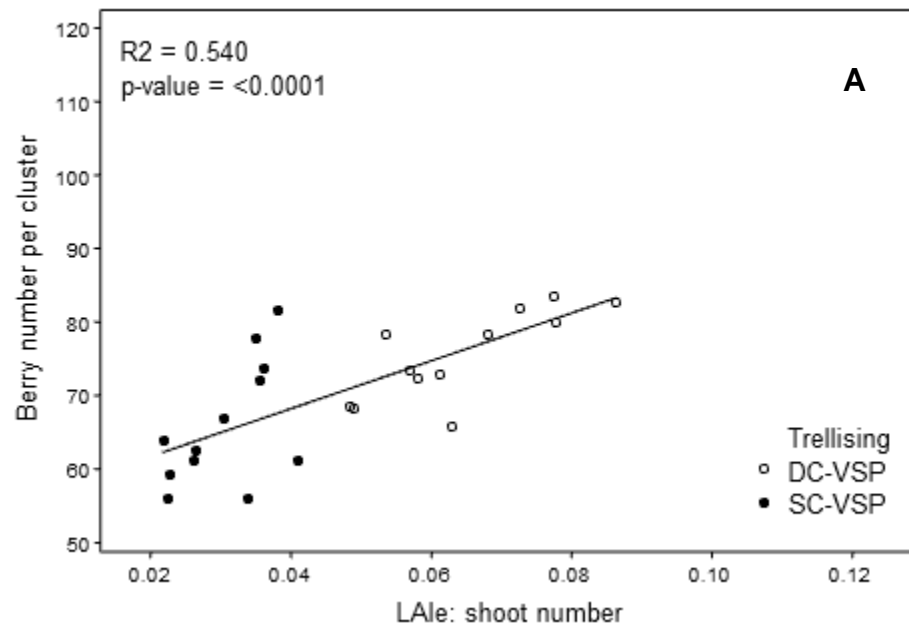


Figure 3.4 Effects of the ratio of LAle to shoot number on berry number per cluster in 2018 (**A** and **B**) and 2019 (**C** and **D**). DC-VSP (divided VSP) and SC-VSP (vertical shoot positioning) (**A** and **C**). HIGH = 26 buds per m of row; MED = 20 buds per 1 m of row; LOW = 13 buds per m of row. The bud densities were set through dormant pruning. (**B** and **D**). Regression lines from both years are linear.

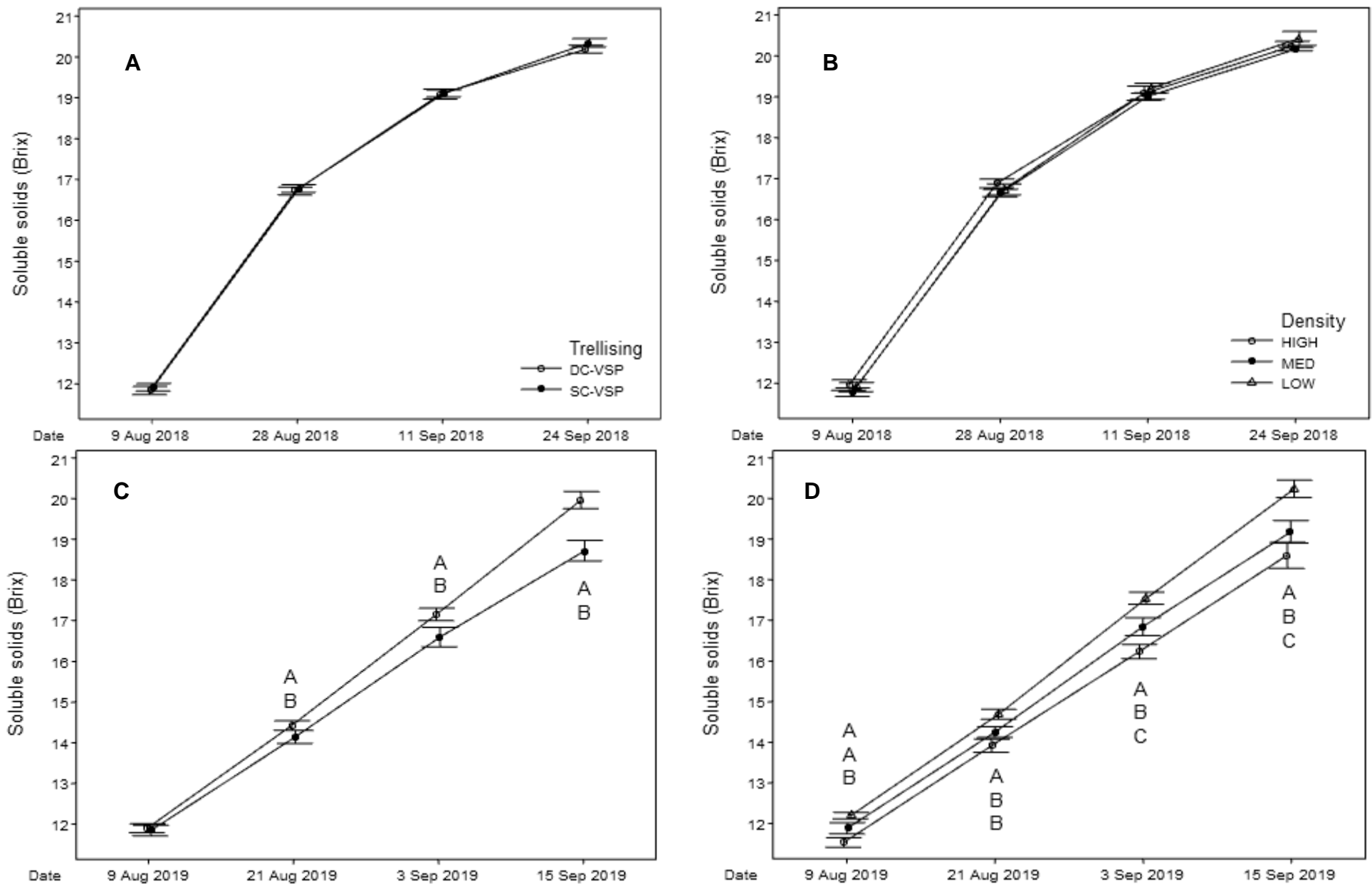


Figure 3.5 Effects of trellising and density treatments on Brix accumulation in 2018 (**A** and **B**) and 2019 (**C** and **D**). DVSP (divided VSP) and VSP (vertical shoot positioning) (**A** and **C**) over post veraison periods in 2018 and 2019. HIGH = 26 buds per m of row; MED = 20 buds per 1 m of row; LOW = 13 buds per m of row. The bud densities were set through dormant pruning. (**B** and **D**). Means within the same date not sharing the same letter were statistically significantly different, and means within the same date without letters were not statistically significantly different ($\alpha = 0.05$, Student's T-test (Trellising experiment) and Tukey's honest significant difference (Density experiment)). Error bars indicate the standard error; $n=4$.

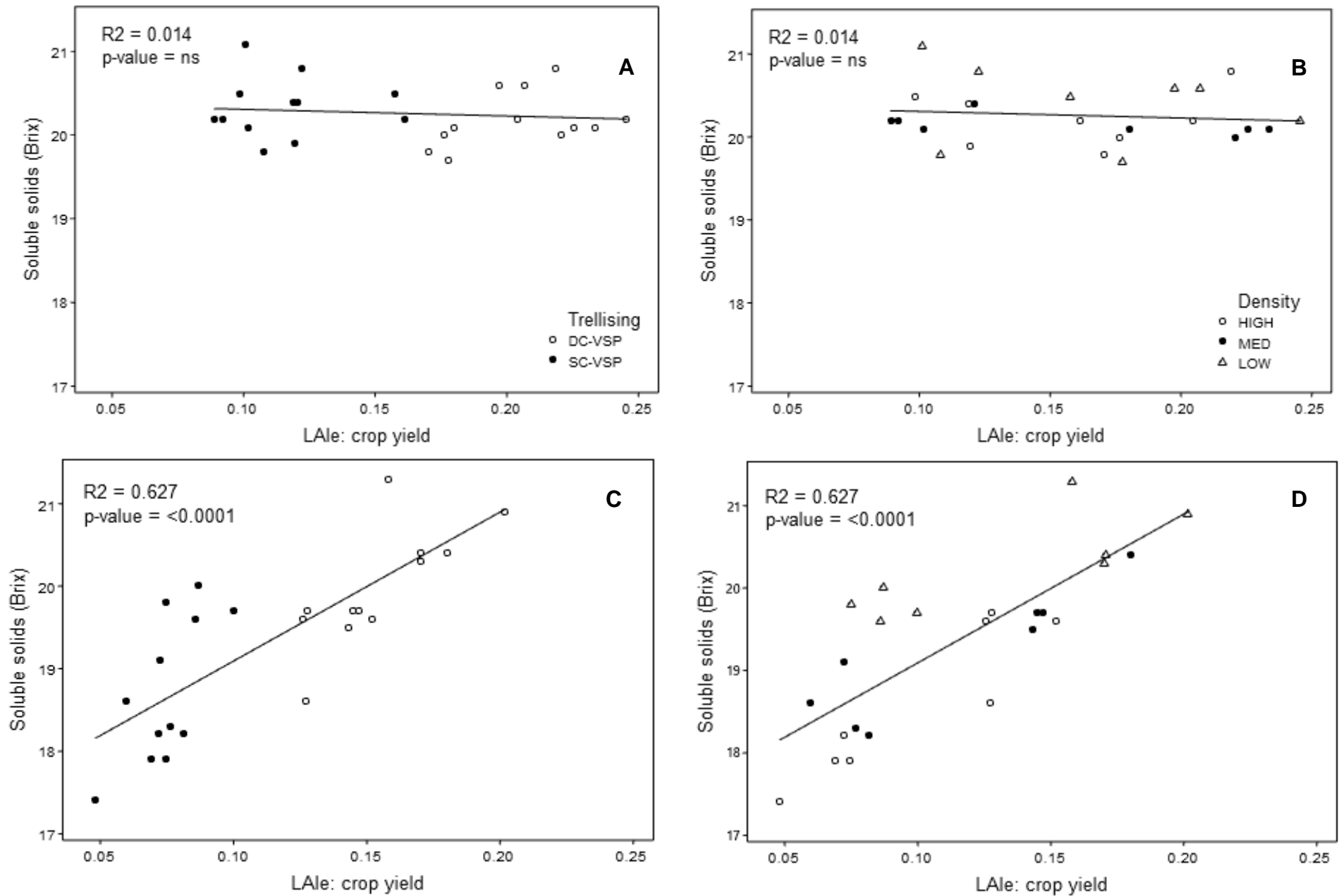


Figure 3.6 Effects of the ratio of LAle to crop yield on soluble solids in 2018 (**A** and **B**) and 2019 (**C** and **D**). DC-VSP (divided VSP) and SC-VSP (vertical shoot positioning) (**A** and **C**). HIGH = 26 buds per m of row; MED = 20 buds per 1 m of row; LOW = 13 buds per m of row. The bud densities were set through dormant pruning. (**B** and **D**). Regression lines from both years are linear.

CHAPTER 4

EVALUATION OF PRUNING TO DIFFERENT BUD DENSITIES ON TRAMINETTE IN GEORGIA³

³ White, R., S. Patrick, and C. Hickey. To be submitted to *Catalyst: Discovery into Practice*

Abstract

Dormant pruning to different bud densities has been shown to impact crop yield, primary chemistry, and disease prevalence in some cases in bunch wine grape vineyards. The industry standard recommendation for spur pruning wine grape cultivars is to retain 13 buds per linear meter of cordon; however, the site and cultivar have a great bearing on optimal bud densities for the economic production of quality grape crops. The effect of bud density on crop yield and fruit composition was evaluated in the French-American hybrid Traminette. Treatments were 20 buds per m of cordon and 16 buds per m of cordon and an industry standard of 13 buds per m of cordon. Increasing bud density to 20 buds per m of cordon resulted in 32% greater crop yield compared to the industry standard bud density of 13 buds per m of cordon over two years. Treatments did not consistently impact primary chemistry. Our results suggest that retaining greater bud densities than currently recommended in Traminette can result in greater crop yield without affecting primary fruit chemistry.

