DEVELOPING SUSTAINABLE IRRIGATION PRACTICES IN CABERNET SAUVIGNON 
AND CONCORD VINEYARDS IN CENTRAL WASHINGTON

By

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A dissertation submitted in partial fulfillment of 
the requirements for the degree of

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To the faculty of Washington State University:

The members of the committee appointed to examine the dissertation of JASON EDWARD STOUT find it satisfactory and recommend that it be accepted.

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DEVELOPING SUSTAINABLE IRRIGATION PRACTICES IN CABERNET SAUVIGNON AND CONCORD VINEYARDS IN CENTRAL WASHINGTON

Abstract

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Regulated deficit irrigation (RDI) is a management technique used in wine grape (Vitis vinifera L.) production to control vegetative growth and improve fruit quality. However, the severity of the deficit imposed varies widely among growers. RDI also has the potential to reduce water use in juice grape (Vitis labruscana Bailey) production, as current strategy is to fully irrigate throughout the season. The objectives of this project were to evaluate the effects of a range of deficit irrigation treatments on: (a) the temporal and spatial variation in soil water content, (b) the yield and quality of ‘Cabernet Sauvignon’ wine grapes, and (c) the yield and quality of ‘Concord’ juice grapes.

Field study was conducted over four years in both a commercial ‘Cabernet Sauvignon’ and ‘Concord’ vineyard. The ‘Cabernet Sauvignon’ trial increased the water application by one third of the current practice (extreme deficit) based on grapevine phenology, while the ‘Concord’ treatments reduced the amount of water applied from bloom to veraison. Soil was intensively sampled three times during the growing season to determine seasonal and spatial variation in
water availability. Shoot growth and shaded area under the canopy were measured as plant stress indicators. Yield and fruit quality were analyzed for differences between treatments.

Soil water distribution data indicated that increased distance from the drip emitter decreased soil water content. The majority of the plant available water was within 50 cm of the emitter. In the ‘Cabernet Sauvignon’ increasing the amount of water applied increased yield, but not significantly. However, reducing water in the ‘Concord’ grapes resulted in a significant decrease in yield, but after a period of adaptation, the yield of the RDI vines was the same as the control. There were no statistical differences in the quality of either the ‘Cabernet Sauvignon’ or ‘Concord’ grapes.

RDI significantly reduced soil water availability at veraison, but the deficit was replenished by the end of the season. Water use efficiency was maximized in ‘Cabernet Sauvignon’ when additional water was applied post-veraison. RDI in ‘Concord’ initially reduced yields, but the vines adapted over time.
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This dissertation is dedicated to my wife Renae, my son Jacob, and daughter Abigail. I could not have hoped to accomplish this task without your love.
Chapter 1

Literature Review

Washington State grape (Vitis spp.) production is an increasingly important sector of the Washington State economy, which includes both wine (Vitis vinifera L.) and juice (Vitis labruscana Bailey) grape production. Wine grapes are the third most valuable crop in Washington behind apples (Mallus domestica Borkh.) and cherries (Prunus avium L.) (Stonebridge, 2012). Furthermore, the grape and wine industry has grown significantly over the past decade. Wine grape acreage increased from a total of 4,492 hectares in 1993 to over 17,700 hectares in 2012 (Knopf and Koong, 2011; USDA, 2013). The cultivar ‘Cabernet Sauvignon’ is one of the most popular cultivars in Washington and accounted for 23.5% of total wine grape acreage in 2011 (Knopf and Koong, 2011). Similarly, Washington is the largest producer of juice grapes in the United States, accounting for approximately 45% of total U.S. production (USDA, 2013). Despite being the largest producer of juice grapes, the acreage of juice grapes in Washington has remained steady at 10,500 hectares for several years (USDA, 2013). The majority of the State’s grapes comes from central and eastern Washington, which is responsible for 95% of Washington’s grape production (Elsner et al., 2010; Stonebridge, 2012).

Wine and juice grape production are influenced by very different drivers. Wine grapes are sold by tonnage or acreage contracts, with provisions that provide a premium for quality (WWIF, 2011). The average price for a ton of wine grapes in 2012 was $990 and has remained steady for several years. However, differences in prices can range widely based on American Viticultural Area (AVA), the producer’s history of quality, and the variety being sold (USDA,
Comparatively, juice grapes have a much lower value than wine grapes. They are sold strictly on tonnage contracts, that do not include premiums for quality, and fruit that does not meet minimum standards at processors is rejected (WWIF, 2011). The average price for a ton of juice grapes in 2012 was $285 (USDA, 2013). This price has dropped significantly in the last few years, and the average price per ton in 2014 was $110 (J. Davenport, personal communication). Consequently, the wine grape industry is primarily driven by quality while the juice grape industry focuses on yield (Poni et al., 1994). This is an important difference that is reflected in every aspect of vineyard management.

Washington State Climate.

One of the largest factors that directly impacts the economics of the grape and wine industry is climate. The Pacific Northwest has a variable climate that is shaped by seasonal weather patterns and regional mountain ranges. Approximately two-thirds of the annual precipitation falls between October and March with the majority falling in the coastal mountain ranges. In Washington State, the Cascade mountain range serves as a dividing line between two significantly different climates (Elsner et al., 2010; Climate Impacts Group, 2014). The climate in western Washington is characterized by mild, year-round temperatures and abundant winter rains. The low-lying valleys can receive approximately 750 mm of precipitation annually, while the western slopes of the Cascades receive upward of 3,000 mm annually (Climate Impacts Group, 2014), resulting in an average of 1,250 mm in western Washington (Elsner et al., 2010).

In contrast, central and eastern Washington primarily experience sunny and dry conditions because the mountains create a rain-shadow effect. Many areas of central and eastern Washington receive an average annual precipitation of less than 300 mm (Elsner et al., 2010), with some areas receiving less than 180 mm annually (Climate Impacts Group, 2014). This area
is categorized by Fischer and Turner (1978) as semiarid due to low moisture index, and further
classified as steppe because of its latitude, between 40° to 50° latitude, temperature, cold winter
with a spring and/or summer growing season, and when precipitation is likely to occur, over
winter (1 November to 31 March). Two unique features of a steppe region are that some
precipitation occurs as snow and the growing season begins with a substantial amount of
available soil water (Fischer and Turner, 1978). Additionally, central and eastern Washington
experience a wider temperature range than in western Washington, resulting in warmer
temperatures in the summer and colder temperatures in the winter (Climate Impacts Group,
2014).

**Evapotranspiration and Crop Coefficient**

There are a large number of factors that influence vine water use, including cultivar, soil
structure and depth, cultural practices, vine/row spacing, exposure, trellis height and width
(Williams and Ayars, 2005), water management programs, and climate (Evans et al., 1993).
Estimates for non-limiting yearly water requirements of all grape cultivars for south central
Washington are 650 mm to 900 mm (Evans et al., 1993). However, the steppe climate of eastern
and central Washington receives 300 mm or less of precipitation annually (Fischer and Turner,
1978; Elsner et al., 2010; Keller et al., 2008). As precipitation accounts for at most half of an
average grapevine water yearly requirement, it is necessary to apply supplemental irrigation.

Generally in agriculture, growers apply irrigation when a water deficit resulting from a
lack of precipitation would reduce crop production (Fereres and Soriano, 2006). The amount of
water applied is determined by evapotranspiration (ET), a combination of two separate
processes, evaporation and transpiration (Allen et al., 1998; Fereres and Soriano, 2006; López-
Urrea et al., 2012). Evaporation is the conversion of liquid water to vapor along the evaporating
surface, in this case the soil surface, caused by the influx of energy from solar radiation. Transpiration is the loss of water vapor from plant tissue through the stomata. These two processes occur simultaneously and it is difficult to distinguish between them in a field situation (Allen et al., 1998). The magnitudes of the separate components that comprise ET, evaporation and transpiration, change based on the growing season. Early in the season when the crop canopy is small, evaporation dominates because the majority of the soil surface is exposed to solar radiation. While later in the season transpiration becomes the dominant process as the canopy increases in size and water is lost from the plant tissue (Allen et al., 1998; López-Urrea et al., 2012).

Evapotranspiration is influenced by weather, crop factors, and management techniques. The main weather parameters affecting ET are net radiation, air temperature, humidity, and wind speed (Allen et al., 1998). Net radiation is the sum of all of the radiation, short and long wave, intercepted by the crop canopy. As the net radiation increases the ET rate increases. High air temperatures and wind speeds also increase rate of ET. However, high humidity will decrease the ET rate because the vapor pressure deficit is small, as the air is closer to saturation at high humidity resulting in less movement of water molecules from a saturated (leaf) conditions to the atmosphere (Allen et al., 1998; Campbell, 1998). Crop factors that influence ET include the type of crop, variety, and developmental stage (Allen et al., 1998). Any management strategy that manipulates the canopy of a grapevine will effect ET. For example, leaf thinning from the fruit zone can reduce ET, while canopy positioning can increase ET because of better light interception (Wample and Smithyman, 2002; Williams and Ayars, 2005).

Theoretically, the ET for a specific crop (ETc) is the amount of water a crop needs to replace all the water lost due to ET and thus avoid water stress (Stevens and Harvey, 1996).
When determining ETₐ, it is common to use a reference ET (ETₒ) and a crop coefficient (Kₑ) (Williams and Ayars, 2005) because the depletion of soil water by evaporation and transpiration has been positively correlated with ETₒ values (Stevens and Harvey, 1996). The ETₒ is an ET rate from a reference crop, typically grass (Poa pretense L.) or alfalfa (Medicago sativa L.), that completely covers the ground and is well watered (Allen et al., 1998). Reference ETₒ is commonly calculated using the Penman-Monteith equation, which uses the weather parameters listed above and therefore can be computed from weather data (Allen et al., 1998).

The Kₑ is used to modify the ETₒ to better reflect the ET of a specific crop (Wample and Smithyman, 2002). Kₑ values can range greatly between crop types and are dependent on crop characteristics related to canopy size, height, coverage, and architecture (López-Urrera et al., 2012). Also, Kₑ is highly correlated with the leaf area, leaf area index (LAI), canopy cover, and fraction of light intercepted by the canopy (Williams and Ayars, 2005). It has been found that the shaded area cast on the ground by the canopy is the best predictor of grapevine water use and Kₑ (Williams and Ayars, 2005).

Wine grapes, because they are adapted to drought conditions, typically have Kₑ values of less than 1 (Wample and Smithyman, 2002). Grapevines between full bloom and harvest typically have a maximum Kₑ value between 0.6 and 0.7 (López-Urrera et al., 2012; Stevens and Harvey, 1996). However, the Kₑ value is not constant throughout the season as it is closely related to canopy size (Wample and Smithyman, 2002). Therefore, Kₑ values for wine grapes generally follow a trend of increasing linearly in the spring as the canopy fills out, peaking by veraison (beginning of berry ripening), and slightly decreasing post veraison due to leaf senescence and leaf thinning (López-Urrera et al., 2012). However, this trend also depends on
canopy management practices (Williams, 2000; Williams and Ayars, 2005). 

\[ ET_o \times K_c = ET_c \]

The ETc is then used to determine water consumption over a given time period by summing the daily ETc values. This total then serves as a baseline for determining irrigation amounts.

Three distinct stages in seasonal changes of ETc in the wine grape cultivar Tempranillo were identified when measured by a weighing lysimeter (López-Urrea et al., 2012). The first stage was from bud break to flowering and the ETc values remained constant. During the second stage (fruit set-veraison) ETc values increased rapidly and maximum values were obtained near veraison. Finally, the third stage was characterized by a steady decline in daily grapevine ETc through harvest (López-Urrea et al., 2012). This corresponds with previous research by Evans et al. (1992).

**Climate Change in Pacific Northwest**

The average global surface temperature has increased by 0.6 ± 0.2°C during the 20th century (Casola et al., 2005). This has resulted in an increased retreating of glaciers, a decrease in snow cover, a reduction in sea-ice thickness and coverage, and an increase in sea level. The 21st century is projected to see a range of temperature increase from 1.4 to 5.8°C, resulting in the continuing loss of sea-ice and snow coverage, along with an increase in sea level. Additionally, there is an increased likelihood of extreme warm events and intense precipitation events. Also, the interior of many continents are expected to experience drier conditions during summer (Casola et al., 2005).

In the Pacific Northwest there was an increase in the average temperature of 0.8°C over the last century, which was the primary driver for the loss of snowpack during this time (Casola et al., 2005).
et al., 2005). Furthermore, multiple climate models have predicted increased temperatures in Washington over the next century. Casola et al. (2005) projected temperature increase across all seasons of 1.4 to 2.1°C by 2020 and 1.7 to 2.9°C by 2040, while Mote and Salathé (2010) predict an average warming of 0.1°C to 0.6°C per decade, resulting in a total increase in temperature of 3.0°C by the 2080’s. Regardless of the model used, the beginning of snowmelt and peak streamflow in snow-fed rivers are predicted to shift earlier in the year due to increased temperatures (Casola et al., 2005; Mote and Salathé, 2010).

Precipitation is predicted to increase annually (Casola et al., 2005; Elsner et al., 2010), but summertime precipitation is expected to decrease (Mote and Salathé, 2010). The majority of the increased precipitation is predicted to fall during the winter (October to March) (Casola et al., 2005; Elsner et al., 2010) and as rain instead of snow (Casola et al., 2005; Mote and Salathé, 2010). The reduction in summertime precipitation is predicted to range between 20-40%, which translates to a loss of 30-60 mm over the season (Mote and Salathé, 2010) when demand is the highest.

Increased average temperatures (Anderson et al., 2006) coupled with reductions in stream flows during the summer (Casola et al., 2005) has the potential to severely limit crop production especially in water short (drought) years. Drought is a regular part of the Pacific Northwest climatic cycle; however, droughts are becoming unusually frequent and severe (Anderson et al., 2006). A drought, as defined by the State of Washington, consists of two parts: an area that is experiencing or is projected to experience a water supply below 75 percent of normal, and where water users will likely incur undue hardships as a result of the shortage (Anderson et al., 2006).

There are three different causes of drought in the Pacific Northwest: 1) exceptionally low winter precipitation (2001 in WA and OR, 2005 OR), 2) a warm winter and exceptionally low
summer precipitation (2003, WA and OR), and 3) a series of short warm temperature anomalies during precipitation events in the winter (Bumbaco and Mote, 2010). In drought situations agriculture is low priority, and supplies can be severely cut (Fereres and Soriano, 2006). Such reductions in water supply directly inhibit the productivity of high-value perennial crops such as apples, cherries, and grapes (Casola et al., 2005).

**Water Rights**

Furthermore, water rights play a major role in determining who receives water during drought years. In Washington, water is a publicly held resource and cannot be owned by an individual; however, an individual can obtain a private right to that resource (Pharris and McDonald, 2000; Peters, 2009). A private right means that a right-holder can use a public resource in a determined amount for private enterprise. In order to maintain a water right, the right holder must put the water to beneficial use, such as irrigation, mining, and manufacturing. Furthermore, Washington operates its water permits on a prior appropriation system (Pharris and McDonald, 2000). In other words, senior water rights are held by those who were first to develop water resources. All subsequent requests for water rights for the same water resource are considered junior to the initial holder. Therefore, during drought situations, those who hold junior rights must reduce or stop their water use in order to preserve the use by senior right holders (Pharris and McDonald, 2000; Peters, 2009).

**Irrigation Strategies**

Deficit irrigation (DI) is one way growers can cope with restricted water availability. Deficit irrigation is the practice of applying water at a rate below ETc. Deficit irrigation is typically applied across the entire season, and is more effective in perennial crops than field
crops for several reasons. A reduction in water applied to vines or trees will result in a greater net water savings than a similar reduction in field crops because of the difference in canopy size. The reduction in stomatal conductance is scaled up due to the larger and rougher size of the canopy (Fereres and Soriano, 2006). Additionally, economic return in perennial fruit crops (e.g., wine grapes) is often more associated with quality than with biomass production and water use. Therefore, when compared with annual cropping systems, DI has minimal negative impact on economic return because water stress has little negative affect on wine grape quality, and in some cases can be beneficial. However, DI can limit yield when imposed during flowering and initial berry development. Additionally, micro-irrigation systems are more common in perennial cropping systems, which allows for greater control of water application and stress management (Fereres and Soriano, 2006). However, because grapevines are a perennial crop, water stress can have a negative effect on yield the following season even if the original stress factor is no longer present (Petrie et al., 2004).