Summary.

Goals: Dormant vine pruning can affect vineyard health, longevity, and crop yield. Previous studies with Traminette show that pruning and training have little impact on crop yield, even in divided canopy systems. However, despite it being a popular, hybrid wine grape cultivar in the Midwestern and eastern US, research on Traminette is limited. The goal of this project was to evaluate if retaining different bud densities at dormant pruning would affect crop yield in Traminette.

Key Findings:

- 10% more shoots were produced than buds retained at dormant pruning in 2018 but not in 2019.
- As bud density increased from 13 to 20 buds per m cordon, fruit zone shading (occlusion) layer number increased by an average of 23% over two years.
- Retaining 20 buds per m cordon increased cluster number by an average of 37% and crop yield by an average of 34% when compared to the industry standard 13 buds per m cordon over two years.
- Though pruning to 20 and 16 buds per m cordon increased crop yield by an average of 26% when compared to the recommended 13 buds per m cordon over two years, primary juice chemistry at harvest was minimally impacted by pruning density.

Impact and Significance:

Overview.

Traminette is a French-American, hybrid wine grape that was initially bred at the University of Illinois from a cross of Joannes Seyve 23.416 x Gewurztraminer. The seed from that cross was given to Cornell's grape breeding program in 1968. ¹ Cornell released Traminette as a cultivar

that had “superior wine quality combined with good productivity, partial resistance to several fungal diseases, and cold hardiness superior to its acclaimed parent Gewurztraminer”.¹ In the southeastern US, Traminette is a moderate- to low-cropping cultivar that produces excessive vegetative growth that shades the fruit zone and reduces the aromatic potential of the wine.²⁻⁴ Monoterpenes are odor-active compounds, synthesized in the plastids of the cells present in the grape exocarp, that give some aromatic grape cultivars their characteristic pungency.⁴ Sunlight exposure has been shown to increase the monoterpene level in aromatic cultivars, including Traminette.^{2,4} However, given the inherently high vegetative vigor in Traminette, monoterpenes may be limited due to shaded fruit zones.

Pruning to a higher bud density has been shown to reduce vine vegetative vigor compared to those pruned to a lower bud density.⁵⁻⁷ Considering its excessive vegetative growth, reduced vegetative vigor would not be considered a negative response for Traminette, especially because it is typically grown in regions with supra-optimal soil and nutrient water availability.

Gewurztraminer, one of the parent grapes to Traminette, had a linear increase in crop yield as increasing bud densities were retained.⁸ The increase in crop yield was a function of an increase in bunch number per shoot despite a reduction in cluster weight at the highest bud density.⁸

Retaining higher bud numbers in Traminette following a balanced pruning method was shown to increase yield without negative impacts on primary chemistry in Kentucky.³ That study also showed that the different cropping levels had minimal impacts on primary bud cold tolerance.³

Thus, retaining greater bud densities than the standard commercial recommendation of 12 to 15 buds per m of cordon could be beneficial for Traminette cultivation in Georgia.⁹ It is possible that retaining greater bud densities per m cordon would result in two positive responses in Traminette – increased crop yield and attenuated vegetative vigor. We thus sought to evaluate

the effect of pruning to various bud densities on crop yield, canopy architecture, primary fruit composition, and pruning weight in Traminette grown in Georgia.

Major observations and interpretations.

Brief description of experimental settings and treatments. A randomized complete block design was replicated five times within a commercial Traminette vineyard planted in 2015 in Habersham County, Georgia. Vines were grafted to 3309-C rootstock and trained to bilateral cordons with vertical shoot positioning (VSP). The VSP system used a series of four catch wires ascending the trellis post along with a movable catch wire to help train the shoots vertically. Treatments were implemented by dormant pruning to three different bud densities: 13 buds per m cordon (LOW), 16 buds per m cordon (MED), and 20 buds per m cordon (HIGH).

Dormant cane pruning weight and shoot counts. Pruning weights were not impacted by pruning to different bud densities in 2018 (Table 1) and all fell within the recommended 0.3 to 0.6 kg per m row.⁹ Thus, while Traminette is considered to be a vegetatively vigorous cultivar, the vines used in this experiment would be considered in healthy vegetative balance⁹; this was perhaps a function of their relatively young age during the experiment. While we dormant pruned to defined bud densities, some buds produced more than one count shoot. In the 2018 season, 105%, 106%, and 123% of the buds retained turned into shoots in HIGH, MED, and LOW, respectively. In 2019, 95%, 100%, and 100% of buds retained turned into shoots in HIGH, MED, and LOW, respectively.

Veraison fruit zone Point Quadrat Analyses. Treatment had a significant impact on fruit zone leaf layer number in 2018 and impacted occlusion layer number in 2018 and 2019 (Table 2). HIGH increased fruit zone leaf layer number by 25% compared to MED and LOW in 2018 only. Occlusion layer number was increased by HIGH when compared to LOW by roughly the same

percentage (~23%) in both years. The increase in occlusion layer in HIGH was probably due to an increase in leaf and cluster contacts in the fruit zone. The LLN in all treatments fell within the recommended 1 to 2 layers per insertion, which was likely aided by fruit zone leaf removal that was evenly implemented across all experimental units before PQA was performed.^{9,10} CEL is the number of shading layers between clusters and the nearest canopy boundary. CEL fell below 0.5 layers in both 2018 and 2019 indicating clusters in all treatments were well exposed to solar radiation. Fruit zone sunlight exposure was also found in LEL (number of shading layers between leaves and the closes canopy boundary) as well as it fell below 0.3 shading layers.

Crop yield components. HIGH produced the greatest crop yield in both years (Table 3). HIGH produced 40% greater crop yield compared to LOW while MED increased crop yield by 24% compared to LOW in 2018. In 2019, HIGH increased crop yield by 14% compared to MED and 28% compared to LOW. In both years, HIGH had greater cluster numbers per vine when compared to LOW (31% and 43% in 2018 and 2019, respectively) and MED (11% and 19% in 2018 and 2019, respectively). However, the greater cluster number in HIGH did not result in lowers cluster weight relative to MED and LOW. Crop load was not significantly different between the treatments. However, crop load for all treatments fell below the recommended 5 to 10 (3.39 average of all treatments).⁹ This indicates that vines were under-cropped, even when compared to the “balanced” pruning weights (Table 1). This finding thus supports the industry anecdote that Traminette is a low cropping cultivar, particular in regard to the vegetative growth. A previous study in Traminette showed that yearly weather variation has a significant impact on the crop yield and clusters per vine.³ That study also noted that, despite differences in crop yield and cluster number per vine, there was minimal effect on overall crop load expressed as Ravaz index.³ Our results support that weather patterns can impact crop yield and Traminette, and we

suspect that the rainy bloom time weather in 2018 attenuated fruit set and thus crop yield when compared to the warm, dry year in 2019.

Primary fruit composition. Treatment had no impact on primary fruit chemistry other than titratable acidity (TA) in 2018 (Table 4). The 7% higher TA found in HIGH compared to LOW was indicative that HIGH was less ripe compared to LOW; however, the 0.25 g/L difference in acid concentration would likely not be of significance for commercial winemaking purposes. Since there were no primary fruit composition trends that persisted year to year, it can be concluded that the different pruning measures produced crops of similar ripeness, at least concerning primary fruit composition. A previous bud density study in Traminette also showed that different cropping level did not result in appreciable differences in primary fruit composition.³ This contrasts other studies that have shown that manipulating the shoot density can reduce soluble solids concentration and reduce ripeness of fruit.^{5,7,11} Thus, unlike other cultivars, Traminette fruit maturity may not be greatly impacted by changes in crop yield; this may be a function of the lower crop loads in Traminette due to sufficient vegetative growth and/or low crop yields.

Broader impact.

Dormant pruning is an important consideration for canopy and crop load management year to year. There have been few dormant pruning trials completed on the French-American hybrid Traminette despite its popularity and tendency to have vigorous vegetative growth compared to the amount of fruit produced. Increasing bud density to 20 buds per m cordon augmented yield by 28% compared to the industry standard 13 buds per m cordon in the second year of the trial. That increase in crop yield was a function of an increase in cluster number (43%) and did not result in a practical impact on primary fruit chemistry. These results indicate that retaining

greater bud densities than currently recommended can increase crop yield and maintain primary fruit composition, and crop load.

Experimental design.

The experiment was conducted in a commercial Traminette vineyard planted in 2015 in Habersham County, Georgia. Vines were grafted on C-3309 rootstock and planted 1.83 m apart in rows that were 2.75 m apart and oriented east to west. The soil was Cecil sandy loam on 10% to 25% slopes and considered eroded or severely eroded.¹² Vines were trained to low, bilateral cordons at approximately 100 cm above the ground and shoots were positioned vertically with the aid of four of trellis catch wires positioned at 25 cm, 40 cm, 60 cm and 85 cm above the fruiting wire. Training was aided by the use of a trellis catch wires to ensure shoots remained within the trellis. Vines were hedged periodically to 0.61 meters above the top catch wire to prevent shoot draping and canopy shading. Fruit zone leaf removal was implemented between EL stages 29 to 31 by removing two leaves and the associated laterals from the two cluster bearing nodes. The pest management program was standard for the region and generally effective at managing insect and disease pests, although there was a greater amount of undefined cluster disease present in 2018 (the “wet year”) relative to 2019 (the “dry year”).

A complete randomized block design was implemented in five blocks. Experimental units consisted of four vines. There were three pruning treatments implemented during dormant cane pruning in the winters of 2018 and 2019: 13 buds per m cordon (LOW); 16 buds per m cordon (MED); 20 buds per m cordon (HIGH).

Dormant cane pruning weight and growing season shoot counts. Cane pruning weights were measured by vine with a field scale during the dormant season. Count shoot numbers were counted by vine in July, pre-veraison (EL 27 to 31).¹³

Veraison fruit zone Point Quadrat Analysis. Point Quadrat Analysis (PQA) was completed at veraison (modified Eichorn-Lorenz stage 35).^{9,13} A thin, metal probe was inserted every 30 cm through the fruit zone that was parallel to the vineyard floor. The tissue contacts (leaf, cluster, or gap - if there no contact was made as the probe passed) were recorded in the order in which they were contacted as the probe transected the fruit zone.⁹ The probe insertion results were used to produce the following PQA metrics: leaf layer number (number of leaves per transection), occlusion layer number (number of shade producing objects per transection), leaf exposure layer (number of shading layers between leaves and the nearest boundary), and cluster exposure layer (number of shading layers between clusters and the nearest boundary).¹⁴

Components of crop yield. Harvest occurred on 19 Sep 2018 and 5 Sep 2019. Vines were harvested and cluster counts recorded on a per vine basis. The crop weight of each vine was measured with a field scale. Cluster weight was determined by dividing the total crop yield per vine divided by the cluster number from that same vine. Berry number per cluster was determined by taking the cluster weight divided by the individual berry weight, the latter of which was calculated from the composite berry sample taken from each experimental unit immediately before harvest (as per the primary fruit composition chemistry methods, below). Crop load was determined by dividing the weight of crop yield by the weight of dormant cane pruning produced from the same vine within the same growing season.

Primary fruit composition. Immediately before harvest in 2018 and 2019, equal amounts of berries (60 berries) were randomly sampled from both canopy sides of each vine, resulting in a composite sample of 120 berries taken from each experimental unit. Berries were hand-pressed in a plastic bag to express juice, which was collected in a 50 mL tube and centrifuged at 4000 RPM for five minutes before analyzing for sugars, acidity, and pH, as follows. Soluble solids

(°Brix) were measured using an Atago PAL-1 Digital Refractometer. The TA and pH were measured with a Titrino 848 Plus auto titrator (Metrohm, USA, Riverview, FL). Juice TA was measured by titrating a solution of 5 mL of grape juice and 40 mL of distilled water to an endpoint pH of 8.2 with a 0.1 M NaOH base following previously described protocols.¹⁵ The pH probe of the Titrino 848 Plus was used to measure pH on undiluted grape juice.

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Table 4.1 Pruning density treatment effect on Traminette dormant pruning weight and shoot counts in 2018 and 2019

Treatment effects	Pruning Weight (kg/m row)	Shoot Number (#/ m row) ^a	
	2018	2018	2019
Pruning ^b			
HIGH	0.43	21 a	19 a
MED	0.44	17 b	16 b
LOW	0.43	16 b	13 c
Significance ^c	ns	0.0004	<0.0001

^a Shoot numbers were taken between EL stages 27 to 31 (bloom)

^b HIGH = 20 buds per m cordon; MED = 16 buds per m cordon; LOW = 13 buds per m cordon

^c Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Tukey's honest significant difference.

Table 4.2 Pruning density treatment effect on select fruit zone enhanced point quadrat analyses, as measured at veraison in Traminette in 2018 and 2019.

Treatment effects	Leaf Layer Number (LLN)		Occlusion layer number (OLN)		Cluster exposure layer (CEL)		Leaf exposure layer (LEL)	
	2018	2019	2018	2019	2018	2019	2018	2019
Pruning^a								
HIGH	1.52 a	1.54	2.46 a	2.79 a	0.36	0.43	0.22	0.28
MED	1.21 b	1.26	2.09 ab	2.37 ab	0.37	0.31	0.14	0.19
LOW	1.21 b	1.33	2.00 b	2.28 b	0.33	0.34	0.14	0.21
Significance^b	0.0441	ns	0.0389	0.0451	ns	ns	ns	ns

^a HIGH = 20 buds per m cordon; MED = 16 buds per m cordon; LOW = 13 buds per m cordon

^b Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Tukey's honest significant difference.

Table 4.3 Pruning density treatment effect on components of crop yield and crop load in Traminette in 2018 and 2019.

Treatment effects	Crop yield (kg/ vine)		Cluster number		Cluster Weight (g)		Berry # / Cluster		Berry Weight (g)		Crop Load
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	
Pruning^a											
HIGH	3.04 a	5.53 a	51 a	49 a	59.52	112.09	31	50	1.91	2.22	3.95
MED	2.70 ab	4.83 b	45 ab	42 b	59.84	116.47	31	51	1.95	2.35	3.32
LOW	2.17 b	4.31 c	38 b	35 c	56.01	124.49	28	53	1.97	2.33	2.91
Significance^b	0.0395	<0.0001	0.0072	0.0002	ns	ns	ns	ns	ns	ns	ns

^a HIGH = 20 buds per m cordon; MED = 16 buds per m cordon; LOW = 13 buds per m cordon

^b Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Tukey's honest significant difference.

Table 4.4 Pruning effect on primary juice composition in Traminette at harvest in 2018 and 2019.

Treatment effects	Soluble solid content (°Brix)		pH		Titratable Acidity (g/L)	
	2018	2019	2018	2019	2018	2019
Pruning^a						
HIGH	19.88	20.02	3.41	3.23	4.00 a	4.60
MED	20.10	20.14	3.44	3.24	3.89 ab	4.43
LOW	20.72	20.24	3.45	3.26	3.75 b	4.43
Significance^b	ns	ns	ns	ns	0.0155	ns

^a HIGH = 20 buds per m cordon; MED = 16 buds per m cordon; LOW = 13 buds per m cordon

^b Statistical significance of treatment effects ($p > F$; ns = not significant at 0.05 level). Means in same treatment group (i.e., columns) not followed by the same letter were statistically significantly different at $\alpha = 0.05$ based on adjusted p values using Tukey's honest significant difference.

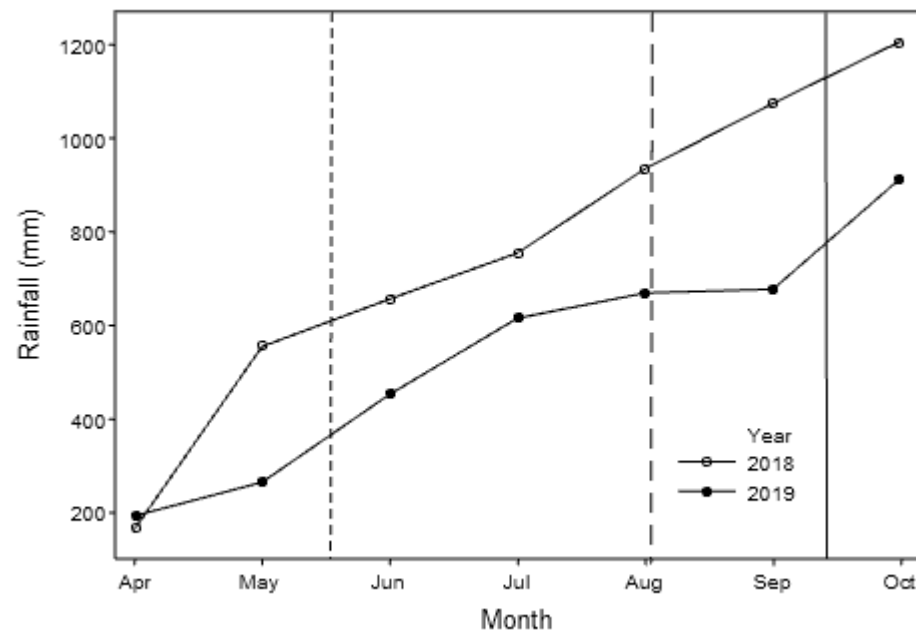
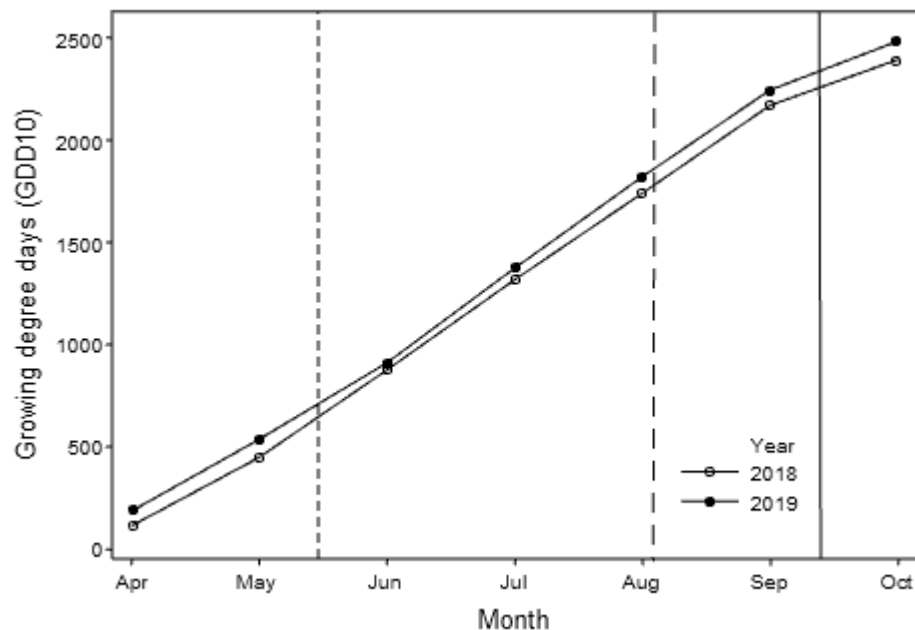


Figure 4.1 Growing Degree Day and Rain accumulation for 2018 and 2019 taken from a weather station 17 km away in another vineyard. Growing degree days were calculated using a base line of 10°C. The first dashed vertical line indicates when the vineyard was at 50% bloom. The second dashed vertical line indicates the start of veraison. The solid vertical line indicates approximately when harvest occurred. The asterisk (*) indicates that weather from 15 through 30 Jun was recorded approximately 30 km away from the vineyard due to a lapse of data logger failure at the vineyard site.

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APPENDIX A

INTRODUCTION TO WINE GRAPE TRELLISING AND PRUNING TERMS: EXTENSION PUBLICATION

There are many ways to manage the growth of wine grapevines and each wine growing region has different preferred methods. Vine growth management is achieved by applying a trellising system; a framework of metal cross arms, wires, and support posts that are used to direct grapevine vegetation to maximize fruit quality and production. Trellising and pruning combinations will sometimes be referred to as “training” systems, but trellising, training, and pruning are not interchangeable terms. Understanding the different forms of trellising and pruning can be a challenge for new growers. The goal of this publication is to provide a general introduction to some of the more common trellising and pruning system terms used when describing grapevine management systems. There is a glossary of definitions of terms at the end of this paper.

Each vineyard site and grape cultivar is different, and management can differ dramatically from one vineyard to another, even within a single vineyard if multiple cultivars are used. There is no one, perfect, trellising and pruning system combination that is optimal for every site or cultivar (e.g. Chardonnay and Norton have drastically different trellising and pruning goals). In fact, different trellising systems can be used successfully for the same cultivar, although one may be more productive than another.

Pruning methods can be changed after the vineyard has been in production for several years. However, the initial pruning decisions impact the early growth of the vineyard as well as ease of establishment and early management (Figure 1 shows establishment of cordon training and spur pruning in a young vineyard). Conversely, trellising systems are not easily changed once the grapevines reach the fruiting wire. In some cases, in order to change a trellising system, the entire vineyard needs to be replaced. For this reason, initial choice of a trellising system and the associated pruning strategy will be two of the most important decisions in the life of the vineyard.

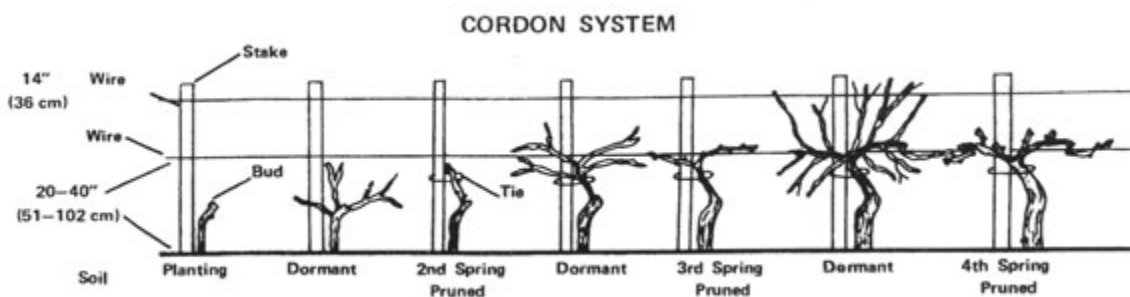


Figure A1. Changes in pruning through the lifecycle of a grapevine (taken from "Growing Grapes in New Mexico" by Esteban Herrera)

There are several considerations when choosing a trellising system, including cultivar vigor and soil available resources. Vigor is simply the rate of shoot growth and can be estimated in annual shoot length. For example, single canopy trellising systems (see below) are generally better suited for less vigorous cultivars and sites where vines do not grow as quickly due to environmental conditions. A divided canopy system (see below) may be better suited on a site that has nutrient rich soil and/or has environmental conditions that foster rapid plant growth and vigorous cultivars. The vigor of a site can differ even between vineyards in close proximity. Budget also plays a considerable role, as divided canopy systems initially cost more in trellis infrastructure compared to single canopy systems. Growth habit of the cultivar selected should also be taken into consideration. Some cultivars have a “trailing” habit and lend themselves to a

trellising method that allows the vine growth to drape and sprawl (e.g. ‘Norton’ on high wire), whereas others have an upright habit that easily allows for management in an upright system [e.g. ‘Chardonnay’ on Vertical Shoot Positioning (VSP)]. Throughout most of the Southeastern US, the most common way to train *Vitis vinifera* and their hybrids is VSP trellising with spur pruning. Let’s go into more detail about trellising systems and their importance.