Regulated deficit irrigation (RDI) is the imposition of periods of water stress during part(s) of the plant development cycle (Keller, 2005). The level of stress applied is typically limited by length or severity to accomplish desired goals such as control vegetative growth and limit berry size (Kriedemann and Goodwin, 2003; Fereres and Soriano, 2006). The water deficit is typically measured by plant water potential (midday leaf water potential, stem water potential) (Hardie and Considine, 1976), but soil moisture availability is also taken into account (Kriedemann and Goodwin, 2003). This concept was first used to control vegetative growth in peach (Prunus persica L.) orchards without reducing yields (Chalmers et al., 1981; Fereres and Soriano, 2006).
Regulated deficit irrigation is an established practice in many parts of the world for red grape growers as °Brix, anthocyanin, and polyphenol concentrations, along with other quality factors are enhanced under RDI (Acevedo-Opazo et al., 2010; Basile et al., 2011). Chalmers et al. (2010) found that the color density of wine made from ‘Cabernet Sauvignon’ grapes was significantly higher when the grapes experienced a sustained deficit of 43% of ETc. Additionally, the concentration of total anthocyanins and total phenolics were significantly higher in wines made from grapes that experienced moderate sustained DI (52% and 43% of ETc) than fully watered vines (100% of ETc) after 6 months of bottle aging (Chalmers et al., 2010). However, white grapes do not respond in the same way because the loss of tonnage due to water stress is not compensated for by an increase in quality (Kriedemann and Goodwin, 2003). Therefore, RDI in white grapes is used primarily to control canopy without inducing severe water stress, especially during veraison (Moyer et al., 2013). Deficit irrigation and RDI are widely used in Washington vineyards, where approximately 45% of grape acreage is under DI/RDI (Davenport et al., 2008).

There are three ways irrigation typically is applied in vineyards: surface, sprinkler, and drip (trickle). Surface irrigation requires large amounts of water and is the least efficient. Sprinkler application is more efficient and requires less water, but drip irrigation is the most efficient and allows a grower to apply water daily because of the low volume of water applied during each application (Peacock et al., 1977; Peters, 2014). Also, low volume applications minimize the risk of deep percolation thereby increasing the amount of water available for uptake (Goldberg et al., 1971). A daily soil-water recharge schedule can be used to meet ETc, minimizing the amount of water that flows below the root zone. This, along with reduced surface evaporation, increases water use efficiency, which is the main benefit of drip (Peacock et al.,
However, all three irrigation techniques have been used in vineyards (Peacock et al., 1977; Araujo et al., 1995b) and successfully with RDI (Kriedemann and Goodwin, 2003).

**Soil Water Distribution**

The distribution of soil water content under drip irrigation varies both spatially and temporally (Davenport et al., 2008). The spatial distribution of soil water content under drip irrigation is roughly two dimensional when the wetted spheres overlap along the drip line (Goldberg et al., 1971). The highest quantity of available soil water is located within a 100 cm strip of the drip line (Goldberg et al., 1971; Andreu et al., 1997). Additionally, average soil moisture decreases as soil depth and distance from the emitter increase (Araujo et al., 1995a; Andreu et al., 1997; Davenport et al., 2008). Fuentes et al. (2003) found that soil water content after a 5 hour irrigation event under a single drip emitter on sandy loam soil was best described as an elliptic paraboloid. The paraboloid shape is a result of the interaction of the discharge rate of the emitter and the soil hydrological properties, such as the saturated conductivity (Bresler, 1978; Zur, 1996). Zur (1996) calculated the wetted soil dimensions for three different soil types, clay loam, sandy loam, and sand, based on the management controlled wetted soil volume, V_m, which is defined as the wetted soil volume necessary to meet peak seasonal ET between irrigation events within the allowed deficit fraction of available soil water. From these calculations, and additional research, it is clear that increasing the discharge rate in a soil with low saturated conductivity results in an increase in the horizontal component of the wetted area while reducing the wetted depth (Bresler, 1978; Zur, 1996).

Soil moisture distribution also changes based on the time of year (Davenport et al., 2008). In the spring the soil water content is typically high as winter precipitation has refilled the soil with available soil moisture (Fischer and Turner, 1978). However, the soil begins to dry down in
the early summer resulting in a narrowing of the total wetted volume, concentrating it under the drip emitters. Even when water is applied to replace what is lost to ET the original wetted volume is not regained and remains concentrated under the drip line. Typically soil water content does not fully recover to early spring levels until after harvest and large quantities of water are applied to increase the wetted soil volume to protect roots from winter damage. Knowing the spatial and temporal distribution of soil water content helps locate where soil water deficits are occurring when DI or RDI are utilized.

**Grapevine Water Requirements**

Wine grapes typically adapt well to water stress because their root systems can effectively search out soil moisture (Moyer et al., 2013). Values of soil water depletion under large grapevines range from 0.1 to 13.6 mm/day; however, vine water use declines as soon as soil has drained to field capacity (Stevens and Harvey, 1996). In other words, grapevines adapt to the quantity of water that is available by closing the stomata to limit the loss of water due to transpiration. Thus, ETc will decrease as soil water availability decreases (Araujo et al., 1995b). However, when supplied with adequate or excess water all grape varieties will increase vegetative production (Moyer et al., 2013).

Grape vine water requirements change based on their growth stage, and it is important to design an irrigation strategy to reflect these changes (Basile et al., 2011). Early in the season (pre-budbreak) water is taken up by the roots to hydrate young buds and aid in budbreak (Moyer et al., 2013). During this time period it is common for cut surfaces on the vine to “weep” as a result of root pressure (Williams, 2000) that is caused by the remobilization of stored nutrients and unloading of solutes into the xylem (Keller, 2005).
As the season progresses and the canopy develops, transpiration increases resulting in negative pressure or tension that drives the movement of water in the plant (Keller, 2005). Additionally, between budbreak and bloom the vine undergoes major developmental changes such as pollen formation and cell division in the inflorescence anthers and ovaries. Water stress during this period has the potential to reduce vegetative growth (Araujo et al., 1995b), induce pollen sterility, and reduce the number of cells in the resulting berry (Keller, 2005). Pollen sterility reduces fruit set and a reduction in the number of cells reduces overall yield (Hardie and Considine, 1976; Moyer et al., 2013). Also, polyphenol and anthocyanin concentrations can be reduced when water stress is applied during this period (Basile et al., 2011).

Fruit set occurs just after bloom and this is when the pollinated berries begin to grow while the un-pollinated desiccate and fall off. Water stress at fruit set can cause lower fruit set or a lower number of berries per cluster (Hardie and Considine, 1976). Between bloom and veraison the canopy continues to grow and the overwintering compound buds develop, which determines the following year’s crop load (Williams, 2000; Wample and Smithyman, 2002). It is important that these buds receive adequate exposure to sunlight and warmer temperatures because it increases the development of inflorescence primordia. Deficit irrigation during this time period is typical and used to control excessive vegetative growth. However, a severe deficit should be avoided because it could reduce the following year crop potential by inhibiting the development of inflorescence primordia (Matthews and Anderson, 1989; Wample and Smithyman, 2002). The berry also goes through developmental changes at this time, and water stress within a few weeks after fruit set can limit cell division and expansion reducing total yield, (Hardie and Considine, 1976; Matthews and Anderson, 1989; Romero et al., 2010) and cause the berries to shrivel (Hardie and Considine, 1976). However, mild stress can increase anthocyanin
and polyphenol concentrations in the berry skin (Romero et al., 2010; Chalmers et al., 2010; Basile et al., 2011).

Post veraison berries become less responsive to vine and soil water levels because they severely restrict the amount of water imported from the xylem (Rogiers et al., 2001). During this point in the growth stage, berries import water and carbohydrates through the phloem, which is more resistant to changes in vine water status than the xylem (Moyer et al., 2013). However, a severe water deficit during this time period can cause a delay or a lack of ripening (Hardie and Considine, 1976). Mild water stress during this period can aid in preparation for winter dormancy and increase anthocyanins and polyphenol concentrations (Evans et al., 1993; Romero et al., 2010; Basile et al., 2011).

After harvest there is a second flush of root growth increasing the root volume which acts as a storage organ for nutrients over the winter during the dormancy period (Keller, 2005). Also, additional water content in the soil during the dormancy period can prevent cold damage to the roots because water acts as an insulator. Finally, a late season irrigation application is often used to maintain adequate soil moisture for budbreak in the spring (Moyer et al., 2013).

Cluster weight is more sensitive to water stress than cluster number, due mainly to reductions in berry size (Smart et al., 1974; Lakso et al., 1999). If water stress is applied prior to veraison, berry size is limited, and even with increases in irrigation post-veraison, berry size will not recover (Smart et al., 1974; Hardie and Considine, 1976; Keller, 2005). Consequently, both yield and vegetative growth can be reduced by water stress (Smart et al., 1974; Hardie and Considine, 1976). However, a limitation on grapevine evapotranspiration induced by insufficient soil water availability may not necessarily affect total yield. Therefore yield is less sensitive to soil water deficit than vegetative growth. (Stevens and Harvey, 1996; Keller, 2005).
Irrigation strategies for wine grapes in semi-arid and arid growing regions are designed to optimize fruit quality and limit vegetative growth (Keller, 2005; Moyer et al., 2013). Central Washington’s dry climate in combination with the use of drip irrigation makes irrigation the single most controllable factor in vineyard operation that influences yield, fruit quality, and winter hardiness (Evans et al., 1993). However, when using DI or RDI it is important to monitor the soil and/or plant water status in order to minimize the risk of over-stressing plants (Fereres and Soriano, 2006) because even well watered vines experience some stress at the peak of the growing season (Hardie and Considine, 1976).

**Current Irrigation Strategies**

In Washington, it is common to fully irrigate red wine grape vines from budbreak through fruit set to establish good canopy coverage, ensure fertile pollen and adequate flower pollination (Keller, 2005). However, shortly after fruit set many viticulturists implement RDI at a rate of 50% to 75% of ET$_c$ through harvest (Keller et al., 2008). After harvest the top 60 to 90 cm of soil is filled to field capacity (Keller, 2005; Keller et al., 2008).

This RDI strategy is typical for production of a red wine grape; however, it is not typical for white wine grape production (Moyer et al., 2013). Severe RDI in white wine grapes has been associated with atypical aging, where varietal characteristics are lost more rapidly than normally expected. Currently, it is recommended, that if RDI is used for canopy management in white varieties, not to reduce the water application below 75% of ET$_c$ (Moyer et al., 2013).

Irrigation strategies for ‘Concord’ grapes in Washington are very different from strategies in other parts of the nation, especially where they originated in the Northeast. In the other ‘Concord’ growing regions, mainly New York, Michigan, Ohio, and Pennsylvania, ‘Concords’ do not typically receive supplemental irrigation because seasonal precipitation satisfies the ET$_c$
requirement. However, there can be drought periods lasting from 2 to 8 weeks (Lakso et al., 1999). These periods of dry weather can cause crop reduction if a severe soil water deficit develops. This has prompted studies to determine if supplemental irrigation would be beneficial in these regions.

There are two main pruning strategies used in ‘Concord’ production, balanced pruned and minimally pruned. In balanced pruned systems a specified number of buds are left on the vine based on the amount of pruning weight, i.e. 20 nodes/lb of pruning weight. Minimally pruned systems typically only undercut the canopy to keep it off the ground, but no other shoots are removed. This dramatically increases the canopy size thereby increasing sunlight capture and a higher yield potential (Lakso et al., 1998). The larger canopy size will also increase the vine’s water use, which gives rise to the need for supplemental irrigation. Research in New York found that supplemental irrigation in minimally pruned vines maintained higher yields than those that experienced a water deficit (Lakso et al., 1998, 1999). The difference in yield was attributed to decreases in berry weight rather than decreases in cluster numbers. There also were some carryover reductions in yield in the drought stressed vines because of lower numbers of live shoots (Lakso et al., 1999). Additionally, the study found the extra yield could easily pay for the irrigation system and maintenance, but not the cost of bringing water to the vineyard. Also, supplemental irrigation reduced variability among plots where soils had different water holding capacities (Lakso et al., 1998).

There has been some research using both deficit and supplemental irrigation in ‘Concord’ vineyards. For example, one study examined how differences in crop levels affect a grapevine’s ability to withstand moisture stress caused by a soil water deficit. They found that crop level did not affect the vines’ soil water use; however, their soil water deficit developed gradually and did
not reach its peak until after veraison (Poni et al., 1994). Another study showed that supplemental irrigation can indirectly increase yields by increasing vine vigor and allowing for more buds to be left during balance-pruning (Morris et al., 1983a). Additionally, supplemental irrigation increased the soluble solids on a per hectare basis due to the increase in yield/ha (Morris et al., 1983a). However, increased yield is also inversely related to juice quality (Morris et al., 1983b).

In a study investigating gas exchange and water relations of ‘Concord’ grapevines it was found that deficit irrigation in ‘Concord’ results in a decrease in diurnal leaf assimilation rate and stomatal conductance. However, in fully irrigated vines, the leaf assimilation rate slightly increased, then decreased, while the stomatal conductance remained constant (Naor and Wample, 1994). Additionally, there was a significant difference in the leaf water potential at the beginning of the day (8:00 am), but that difference decreased as time approached 4:00 pm. Thus, they found that despite low leaf water potentials the well watered vine maintained its stomatal conductance indicating the importance of root signals in stomatal control and stomatal conductance was the main controlling factor of assimilation rate (Naor and Wample, 1994).

Supplemental irrigation is beneficial in attaining acceptable quality levels and maintaining vine size when vines are less severely pruned (Morris et al., 1983b). ‘Concords’ vineyards in Washington are typically manually pruned to a 50+10 system and irrigated to simulate the high rainfall conditions of the Northeast (750 to 1300 mm) (Moyer et al., 2013). ‘Concord’ producers are less concerned with quality factors such as aromatic compounds and more concerned with sugar accumulation and yield. It is common for ‘Concord’ vineyards to be irrigated in excess of ETc. Yet, ‘Concord’ producers can experience major losses on years when water resources fall short of demand.
Experimental Goals

The goals of this project were to determine the effects of a range of water deficits on the seasonal distribution of soil water content in a ‘Cabernet Sauvignon’ wine grape and ‘Concord’ juice grape vineyard, determine the effect of four levels of deficit irrigation on yield and quality of ‘Cabernet Sauvignon’ wine grapes, and assess the impact of a reduction in water supplied between bloom and veraison on yield and grape quality in ‘Concord’ juice grapes. The ‘Cabernet Sauvignon’ irrigation schedule was determined by growth stage. The application of the water deficit in the ‘Concords’ was limited to the time period between bloom and veraison, and the quantity of water applied in the ‘Concord’ grapes was reduced from current “well watered” practices. The results of this project will help to better optimize water usage in drought years when water is limited.
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Chapter 2

SEASONAL SOIL WATER DISTRIBUTION IN VITIS VINIFERA L. CV. CABERNET SAUVIGNON AND VITIS LABRUSCANA BAILEY CV. CONCORD

VINEYARDS UNDER DRIP IRRIGATION

Introduction

Surface drip irrigation is the precise application of irrigation water to plants via low flow drip emitters. This type of irrigation is commonly used to irrigate grape vines (Vitis sp.) and other perennial crops as it is able to deliver water directly to the plants. There are many advantages to using drip irrigation: 1) improved application efficiency, 2) fertigation, 3) improved weed control, 4) yield and/or quality enhancements, and 5) lower costs (Schwankl and Hanson, 2007). Drip irrigation is very efficient (approximately 90%) as evaporative loss is minimized due to a smaller wetted surface area compared with sprinkler or flood irrigation (Schwankl and Hanson, 2007; Moyer et al., 2013; Peters, 2014). Low application volume, accomplished with drip, minimizes the risk of deep percolation, increasing the amount of water available for plant uptake (Goldberg et al., 1971).

There are drawbacks to drip irrigation: high initial installation costs, limitations on the size of the wetting zone, difficulty in establishing cover crops, and potential for deep percolation if large volumes of water are applied. Andreu et al. (1997) found that excessive irrigation events early in the season (April) resulted in drainage losses (deep percolation) under the drip emitter, resulting from already high soil water content from winter refill. However, the drainage losses were coupled with capillary rise in the soil volume outside of the wetted volume, which could lead to water becoming available for plant uptake or evaporation (Andreu et al., 1997). Many of
the advantages of drip irrigation are lost when irrigation cannot be performed frequently (Schwankl and Hanson, 2007).