Trellising Systems

Trellising systems generally refer to the infrastructure system of wires and posts needed to support and direct the canopy of a grapevine. The canopy of the grapevine refers to the green, growing areas of the vine; including leaves, flowers/fruit, and shoots. The goal of a trellising system is to not only manage the vines based upon the vigor of a site (as covered previously), but

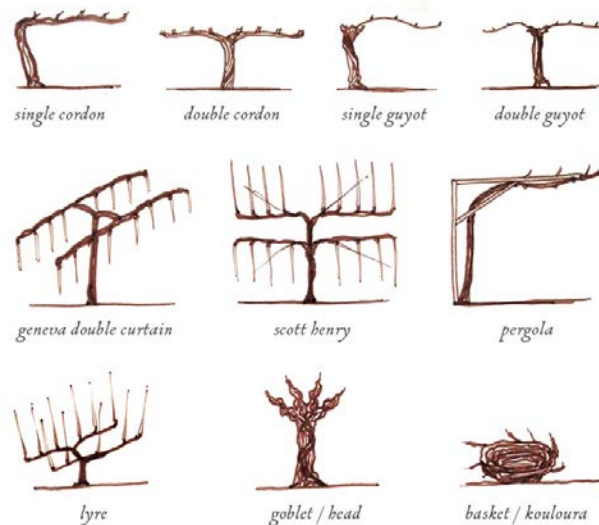


Figure A2. Vine trellising methods without the wire and post support system. Line 1 shows examples of trellising systems based on the pruning technique used in VSP trellising. Line 2 shows two divided canopy systems (GDC and Scott Henry) and one single canopy with a draping habit (Pergola) that is commonly used in garden settings. Line 3 describes one divided canopy system (Lyre) and two regionally used trellising systems (basket and goblet) that are not commonly used in the U.S. Taken with permission from Wine Folly.

also to maximize the sunlight exposure of the leaves, which leads to maximum fruit production

and high-quality fruit. Depending on the trellising system selected, growth can be oriented into single or divided canopies (Figure 2).

Single Canopy

Single canopy systems were developed in drier climates (e.g. California, Italy, and Spain) and don't produce as much fruit per vine compared to divided canopy systems. However, they are sustainable on a lower vigor site, are easier to install and manage, and more vines can be planted per acre compared to divided canopy systems. The most common trellising system on the East Coast of the U.S. is a single canopy system called Vertical Shoot Positioning (VSP). VSP can be adapted for different pruning methods (see Pruning section) and is one of the easier, most cost-

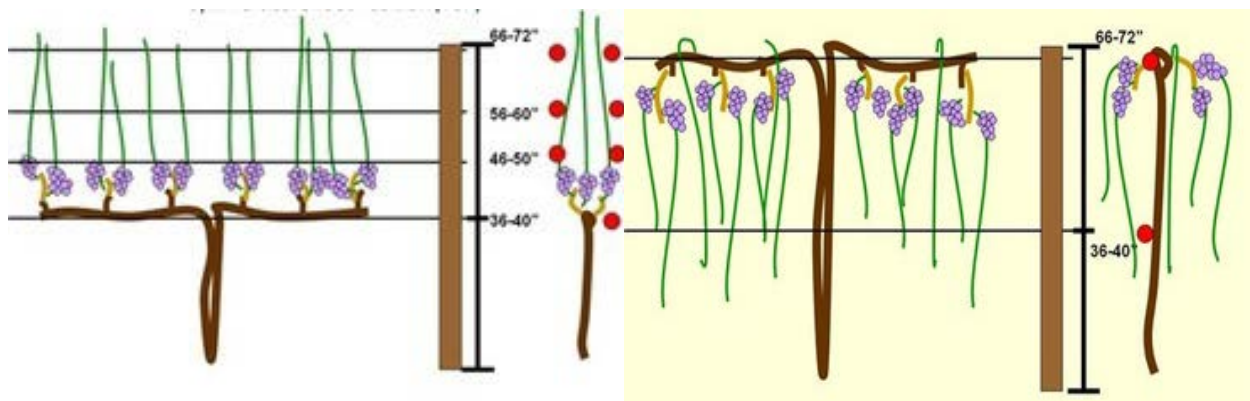


Figure A3. Low fruiting wire depicted here in a Vertical Shoot Positioned system on the left where the fruiting wire is between 36 and 40 inches from the ground. The shoots in this system are then trained upward in a single canopy. The image on the right depicts a high wire training system with the fruiting wire placed 66 to 72 inches from the ground. This is a semi-divided canopy with the shoots trained downward. (Taken from <https://go.dmac.edu/programs/viticulture>)

effective, trellising systems to establish. This system requires two to four sets of catch wires positioned vertically on either side of the support posts to guide shoot growth vertically (upward) with a low fruit zone (Figure 3). VSP allows for more vines per unit of land which can make up for decreased production per vine compared to horizontally divided canopy systems. VSP is also easily maintained throughout the growing season compared to most divided canopy systems.

Divided Canopy

Generally, vigorous sites and cultivars are more appropriate for divided canopy trellising systems. Divided canopies separate the canopy horizontally or vertically using more wires and cross arms than single canopy systems in order to obtain two canopies. Across the Southeast, where rainfall provides ample soil moisture, divided canopy systems are more productive. Given optimal environmental conditions, a divided canopy intercepts more sunlight and can produce a higher crop yield per vine compared to single canopy systems. However, the number of vines planted per acre is typically less because the width of each row must be wider to accommodate this type of trellising system, especially horizontally divided systems. There are variations to consider within a divided canopy system. The canopy can either be divided horizontally, such as in the Lyre or Geneva Double Curtain methods; or vertically such as in the Scott-Henry or Smart Dyson methods (Figure 2). Finally, a critical decision to make when selecting a trellising system is wire placement. The fruit zone can be trained to a high fruiting wire (at eye level – approximately 5 feet) or low fruiting wire (around waist level – approximately 3 feet). Shoot growth can then be directed vertically, downward, or draping depending on the trellising system (Figure 3).

Horizontally Divided Canopies

Horizontally-divided canopies are some of the more commonly implemented divided canopy management systems. They generally take up more space than single canopy or vertically divided canopy systems. The benefit of horizontally-divided canopy systems is that they can produce more fruit per vine. However, they have increased initial costs due to the need for more wires and hardware. Divided canopies have the potential for increased fruit production per vine compared to single canopy systems due to a doubling of the photosynthetically active leaf area

and the fruit zone. Some horizontally divided systems employ a low-wire with shoots trained upward, as in the Lyre system (Figure 4). Alternatively, a high wire system can be installed whereby vines are trained in a draping fashion, termed the Geneva Double Curtain system (GDC; Figure 2).

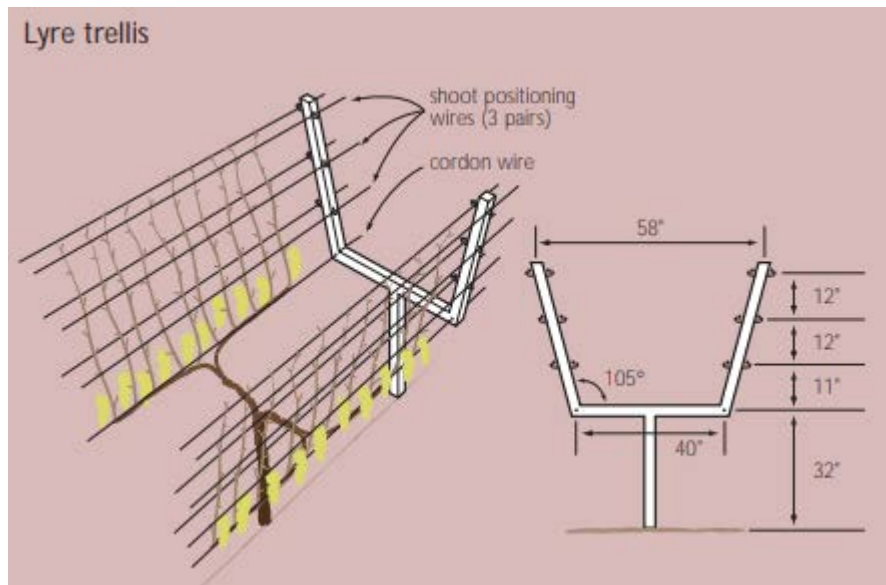


Figure A4. Diagram of the Lyre trellis that divides the fruit zone horizontally while positioning the shoots upward (Taken from “Trellis Selection and Canopy Management” by Nick Dokoozlian

Vertically Divided Canopies

One way to increase the number of vines planted per acre is to divide the canopy vertically, as in the Scott Henry or Smart Dyson trellising systems. Scott Henry (Figure 5) has a divided fruit zone with one vegetative canopy trained upward and another trained downward. Smart Dyson (Figure 6) has a similar trellising method, however there is only one fruit zone. Vertically divided systems involve a large amount of upkeep to maintain shoot positioning and prevent the lower division from reaching the vineyard floor.

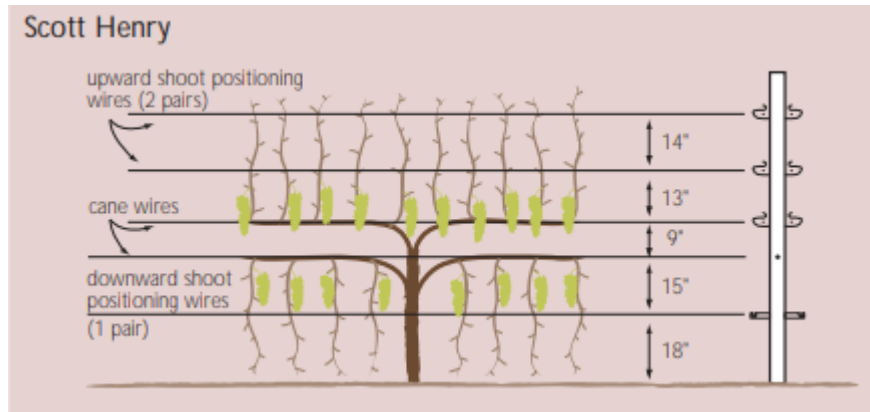


Figure A5. Scott Henry trellising system with divided fruit zone and divided vegetative canopy (Taken from “Trellis Selection and Canopy Management” by Nick Dokoozlian)

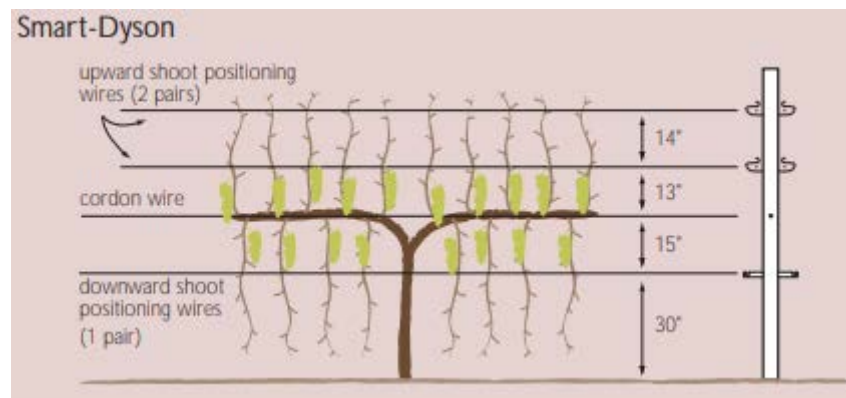


Figure A6. Smart Dyson trellising method with one fruit zone but a divided vegetative canopy (Taken from “Trellis Selection and Canopy Management” by Nick Dokoozlian)

Dormant Pruning

Pruning is the method by which one removes excessive, older wood from the grapevine, leaving selected growing portions of the plant for the upcoming season. Pruning is conducted in the dormant season (December to February) and is essential throughout the life of the vineyard to prevent overgrowth and reduce perennial wood diseases. Most fruit is born off of shoots that grow from one-year-old wood, thus, maintaining differing amounts of the one-year-old wood can impact crop yield. In the first two years of establishing new grapevines, pruning directs vine growth and selects the strongest shoots, which become the trunks and main growing regions of

the vine. In the first or second year after establishment, the vine can be trained onto the chosen trellising system to direct new growth. There are two main types of pruning: cane and spur pruning. Cane pruning is also referred to as “guyot” in a VSP trellising system (Figure 2).

Cane Pruning

Cane pruning retains one-year-old, dormant wood, shoots from the previous year, by laying it on the fruiting wire (Figure 7). Canes have buds which become the shoots that produce flowers and fruit in the upcoming growing season. Cane pruning has less retained perennial wood retained than cordon/spur system training with spur pruning. This method can be beneficial in reducing perennial wood diseases.



Figure A7. A dormant cane pruned vine

Spur Pruning

Spur pruning occurs after a cordon is established by laying canes on the established fruiting wire in the second or third year of growth. Those two canes become cordons after they have two seasons of growth. Shoots that grow off of the cordons are then cut back to one to three buds (Figure 8). This pruning method is repeated in the dormant season every year. Cordons need to be renewed every 5 to 10 years, depending on the productivity of the vine.



Figure A8. Two buds on a spur

On the East Coast of the U.S., one of the most common pruning systems is spur pruning with bilateral cordons and VSP trellising due to the ease of establishment and management. Outreach efforts from the UGA Viticulture Team have prompted several vineyard growers to use the Lyre, Watson, and other divided canopy trellising systems that are better suited to Georgia's humid climate. This publication was to serve as an introduction to many of the different pruning and trellising methods found in southeastern wine grape growing. There is further reading below that

delves deeper into some of the training systems and science behind grape growing. In upcoming publications from UGA, several trellising systems will be investigated in depth.

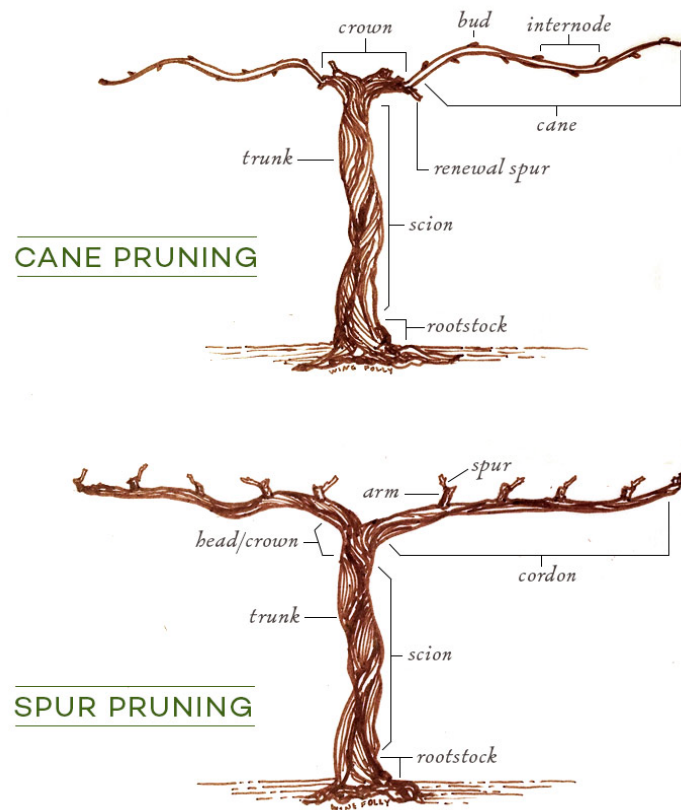


Figure A9. Pruning methods commonly used as described above. Used with permission from Wine Folly.

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Glossary of Terms

Bud – Typically refers to the buds contained only on one-year-old grapevine wood (e.g. canes and spurs) and from which fruitful shoots grow in the spring.

Cane – A former green, vegetative shoot that has hardened off and become dormant; one-year-old grapevine wood which generally contains fruit-producing buds.

Catch wire – The trellising system wire used to guide canopy growth and maintain its physical position to optimize leaf exposure.

Cordon – A former cane that is a lateral extension of the trunk along the fruiting wire and at least two-years-old; refers to a training type (“cordon training”) with which spur pruning is commonly implemented.

Dormant Pruning – The selection and retention of fruitful, one-year-old grapevine wood through cutting and discarding older, undesirable, and diseased grapevine wood; spur or cane pruning methods are most common.

Fruiting Wire – The wire on which the fruiting cane or cordon is tied; becomes the crop load bearing wire.

Head – The region of a vine where the vertical grapevine trunk meets the horizontal fruiting wire; refers to a training type (“head training”) with which cane pruning is commonly implemented. Can also be referred to as the “crown” region.

Shoot – The green stems and leaves that grow from dormant grapevine wood. Shoots grow from buds in the spring then become canes once they drop leaves and become dormant in the fall.

Spur – One-year-old grapevine wood that is cut back to one to three buds which bear new shoots the following season; a “Short”, or “spurred” cane position.

Training – Used to describe the grapevine training method for which one-year-old grapevine wood is retained to produce fruit-bearing shoots; the two most common training methods are cordon training (with spur pruning) and head training (with cane pruning).

APPENDIX B

WATSON TRAINING SYSTEM FOR BUNCH WINE GRAPES: EXTENSION

PUBLICATION

Rachael White, Paula Burke, Fritz Westover, Justin Scheiner, and Cain Hickey

Introduction

Grapevine training and trellising systems were discussed in a previous UGA Extension publication (Introduction to Wine Grape Trellising Terms). There are two main trellising system categories; divided and single canopy. Jerry Watson, a grape grower and owner of Austin County Vineyards in Cat Spring, Texas developed the divided canopy "Watson System" in 2002 to solve some issues he was having with bunch rot management and harvest inefficiency in his Blanc Du Bois and Lenoir vineyards. By adding a series of cross arms and catch wires to his High Wire system, Jerry was able to improve spray penetration to the fruit zone and increase picking efficiency at harvest. The Watson hardware and wires separate clusters from the canopy foliage and limit cluster touching compared to a standard, single High Wire system. The Watson system has since been employed in the southeastern US and can be found as far west as California. The Watson system is currently used for training hybrid and trailing grape cultivars such as, but not limited to, Blanc du Bois, Norton, Lenoir, Lomanto, Crimson Cabernet, and Villard blanc. A High Wire-trained vineyard, such as those planted with Chambourcin, Seyval blanc, Vidal blanc, Traminette, and other cultivars could be retrofitted to Watson training with success. Future research will evaluate hybrid and *vinifera* cultivars that have yet to be evaluated for training on the Watson system.

Structure, Design, and Relative Cost

The Watson system employs a divided canopy that promotes grapevine vegetative growth to grow out, over, and “rest” on trellis catch wires without requiring intensive training. Canopy division is aided by a four-foot-wide cross arm with two wires on each side to guide the shoot growth outward (Figure 1). The Watson cross arms have a 120° angle which enables the “sprawl” nature to the divided canopy (Figures 1 and 2). Five total wires are necessary to train the Watson system: one cordon wire at approximately five to six feet (60-72 inches) above the ground, two catch wires placed 12 inches from the fruiting wire, and two catch wires placed 24 inches from the fruiting wire. An additional wire will be needed if drip irrigation is desired. Table 1 shows the hardware cost per acre for establishing popular single and divided canopy trellising systems. The cross arms for the divided canopy systems results in an increased cost compared to standard High Wire. Note that a decreased distance between rows will increase trellis system costs per acre; for example, by spacing the Watson system at 11 foot as opposed to 12-foot spacing.

Table B1. Estimated cost analysis of popular training systems ^a				
	High Wire	VSP ^b	GDC ^b	Watson
Between-row spacing	9 feet	9 feet	12 feet	12 feet
Plants/Acre	807	807	605	605
Wire Number/Row ^c	2	7	3	5
Feet of wire needed/Acre	~10,000 feet	~35,200 feet	~11,300 feet	~18,800 feet
Cost of Wire	~\$310	~\$1,100	~\$350	~\$575
Line Posts/Acre ^d	191	191	136	136
Cross Arms	N/A	N/A	\$6.50 per cross arm	\$6.00 per cross arm
Total Cost	\$2,600	\$3,400	\$2,900	\$3,100

^a All costs were calculated on a per acre basis and do not include labor, end post structures, or other variable costs. Costs calculated on six foot between-vine spacing with 24-foot post spacing within the row.

^b VSP = Vertical Shoot Positioning, GDC = Geneva Double Curtain

^c Wire number per row is calculated without an irrigation wire

^d Line post cost based off of metal t-posts. Pressure treated lumber t-posts would increase the cost per acre.

Due to the separated fruit zone created by the Watson system (Figure 3), there is greater potential for increased air movement through the fruit zone and increased spray coverage on fruit when

compared to the standard, single high-wire system. The Watson system is hedged, or “skirted”, throughout the season by hedging the bottoms of the shoots at roughly waist height (3 feet above the ground) to encourage airflow and spray penetration into the fruit zone.

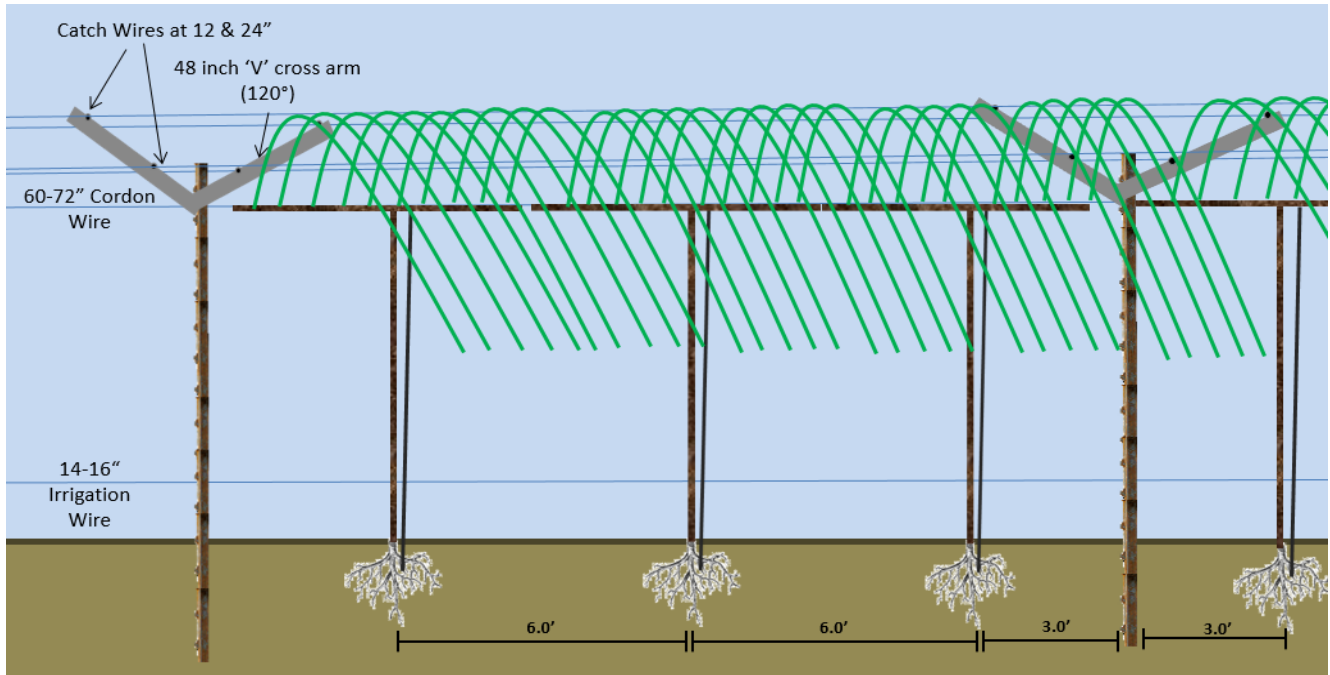


Figure B1. Dimensional outline of the Watson training system from a perspective of looking across-the-row from standing within the row.