Soil water content (SWC) distribution varies both spatially and temporally (Araujo et al., 1995a; Fernández-Gálvez and Simmonds, 2006; Davenport et al., 2008) and is influenced by emitter spacing, line spacing, discharge rate, soil hydraulic properties, and quantity of water applied (Schwankl and Hanson, 2007). The spatial distribution of soil water under drip irrigation is roughly two dimensional when the wetted spheres overlap along the drip line (Goldberg et al., 1971; Raine et al., 2007). The highest quantity of available soil water is located within a 100 cm strip of the drip line (Goldberg et al., 1971; Andreu et al., 1997). Average soil moisture decreases as soil depth and distance from the emitter increase (Araujo et al., 1995a; Andreu et al., 1997; Davenport et al., 2008).

Fuentes et al. (2003) found that after a 5 hour irrigation event on sandy loam soil, the wetted soil volume was best described as an elliptic paraboloid. The paraboloid shape is a result of the interaction of the discharge rate and the soil hydrological properties, such as its saturated conductivity (Bresler, 1978; Zur, 1996). Zur (1996) calculated the wetted soil dimensions for three different soil textures, clay loam, sandy loam, and sand, based on the management controlled wetted soil volume, \( V_m \), which is defined as the wetted soil volume necessary to meet peak seasonal ET between irrigation events within the allowed deficit fraction of available soil water. From these calculations, and additional research, it is clear that increasing the discharge rate in a soil with low saturated conductivity results in an increase in the horizontal component of the wetted area while reducing the wetted depth (Bresler, 1978; Zur, 1996).

Soil moisture distribution also changes based on the time of year (Davenport et al., 2008). In the spring the soil water content is typically high as winter precipitation has refilled the soil.
with available soil moisture (Fischer and Turner, 1978). However, the soil begins to dry down in the early summer resulting in a narrowing of the total wetted volume, concentrating it under the drip emitters. This is especially the case in vineyards that implement regulated deficit irrigation (RDI) as the typical regime recommends allowing soil water to decrease until the canopy is controlled and then apply a deficit of approximately 50 to 75% of crop evapotranspiration until harvest (Keller et al., 2008; Moyer et al., 2013). Full irrigation is resumed after harvest and soil water content begins to increase, but may not fully refill to early spring levels before winter. In central Washington, additional water cannot be applied over the winter months to refill the profile because the irrigation canals are drained in late October and water is not available again until late March to early April (Schmitt, 2000).

The objectives of the study were to (a) characterize the temporal and spatial patterns of soil moisture distribution during the growing season (April-October) in two drip irrigated vineyards that were managed using different deficit irrigation regimes, (b) determine soil moisture differences resulting from deficit irrigation regimes, and (c) ascertain if soil moisture can be replenished to pre-deficit levels prior to loss of irrigation (November).

Materials and Methods

Plot Design. This study was conducted in a 6 ha ‘Cabernet Sauvignon’ and a 10 ha ‘Concord’ vineyard in the Yakima Valley American Viticultural Area (Sunnyside, WA) (lat. 46˚ 20’ 21"N and long. 119˚ 55’ 34“W) and was conducted from May 2012 to October 2013. Both vineyards were located on a uniformly deep Warden silt loam soil (Warden coarse-silty, mixed, superactive, mesic Xeric Haplocambid) (Soil Survey Staff, 2014). Field capacity (FC) of Warden fine sandy loam was determined by Evans et al. (1993) at approximately 25% and permanent
wilting point (PWP) at 8% by volume using a pressure plate method (Gardner, 1965). However, these values were relative and not based on the plant permanent wilting point, which was lower.

The ‘Cabernet Sauvignon’ vineyard was planted in 1990 using own-rooted vines with a vine by row spacing of 1.8 m by 3 m. The drip tube was located 30 cm above the soil surface with an emitter spacing of 0.9 m and flow rate of 2.3 L/h per emitter. Vine rows were oriented north-northeast to south-southwest and vines were trained to two trunks to a bilateral cordon at 80 cm height and shoots were positioned using two sets of canopy wires at 105 and 130 cm above the soil surface. The vines were spur-pruned to ~ 30 nodes/vine. The vines were shoot thinned and the canopy wires raised prior to bloom. Leaves were mechanically removed in the fruiting zone from the north side of the canopy twice during the season, just after bloom and again at fruit set. Two sets of catch wires were raised to approximately 105 and 130 cm height, which significantly reduced the width of the canopy thereby reducing the total shaded area under the canopy. All fertilizer applications were applied via the drip system and were identical between treatments. Disease and pest management were applied based on commercial practices as uniformly as possible across the vineyard (Moyer and O’Neal, 2013).

The ‘Concord’ vineyard was planted in 1990 using own-rooted vines with a vine by row spacing of 1.8 m by 3 m. The vines were oriented in the same direction as the ‘Cabernet Sauvignon’ and the same drip tube was used. The vines were trained on a single trunk to a 1.8 m above the soil surface wire. The canopy was allowed to sprawl from the cordon wire and was minimally pruned. Foliar fertilizer was applied uniformly throughout the vineyard and were approximately identical total seasonal amounts. Disease and pest management were applied based on commercial practices as uniformly as possible across the vineyard (Moyer and O’Neal, 2013).
In both vineyards the plots were arranged in a random block design. Each vineyard contained four blocks, with one replication of each of the four treatments for a total of 16 plots per variety. The order of the treatments in each block was determined by a random number generator. The first row of each vineyard was skipped to provide an additional buffer and the first block began on the second row. A plot consisted of a 30 m section of three rows. The first plot consisted of rows 2, 3, and 4. Measurements and samples were taken from the center 10 vines of the center row, row 3 in the previous example.

The ‘Cabernet Sauvignon’ treatments were four different levels of deficit obtained by increasing the amount of water applied by 1/3 of commercial application (extreme deficit) based on grape vine developmental stages for the entire season (Table 2.1). The low deficit increased the amount of water applied for the entire season, the moderate deficit increased the water applied pre-bloom and post-veraison, and the high deficit treatment increased the water applied post-veraison. The extreme deficit treatment was the grower standard practice. The treatments in the ‘Cabernet Sauvignon’ were increased as part of an additional study examining the effects on different levels of deficits on yield and quality of ‘Cabernet Sauvignon’ grapes. As the standard practice for the grower was an extreme deficit, the treatments increased the water applied instead of reducing to an even greater extent, which would have had a significant negative effect on vine health.

The ‘Concord’ treatments were opposite of the ‘Cabernet Sauvignon’ in that the amount of water applied was reduced from the grower’s practice, and the treatment period was limited to between bloom and veraison. The period of RDI was limited in order to minimize potential effect on flowering and fruit set within the current season and the development of inflorescence for the next season. The treatments reduced the amount of water applied because current practice was to
fully water vines, resulting in a saturated soil profile. The high treatment was the grower control. The moderate, low, and very low treatments reduced the amount of water applied by approximately 25, 33 and 45% of the control (Table 2.2).

Climate data was monitored throughout the experimental period. Data was obtained from the Washington State University weather station network (Ag Weather Net Staff, 2014) Snipes weather station (46° 17’ 56.4”, -119° 54’ 59.22”), which was located less than 5 km from the plots. Reference ET data was collected from the Snipes weather station ET calculator, which uses the ASCE standardized Penman-Monteith equation (Ag Weather Net Staff, 2014). Growing degree days (GDD) were also downloaded from the GDD calculator. GDD were calculated by determining the average daily temperature and subtracting a base temperature, the base temperature for grapevines is 10°C (Amerine and Winkler 1944).

Soil sampling. During 2012 and 2013, temporal changes in soil water content were investigated by taking soil cores three times during the growing season: 3 to 4 leaf stage (spring), veraison, and after the final irrigation of the season in mid-October (fall) (Table 2.3). The sample times corresponded to important phenological stages of development and changes in irrigation treatments. Spring sampling corresponded to early season vine development. During this period, adequate water was provided to remobilize stored nutrients, support actively growing shoots, help promote pollen formation, and ensure adequate cell division in the inflorescence anthers and ovaries (Araujo et al., 1995b). Water stress during this time period can result in pollen sterility, which causes poor fruit set and smaller berries (Hardie and Considine, 1976; Keller, 2005). Therefore, producers will apply early season irrigation to ensure adequate water during this critical period. The goal of sampling in the spring was to characterize overwinter refill of the soil profile from precipitation and early season irrigation.
Veraison was chosen as the second sampling time because it was the beginning of the period of berry ripening. Between veraison and the previous sample point in the spring the vines underwent major physiological changes, including canopy establishment, bloom, fruit-set, and early berry development. Overwintering buds were developing during this period and severe deficits could impact future crop yield (Matthews and Anderson, 1989; Wample and Smithyman, 2002). However, after fruit-set, vine water status was not as sensitive and mild deficits were used to control vine vigor. Veraison was the driest period during the growing season (late July to early August). All of the ‘Concord’ treatments ended at veraison, and increases in the moderate and high deficit treatments in the ‘Cabernet Sauvignon’ started at veraison. This was when the maximum difference between treatments were expected.

Fall was selected in order to determine if any differences present at veraison would persist throughout the remainder of the growing season and if it was possible to refill the soil profile after a period of sustained deficit irrigation. Berries were less responsive to water stress post veraison because they restrict how much water was imported from the xylem (Rogiers et al., 2001). However, severe water deficits can delay ripening (Hardie and Considine, 1976). After harvest, growers return to full irrigation to prevent cold damage to roots and maintain adequate soil moisture for budbreak (Moyer et al., 2013).

Spatial distribution of soil water was determined by using a radial pattern of sampling, which was centered on a drip emitter. Core locations were positioned directly under a drip emitter and along three radii at a distance of 50, 100, and 150 cm from the drip emitter. Eight sample locations were positioned along each radius corresponding to the cardinal directions with respect to the vine row (N, NE, E, SE, S, etc.) (Fig. 2.1). It was determined to sample four depths from each location, 0-20, 20-40, 40-60, and 60-80 cm based on previous research conducted by
Davenport et al. (2008) on soil moisture distribution in wine grape vineyards. A total of 100 soil cores were taken from each plot sampled at each sampling time. Only three of the original four blocks were sampled, blocks 1 – 3, because of the large number of samples taken at each site.

Cores were taken starting between vines 1 and 2 for the first sampling time and moving to the next vine with each successive sampling. Thus, at veraison cores were taken between vines 2 and 3, and between vines 3 and 4 post-final irrigation, ensuring that sampling was not repeated at the same site. This technique was repeated in 2013. Cores were taken using replaceable tip soil probes (Model 425.50, AMS, American Falls, ID), inside diameter of 1.8 cm, and slide hammer extensions (Model 400.99, AMS, American Falls, ID). The probes were driven into the soil using the slide hammer extensions in 20 cm increments. The core was removed from the probe, placed in a 18.9 L bucket, and transferred into a numbered, pre-weighed soil can, model # 77045 (Fisher Scientific, Pittsburgh PA), designed to retain soil moisture, and sealed. This process was repeated for each depth and location. However, at veraison, soil cores were not sampled at the 150 cm distance because it was extremely difficult to physically insert the probe into the soil to collect a core. The volumetric soil water content was very low (approaching PWP) and prevented sample collection.

The soil wet weight was measured on an APX-1502 Model balance (Denver Instrument, Bohemia, NY). The soil was then dried for 60 hours at 70°C in a built-in oven (manufacturer unknown) and reweighed using the same balance to determine gravimetric water content, which differs from the recommendations of 24 hours at 105°C (Gardner, 1965), but the additional time at a lower temperature ensured sample dryness. Volumetric water content ($\theta_v$) was determined by the following formula:

$$\theta_v = \theta_g \times \frac{p_b}{\rho_w}$$

1

31
(Jury and Horton, 2004). Where θ₉ was the gravimetric water content, ρₜ was the bulk density of the soil and ρᵢ was the density of water. The bulk density was determined by dividing the dry weight of the soil by the calculated volume extracted by the probe for each sample (50.89 cm³). Mean bulk density was used to calculate the volumetric water content.

Statistics. The raw data was analyzed using SAS 9.4 Version 6.2.9200 (SAS Institute Inc., Cary, NC). The variance in the data (ANOVA) was tested using Proc GLM. Main effects were identified: year (YR), sample time (ST), treatment (TRT), depth (D), and distance from emitter (DFE). After initial analysis, data was further analyzed for the interactive effects: DFE*D, TRT*D, TRT*DFE, ST*YR and YR*TRT, also using Proc GLM. The data was sorted by sampling time and analyzed to determine the significance of YR, TRT, and DFE. In addition, the Duncan-Waller means separation test was used to determine the separation of means by treatment and DFE.

Visualizations. Graphical representations of the mean volumetric water content were created using ArcGIS v.10.2.2 (ESRI, Redmond, CA). The graphics represented two soil profiles, one in line with the vine row, and one perpendicular or between rows. The first profile was composed of data gathered from sample locations that ran along the vine row (locations 3, 7, 11, 15, 19, 23, and 25) (Fig. 2.1). This plane included three different drip emitters, whose positions were indicated in the graphics with water droplets. The raw volumetric data was averaged from the three replicated plots. The average volumetric water content that corresponded to the selected locations was organized in an Excel table (Microsoft Inc., Redmond WA) and assigned x, y coordinates, with location 25 serving as the origin. The data was then imported to ArcGIS and a mask was created by creating a new feature class the same size as the sample area, 3 m by 0.8 m. The mask was used to limit any subsequent spatial analysis to the sample area.
The data for the indicated locations was interpolated using inverse distance weighting (IDW) with a power of 3 and a fixed search radius of 100 cm. The power of 3 was chosen to limit the influence of sample points that were farther away from the cell being interpolated. Also, a fixed search radius limited the number of points included in the interpolation to a maximum of 14 points. The same procedure was repeated using locations 1, 5, 9, 13, 17, 21, and 25 to create the between-row profile (Fig. 2.1). The between-row planes included a single drip emitter, again symbolized with a water drop.

The soil water content was categorized into five groups: below permanent wilting point (< 8%), low availability (8 - 14%), moderate availability (14 - 20%), high availability (20 - 25%), and above field capacity (> 25%). The PWP and FC were estimated by Evans et al. (1993) and were based on soil measures. These categories were chosen to best estimate the plant available water in the soil. As plants cannot extract water from the soil below permanent wilting point (PWP) that served as the lowest category, while field capacity (FC) was the maximum value as anything over FC quickly drains through the profile. This method is consistent with previous research conducted by Davenport et al. (2008) who used FC and PWP to define plant available water.

**Results and Discussion**

The five year average accumulated growing degree days (GDD) for Snipes weather station from April 1st to October 31st was 1711 (10°C). In 2012 the accumulated GDD reached 1722 GDD, while in 2013 the accumulated GGD reached 1835 GDD (Ag Weather Net Staff, 2014). Thus, 2012 was an average year in terms of heat accumulation and 2013 was a warm year.

‘Cabernet Sauvignon.’ In 2012, the spring sampling along the vine row showed medium to high SWC throughout the profile. All of the treatments were relatively uniform in wetness
The low and high deficit treatments had areas of high SWC to depths of 60 cm, while the moderate and extreme deficit treatments extended to 40 cm. There was some variability in the pattern of soil water distribution as some sections between drip emitters in the low, moderate, and high deficit treatments had medium SWC at the surface. This could have resulted from uneven pooling of water on the soil surface caused by sagging drip lines or changes in soil grade.

The SWC decreased dramatically between spring and veraison. The moderate, high, and extreme deficit treatments were uniformly dry. The majority of the sample area was below the estimated PWP, with small areas of low availability concentrated under drip emitters. The low deficit treatment was able to retain more SWC as the majority of the area had low water availability. Also, there was a small pocket of medium and high water availability in the 60 to 80 cm depth (Fig. 2.2). The soil was below estimated PWP at veraison because of the RDI treatments; however, the plants did not permanently wilt, thus the plant PWP was below 8% soil water. The period of RDI lasted from fruit set until harvest. During this time period, irrigation events were limited to approximately 10 hour irrigation sets applied once a week, which added 8 mm of water per event, while the average reference ET ($ET_o$) was 6 mm per day (Ag Weather Net Staff, 2014).

In the fall there was refilling of the profile. Irrigation typically increased in duration to approximately 18 hours per event for a total application of 14.5 mm/event. At the same time the $ET_o$ decreased to 3.25 mm/day on average (Ag Weather Net Staff, 2014). The low, moderate, and high deficit treatments increased the SWC so that there was on average high availability from 0 to 40 cm, with low availability from 40 to 80 cm. The extreme deficit treatment also had medium availability from 0 to 60 cm, but was still slightly dryer than the other treatments (Fig. 2.2).
The 2013 patterns of soil water distribution were consistent with the 2012 patterns. In spring all of the treatments were uniformly moist with medium to high availability throughout the profile with some variability between emitters. There was significant soil drying at veraison. In the moderate, high, and extreme deficit treatments, the entire profile was below estimated PWP (Fig. 2.3). While the low deficit retained low water availability beneath the drippers from 40 to 80 cm depth. In the fall, the soil profile had increased SWC. There was medium availability from 0 to 40 cm and low availability from 40 to 80 cm in the low, moderate, and high deficit treatments. Soil water availability in the extreme deficit treatment was limited to beneath the drip emitters and medium availability was limited to the top 20 cm, with low availability continuing through the profile (Fig. 2.3).