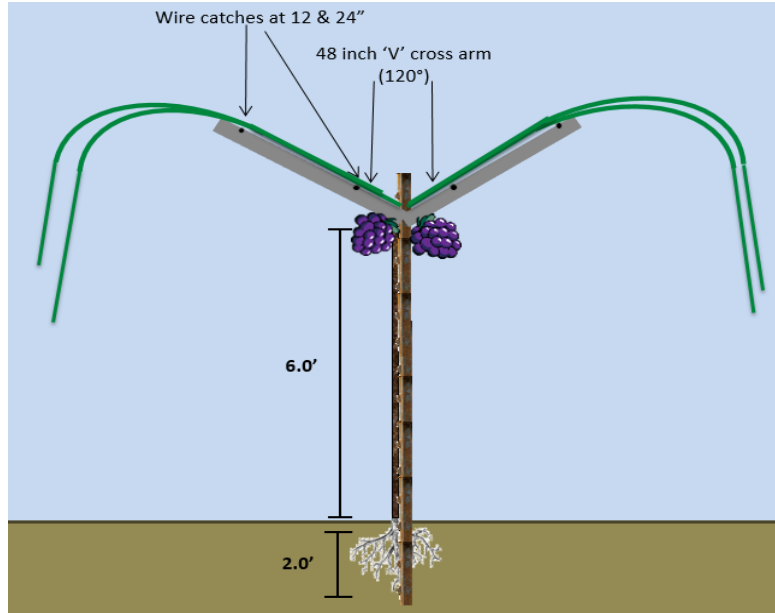


Figure B2. Dimensional outline of the Watson training system from a perspective of looking down-the-row from standing at row end.



Figure B3. The Watson training system viewed underneath, showcasing the fruit separation and open canopy in Norton (left) and Villard blanc (right).

Pruning, Training, and Management

In years one and two, the goal is to train the vines with a trunk and cordons per recommended vineyard establishment protocol (Wolf, 2008). During the following two years, the vine training is refined for the intended training and trellising system. After shoot growth extends upward and outward (toward the vineyard alleys) beyond the top wires of the cross arms, it then drapes downward (Figure 4 and Figure 5). The cordon height and separation of the fruit zone through the offset spurs (Figures 3 and 6) results in efficient hand harvesting of the crop. The Watson system cannot be mechanically harvested with standard over-the-row harvesting machines due to the size of the cross arms. However, research is in progress to evaluate adapting the Watson system to enable mechanical harvest.



Figure B4. View of Watson Training system from end rows. Used with permission from Bruce Cross.

The Watson system is cordon trained to a wire placed at five to six feet above the ground. The Watson system employs spur pruning. An average of four buds per linear foot of row are retained when spur pruning in non-divided, single canopy training systems such as VSP (Table 2). Greater bud densities per linear foot of row can be retained in the Watson system due to the



Figure B5. Watson trellis system in practice in Lenoir vineyards in Georgia. Left picture used with permission from Bruce Cross.

vertically offset angles of the spurs (Figure 6). The horizontal canopy division created at the cordon results in spurs (and consequently shoots and clusters) that are spaced farther apart relative to a non-divided system with inherent space limitations within the fruit zone (Figure 5 and Figure 6). Once the well-trained shoots of the divided canopy become dormant canes and are pruned to the desired density, the resulting spurs are already positioned in the desired, vertically offset angles. In an attempt to reduce bunch rot, the increased space between the clusters and shoots increases air movement in the Watson system relative to the highly congested fruit zones often observed in single High Wire systems. Thus, roughly six to eight buds per linear foot of row can be retained when spur pruning in the Watson system (Table 2). Different vineyard management techniques are required in Watson compared to other popular training systems as outlined in Table 2. Variable management will result in different labor costs over the course of the growing season, during harvest, and during the dormant season.

Table B2. Bud density, pruning, and management differences for popular training systems.				
	High Wire	VSP	GDC	Watson
Number of cordons per vine	2	2	4	2
Average number of buds per linear foot of cordon / linear foot of row	3-5 / 3-5	3-5 / 3-5	3-5 / 6-10	6-8 / 6-8
Shoot positioning	Draping	Vertical	Draping	Draping
Summer pruning	Skirting	Topping	Skirting	Skirting
Type / relative ease of bird netting placement	Overhead / Moderate	Zone or Overhead / Easy	Overhead / Difficult	Overhead / Moderate
Mechanically harvestable?	Yes	Yes	No	No



Figure B6. The angled spur positions in Watson are created by pruning the dormant canes from previously, well-trained and divided vegetative shoots. These offset spur positions enable high bud densities to be retained with diminished cluster crowding and fewer leaf layers blocking fruit.

Harvest Parameters

Harvest considerations include crop yield and grape maturity. Comparable fruit maturity was observed in Blanc du Bois grown on both a Watson and VSP in the Rio Grande Valley of Texas (data not shown). The same study found an average of 52% increase in crop yield in Watson compared to VSP over three years (Table 3). A study in Georgia showed similar crop yield results with a slight increase in Brix in Watson over VSP (5%) (Table 4) with no differences in titratable acidity (data not shown). In 2015, the crop yield was consistently increased where 2016

Year	Watson (tons/acre)	VSP with Cordon (tons per acre)	High Wire Quadrilateral Cordon (tons per acre)
2012	1.20	0.52	2.48
2013	3.61	2.03	5.95
2014	8.57	9.21	10.60

^a Yield calculated on a per acre basis

^b Vineyard planted in 2009.

the results were variable (Table 4). In 2015, the Watson increased yield in Lenoir by an average of 51% compared to GDC and VSP, where Villard Blanc with an average of 14% compared to GDC and VSP (Table 4). In 2016, the Watson system had less consistent results with Lenoir showing an 15% increase over VSP and Villard Blanc showed no difference between Watson and GDC, but both cultivars in Watson had a 30% decrease in crop yield compared to GDC (Table 4).

Table B4. Effects of different training systems on the yield ^a and Brix of four different cultivars in Western Georgia over 2 years. ^b						
2015						
	Watson		GDC		VSP with Bilateral Cordon	
	Yield (tons/acre)	Brix	Yield (tons/acre)	Brix	Yield (tons/acre)	Brix
Blanc du Bois	3.16	20.6	7.32	15.6	4.13	18.3
Villard Blanc	9.35	18.0	9.11	17.8	7.47	17.3
Norton	2.92	21.8	1.85	19.4	1.75	19.7
Lenoir	8.75	19.6	6.61	20.4	5.16	20.7
2016						
	Watson		GDC		VSP with Bilateral Cordon	
	Yield (tons/acre)	Brix	Yield (tons/acre)	Brix	Yield (tons/acre)	Brix
Blanc du Bois	4.29	21.6	7.62	19.9	2.14	21.5
Villard Blanc	6.55	20.3	6.49	19.8	8.50	18.8
Norton	2.74	23.4	2.62	23.3	2.38	23.4
Lenoir	8.10	22.6	10.54	20.9	7.07	23.0

^a Yield calculated on a per acre basis

^b Vineyard planted in 2013

Conclusion

The Watson training system has been shown to increase crop yield roughly 42% over two years of data in Georgia. Some growers have reported reduced labor costs in the Watson training system compared to GDC and VSP, and this has been primarily attributed to savings on shoot training and positioning. Bruce Cross, a vineyard owner in Bremen, Georgia who primarily implements GDC has said, “When we expand, we are training all newly planted vineyards to the Watson. Other growers in our region are doing the same with their expansion” (Bruce Cross, Personal Communication). Cross also stated the benefits of the Watson system in small vineyards that do not have land for expansion of acreage. “While the Watson system reduces vine planting density per unit land compared to non-divided systems,” Cross stated, “the crop yield increase per Watson-trained vine can offset that reduction in planted vine number. Thus, the Watson system is a good trellis for vineyards that do not have room to expand the vineyard

but want to expand production”. While the Watson system does have disadvantages in the cost of establishment, the inability to mechanize harvest, and the between-row spacing required for its establishment, the economical crop yield and decreased labor make the Watson system worthy for consideration in some commercial vineyard situations.

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APPENDIX C

ATHENA: A NEW TRAINING SYSTEM FOR BUNCH WINE GRAPES: EXTENSION PUBLICATION

Rachael White, Clark MacAllister, Nathan Eason, John Scaduto, Melissa Mattee, and Cain
Hickey

Introduction

Trellising, training, and dormant pruning represent a large portion of efforts undertaken and expenses required to cultivate bunch wine grapes. The University of Georgia Extension Viticulture Team has created a novel training system that combines canopy and fruit zone division to increase leaf exposure and fruit production and uses cane pruning to reduce springtime shoot thinning requirements. This system is named the Athena training system (henceforth called “Athena”). Grapevine pruning and trellising systems, and common terminology thereof, were described in a previous extension publication (Introduction to Wine Grape Trellising and Pruning Terms). For novice growers, it may be beneficial to review that introductory publication before reading this publication on Athena. For convenience, a glossary of terms exists at the end of this publication.

Concept of Design

One of the most common training systems used for bunch wine grape production in the eastern US is bilateral cordon training with spur pruning and vertical shoot positioning (VSP) (Figure 1; Hickey and Hatch, 2018). The VSP system is a single-canopy system that is less expensive to establish than divided canopy systems because only wires and posts are needed for its construction; cross arms are not needed. The VSP system also allows for narrower row spacing

and thus greater vine planting densities when compared to divided canopy systems. VSP is often the system of choice for upright-growing varieties having low to moderate vigor. The Lyre system is the divided canopy system used for more vigorous, upright-growing varieties. Cordon training with spur pruning often requires extensive shoot thinning in the spring to remove excessive shoots arising from basal or latent buds on grapevine wood that is two years or older (Hickey, 2019). Unfruitful, or less fruitful, shoots are generally undesirable as they crowd the fruit zone and canopy limiting light, air movement, and spray penetration, yet do not contribute crop yield. Cordon trained, spur pruned vines are ideally thinned to three to five shoots per linear foot of cordon in a single canopy trellising system. A very narrow window of opportunity exists in the spring for proper shoot thinning and is often not completed before shoots begin to lignify at their junction with the cordon and grab neighboring shoots with tendrils; the result is often undesirable urgency and possible damage to retained shoots.



Figure C1. Bilateral cordon training with spur pruning (left) and a standard VSP system (right).

The alternative to bilateral cordon training and spur pruning is head training with bilateral cane pruning, also referred to as “cane replacement” pruning (Figure 2; Hickey and Hatch, 2018). Head training with bilateral cane pruning involves selecting a cane (previous season’s green shoots; one-year-old wood) on each side of the trunk and securing these canes to the fruiting wire. When necessary, some canes in the head region are pruned back to two-bud spurs to serve as a site for replacement canes to be used in the following year. With cane pruning, fruitful shoots typically emerge from the buds along the cane. Cane pruning does not require extensive shoot thinning as unfruitful shoots generally only grow from the head/crown region (where trunk and fruiting wire meet) of the vine (Figure 2). Whereas cordon training/spur pruning requires timely shoot thinning labor in the spring, head training/cane pruning involves greater labor in the dormant period to select canes and tie them to fruiting wires (Hickey and Hatch, 2018). However, some studies have reported an approximately 40% reduction in crop yield with cane pruning compared to cordon training with spur pruning (Howell et al., 1987). Bud fruitfulness ascending the cane varies across cultivars; therefore, pruning method will differentially impact crop yield across cultivars.

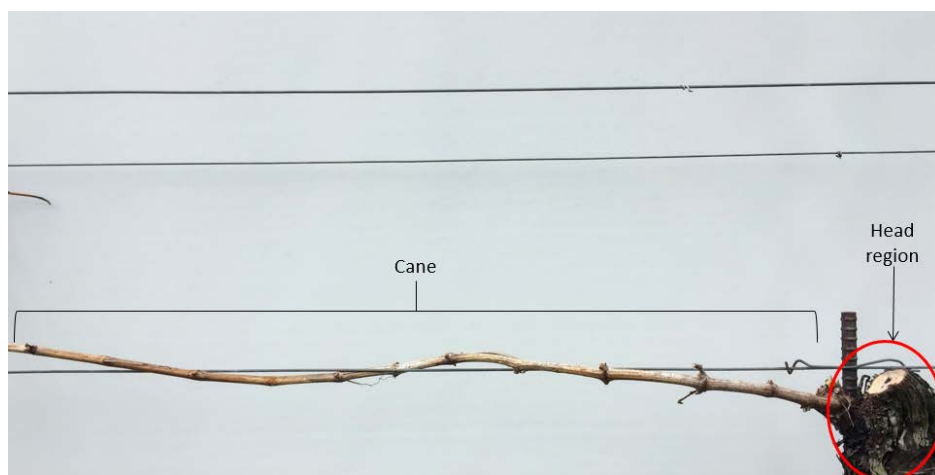


Figure C2. Head training / cane pruning involves training canes (see arrow) out on the fruiting wire from the head region of the vine (circled).

Various combinations of pruning, trellising, and training techniques have resulted in the creation of several training systems, such as the Smart-Dyson, Scott-Henry, Geneva Double Curtain (GDC), Lyre, and Watson. The Watson system, which was discussed in depth in Watson Training System for Bunch Wine Grapes (White et al., 2020), is a modification of the standard high wire system to improve spray penetration and reduce bunch rot in the production of Pierce's disease-tolerant hybrid bunch wine grapes in Texas and Georgia. Training systems often evolve and become adapted using minor modifications to aid in the production of optimal quality and quantity of grape crops from regionally important cultivars. While some of the aforementioned training systems are still used today, none are as popular as the VSP or single high wire systems, which are largely used for production of bunch wine and juice grapes, respectively. VSP and single high wire systems are easy to set up and are relatively inexpensive to implement compared to their divided canopy counterparts.

The University of Georgia Extension Viticulture Team has developed Athena, a new training system for bunch wine grape production in eastern US vineyards. Athena incorporates the benefits of cane pruning with horizontally divided canopy and fruit zone while using narrower row spacing than popular, horizontally divided systems such as Lyre and GDC. There are only small modifications to trellising structures, wires, and pruning methods that result in novel training systems. The Athena may immediately appear to be a narrower Lyre system. And it may be viewed as such. Reading further will reveal the nuances that make the Athena unique from the Lyre system. For example, the Athena: (1) may be an easier retrofit from a single canopy system (such as VSP) in which between row spacing can be 10 feet or less; (2) employs annual quadrilateral cane pruning compared to the quadrilateral cordon training with spur pruning of the Lyre system; (3) trellis structure accommodates quadrilateral cane pruning through a narrower

fruit zone division than the Lyre; and (4) canopy is trained into a “V-shape” above the fruit zone while the Lyre is trained vertically in an attempt to intercept more sunlight.

Putting Concept into Practice

Athena was initially tested as a retrofit of an established Petit Manseng vineyard trained to VSP with bilateral cordon training and spur pruning, the suggested training system for this low-yielding, late-ripening cultivar. The vineyard was seven years old with six feet between vines and nine feet between rows (Figure 3). Preliminary results showed that Athena (without shoot thinning) produced greater crop yield while maintaining similar primary fruit chemistry relative to VSP with bilateral cordon training (with shoot thinning to four shoots per linear foot of cordon). The vineyard was retrofitted to Athena during the dormant season. Similar field trials were conducted in commercial blocks of Cabernet Franc (an upright growing cultivar that lends itself to cordon training with spur pruning or head training with cane pruning) and Traminette (a low-yielding, French-American hybrid cultivar with excessive vegetative growth that has been trained successfully to both high wire and low wire systems).



Figure C3. Above-head view of Athena, showing the “V”-shaped nature to the divided canopy.

Pruning

Athena uses head training with quadrilateral cane pruning (four canes total; tied to two horizontally separated fruiting wires) and a V-shaped, divided trellis structure (Figures 3, 4, and 5). In an attempt to increase fruitful bud number per linear foot of trellis, Athena uses four canes, twice that of standard, bilateral cane pruning (Figure 4). Two fruiting wires are separated by 14 inches using a cross arm that is fastened to trellis posts at 36 to 42 inches above the ground (Figure 4 and Figure 5). The canes are laid in an “X” shaped pattern extending from the head region of the vine onto the horizontally separated fruiting wires.



Figure C4. Above-head view of head training with quadrilateral cane pruning.

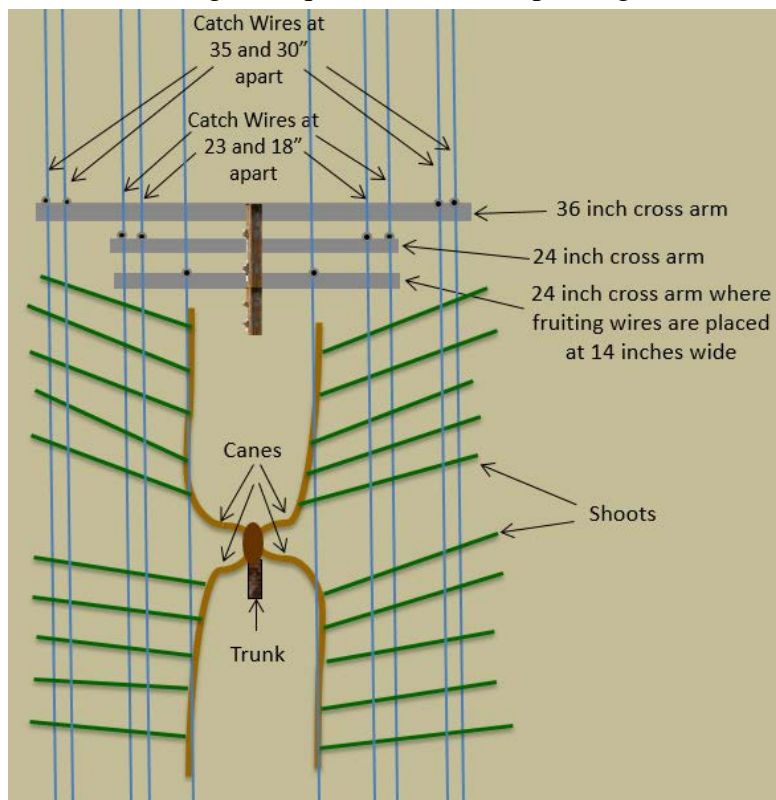


Figure C5. Above-head diagram of the quadrilateral cane pruning and "V"-shaped canopy division.

Trellising and Training

Athena divides the VSP trellising system to create two, horizontally offset canopies. The shoot training is accomplished via two cross arms (or more if greater shoot support is desired) placed on vineyard trellis posts. The cross arm placement gives the divided trellising a “V-shape” and, with proper shoot positioning, increases the leaf area exposed to sunlight when compared to standard VSP (Figure 6). The first cross arm is two feet long with a set of catch wires in notches at 23 and 18 inches apart. The second cross arm is three feet long with a set of catch wires in notches at 35 and 30 inches apart (Figure 6 and Figure 7). The canopy division in Athena was shown to reduce canopy density by 56% when compared to standard VSP (White et al., 2020). Leaf area index was increased by 60% in an Athena-like divided canopy when compared to standard VSP (White et al., 2020). With high bud densities (as with the adopted quadrilateral cane pruning practice of Athena), the increased exposed leaf area that results from canopy division can enhance radiation interception and maintain a healthier vine carbon balance relative to crowded, highly self-shaded canopies (such as those observed in high vigor vines trained to VSP). Reduced lower canopy congestion will further enhance foliar drying and spray penetration through the canopy. To further reduce canopy congestion, shoots should be removed from the bases of the canes and from the head region of the vine. Aggressive fruit zone leaf thinning may also aid in spray penetration through the divided fruit zone, which may be particularly important in rot susceptible cultivars.

In order to maintain canopy division, and the benefits thereof, it is important that the middles of the canopy are open and free of lateral growth. It is important that shoot positioning into the divided catch wires occurs as soon as shoots are long enough to reach the first catch wire and before tendrils begin to grab neighboring shoots and, thus, precluding efficient shoot positioning. Aside from the differences in dormant pruning strategy and decongesting the middle of the divided canopy, the Athena system can be managed similarly to VSP and Lyre in terms of shoot positioning, shoot training, and shoot hedging.



Figure C6. Greater leaf area is exposed to sunlight in the divided canopy. This is shown within our retrofitted V-shaped trellis structure.

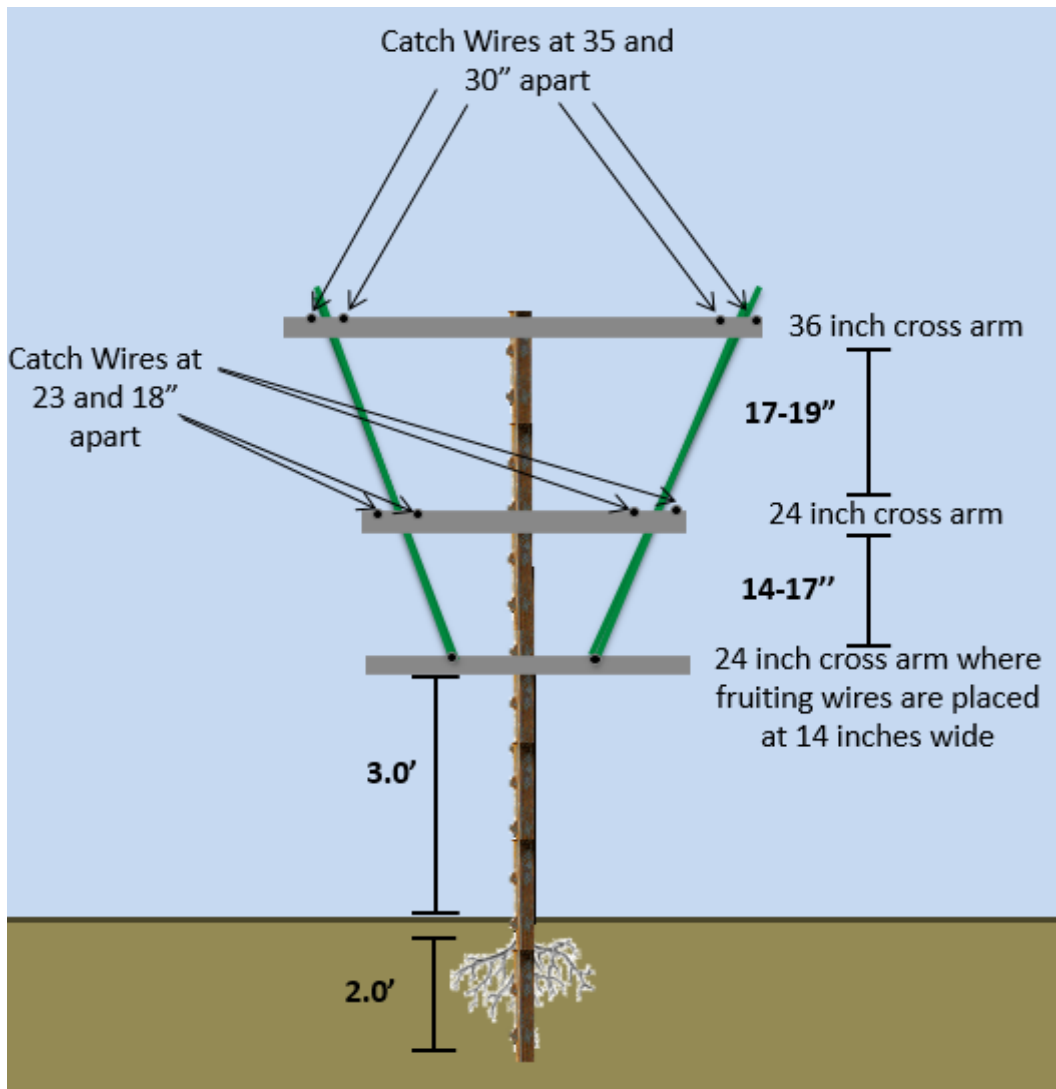


Figure C7. Figure of Athena hardware from looking down the row.