Winter precipitation of 80.23 mm increased the soil water availability from fall 2012 to spring 2013. The fall 2012 profile had a high water availability in the top 40 cm of soil, and in the spring of 2013 it increased to high water availability throughout the profile. In Washington, irrigation water is not available during the winter (~ 20 October to 1 April) (Schmitt, 2000), so winter precipitation was primarily responsible for the additional SWC in the spring. Additionally, the grower typically applied 24 hour irrigation sets in the spring prior to bud break to ensure adequate soil water availability.

The between row profiles for 2012 and 2013 exhibited the same seasonal trend as the in row profiles. There was an increased SWC in the spring, followed by a soil drying to the estimated PWP at veraison. The profile was then re-wetted in the fall (Figs. 2.4, 2.5). However, the between row profiles indicated the limited area of soil moisture available to the plant. The majority of the SWC was concentrated within a 100 cm strip centered on the drip emitter. In spring 2012, there was high water availability directly under the drip emitter, medium
availability extended to 50 cm on either side of the emitter, and low availability extended to approximately 100 cm on either side of the emitter in all treatments (Fig. 2.4). This corresponds with previous research which found that there is low SWC at distance greater than 100 cm from drip emitter (Araujo et al., 1995a). There was higher SWC in spring 2013, with soil moisture in the entire profile above the estimated PWP (Fig. 2.5). Veraison was uniformly dry in all treatments, both years, with the exception of the low deficit treatment, which had low soil water availability below 40 cm. In the fall, the SWC was again concentrated underneath the drip emitter, but it was also shallower than in the spring. During the fall sampling period in 2012, soil water content was in the medium range of availability between the 40 and 60 cm depth, while in 2013 medium soil water availability it was limited to 40 cm (Figs. 2.4, 2.5).

The data from both the along row and between row profiles, when combined, illustrated a very restricted wetted zone. The three dimensional distribution of grapevine roots has been positively correlated with soil water availability (Soar and Loveys 2007). As a result of the concentrating of water under the drip emitters, the vines needed to concentrate their roots in the wet zone in order to obtain necessary water for continued growth. Soar and Loveys (2007) found that root densities of structural roots increase under the drip line over a 5 year period after conversion from sprinkler irrigation. They postulated that the increase in structural roots were supporting greater proliferation of fine roots in the wetting zone during the season. Stevens and Douglas (1994) reported that under drip irrigation 50% of the vine’s root length was within 45 cm of the vine row, which corresponds well to this study in that the highest concentration of soil water was within 50 cm of the vine row.

Further, during the study, the soil was uniformly dry at veraison and was below the estimated PWP from 0 and 40 cm. However, there were small areas of low water availability
directly below the drip emitter at a depth of 40 to 60 cm (Figs. 2.4, 2.5). The region of low soil water availability was likely a result of soil water moving through the root zone before it could be taken up by the plant. The root zone for a ‘Cabernet Sauvignon’ vine will vary based on soil type, climate conditions, and irrigation regime (Iland et al., 2011), however, Soar and Loveys (2007) conducted their experiment on a similarly textured soil and with the same drip emitter rate (2.3L/h) and found that the highest density of roots were 0 to 50 cm in depth. Davenport et al., (2008) found that the depth of a ‘Cabernet Sauvignon’ root zone was confined to the top 45 cm of the soil and soil water below that depth remained as storage and was not taken up by the plant. The root zone in other perennial crops was also limited when under drip irrigation. Research conducted by Andreu et al. (1997) found the root system of drip irrigated almond trees was restricted to approximately 1 m in depth and soil water content below was still relatively high.

The main effects, ST, YR, TRT, DFE, D, DFE*D and ST*YR were statistically different (α = 0.05) (Table 2.4), which corresponded with previous research that found sampling time, depth, and distance from emitter were statistically different in ‘Cabernet Sauvignon’ and ‘Merlot’ wine grapes (Davenport et al., 2008). The average volumetric water content by ST was 15.14, 7.35, and 10.24% in spring, veraison, and fall respectively. The statistical difference in ST supported the hypothesis that the soil water content varies seasonally. The volumetric water content between sample years was 11.51 % in 2012 and 11.16 % in 2013, which corresponds with the differences in accumulated heat (GDD) over the two seasons, 2013 was a warmer season than 2012 resulting in less volumetric water content. The average soil moisture for the treatments was 11.42, 11.84, 11.29, and 10.79% for the low, moderate, high, and extreme deficits over all sampling times and treatment years. This highlighted that while there were minor
differences between the applied treatments (low, moderate, and high), the major difference was between these treatments and the current practice of extreme deficit. The average SWC decreased with depth except the 60 to 80 cm depth as it remained the same as the previous depth (Table 2.4).

The average soil moisture decreased with increasing DFE. At the emitter (0 cm) the average soil moisture content was 15.46 % and it decreased to 12.0, 10.81, and 10.40% as the distance increased from 50, 100, to 150 cm from the emitter. However, these differences reflect moving from below the vine row out into the between row space because there is overlapping of the wetting zone in the in row direction. Thus, the decrease in SWC between emitters in the in row direction is much less severe than moving into the between row space (Figs. 2.2 – 2.5). Therefore, the reduction in average SWC represented here likely underestimates the severity of the decrease in the between row direction (Figs. 2.4, 2.5).

The interactive effects TRT*D, TRT*DFE, and YR*TRT were not statistically different. Data analysis by ST indicated that SWC was significantly different by TRT and DFE ($P < 0.05$). In the spring, the mean volumetric SWC was consistent across all four treatments clustered at 15% with minimal statistical differences (Fig. 2.6). This was consistent with the findings by Wample and Smithyman (2002) of no significant differences between soil water content in the top 1 m of soil in April between different irrigation treatments in the Horse Heaven Hills region of Washington. The SWC decreased at veraison and there were statistical differences between treatments; however, all of the treatments were at or below the estimated PWP (8%). This implies that all of the water that was applied during this time period was either taken up by the plant or lost to evaporation. There was not enough water supplied to replenish storage of soil water. This resulted from the RDI regime, which purposely applied less water than was being
lost to ET in order to impose water stress on the vines. In the fall there was an increase in SWC across all treatments, but a greater increase in the low, moderate, and high deficit treatments, which are grouped statistically (Fig. 2.6). The difference in magnitude was due to the treatments. The extreme treatment did not receive any increase in water applied, while the low, moderate, and high treatments all received increases from veraison to the end of the growing season.

The SWC was also affected by DFE. In the spring, SWC decreased as DFE increased (Fig. 2.7). At 0 cm the SWC was 21%, at 50 cm it decreased to 18%, at 100 cm it was 15%, and at 150 cm it was 12%. There was a statistical difference between the mean SWC at each distance (0, 50, 100, 150 cm). At veraison the 0 cm distance was at the estimated PWP and statistically different from the 50 and 100 cm distances, which were both below the estimated PWP and not statistically different from each other. This was again the result of the RDI regime. In the fall, 0 cm was significantly higher than all other distances at 17%, 50 and 100 cm were grouped statistically at 11 and 10% respectively, and 150 cm was the lowest value at 9%. The differences in the SWC between the 50, 100, and 150 cm distance and the 0 cm distance illustrated the slow lateral distribution of SWC when rewetting the soil profile.

‘Concord’. In spring 2012, the in row SWC in the ‘Concord’ vineyard was high. The profile of the high treatment was above FC (Fig. 2.8). The moderate and low treatments also had some areas that were above FC, typically under the drip emitters. However, the very low treatment had a small area above FC, the majority of the profile had medium soil water availability (Fig. 2.8). There was a period of soil drying corresponding to the deficit treatment period, which resulted in uniformly dry soil in the moderate, low, and very low treatments at veraison, whereas the high irrigation application rate had medium soil moisture availability. The lack of SWC in the moderate, low, and very low treatments indicated that all of the water applied
was being taken up by the plant or lost to evaporation, with no excess water left in reserve in the profile. The profile was completely refilled by the fall sampling time above FC, on average, to a depth of 60 cm. This suggests that despite a prolonged period of deficit irrigation, to the point where the soil reached the estimated PWP, the profile could be refilled.

The SWC in the spring of 2013 was above FC or in the high availability range in the high treatment, and high to medium availability, with a few spots above FC, in the moderate, low, and very low treatments. This indicated that overwinter precipitation and early season irrigation applications maintained the SWC (Fig. 2.9). There was a similar drying trend from spring to veraison, but not as severe as in 2012. Soil water content was mainly at medium and low availability in the moderate, low, and very low treatments at veraison. The high treatment remained above FC for the entire season. In the fall, there was a rewetting of the deficit treatments to high availability or above FC down to the 80 cm depth (Fig. 2.9).

The between row profiles reflected the same trends as the in row. There was high SWC in both the spring and the fall and a dry down at veraison. The highest concentrations of SWC were limited to within 100 cm of the drip emitter. However, because of the higher amount of water applied as compared to the ‘Cabernet Sauvignon’ across the entire season, there was medium to low water availability routinely out to the 150 cm distance away from the emitter (Figs. 2.10, 2.11).

There were some visible differences in soil water content between fall in 2012 and 2013. When comparing the in row profiles there were minimal differences, 2013 had slightly higher percentage of the total profile above FC, but both had high available soil water content. However, when comparing the between row profiles, there were major differences at veraison and fall. At veraison, the between row profile in 2012 was below the estimated PWP in the
moderate, low, and very low treatments, while in 2013, there was medium and low water availability. In fall 2012, all of the treatments were above FC under the drip emitter from 0 to 40 cm minimum, high to moderate availability extending to 50 cm from the emitter, and low availability to 150 cm. In 2013, the high, low, and very low were above FC extending 50 cm from the drip emitter and to 80 cm depth, while the moderate treatment had high water availability. SWC in the rest of the profile decreased incrementally, with high to moderate availability extending from 50 to 100 cm from the emitter, and low availability from 100 to 150 cm. The difference in the between row profiles in the two years reflected the differences in applied water between the two years.

The wetting zone of the ‘Concord’ vineyard was not as restricted as the ‘Cabernet Sauvignon’ because of the larger quantity of water applied over the entire season. However, there was still significant dry down at veraison. This lead to less water availability within the root zone at veraison potentially reducing root growth, which peaks at or before veraison in ‘Concord’ vines under irrigation (Comas et al., 2005). Araujo et al., (1995a) found that ‘Thompson Seedless’ grapevines concentrated their root growth at the surface and within the wetted area under drip irrigation. Further reducing the total wetted volume at veraison could concentrate the ‘Concord’ vine root mass to an even greater extent. Similarly, annual root growth in ‘Concord’ vines was found to be highest in the top 40 cm of the soil and occur earlier in the season in minimally pruned vines as compared to severely pruned vines (Comas et al., 2005). The flush of root growth prior to veraison was attributed to earlier canopy development in the minimally pruned vines (Comas et al., 2005).

The main effects, ST, YR, TRT, DFE, D, DFE*D, TRT*D, TRT*DFE, ST*YR and YR*TRT were statistically different ($\alpha = 0.05$) (Table 2.5). SWC varied dramatically based on
ST. The average SWC was 18.78, 9.91, and 19.03% at spring, veraison, and fall respectively. This supports the hypothesis that the soil profile can be refilled after a period of deficit irrigation as evidenced by the change from veraison to fall. It also illustrated the significant decrease in SWC as a result of deficit irrigation. The difference between the average SWC for 2012 and 2013 was significant (13.35% in 2012 and 19.50% in 2013). Instead of reflecting seasonal differences in heat accumulation like the ‘Cabernet Sauvignon,’ this data reflected the difference in water applied over the treatment period. The water applied increased by approximately 50% from 2012 to 2013 across all treatments due to changes in grower management and temperature differences between the two years, 2013 was much warmer than 2012.

The mean SWC by TRT over the season was very close, the moderate, low, and very low treatments were 15.17, 15.67, and 15.18% respectively, except for the high treatment, which had a SWC of 19.06% for the season. The large difference in SWC was due to the application of deficit irrigation treatments in the moderate, low, and very low treatments.

The change in SWC with depth was very similar to the ‘Cabernet Sauvignon’ except that there was more SWC to start with in the ‘Concord’ vineyard. There was an average of 17.27% water within the first 20 cm of soil and that decreased to 15.12% at the 60 – 80 cm depth, for about a 12% loss in the ‘Concord’. The ‘Cabernet Sauvignon,’ saw a decrease in SWC from 12.86% to 10.68% over the same depth. The decrease in SWC from the initial depth (0-20 cm) to the final depth (60-80 cm) was statistically significant ($P > 0.0001$) in both the ‘Cabernet Sauvignon’ and the ‘Concord’ vineyard (Tables 2.4, 2.5).

Data analysis by sampling time indicated that soil water content was significantly different by TRT and DFE ($P < 0.05$). In spring the volumetric water content was high, especially the high treatment (21%), which might have resulted from previous season
accumulation. The moderate and low treatments were grouped together (18% and 18.5% respectively) and the very low treatment was slightly lower (17%) (Fig. 2.12). At veraison the high treatment remained significantly higher than all other treatments (15%) because of the continued application of large quantities of water. The moderate treatment was lower at 9% and the low and very low treatments were 7.7% and 8% respectively. The moderate, low and very low treatments were all deficit treatments and minimal available water in the soil was likely a result of plant extraction of stored water during the treatment period and evaporation. In the fall, the volumetric water content for the high treatment remained constant at 20%. The low and very low treatments were grouped statistically at 19.2% and 18.9%, while the moderate treatment had the lowest volumetric water content at 17.6%. This showed that despite a period of RDI where the soil reached the estimated PWP, the stored water could be replaced before the end of the irrigation season (mid-October).

Volumetric SWC decreased with increasing DFE. In the spring, volumetric SWC decreased as DFE increased (Fig. 2.13), and there were statistical differences between each sampling interval. At veraison, the same relationship between SWC and DFE was observed. In the fall, the decrease in SWC between each interval was greater than the prior two sampling times indicating a greater drop in SWC as DFE increased. The average SWC was statistically different by DFE for each treatment in the fall. On average, the change in SWC as the DFE increased, across all sampling periods, was very similar to the ‘Cabernet Sauvignon,’ but the ‘Concord’ started with a higher average SWC and lost a greater quantity from 0 to 150 cm. The ‘Cabernet Sauvignon’ lost approximately 33% of the SWC present at the 0 cm distance by the 150 cm distance, while the ‘Concord’ lost 40%. Thus, the 0 cm distance was statistically higher than the 150 cm distance ($P < 0.0001$) in both vineyards (Tables 2.4, 2.5).
Conclusions

Soil water content under deficit irrigated grapevines varied temporal and spatially. The soils in both vineyards followed the same general trend. In the spring, soil water content was high due to overwinter refill coupled with early season irrigation applications, leading to relatively uniform spatial distribution of the soil water under the drip line in both vineyards. The soil then dried to the estimated permanent wilting point at veraison as a result of the deficit irrigation treatments. However, the vines did not permanently wilt, which indicated that the permanent wilting point of the plants was below what was estimated for this soil series. At veraison, all of the water being applied was taken up by the plant or lost to evaporation. There was no water left to remain as a reserve in the profile. After the end of the deficit period it was possible to refill the soil profile as evidenced by the high level of soil water availability during the fall sampling period. The available water in the fall was increased by winter precipitation resulting in a peak of soil water content in the spring.

There were some differences between the two vineyards. The ‘Concord’ vineyard received more water over the entire season than the ‘Cabernet Sauvignon’ and, as a result, the spring and fall profiles had higher available soil water content when compared with the ‘Cabernet Sauvignon’. Subsequently, the ‘Concord’ vines had a much larger wetted area from which to draw from when ET increased. However, the “full” irrigation of the ‘Concord’ vineyard could have led to some water loss to deep percolation. For example, in the fall of 2013, both the in row and between row profiles indicated that the soil directly under the drip emitter/line and extending approximately 25 to 50 cm out from the drip emitter were above field capacity from 0 to 80 cm in depth. This could lead to the leaching of nutrients from the root zone and loss of available water. This could be a possible area for potential water savings, as reducing water
application between veraison and harvest in ‘Concord’ production would alleviate the current over-supply. However, further research is necessary to assess the potential impacts of reducing current water applications between veraison and harvest on yield and berry quality.

Spatially, the soil water content decreased as the distance from the drip emitter increased in both vineyards regardless of sampling time. Thus, as water was restricted under deficit irrigation in both vineyards, it limited the lateral movement of soil water resulting in a narrow zone of wetting within the vineyard row along the drip line. In the ‘Cabernet Sauvignon’ the wetted zone was shallow, often reaching only 40 to 60 cm. However, in the ‘Concord’ the width and depth of the wetted zone was much larger, possibly extending beyond the sampling area, as a greater amount of water was applied to the ‘Concord’ vines. This restriction in wetting zone has the potential to confine the root zone to these wetted zones, reducing the total volume of soil explored by the roots and limiting nutrient uptake.
Literature Cited


Table 2.1: Amount of irrigation water applied to a ‘Cabernet Sauvignon’ vineyard over two growing seasons in a deficit irrigation trial and the corresponding percent increase.

<table>
<thead>
<tr>
<th>Degree of Deficit</th>
<th>Amount Increase</th>
<th>Growth Stage Applied</th>
<th>Total water applied (mm)(^a)</th>
<th>% Increase water applied (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1/3 of total applied</td>
<td>All Season</td>
<td>304</td>
<td>289</td>
</tr>
<tr>
<td>Moderate</td>
<td>1/3 of total applied</td>
<td>Prior to Bloom, Post Veraison</td>
<td>289</td>
<td>264</td>
</tr>
<tr>
<td>High</td>
<td>1/3 of total applied</td>
<td>Post Veraison</td>
<td>260</td>
<td>230</td>
</tr>
<tr>
<td>Extreme</td>
<td>None</td>
<td>All Season</td>
<td>228</td>
<td>217</td>
</tr>
</tbody>
</table>

\(^a\) Based on a time period of 1 May to 31 October
Table 2.2: Amount of irrigation water applied between bloom and veraison to a ‘Concord’ vineyard over two growing seasons. The day of year (DOY) for the start and end of the treatment period were noted along with the total number of days during the treatment period.

<table>
<thead>
<tr>
<th>Water Application</th>
<th>Percentage Reduced from Control</th>
<th>Total Water Applied (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2012</td>
</tr>
<tr>
<td>High</td>
<td>0</td>
<td>125.6</td>
</tr>
<tr>
<td>Moderate</td>
<td>~ 25%</td>
<td>94.0</td>
</tr>
<tr>
<td>Low</td>
<td>~ 33%</td>
<td>81.6</td>
</tr>
<tr>
<td>Very Low</td>
<td>~ 45%</td>
<td>68.7</td>
</tr>
<tr>
<td><strong>Start and End of Treatment Period (DOY)</strong></td>
<td></td>
<td>155</td>
</tr>
<tr>
<td><strong>Total Days in Treatment Period</strong></td>
<td></td>
<td>81</td>
</tr>
</tbody>
</table>
Table 2.3: Sampling dates for collecting soil cores from deficit irrigated vineyard trial sites. The growth stage, date of sampling, and day of year (DOY) are listed for each cultivar and each year sampled.

<table>
<thead>
<tr>
<th>Cultivar/Year</th>
<th>Growth Stage</th>
<th>Date</th>
<th>DOY</th>
<th>Date</th>
<th>DOY</th>
<th>Date</th>
<th>DOY</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Cabernet Sauvignon’ 2012</td>
<td>3 to 4 leaf stage</td>
<td>May 23</td>
<td>144</td>
<td>August 21</td>
<td>234</td>
<td>October 30</td>
<td>304</td>
</tr>
<tr>
<td>‘Cabernet Sauvignon’ 2013</td>
<td>Veraison</td>
<td>May 17</td>
<td>137</td>
<td>August 8</td>
<td>220</td>
<td>October 31</td>
<td>304</td>
</tr>
<tr>
<td>‘Concord’ 2012</td>
<td>Post final irrigation</td>
<td>May 11</td>
<td>132</td>
<td>August 14</td>
<td>227</td>
<td>October 23</td>
<td>297</td>
</tr>
<tr>
<td>‘Concord’ 2013</td>
<td></td>
<td>May 8</td>
<td>128</td>
<td>August 1</td>
<td>213</td>
<td>October 23</td>
<td>296</td>
</tr>
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Table 2.4: Average soil volumetric soil water content for main effects of impact of deficit irrigation level ‘Cabernet Sauvignon’ vineyard monitored for spatial and temporal water distribution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>n/df</th>
<th>Average soil moisture (% by volume)</th>
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</thead>
<tbody>
<tr>
<td><strong>Sampling time (ST)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>2389</td>
<td>15.14</td>
</tr>
<tr>
<td>Veraison</td>
<td>1630</td>
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</tr>
<tr>
<td>Fall</td>
<td>2389</td>
<td>10.24</td>
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<td></td>
</tr>
<tr>
<td>2012</td>
<td>3209</td>
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<tr>
<td>Low</td>
<td>1594</td>
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</tr>
<tr>
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<td>1594</td>
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</tr>
<tr>
<td>High</td>
<td>1599</td>
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</tr>
<tr>
<td>Extreme</td>
<td>1614</td>
<td>10.79</td>
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<tr>
<td><strong>Distance from emitter (DFE)</strong></td>
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<td></td>
</tr>
<tr>
<td>0</td>
<td>287</td>
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</tr>
<tr>
<td>50</td>
<td>2254</td>
<td>12.00</td>
</tr>
<tr>
<td>100</td>
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<td>10.81</td>
</tr>
<tr>
<td>150</td>
<td>1644</td>
<td>10.40</td>
</tr>
<tr>
<td><strong>Depth (D)</strong></td>
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<td></td>
</tr>
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<td>0-20</td>
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<tr>
<td>20-40</td>
<td>1623</td>
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<tr>
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<tr>
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<td>D</td>
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<td>0.0001</td>
</tr>
<tr>
<td>DFE</td>
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</table>
Table 2.5: Average soil volumetric soil water content for main effects of impact of deficit irrigation level ‘Concord’ vineyard monitored for spatial and temporal water distribution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>n/df</th>
<th>Average soil moisture (%) by volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampling time (ST)</strong></td>
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<td></td>
</tr>
<tr>
<td>Spring</td>
<td>2384</td>
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<td>Veraison</td>
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<td>Fall</td>
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<td><strong>Year (YR)</strong></td>
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<td></td>
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<td>2013</td>
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<td><strong>Treatment (TRT)</strong></td>
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<td></td>
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<tr>
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<td>Moderate</td>
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<td>Low</td>
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<td><strong>Distance from emitter (DFE)</strong></td>
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<td><strong>Depth (D)</strong></td>
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<td>0-20</td>
<td>1689</td>
<td>17.27</td>
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<td>ST</td>
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<td>YR</td>
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</tr>
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<td>TRT</td>
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<td>0.0001</td>
</tr>
<tr>
<td>DFE</td>
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<td>D</td>
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<td>DFE*D</td>
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<td>ST*YR</td>
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</tr>
<tr>
<td>YR*TRT</td>
<td>3</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
Figure 2.1: Soil sampling design for determining soil water content in response to different deficit irrigation treatments in ‘Cabernet Sauvignon’ and ‘Concord’ vineyards. This diagram shows the locations of each of the 25 sample locations as they were arrayed around the drip emitter. There are three sample locations in each cardinal direction (N, NE, E, SE, etc.) where the radii intersect each line segment. Every numbered intersection corresponds to a sample location (1-25).
Figure 2.2: Average volumetric soil moisture in a ‘Cabernet Sauvignon’ vineyard shown as an interpolated area along the row in 2012.
Figure 2.3: Average volumetric soil moisture in a ‘Cabernet Sauvignon’ vineyard shown as an interpolated area along the row in 2013.
Figure 2.4: Average volumetric soil moisture in a ‘Cabernet Sauvignon’ vineyard shown as an interpolated cross sectional area with the row in 2012.
Figure 2.5: Average volumetric soil moisture in a ‘Cabernet Sauvignon’ vineyard shown as an interpolated cross sectional area with the row in 2013.
Figure 2.6: Average volumetric soil water content (SWC) in ‘Cabernet Sauvignon’ by treatment. The values correspond to the mean volumetric SWC grouped by sampling time. Different letters above bars indicate statistical differences by treatment as determined by Duncan-Waller mean separation (α <0.05). The red line on the graph corresponds to the permanent wilting point.

Figure 2.7: Average volumetric soil water content (SWC) in ‘Cabernet Sauvignon’ by distance from emitter (DFE): The values correspond to the mean volumetric SWC grouped by sampling time. Different letters above bars indicate statistical differences by treatment as determined by Duncan-Waller mean separation (α <0.05). The red line on the graph corresponds to the permanent wilting point.
Figure 2.8: Average volumetric soil moisture in a ‘Concord’ vineyard shown as an interpolated area along the row in 2012.
Figure 2.9: Average volumetric soil moisture in a ‘Concord’ vineyard shown as an interpolated area along the row in 2013.
Figure 2.10: Average volumetric soil moisture in a ‘Concord’ vineyard shown as an interpolated cross sectional area with the row in 2012.
Figure 2.11: Average volumetric soil moisture in a ‘Concord’ vineyard shown as an interpolated cross sectional area with the row in 2013.
Figure 2.12: Average volumetric soil water content (SWC) in ‘Concord’ vineyard by distance from emitter (DFE). The values correspond to the mean volumetric SWC grouped by sampling time. Different letters above bars indicate statistical differences by treatment as determined by Duncan-Waller mean separation (α <0.05). The red line on the graph corresponds to the permanent wilting point.

Figure 2.13: Average volumetric soil water content (SWC) in ‘Concord’ vineyard by distance from emitter (DFE). The values correspond to the mean volumetric SWC grouped by sampling time. Different letters above bars indicate statistical differences by treatment as determined by Duncan-Waller mean separation (α <0.05). The red line on the graph corresponds to the permanent wilting point.
Chapter 3

EVALUATION OF MULTIPLE LEVELS OF DEFICIT IRRIGATION ON SOIL WATER DISTRIBUTION, YIELD, AND QUALITY OF Vitis vinifera cv. Cabernet Sauvignon

Introduction

Wine grapes (Vitis vinifera L.) are grown extensively in Washington State and are its third most valuable crop (Stonebridge, 2012). Red wine grapes make up a majority of the total acreage at 57% and ‘Cabernet Sauvignon’ is one of the most popular cultivar accounting for 41% of the red wine grape acreage (Knopf and Koong, 2011). The climate in Washington is well suited to red wine grape production, the major grape growing areas in central and eastern Washington are classified as a semiarid steppe (Fischer and Turner, 1978), which is characterized by warm and dry summers and cold winters. Annual precipitation in this area is typically less than 300 mm with the majority falling in the winter (October-March) (Elsner et al., 2010). Due to the extremely low precipitation, irrigation is required for grape production. The majority of wine grape vineyards in central and eastern Washington use drip irrigation. Drip irrigation is very efficient (~ 90%) (Peters, 2014) and can be applied daily due to the slow discharge rate (Peacock et al., 1977). The combination of central and eastern Washington’s warm/dry summers and the use of drip irrigation makes irrigation the most controllable factor in vineyard operations (Evans et al., 1993).

Water stress can dramatically influence the vegetative and reproductive development of red wine grapes (Hardie and Considine, 1976; Matthews and Anderson, 1989; Keller, 2005; Basile et al., 2011). Grape vine sensitivity to water stress is dependent on growth stage (Basile et
al., 2011). Water stress between budbreak and bloom can cause pollen sterility and reduce cell division in the inflorescence anthers and ovaries, thereby reducing berry size (Hardie and Considine, 1976; Keller, 2005). However, as the berries develop they become less sensitive to water stress. Yet, water stress both pre- and post-veraison has been shown to improve berry quality by increasing concentrations of anthocyanin and polyphenol in the berry skin (Romero et al., 2010; Chalmers et al., 2010; Basile et al., 2011).

Irrigation management techniques such as deficit irrigation (DI) and regulated deficit irrigation (RDI) are designed to take advantage of the grape vine physiological response to water stress. DI applies a prescribed deficit for an extended time period, while RDI applies a short period of water deficit. A typical RDI regime in Washington imposes a deficit of 50% to 75% of crop evapotranspiration (ETc) right after fruit set extending until harvest (Keller et al., 2008). The deficit reduces vegetative growth, because shoots are extremely sensitive to water stress (Smart, 1974; Stevens and Harvey, 1996), limits total berry size (Smart et al., 1974), and increases anthocyanin and polyphenol content in the berry skin (Basile et al., 2011). However, after harvest, the deficit is reduced and the soil is returned to field capacity in order to protect the grape vine roots from extreme cold events (Wample and Smithyman, 2002; Keller et al., 2008).

Wine grape producers in central and eastern Washington have readily adopted RDI; over 75% of grape acreage is under deficit irrigation or RDI (Davenport et al., 2008). Producers that grow premium or ultra-premium wine grapes have imposed even more severe deficits than average. However, such severe deficits have not consistently proven to be beneficial to yield or quality (Keller et al., 2008). The objectives of this project were to determine the effects, in terms of yield and fruit quality, of several different levels of regulated deficit irrigation on ‘Cabernet
Sauvignon’ wine grape, and to characterize the changes in seasonal soil water content (SWC) by treatment and the dry down period after a single irrigation event.

**Materials and Methods**

**Plot Design.** This study was conducted in a 6 ha commercial ‘Cabernet Sauvignon’ vineyard in the Yakima Valley American Viticultural Area (Sunnyside, WA) (46° 20' 21" and -119° 55' 34") from January 2011 to February 2015. Vineyard layout along with pruning, fertilizer, pest, and canopy management was outlined in Chapter 2 (pg. 27).

The plots were arranged in a random block design as described in Chapter 2 (pg. 28). The vineyard was irrigated using drip emitters (flow rate 2.27 L/h) that were spaced every 0.9 m. Winter precipitation was usually insufficient to completely refill the soil profile, so irrigation was applied until the soil reached field capacity prior to or immediately after bud-break (Table 3.1). The soil was then allowed to dry down to control shoot growth (M. Miller, personal communication 2011).

The treatments were designed to simulate several levels regulated deficit irrigation ranging from low to extreme (Table 3.2). The low, moderate, and high deficit treatments increased the amount of water applied to the vines by 1/3 of the volume applied by the grower (extreme deficit). The timing of this increase was determined by phenological stages of vine development (Table 3.2): low deficit increased the water applied all season, moderate deficit increased the water applied pre-bloom and post-veraison, and high deficit increased the water applied post-veraison.

Additional irrigation lines were added to the low, moderate, and high deficit treatments to increase the amount of water applied. All PVC fittings and pipe were schedule 40 and were purchased from Valley Pipe Co (Prosser, WA). The fittings were produced by one of three
manufacturers: Dura Plastic Products, Inc (Beaumont, CA), Lasco Fittings, Inc. (Brownsville, TN), or Spears Manufacturing Company (Sylmar, CA). All of the piping used was 1.9 cm schedule 40 PVC (Ridgeline Pipe Manufacturing, Eugene OR). The new piping was connected to the existing drip line with a compression tee that was threaded on one side with a diameter of 1.9 cm. The threaded connection was connected to a 1.9 cm PVC 90° elbow. A short section of 1.9 cm pipe was glued in to the elbow and a 1.9 cm ball valve. The pipe continued out of the ball valve and into another tee oriented vertically. Another short section of pipe was inserted vertically with an elbow and a barbed nipple that connected to the new drip tubing. Out of the other side of the tee the pipe was connected to an elbow oriented downward, sending the supply line underground. The pipe was then split with another tee sending lines across the aisles to the two buffer rows. On the north side buffer the pipe was brought to vertical with an elbow and another elbow with a threaded connection is used to connect to a barbed nipple. On the south side, the line was split with a tee, one side was identical to the north side, and the other side of the tee had a 1.9 cm ball valve connected to it (Fig. 3.1). This was to drain the lines in the winter. A 0.9 m section of 7.62 cm pipe was notched and placed over the drain valve to provide access. The additional tubing was forced over the barbed nipples and secured with wire ties or hose clamps. It had drippers spaced 2.5 m with a flow rate of 2.27 L/h, in order to apply the desired increase in water applied.

Climate data was monitored throughout the experimental period using raw data from the Washington State University weather station network (Ag Weather Net, 2014) Snipes weather station (46° 17’ 56.4”, -119° 54’ 59.22”), which was located less than 5 km from the field plots. Reference ET data was collected from the Snipes weather station ET calculator, which uses the ASCE standardized Penman-Monteith equation (Ag Weather Net Staff, 2014). Growing degree
days (GDD) were also downloaded from the GDD calculator which were calculated using the standard method and base temperature for grapevines is 10°C as determined by Amerine and Winkler (1944).