Crop Yield and Fruit Composition

The Athena system increased crop yield in the above-mentioned Petit Manseng vineyard by 47% in 2017, 79% in 2018, and 62% in 2019 compared with VSP with bilateral cordon and spur pruning and shoot thinning during the second year of the trial (Table 1). In our studies, those annual percent increases amounted to a 1.48 tons/acre increase in crop yield in 2017, 2.3 tons/acre increase in crop yield in 2018, and 1.69 tons/acre increase in crop yield in 2019 (Table 1). There were no differences in the sugar concentration of the fruit (Brix) between the different pruning and trellising treatments at commercial harvest. While Cabernet franc crop yield was not

favorably affected by Athena in the first year of evaluation, it was doubled when compared to VSP in the second year of evaluation. Though only one season of data was collected in the Traminette experiment, the Athena produced 82% increase in crop yield compared to VSP. The goals of the experiments mentioned herein were to evaluate crop yield and fruit chemistry responses when implementing Athena as a retrofit in a vineyard already established to VSP in vineyard with narrow between-row spacing. Note that Athena has a divided fruit zone and, therefore, greater bud amounts per linear foot of row compared to a non-divided training system such as VSP. Thus, comparing the performance of Athena and Lyre would provide important information to those who have yet to decide on a training system in a yet-to-be established vineyard. Please note that while trials have been conducted across multiple cultivars to-date, results are still preliminary and may differ across site and cultivar over time.

Table C1. Crop yield and Brix in Athena compared to Standard VSP with Bilateral Cordon pruning					
Cultivar	Year	Athena ¹		VSP with Bilateral Cordon ¹	
		Yield (tons/acre)	°Brix	Yield (tons/acre)	°Brix
Traminette	2017	5.28	20.83	2.90	19.96
Cabernet Franc	2017	4.79	20.62	5.41	20.00
Cabernet Franc	2018	10.65	21.10	5.25	20.90
Petit Manseng	2017	4.62	24.12	3.14	24.42
Petit Manseng	2018	5.19	22.55	2.89	23.12
Petit Manseng	2019	4.40	24.50	2.71	24.40

¹ Athena was not shoot thinned; VSP was thinned to 4 shoots per linear foot of row.

Limitations

There is no single, universally “best” trellising and training system for all types and cultivars of grapes, sites, soils, management, and labor and the Athena system is no exception. While we

have found encouraging results with Athena, there are limitations. Greater costs are due to the three to four cross arms that are necessary to divide the canopy and fruit zone and four extra wires that are necessary to maintain canopy division (Table 2). However, a rough economic assessment shows those one-time input costs would be quickly recovered by repeated, perennial crop and/or wine sales (Table 2). While climatic and soil conditions in the Eastern US are generally conducive to ample vine vigor, implementing quadrilateral cane pruning may reduce vine size over time where vine growth is already limited by other factors such as the combination of cultivar, rootstock, and site. Another concern of cane pruning is retaining dormant wood that may have a greater probability of Pierce's disease infection relative to spurs (Varela et al., 2001). Athena should not be adopted if there are concerns about vineyard equipment hitting the cross arms; for instance, in vineyards with tight row spacing (e.g. less than nine feet), extreme slopes, or use of tractors and equipment with wide wheelbases. Because Athena utilizes a three-foot-long cross arm, it will effectively reduce row width by three feet. However, these issues are of less concern for new growers that can space rows to accommodate Athena at the time of planting; we recommend row spacing of at least nine feet. If bird netting is deployed at veraison, the Athena system requires over-row netting to prevent birds from entering the middle of the canopy from above to access the fruit zone. Extra labor may also be required to maintain canopy separation and harvesting two fruit zones instead of one; additional research and experimentation is required to further define the labor inputs of Athena to compared to other popular training systems. This outlines a few of the concerns when deciding on a trellis and training system.

Table C2. Costs and crop yield comparison between Athena and Standard VSP with Bilateral Cordon pruning.							
One-time input costs					Crop yield		
System	Wires Needed	Wire Cost (per acre)	Cross Arms	Total Cost ¹	Crop yield ² (tons/acre)	Fruit Sale ³	Wine Sale ⁴
Athena	10	~\$1,450	\$8.50 per post	~\$3,100	6.85	\$11,645	\$123,300
VSP	7	~\$1,100	N/A	~\$1,100	4.61	\$7,837	\$82,980

¹Costs evaluated per acre assuming the same vine and row spacing and does not include posts, labor, end post structures, or any other variable costs. Costs are reflective of the use of three total cross arms, including the fruit zone; costs will increase if additional cross arms and wires are employed.

²Crop yield calculated as an average of all of crop yield data reported in Table 1

³Fruit prices based on \$1,700 cost estimate per ton.

⁴Wine produced based on an estimated 1 barrel (60 gal.) produced per half of ton of grapes. Price point based on an estimated \$25 per bottle of wine. Does not include wine production costs.

Grower Testimonials and Modification Opportunities

Growers have provided feedback on Athena. Eric Seifarth, vineyard owner in Young Harris, GA and owner of the above-mentioned Traminette vineyard, has since switched every other row of his bilateral cordon trained and spur pruned VSP trellised Traminette to the Athena system.

Seifarth has a unique perspective on the Athena system when comparing it to a Lyre system also on his property. He emphasized the ease of conversion and the cost effectiveness of the Athena system being desirable over the Lyre. Carl Fackler and Mark Diehl, vineyard owners in Tiger, GA and some of the initial adopters of the Athena trellising system in a Petit Manseng vineyard, praised the Athena due to increased yields and decreased labor for shoot thinning. However, Diehl did express the issues of Athena in tighter row spacing (nine feet in his case) resulting in less-than-optimal spraying efficiency with a larger tractor and sprayer. The double cane pruning method of the Athena does open the fruit zone, stated Diehl, and the divided canopy does seem to help spray penetration within the canopy. Diehl and Fackler have worked on adapting the quadrilateral cane pruning aspect of Athena on most of their cultivars, including Cabernet Franc

and Malbec. Greg Crumly, a vineyard owner and operator in Cleveland, GA, echoed Diehl's sentiment about the divided trellis. Crumly noted how the divided trellis seemed to increase sunlight interception of Chambourcin grapes and allow for quicker drying and better spray penetration through the canopy. Eric Case, a vineyard manager in North Carolina, knew his nine-foot-spaced vineyard rows were too close together for a full Athena system and still allow the passage of the conventional tractor. Instead, he implemented a modified Athena with 24-inch cross arms at the fruit zone and canopy positions (Figure 8). Case did note one drawback of the system; the divided canopy prevented his mechanical leaf puller from pulling leaves out of the middles of the fruit zone. Though it is early in its implementation, Case is expecting to nearly double the yield compared to the standard VSP and spur pruned Petit Manseng. Case is planning on planting a new vineyard this year and is planning on implementing a full Athena system throughout this new planting.



Figure C8. A modified version of the Athena system put in place by Eric Case that reduces the cross arm obstruction into the row by using shorter cross arms.

In vineyards wishing to retrofit their already-established vineyard with nine foot or closer spacing between rows, or on a heavily sloped site, there are several modifications that could be

made to reduce the spacing necessary to implement Athena. Using shorter trellis cross arms would not result in a “V-shaped” canopy division but would reduce cross arm extension into the row and save space for the passage of vineyard equipment. Even if the canopy is not “V-shaped”, we anticipate crop yield and leaf area exposed to sunlight would be greater in the modified Athena when compared to standard VSP. Other modifications could include a shorter cross arm for the fruit zone to slightly reduce cost and reduce the between row spacing needed to implement the divided fruit zone. The next smallest cross arm the authors have seen for sale is a 12-inch cross arm, which would reduce the fruit zone separation by approximately two inches compared to the method described here.

Conclusion

In summary, Athena is a new combination of trellising and pruning that may increase crop yield per unit land without decreasing fruit quality and with relatively fewer input costs, namely those associate with springtime shoot thinning. Athena can be implemented on newly planted vineyards or used to retrofit currently established VSP vineyards to obtain the benefits of cane pruning with a divided canopy. Further studies need to be conducted on different cultivars, in different regions, and over longer time periods. However, our preliminary results from our initial studies in an already established Petit Manseng vineyard are encouraging. An economic analysis will follow outlining the cost-benefit comparisons between Athena and standard VSP trellising system with bilateral cordon training and spur pruning.

Glossary of Terms

Bud – Typically refers to the buds contained only on one-year-old grapevine wood (e.g. canes and spurs) and from which fruitful shoots grow in the spring.

Cane – A former green, vegetative shoot that has hardened off and become dormant; one-year-old grapevine wood which generally contains fruit-producing buds.

Catch wire – The trellising system wire used to guide canopy growth and maintain its physical position to optimize leaf exposure.

Cordon – A former cane that is a lateral extension of the trunk along the fruiting wire and at least two-years-old; refers to a training type (“cordon training”) with which spur pruning is commonly implemented.

Dormant Pruning – The selection and retention of fruitful, one-year-old grapevine wood through cutting and discarding older, undesirable, and diseased grapevine wood; spur or cane pruning methods are most common.

Fruiting Wire – The wire on which the fruiting cane or cordon is tied; becomes the crop load bearing wire.

Head – The region of a vine where the vertical grapevine trunk meets the horizontal fruiting wire; refers to a training type (“head training”) with which cane pruning is commonly implemented. Can also be referred to as the “crown” region.

Shoot – The green stems and leaves that grow from dormant grapevine wood. Shoots grow from buds in the spring then become canes once they drop leaves and become dormant in the fall.

Shoot Thinning – A practice that removes the shoots that do not bear fruit clusters and shoots in highly dense areas on the vine early in the spring before the shoots harden onto the vine and become difficult to remove

Shoot training/positioning – A management practice that tucks shoots “flopping” into the row between trellis catch wires to prevent damage to the shoots and maintain canopy structure

Spur – One-year-old grapevine wood that is cut back to one to three buds which bear new shoots the following season; a “Short”, or “spurred” cane position.

Grapevine Training – Used to describe the grapevine training method for which one-year-old grapevine wood is retained to produce fruit-bearing shoots; the two most common training methods are cordon training (with spur pruning) and head training (with cane pruning).

Training Systems – Refers to combinations of trellising systems with the implemented training dormant pruning method; not an interchangeable term with trellising systems.

Trellis – Physical framework of cross arms and wires used to guide and direct grapevine growth.

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