**Shaded area.** A Paso panel was used to measure the shaded area underneath the canopy, which can then be used to calculate the crop coefficient \( (K_c) \) for the specific field location (Battany, 2006). Two Paso panels were constructed at the beginning of the study based on the design by M. Battany (2006). The Paso panel was comprised of a 1.5 m solar panel (R-21, Powerfilm® Solar, Ames, IA) wired to a DT-830 B digital multi-meter (Sinometer, Shenzhen, China) and a momentary switch (Item # 31498, Ace Hardware, Oak Brook, IL) supported by an aluminum frame (Fig. 3.2). The frame was made from 7.6 cm and 5.0 cm aluminum flat bars and 1.9 cm and 1.27 cm channel. All of the aluminum components were affixed using pop rivets (Arrow Fastener Co., LLC, Saddle Brook, NJ) and a riveter tool (Stanley, Towson, MD). The 1.9 cm aluminum channel was used on either side connected together with strips of 7.6 cm flat bar. A center support was made from the 1.27 cm channel. The digital multi-meter was affixed to the center support with self-adhesive Velcro. Sections of 7.6 cm flat bar were bent to a 90° curve and attached as handle supports. The handles themselves were made from a section of 1.9 cm channel covered in a 1.9 cm diameter schedule 40 PVC (Ridgeline Pipe Manufacturing, Eugene OR). The solar panel, digital multi-meter, and momentary switch were wired together using wire nuts and wrapped in electrical tape. The percent shaded area of the solar panel was directly proportional to the current output (Amps) (Battany, 2006). Therefore, the shaded percentage of the solar panel is one minus the ratio of a shaded reading to a full sun reading multiplied by 100.

The percent shaded area under the grapevine was used to calculate the crop coefficient \( (K_c) \) because the percent shaded area has been shown to be linearly correlated to \( K_c \) (Williams
and Ayars, 2005). There were three equations involved in calculating the crop coefficient ($K_c$) value using a Paso panel (Battany, 2006).

\[
Shaded \ percentage \ of \ solar \ panel = \left[ 1 - \left( \frac{Shaded \ Reading}{Full \ Sun \ Reading} \right) \right] \times 100\% \quad (1)
\]

\[
Shaded \ percentage \ of \ field = Shaded \ percentage \ of \ panel \times \left( \frac{Panel \ Length}{Row \ Spacing} \right) \quad (2)
\]

\[
K_c = (0.017 \times Shaded \ percentage \ of \ field) - 0.008 \quad (3)
\]

Equation 1 used “Shaded” (readings taken under the vines) and “Full Sun” (readings taken without shade on the solar panel) readings to calculate the shaded percentage of the solar panel. “Shaded Reading” represented the mean shaded reading for a set of measurements. The result of this equation was used by equation 2 to determine the shaded percentage of the field. This was accomplished by multiplying the result of equation 1 by the Paso panel length divided by the row spacing. Finally, equation 3 was used to calculate the $K_c$ value (Battany, 2006). Equation 3 was the correlation between the $K_c$ and percent shaded area as determined by Williams and Ayars (2005), which had an $R^2$ value of 0.95.

To accurately measure the shaded area under the canopy, readings were taken only under clear sky conditions at within a half an hour of solar noon. Solar noon was approximately 1:00 pm Pacific Standard Time (ESRL, 2005). Additionally, the Paso panel was held level and any inadvertent shading of the solar panel (user shadow, trellis, etc.) was avoided to maintain consistent readings. Also, windy conditions were avoided to prevent fluctuations in shaded area readings. Finally, the circuit was only engaged for one second intervals while taking readings as completing the circuit short-circuits the solar panel and prolonged engagement could burn out the solar panel (Battany, 2006).
Paso panel readings were taken May through July approximately every two weeks. Full sun readings were taken at the beginning of each block. In 2011, three shaded area readings were taken, one reading between vine 3 and 4, 5 and 6, and 7 and 8. However, due to variability in canopy size the number of readings were increased in the subsequent seasons to 9 readings per plot, one reading between each of the 10 sample vines. The mean value for each treatment was determined and used for the “Shaded Reading” in equation 1. The mean of the 4 full sun values was used in equation 1 as the “Full Sun Reading.” The $K_c$ values were then calculated using equations 2 and 3. Once the $K_c$ was calculated it was used to determine the crop specific evapotranspiration ($E_Tc$) by multiplying the reference $ET$ by the $K_c$. The $E_Tc$ was a measure of water use and served as a comparison for established irrigation practices. Reference $ET$ data was collected from the Snipes weather station ET calculator, which uses the ASCE standardized Penman-Monteith equation (Ag Weather Net Staff, 2014).

**Neutron Probe.** Soil moisture measurements were taken using a 503 DR Hydroprobe® (CPN International, Inc., Concord, CA). Prior to the first season of the trial, 16 PVC access tubes were installed, 1 per treatment row between vine 2 and 9, to a depth of 0.9 m. Each tube was located between 20 and 40 cm away from a drip emitter on an approximately 45° diagonal as recommended by Davenport et al. (2008) for moisture monitoring in a drip irrigated, regulated deficit irrigated vineyard. The tubes were made from 1 m lengths of 3 cm diameter schedule 40 PVC pipe (Ridgeline Pipe Manufacturing, Eugene, OR). Rubber stoppers were placed in the top of the tubes to prevent precipitation and debris from accumulating at the bottom of the tubes.

The neutron probe was initially calibrated using the laboratory method as outlined in the user manual (CPN International, 2011). Two barrels of sand were used, one saturated to 32% water by volume and one 0%, were used to plot the low and high standards. This calibration was
the factory calibration method and was applicable for sandy soils without any significant organic matter. The slope was determined to be 2.757 and the intercept was -0.054. This calibration was verified in the field. As the neutron probe tubes were being dug, soil samples were taken corresponding to each sample depth. The soil water content of these samples was determined by gravimetric analysis. Wet samples were weighed using an APX-1502 Model balance (Denver Instrument, Bohemia, NY), then dried at 105° C for 24 hours and reweighed with the same balance to determine water lost (Gardner, 1965). The bulk density was also calculated from the dry weight and the calculated volume of the sample taken. The samples were then converted to volumetric and compared with the corresponding neutron probe readings. The calibration was checked yearly against the standards.

During 2011 measurements were taken on a weekly basis regardless of irrigation application from June to October. Neutron probe measurements were taken at 15 cm increments. After reviewing the 2011 data, the depth of the access tubes was increased from 0.9 m to 1.4 m in 2012 to better characterize soil moisture profile. Additionally, measurements were taken within 24 hours after an irrigation for the duration of the experiment (2012 to 2014).

A series of neutron probe measurements were taken over a 24 hour period after a single irrigation event in order to characterize the re-distribution of soil water. This portion of the experiment was conducted over two seasons (2012 and 2013). In 2012 a 12 hour irrigation set was applied overnight and concluded at 6:00 am. Soil moisture measurements began immediately after the irrigation stopped and were taken at 1.5 hour intervals for 6 hours, then every 3 hours until the total time reached 12 hours (Table 3.4). In 2013 a pre-irrigation and a 24 hour post treatment measurement were added. Additionally, an intensive sampling period was added during soil wetting. Readings were taken at 15 minute intervals over a single block (block
2) (Table 3.4). The intensive measurement period lasted for a total of 2 hours. Once the irrigation was shut off 3 measurements were taken in 1.5 hour increments across the entire field during dry down and a final measurement taken 24 hours after the irrigation was shut off.

The total soil depth measured (140 cm) was divided into two zones: the root zone (≤ 45 cm) as estimated from Davenport et al. (2008) and below the root zone (> 45 cm). The total amount of water in each zone was determined by multiplying the raw data by the depth of the soil represented and summing those values within the desired zone. The four replicates were then averaged to determine the mean total amount of water in the soil at each sampling time. Trends in total water (TW) were then evaluated by graphing the TW by sampling date. Error bars corresponding to one standard deviation from the mean were added in order to visually assess differences in treatments.

**Shoot length.** Total shoot length was measured weekly beginning at the three to four leaf stage until shoot growth stopped. One shoot per vine was identified and tagged for future measurements. The total length of the shoot was determined by measuring from the base of the shoot (connection to previous year growth) to the growing tip. If a shoot was removed from the vine due to shoot thinning, tractor damage, etc., that shoot was not replaced. A note was made as soon as the growing tip either died or was removed due to hedging, leaf thinning, or trellis wire movement and the shoot was measured to the point of injury. If a lateral bud began growing and surpassed the damaged or missing shoot tip, it became the terminus for the shoot length measurement. All shoots were measured until mean total shoot length became steady and more than half of the shoots no longer had growing tips.

The raw shoot length data was transformed into growth rates by estimating the slope of the trend line, based on the plotted points between 130 and 525 GDD (10°C), by means of the
Linest function in Excel (Microsoft, Redmond, WA). Using SAS 9.4 software (version 6.2.9200; SAS Institute Inc., Cary, NC) Proc GLM, the main effects year and treatment and the interactive effect year*treatment were investigated. The data was also sorted by year and tested again with Proc GLM to determine significance by treatment.

**Yield.** The fruit was harvested within two weeks of commercial harvest as indicated by the grower collaborator. Harvest dates were October 10, 2011, October 9, 2012, October 9, 2013, and October 13, 2014. Total yield was assessed by harvesting a 2 vine equivalent (half of vine 4, all of vine 5, and half of vine 6) from the established 10 vine sampling area. All of the clusters from the harvest zone were picked, counted, placed into picking lugs, and weighted using a Pelouze 4040 digital shipping and receiving scale (Rubbermaid, Huntersville, NC). The total cluster count and total weight for the two vine sample was recorded. This information was used to calculate the mean cluster count, mean cluster weight, fruit weight/vine, and total yield (Mg/ha). The data was analyzed using Proc GLM with the main effects year and treatment. In order to remove the year to year variation in yield the data was sorted by year and reanalyzed.

**Grape Quality.** Samples of harvested fruit (20 clusters per sample row) were collected for juice analysis. This fruit was shipped overnight to E. J. Gallo’s research winery (Modesto, CA) and analyzed to determine soluble solids (Brix), pH, titratable acidity (TA), malic acid, potassium, total anthocyanins, linalool, and yeast available nitrogen (YAN) using standard methods (Iland et al., 2004).

**Pruning Weight.** Pruning weight was collected after the 2012, 2013, and 2014 field seasons. They were not collected after the first field season (2011) as the grower pre-pruned before vines could be sampled. Pruning weight was measured on a per vine basis. The ten sample vines were pruned to 2-3 bud spurs, leaving 15 spurs per vine for approximately 30 buds per
vine. The shoots removed were collected into an 18.9 L bucket and weighted using a digital fish scale (Berkley, Spirit Lake, IA). A subsample of ~ 20 0.3 m cuttings were taken from each treatment row. These cuttings were then weighed using an APX-1502 Model balance (Denver Instrument, Bohemia NY), dried in an oven (manufacturer unknown) at 42°C for a minimum of 24 hours, and then reweighed to determine water content. The results were analyzed using Proc GLM to determine the effect of treatment, year, treatment*year on the pruning weights. Also, the data was sorted by year and analyzed using Proc GLM and Duncan-Waller means separation to determine the degree of difference between the means of the treatments. The ratio of pruning weight to shoot length was also calculated in order to determine differences in shoot mass that may have resulted from the treatments.

Results and Discussion

Weather and soil moisture. There was a wide range in temperatures over the trial period. The historical (6 year) average of accumulated growing degree days (GDD) (base 10°C) from the Snipes weather station for 1 April to 31 October was 1749. The historical average was limited to 6 years because the station was installed in 2008. The 2011 season was very cool (1527 GDD), 2012 was average (1722 GDD), 2013 was warm (1835 GDD), and 2014 was extremely warm (1938 GDD) (Table 3.1, Fig. 3.3) which likely accounted for the majority of the variation between years. The wide range of total accumulated heat over the season helped to determine if the deficit treatments were effective over all temperature ranges.

Despite a wide range of accumulated GDD, the ET₀ for the growing season was relatively stable around the mean of 963 mm (Table 3.1). The seasonal precipitation for the same time period was very low. The 2012 growing season had the highest seasonal precipitation with 107
mm and 2014 had the lowest, 57 mm (Table 3.1). The distribution of seasonal precipitation is skewed to the beginning (before July) and end (October) of the season (Fig. 3.4).

The early season precipitation combined with winter precipitation (1 November to 31 March) and irrigation events resulted in high soil water content (SWC), at or above field capacity (25% v/v), which was consistent with findings by Wample and Smithyman (2002) of no significant differences between SWC in the top 1 m of soil in April between different irrigation treatments. The soil water content was then allowed to decrease to approximately 17% (v/v) in the root zone before irrigation was applied, with the length of the drying period dependent on the season (Figs. 3.5 – 3.8) as part of the RDI strategy. The root zone (top 45 cm) contained less total water and showed more variability at the end of the irrigation season. There was higher SWC below the root zone than in the root zone and the SWC remained consistent between the treatments with a decreasing trend throughout the season. Also, there was a period of variability in SWC below the root zone that corresponded to the same period in the root zone, but the fluctuations in SWC were much smaller below the root zone.

The clearest differentiation between treatments was during 2014 in the root zone (Fig. 3.8). At the end of the measurement period (October) SWC of the low and moderate deficit treatments were grouped tightly around 25% (v/v) and high and extreme deficit treatments were tightly grouped at 18% (v/v). However, the differences disappear below the root zone, where all four treatments were closely grouped for the entire season. Generally, the SWC of the low and moderate deficit treatments was slightly higher in both the root zone and below the root zone.

The first time dry down measurements were collected in 2012 there was no change in soil water content over the 12 hour post irrigation period both within and below the root zone (Fig. 3.9). The initial measurements ranged from 25% (v/v) to 14.9% (v/v) in the root zone and 14.6%
(v/v) to 10.9% (v/v) below the root zone (Table 3.5). The highest amount of moisture lost within the 12 hour period was 1% (v/v). In 2013, there was little to no increase in soil water content in the root zone during the intensive sampling period; however, there was a large increase in soil water content between the end of the wetting period and the beginning of the dry down (Fig. 3.10). Both the low and moderate deficit treatments showed higher increases in soil water content than the high and extreme deficit. Below the root zone, the SWC decreased during the wetting period except for the high deficit treatment, which increased in SWC and decreased during the drying period (16 to 24 hour). The other treatments increased in SWC during the dry down period (Fig. 3.10).

The SWC did not change significantly within 24 hours after an irrigation event, indicating that the quantity of water applied at veraison was not sufficient enough to cause losses due to deep percolation. In order to characterize changes in the SWC resulting from plant uptake and evaporative loss after an irrigation event the monitoring period needed to increase to 48 or 72 hours or use a sensor capable of continuous monitoring.

**Crop coefficient and ET\(_c\).** The Paso panel measurements in 2011 extended into September. During this period the canopy continued to fill until growth was controlled by the soil water deficit. The maximum K\(_c\) value for each season (2011, 2012, 2013, and 2014) was 0.60, 0.45, 0.55, and 0.60, respectively. The maximum values were not always on the same day of year (DOY). In 2011 and 2013 the maximum values were reached at the end of the measurement period, DOY 272 and 231 respectively. However, in 2012 and 2014 the maximum K\(_c\) values were reached earlier in the season on DOY 165 and 170 respectively (Fig. 3.11).

Early in the season, the K\(_c\) values calculated from the Paso panel measurements matched existing K\(_c\) values as reported by Evans et al. (1992), with few deviations from existing
convention. Evans et al. (1992) reported their $K_c$ as a function of growing degree days (GDD) (10°C) and the maximum value of 0.85 corresponded to a range of GDD from 974 to 997. In the 2011 season accumulated GDD reached this range on day 231. The closest $K_c$ measurement was on DOY 228 with a value of 0.46. The difference between these two values illustrate the differences between a generalized $K_c$ value based on a fully irrigated ‘Cabernet Sauvignon’ vine and a site specific $K_c$ as determined by the shaded area under the canopy.

The $K_c$ values followed a generally increasing trend, but there was some variation in 2012 and 2014. In these two seasons there was a significant drop in $K_c$ just before DOY 200, from 0.45 to ~0.32 and between 0.55-0.60 to 0.40 in 2012 and 2014 respectively (Fig. 3.11). However, in 2013 there was no major drop in $K_c$ values, instead there were steadily increasing values from 0.30 at DOY 150 to ~0.55 at DOY 231.

The drops in 2012 and 2014 were a result of canopy management operations. The grower kept two sets of catch wires low, allowing the canopy to sprawl until the canopy was the desired size. The wires were then raised, transitioning the canopy from a sprawl to a tight curtain. This significantly reduced the shaded area of the canopy and allowed for better light penetration to the fruit, aiding in ripening. Therefore, $K_c$ values could also be used as a relative measure of canopy size because of their correlation with leaf area index (Williams and Ayars, 2005) and sensitivity to changes in canopy position. All treatments were very tightly grouped, thus there were no major differences in canopy size among the treatments (Fig. 3.11). While the total leaf area did not change during as a result of the wires being raised, the canopy density increased. As a result, some leaves will experience grater shading and reducing potential ET. Thus, the difference in $K_c$ before and after the manipulation of the canopy with wires will still reflect the overall $K_c$ of the vine.
Kc has a major impact on ETc because it is a value used to modify the ETo to match the characteristics of the desired crop (Allen et al., 1998). ETc was calculated by multiplying the ETo by the Kc. The ETc for July was used to compare all four seasons because the number of Paso panel measurements remained consistent for 2012-2014 and this period was likely to reflect very high ET rates. The ETo for July varied greatly from year to year, 183.11 mm in 2011 to 210.20 mm in 2013 (Table 3.3). There was also some variation between treatments, the maximum difference in ETc was 11.91, 4.53, 8.10, and 10.34 mm in 2011, 2012, 2013, and 2014 respectively (Table 3.3). The maximum difference in ETc was not consistent between two treatments indicating that no treatment was consistently high or low. This indicated that the variation in canopy size was not dependent on treatment.

Additionally, the total water applied and percentage of ETc were calculated (Table 3.3). The percentage of ETc varied by year. The extreme deficit treatment was 75, 42, and 32 % of ETc during July in 2012, 2013, and 2014 respectively. There were only minor variations between extreme, high and moderate treatments as they were all receiving the same amount of water during this time period, while the low deficit was increased. This is reflected in the percentage of ETc (Table 3.3).

**Shoot growth rate.** It was shown that DI/RDI can effectively be used to control vigor, with positive benefits from increased light interception in the cluster zone (Chaves et al., 2007) because shoot growth is extremely sensitive to water deficit (Keller, 2005). However, in this study there were no significant differences between the shoot growth rates in any treatment in the first three years of the study. In 2011 the mean growth rate was 1.48 cm/day (Table 3.6). Growth rates were lower in 2012 with an overall average of 0.84 cm/day, but the rate increased in 2013
to an average of 1.50 cm/day. The shoot growth rates decreased in 2014 to an average of 0.29 cm/day.

Lack of differences in shoot growth rates across this study could be explained by: (1) there was not a large enough difference in the amount of water applied to influence shoot growth rate, or (2) the timing of the deficit did not affect the total canopy size. It was most likely due to the latter as, shoot growth was most active prior to fruit set and was found to reach optimum levels (60-90cm) before the implementation of RDI (Keller et al., 2008). Additionally, soil water content in the spring was very high and relatively uniform due to winter precipitation and early spring irrigation sets (Wample and Smithyman, 2002).

The extreme deficit treatment did not reduce shoot growth any more than the other treatments, which is consistent with results from Keller et al. (2008), when a severe deficit irrigation treatment of 20-30% ETc did not control vegetative growth any more than a RDI schedule of 60-70% ETc. Further, Wample and Smithyman (2002) found no carryover effects from the previous season irrigation treatments expressed by lack of differences in shoot length before bloom.

**Yield.** There were no statistical differences in total yield, cluster count, or mean cluster weight between treatments across the entire treatment period (Tables 3.7, 3.8). The variation in the yield data was due to year to year differences (Table 3.7). The extreme deficit yielded 3.86, 5.06, 7.53, 8.89 Mg/ha in 2011, 2012, 2013, and 2014 respectively, which illustrated the degree of variation from year to year and a trend of increasing yield from 2011 to 2014. The yield for the low, moderate, high deficits were summarized in Table 3.7. Both the cluster count and mean cluster weight increased over the trial period resulting in higher yields, neither was statistically significant from the control (extreme) treatment (Table 3.8).
This implies that the treatments did not have a major impact in total yield. However, it was shown that yield can be significantly affected, in terms of reduced cluster weights, if water was withheld pre-veraison (Hardie and Considine, 1976; Matthews and Anderson, 1989) because berries were most sensitive to water stress during lag phase (Hardie and Considine, 1976). The lack of significant differences between cluster weights probably result from the timing of deficit and degree of difference between treatments. At bloom/fruit set, there was still adequate soil water content to support vine development even in the most severe deficit treatments.

Even though there were no statistical differences in total yield, the differences in yield could be biologically/economically significant. For example, comparing the percent increase in water applied to the resulting percent increase in yield, the high deficit treatment showed a 1 to 1 relationship in percent increase in water and yield. However, a 33% increase in total water applied across the entire season (low deficit treatment) had a more varied result, increasing yield by 18% in 2013 and 28% in 2014. Thus, water applied at different growth stages had different water use efficiency as defined in terms of the increase in yield/increase in water consumed. The most efficient increase in water would result in an increase in yield equal to or greater than the increase in water, such as seen in the high deficit treatment.

Grape quality. Average berry quality parameters were significantly different by the year they were sampled, except for YAN (Table 3.9). The variation in the YAN content was small and not related to either the treatments or sample year. Potassium, malic acid, pH, and TA differed significantly by treatment across sample years.

When evaluated on a per year basis there were few significant differences in potassium, malic acid, pH, or TA. In 2013, the potassium content in the low, moderate, high, and extreme deficit treatments were 1385, 1474, 1520, and 1455 ppm respectively and the low deficit
treatment was significantly lower than the high deficit treatment, but not the moderate or extreme treatments. In 2011 malic acid concentration was 3462, 3444, 2892, and 2609 ppm in the low, moderate, high and extreme deficit treatments respectively. The low and moderate treatments were significantly higher than with the extreme deficit (Table 3.9). pH showed no significant differences between treatments on a per year basis. The only significant differences by treatment in TA were found in 2011 when the extreme and low deficit treatments were highest (0.64 ppm) and lowest (0.51 ppm), respectively.

These results are similar to what others have found (Chaves et al., 2007; Keller et al., 2008). There was no evidence of a differential effect of water stress on acidity (Hardie and Considine, 1976) or soluble solids (Hardie and Considine, 1976; Wample and Smithyman, 2002; Chaves et al., 2007). However, Chaves et al. (2007) found that TA increased in fully irrigated vines compared with no irrigation. Romero et al. (2010) found that malic acid concentration decreased with RDI treatments, but did not see the same reductions in pH or other compositional measures. Even through there were some limited differences in berry quality, overall those differences were not sustained throughout the entire sampling period and they did not increase in severity. Therefore, the deficits applied did not significantly influence berry quality parameters.

Pruning Weights. In 2012, the pruning weights for the low, moderate, high, and extreme deficit treatments were 0.73, 0.80, 0.73, and 0.58 kg/vine. All of the pruning weights increased in the 2013 season. The average pruning weight across the treatments was 1.15 kg/vine. The pruning weight dropped slightly between 2013 and 2014. The low to extreme deficit treatments had pruning weights of 0.99, 0.95, 0.76, and 0.62 respectively (Table 3.10). All of the main effects, treatment, year, and treatment*year, were found to be significant (α = 0.05, $P<0.001$, $P<0.001$, and $P=0.0441$). After the data was sorted by year and retested, treatment was
significant in 2012 and 2014 ($\alpha = 0.05$, $P = 0.0033$, $P < 0.001$) but not in 2013 ($P = 0.1019$). The extreme deficit treatment had the lowest pruning weight throughout the trial and was significantly lower than at least one other treatment in each season (Table 3.10). This indicates that the canopy of the extreme deficit treatment was smaller/less vigorous than the other treatments. However, there were no significant differences in the shoot growth rate. The significant result in the pruning weight could be a result of mass rather than length. The pruning weight to shoot length ratio was statistically different for the 2014 season. The extreme deficit treatment had a significantly smaller pruning weight to shoot length ration (6.73 g/cm) than the other treatments, which averaged 9.49 g/cm.

**Conclusion**

The objects of this study were to determine the effect of several levels of regulated deficit irrigation on the seasonal distribution of SWC, yield, and quality of ‘Cabernet Sauvignon’ wine grapes. The soil water content in the root zone was relatively high in the spring and followed a drying down trend as a result of RDI. In order to prevent too severe a deficit, irrigation was applied, but not in significant quantities to refill the soil profile. Instead, the soil water content remained relatively low, but increased immediately after an irrigation event, and rapidly decreased due to plant uptake and evaporation. This pattern continued until harvest after plant growth slows and when water was added to refill the profile.

The soil water content below the root zone followed a similar trend, however, it was not as volatile during the summer. There were small fluctuations, but the soil water content remained relative steady throughout the season. Additionally, the irrigation treatments showed little to no effect on the soil water content below the root zone during the season.
Shoot growth rate was not limited by RDI in this trial likely because the timing of the deficits were not early enough to significantly influence shoot growth. A deficit applied between bloom and veraison or post-veraison is unlikely to significantly reduce shoot growth as canopy size establishes prior to fruit set. Additionally, soil water deficits were difficult to establish early in the growing season due to high SWC from winter precipitation. Any deficit prior to fruit set has the potential to greatly reduce crop load both within season and next season as bud development occurs during this period. Pruning weight indicated that the extreme deficit treatment resulted in less shoot material than the other treatments.

Yields were not significantly different between any treatment, however, it was determined that the timing of the water increase had the potential to increase crop yield at different rates. The most consistent increase in yield resulted from the increase in water applied post-veraison. The high deficit treatment showed a 1 to 1 ratio of increase in water applied to increase in yield. However, increasing water post-veraison does have its limitation as the berries cells are swelling rather than not actively dividing. The low and moderate deficit treatments also resulted in increases, but they were not as consistent across the trial period and had a lower increased water to increased yield ratio.

Deficit irrigation has been found to be beneficial to ‘Cabernet Sauvignon’ grape quality in terms of color, tannin, phenolic concentrations (Basile et al., 2011; Casassa et al., 2013), but limit yields if applied pre-veraison (Matthews and Anderson, 1989). This study did not see any statistical differences in standard berry quality parameters (°Brix, pH, TA), which was consistent with other research conducted by Chaves et al. (2007) and Keller et al. (2008). Therefore, quality is not solely dependent on level of irrigation and extreme deficits do not necessarily improve berry quality over moderate deficits.
Literature Cited


Table 3.1 Summary of climatic data for 2011 through 2014. This table includes cumulative growing degree days (GDD) base 10°C during the growing season (1 April to 31 October), annual and growing season ET$_o$, and precipitation [annual, growing season, and non-growing season (1 November to 31 March)]. All weather data was collected from the Snipes weather station (Ag Weather Net) located at 46° 17’ 56.4”, -119° 54’ 59.22”.

<table>
<thead>
<tr>
<th>Season</th>
<th>GDD (°C)</th>
<th>ETo (mm)</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual</td>
<td>Growing Season</td>
<td>Annual</td>
</tr>
<tr>
<td>2011</td>
<td>1527</td>
<td>1153</td>
<td>964</td>
</tr>
<tr>
<td>2012</td>
<td>1722</td>
<td>1141</td>
<td>953</td>
</tr>
<tr>
<td>2013</td>
<td>1835</td>
<td>1155</td>
<td>975</td>
</tr>
<tr>
<td>2014</td>
<td>1938</td>
<td>1163</td>
<td>972</td>
</tr>
<tr>
<td>Average 2009-2014</td>
<td>1749</td>
<td>1144</td>
<td>963</td>
</tr>
</tbody>
</table>

*Date range from 1 November 2013 to 12 March 2015
Table 3.2 Summary of water applied, by the degree of deficit (low, moderate, high, extreme), amount increase over extreme, timing of increase, the total water applied (1 May to 31 October), and percent increase (1 May to 31 October).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1/3 of total applied</td>
<td>All Season</td>
<td>na</td>
<td>304</td>
<td>289</td>
<td>286</td>
<td>na</td>
<td>33.0</td>
<td>33.2</td>
<td>33.0</td>
</tr>
<tr>
<td>Moderate</td>
<td>1/3 of total applied</td>
<td>Prior to Bloom, Post Veraison</td>
<td>na</td>
<td>289</td>
<td>264</td>
<td>271</td>
<td>na</td>
<td>26.8</td>
<td>21.7</td>
<td>26.0</td>
</tr>
<tr>
<td>High</td>
<td>1/3 of total applied</td>
<td>Post Veraison</td>
<td>na</td>
<td>260</td>
<td>230</td>
<td>236</td>
<td>na</td>
<td>14</td>
<td>6.0</td>
<td>9.8</td>
</tr>
<tr>
<td>Extreme</td>
<td>None</td>
<td>All Season</td>
<td>na</td>
<td>228</td>
<td>217</td>
<td>215</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

<sup>a</sup> Water applications were not tracked during the 2011 season.
Table 3.3: Comparison of July $ETo$ (mm), $ETc$ (mm), water applied (mm), and percentage of $ETc$ for all four field seasons.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Treatment</th>
<th>Year</th>
<th>2011a</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ETo$ (mm)</td>
<td>Low</td>
<td>2011a</td>
<td>183.1</td>
<td>190.1</td>
<td>210.2</td>
<td>196.6</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>2011a</td>
<td>85.8</td>
<td>68.4</td>
<td>103.4</td>
<td>92.9</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>2011a</td>
<td>86.1</td>
<td>66.9</td>
<td>104.6</td>
<td>88.8</td>
</tr>
<tr>
<td></td>
<td>Extreme</td>
<td>2011a</td>
<td>90.6</td>
<td>67.0</td>
<td>96.5</td>
<td>82.6</td>
</tr>
</tbody>
</table>

$Max Difference Between Treatments$

<table>
<thead>
<tr>
<th>Water applied (mm)</th>
<th>Low</th>
<th>2011a</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water applied (mm)</td>
<td>Moderate</td>
<td>na</td>
<td>66.8</td>
<td>53.9</td>
<td>35.5</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>na</td>
<td>50.2</td>
<td>40.5</td>
<td>26.7</td>
</tr>
<tr>
<td></td>
<td>Extreme</td>
<td>na</td>
<td>50.2</td>
<td>40.5</td>
<td>26.7</td>
</tr>
</tbody>
</table>

$% of ETc$

<table>
<thead>
<tr>
<th>Low</th>
<th>2011a</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate</td>
<td>na</td>
<td>104.6</td>
<td>53.8</td>
<td>40.7</td>
</tr>
<tr>
<td>High</td>
<td>na</td>
<td>73.4</td>
<td>39.2</td>
<td>28.7</td>
</tr>
<tr>
<td>Extreme</td>
<td>na</td>
<td>75.1</td>
<td>38.7</td>
<td>30.1</td>
</tr>
</tbody>
</table>

$^a$Water applications were not tracked during the 2011 season.

*Maximum $ETc$

$^\wedge$Minimum $ETc$
Table 3.4: Timing of soil moisture measurements during dry down during the 2012 and 2013 season.

<table>
<thead>
<tr>
<th>Date</th>
<th>Pre-Irrigation</th>
<th>Dry down period</th>
<th>Wetting period</th>
<th>Dry down</th>
<th>24 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>NA</td>
<td>6:00 7:30 9:00 10:30 12:00 15:00 18:00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>Pre-Irrigation</td>
<td>Welling period</td>
<td></td>
<td>Dry down</td>
<td>24 hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17:15 7:22 7:52 8:22 8:37 8:52 9:07 9:22 9:37 9:52 16:00 17:30 19:00 17:15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.5: Dry down measurements for 2012 in % soil water content.

<table>
<thead>
<tr>
<th>Deficit Level</th>
<th>Root zone</th>
<th>Below root zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>23.83</td>
<td>12.81</td>
</tr>
<tr>
<td>Moderate</td>
<td>25.38</td>
<td>14.65</td>
</tr>
<tr>
<td>High</td>
<td>14.96</td>
<td>10.88</td>
</tr>
<tr>
<td>Extreme</td>
<td>19.69</td>
<td>14.31</td>
</tr>
<tr>
<td></td>
<td>24.14</td>
<td>12.79</td>
</tr>
<tr>
<td></td>
<td>24.42</td>
<td>12.79</td>
</tr>
<tr>
<td></td>
<td>24.57</td>
<td>12.66</td>
</tr>
<tr>
<td></td>
<td>24.43</td>
<td>12.66</td>
</tr>
<tr>
<td></td>
<td>24.15</td>
<td>12.66</td>
</tr>
<tr>
<td></td>
<td>24.90</td>
<td>14.65</td>
</tr>
<tr>
<td></td>
<td>24.68</td>
<td>14.65</td>
</tr>
<tr>
<td></td>
<td>24.06</td>
<td>14.65</td>
</tr>
<tr>
<td></td>
<td>14.96</td>
<td>14.65</td>
</tr>
<tr>
<td></td>
<td>14.77</td>
<td>14.65</td>
</tr>
<tr>
<td></td>
<td>19.75</td>
<td>10.88</td>
</tr>
<tr>
<td></td>
<td>19.95</td>
<td>10.88</td>
</tr>
<tr>
<td></td>
<td>19.64</td>
<td>10.88</td>
</tr>
<tr>
<td></td>
<td>18.81</td>
<td>10.88</td>
</tr>
<tr>
<td></td>
<td>23.94</td>
<td>12.91</td>
</tr>
<tr>
<td></td>
<td>24.04</td>
<td>14.22</td>
</tr>
<tr>
<td></td>
<td>14.17</td>
<td>14.22</td>
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<tr>
<td></td>
<td>13.63</td>
<td>13.31</td>
</tr>
<tr>
<td></td>
<td>13.60</td>
<td>13.31</td>
</tr>
<tr>
<td></td>
<td>13.60</td>
<td>13.31</td>
</tr>
<tr>
<td></td>
<td>13.60</td>
<td>13.31</td>
</tr>
</tbody>
</table>
Table 3.6: Average shoot growth rate (cm/day) for the study period (2011 - 2014) by level of deficit.

<table>
<thead>
<tr>
<th>Shoot Growth Rate (cm/day)</th>
<th>Year</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levels of Deficit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td>1.50</td>
<td>0.81</td>
<td>1.62</td>
<td>0.44</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td>1.66</td>
<td>0.88</td>
<td>1.56</td>
<td>0.34</td>
</tr>
<tr>
<td>High</td>
<td></td>
<td>1.29</td>
<td>0.78</td>
<td>1.50</td>
<td>0.10</td>
</tr>
<tr>
<td>Extreme</td>
<td></td>
<td>1.47</td>
<td>0.88</td>
<td>1.32</td>
<td>0.27</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>1.48</td>
<td>0.84</td>
<td>1.50</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 3.7: Summary of total yield (Mg/ha) and the % difference from control (Extreme deficit).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (Mg/ha)</th>
<th>2011</th>
<th>% Diff</th>
<th>Yield (Mg/ha)</th>
<th>2012</th>
<th>% Diff</th>
<th>Yield (Mg/ha)</th>
<th>2013</th>
<th>% Diff</th>
<th>Yield (Mg/ha)</th>
<th>2014</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low deficit</td>
<td>4.65</td>
<td>20.8</td>
<td>6.51</td>
<td>28.7</td>
<td>8.92</td>
<td>18.5</td>
<td>11.34</td>
<td>27.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate deficit</td>
<td>3.22</td>
<td>-16.4</td>
<td>6.58</td>
<td>30</td>
<td>7.51</td>
<td>-0.3</td>
<td>10.3</td>
<td>15.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High deficit</td>
<td>5.26</td>
<td>36.6</td>
<td>5.42</td>
<td>7.1</td>
<td>8.39</td>
<td>11.4</td>
<td>9.86</td>
<td>19.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extreme deficit</td>
<td>3.85</td>
<td>0</td>
<td>5.06</td>
<td>0</td>
<td>7.53</td>
<td>0</td>
<td>8.89</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.8: Summary of average cluster count and average cluster weight (g) over the trial.

<table>
<thead>
<tr>
<th>Cluster Count</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>65.8</td>
<td>103.8</td>
<td>137.5</td>
<td>152.8</td>
</tr>
<tr>
<td>Moderate</td>
<td>55.0</td>
<td>112.5</td>
<td>112.3</td>
<td>142.0</td>
</tr>
<tr>
<td>High</td>
<td>83.8</td>
<td>97.8</td>
<td>122.8</td>
<td>134.3</td>
</tr>
<tr>
<td>Extreme</td>
<td>57.8</td>
<td>83.3</td>
<td>125.8</td>
<td>126.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cluster Weight (g)</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>76.9</td>
<td>68.4</td>
<td>72.5</td>
<td>82.0</td>
</tr>
<tr>
<td>Moderate</td>
<td>63.9</td>
<td>62.5</td>
<td>73.7</td>
<td>80.6</td>
</tr>
<tr>
<td>High</td>
<td>69.5</td>
<td>59.8</td>
<td>75.2</td>
<td>81.2</td>
</tr>
<tr>
<td>Extreme</td>
<td>74.8</td>
<td>66.9</td>
<td>67.8</td>
<td>77.5</td>
</tr>
</tbody>
</table>
Table 3.9 Summary of berry quality analysis. Each value is the mean of four replicates except for the high deficit in 2014 which only has 3 replicates. This was due to the grower cutting the shoots in order to raisin the fruit prior to harvest. Different letters beside the values indicate statistical differences by treatment as determined by Duncan-Waller mean separation (α <0.05). Values with the same letter were not statistically different.

<table>
<thead>
<tr>
<th>Year</th>
<th>Level of Deficit</th>
<th>Linalool (ppb)</th>
<th>Anthocyanins (mg/g berry)</th>
<th>Potassium (ppm)</th>
<th>Malic Acid (ppm)</th>
<th>pH</th>
<th>Soluble Solids (°Brix)</th>
<th>TA (ppm)</th>
<th>YAN (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Low</td>
<td>1.26</td>
<td>1.37</td>
<td>1312</td>
<td>3462 a</td>
<td>3.32</td>
<td>22.2</td>
<td>0.64 a</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>1.45</td>
<td>1.23</td>
<td>1343</td>
<td>3444 a</td>
<td>3.36</td>
<td>22.2</td>
<td>0.60 ab</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.29</td>
<td>1.46</td>
<td>1353</td>
<td>2892 ab</td>
<td>3.37</td>
<td>22.6</td>
<td>0.55 ab</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>Extreme</td>
<td>1.82</td>
<td>1.56</td>
<td>1367</td>
<td>2609 b</td>
<td>3.41</td>
<td>23.0</td>
<td>0.51 b</td>
<td>168</td>
</tr>
<tr>
<td>2012</td>
<td>Low</td>
<td>0</td>
<td>1.58</td>
<td>1500</td>
<td>2503</td>
<td>3.44</td>
<td>23.3</td>
<td>0.61</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0</td>
<td>1.62</td>
<td>1502</td>
<td>2178</td>
<td>3.47</td>
<td>22.8</td>
<td>0.58</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0</td>
<td>1.70</td>
<td>1578</td>
<td>1900</td>
<td>3.53</td>
<td>23.6</td>
<td>0.53</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>Extreme</td>
<td>0</td>
<td>1.56</td>
<td>1523</td>
<td>1913</td>
<td>3.48</td>
<td>23.6</td>
<td>0.54</td>
<td>180</td>
</tr>
<tr>
<td>2013</td>
<td>Low</td>
<td>0</td>
<td>1.08</td>
<td>1385 b</td>
<td>2454</td>
<td>3.52</td>
<td>23.5</td>
<td>0.53</td>
<td>182</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0</td>
<td>1.10</td>
<td>1474 ab</td>
<td>2535</td>
<td>3.56</td>
<td>23.7</td>
<td>0.51</td>
<td>184</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0</td>
<td>1.15</td>
<td>1520 a</td>
<td>2215</td>
<td>3.62</td>
<td>23.9</td>
<td>0.47</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>Extreme</td>
<td>0</td>
<td>1.14</td>
<td>1455 ab</td>
<td>1986</td>
<td>3.61</td>
<td>23.9</td>
<td>0.45</td>
<td>174</td>
</tr>
<tr>
<td>2014</td>
<td>Low</td>
<td>0.98</td>
<td>1.44</td>
<td>.</td>
<td>2026</td>
<td>3.56</td>
<td>23.8</td>
<td>0.46</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>1.33</td>
<td>1.46</td>
<td>.</td>
<td>1929</td>
<td>3.47</td>
<td>23.1</td>
<td>0.47</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.21</td>
<td>1.46</td>
<td>.</td>
<td>1936</td>
<td>3.49</td>
<td>22.4</td>
<td>0.43</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>Extreme</td>
<td>1.10</td>
<td>1.51</td>
<td>.</td>
<td>1614</td>
<td>3.54</td>
<td>22.4</td>
<td>0.43</td>
<td>138</td>
</tr>
</tbody>
</table>
Table 3.10: Summary of pruning weights (kg/plant) for 2012, 2013, and 2014. The red letters beside the values indicate statistical differences by treatment as determined by Duncan-Waller mean separation ($\alpha < 0.05$). Values with the same letter were not statistically different.

<table>
<thead>
<tr>
<th>LEVEL OF DEFICIT</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW</td>
<td>0.73a</td>
<td>1.20ab</td>
<td>0.99a</td>
</tr>
<tr>
<td>MODERATE</td>
<td>0.80a</td>
<td>1.14ab</td>
<td>0.95a</td>
</tr>
<tr>
<td>HIGH</td>
<td>0.73a</td>
<td>1.22a</td>
<td>0.76b</td>
</tr>
<tr>
<td>EXTREME</td>
<td>0.58b</td>
<td>1.04b</td>
<td>0.62b</td>
</tr>
</tbody>
</table>
Figure 3.1: Diagram of irrigation supply lines added to distribute additional water to the treatment rows. PVC lines were placed underground from the measurement row where the water supply connection was made to the buffer rows where it was connected with a barbed nipple to the additional drip tubing. The application of water from the additional tubing was controlled by a manual shut-off valve and the lines were drained in October to prevent the PVC lines from breaking.
Figure 3.2: Paso Panel. This instrument was made using a five foot solar panel, volt meter, and temporary switch. When the switch is engaged the volt meter will read the amp output of the panel. The amp output is directly proportional to the shaded area of the solar panel. This panel was used to calculate the shaded area underneath the canopy.
Figure 3.3: Growing degree day accumulation (base 10°C) at the Snipes weather station (Yakima County, WA) from 1 April to 31 October 2011 to 2014 and six-year mean.

Figure 3.4: Accumulated $ET_0$ for each field season and the respective precipitation events.
Figure 3.5: Percent water both in and below the root zone.
Figure 3.6: Percent water both in and below the root zone for the 2012 season.
Figure 3.7: Percent water both in and below the root zone for the 2013 field season.
Figure 3.8: Percent water both in and below the root zone for the 2014 field season.
Figure 3.9: Dry down measurements for 2012. Measurements were taken over a 12 hour period directly after an irrigation event to determine redistribution of soil water.
Figure 3.10: Wetting and dry down period 2013.
Figure 3.11: Crop coefficients ($K_c$) (2011-2014) derived from Paso panel measurements. $K_c$ decreases at or prior to DOY 200 were due to shoot positioning as the two sets of catch wires were moved into position creating a single canopy curtain.
Introduction

Juice grapes *Vitis labrusca* Bailey cv. Concord are grown throughout the northeastern United States, but Washington is the largest producer of ‘Concord’ grapes, accounting for approximately 45% of total U.S. production (USDA, 2013). Irrigation can be a limiting factor for production in Washington because of the arid steppe climate (Fischer and Turner, 1978), which receive less than 300 mm of annual precipitation (Elsner et al., 2010). Comparatively, Ithaca NY received an average of 932 mm of precipitation annually (1971-2000) (Eggleston, 2007). Therefore, irrigation strategies for ‘Concord’ grapes in Washington are very different from other ‘Concord’ growing regions.

There have been several studies by Morris et al. on the interaction of irrigation, pruning severity, and fertilization on ‘Concord’ yield (Morris and Cawthon, 1982; Morris et al., 1983a; b). However, many such studies dealt with the addition of supplemental irrigation and its effect on yield and quality. Morris et al. (1983a) found that supplemental irrigation can indirectly increase yields by increasing vine vigor resulting in more viable buds that can be left during balanced pruning. However, increased yields were inversely related to juice quality (Morris et al., 1983b).

However, in Washington supplemental irrigation is required to produce a crop. Many growers irrigate heavily to simulate the high rainfall conditions in the Northeast, but there are
some years that irrigation supplies are not sufficient to meet total demand. In those water short years, allotments are often reduced. In 2001, reduced winter and spring precipitation lead to a shortage in irrigation supply. The Roza irrigation district was only able to supply 38% of normal delivery (Keller et al., 2004). Such reductions can lead to large reductions in yield do to the formation of a water deficit leading to a reduction in stomatal conductance and leaf assimilation rate (Naor and Wample, 1994).

Regulated deficit irrigation (RDI) has been studied extensively in wine grape (*Vitis vinifera* L.) production. Regulated deficit irrigation has been shown to increase color and phenolic concentration in ‘Cabernet Sauvignon’ (Romero et al., 2010; Basile et al., 2011). However, there is a potential trade-off with yield, as early season water deficits (pre-veraison) can limit berry size (Hardie and Considine, 1976). There is little research on the impacts of RDI on ‘Concord’ yield and berry quality because RDI has the potential to severely limit yield. Unlike wine grapes, ‘Concord’ production is largely focused on yield and a minimum set of quality standards. There are no premiums for quality that would make up for loss of yield. However, as irrigation supplies become more volatile producers will have to find ways to cope with reduced water allocations.

The goal of this study was to evaluate the potential of RDI as a management strategy in ‘Concord’ production to reduce water use and cope with drought years. This was accomplished by assessing the impact of RDI on yield and fruit quality as well as seasonal soil moisture distribution. Additionally, a novel technique for calculating a crop coefficient (Kc) by measuring the shaded area underneath the canopy was used to determine site specific crop evapotranspiration (ETc).
Materials and Methods

**Plot Design.** This study was conducted in a 10 ha commercial ‘Concord’ vineyard in the Yakima Valley American Viticultural Area (Sunnyside, WA) (46° 20' 21"N and 119° 55' 34"W) from January 2011 to February 2015. Vineyard details including planting date, spacing, trellising, irrigation, fertilizer, pest and disease management were outlined in Chapter 2 (pg. 27).

The plots were arranged in the same random block design as described on page 28. The vineyard was irrigated using the same emitter flow rate (2.27 L/h) and spacing (0.9 m) as the ‘Cabernet Sauvignon’. Due to lack of sufficient winter precipitation, irrigation was applied in the spring until the soil reached field capacity prior to or immediately after bud-break. For the remainder of the growing season, irrigation was applied at weekly intervals throughout the season to prevent any deficit from limiting yields (M. Miller, personal communication 2011). The treatments were the same as outlined in Chapter 2 (pgs.28, 29), but they were applied from 2011 to 2014 (Table 4.1).

The irrigation supply was controlled by installing new main lines. The new main lines were connected to a pressurized source, located at the southwest corner of the vineyard. The new connection was plumbed with a main shutoff valve and connected to a manifold of three timer controlled solenoid valves (Fig. 4.1). All PVC fittings and pipe were schedule 40 and were purchased from Valley Pipe Co (Prosser, WA). The fittings were produced by one of three manufacturers: Dura Plastic Products, Inc (Beaumont, CA), Lasco Fittings, Inc. (Brownsville, TN), or Spears Manufacturing Company (Sylmar, CA). The pipe was manufactured by Ridgeline Pipe Manufacturing (Eugene, OR). A 6.35 cm tee was glued into the existing vertical pipe and reduced to a 5 cm diameter before it was turned to run parallel to the vine row using a 90° elbow. Once parallel to the vine row a 5 cm ball valve was glued in to act as a main shut-off for the new
system. From the shut-off valve the pipe ran into a manifold comprised of three 5 cm tee fittings in short succession. The pipe was extended to the end of the row and another 5 cm valve served as an end cap and provided a drain point in the winter (Fig. 4.1).

Attached to each of the 5 cm tee fittings were 5 cm 45°’s. These were reduced to 1 inch and the connection changed to threaded from slip or glue joints. A short 5 cm long extension was threaded and connected to a 2.54 cm 100-HV-NPT Rain Bird valve (Rain Bird Corporation, Azusa, CA). The solenoid valves that came with the Rain Bird valves were replaced with Galcon GCS3050/3051 solenoid valves (Galcon USA San Rafael, CA). The first two solenoids were wired to a DIG 740 controller and the third to a DIG 710 controller (DIG Corporation, Vista CA) using waterproof electrical connections (manufacturer unknown). The outflow of the valves connected into a 2.54 cm tee that had an air check valve on the top and the mainline turned down to head underground. Once underground, a 90° elbow was used to turn the lines out of the vineyard. The pipe ran approximately 3 m before another 90° elbow was used to turn the three mainlines toward the field plots.

These three new mainlines supplied the drip tubing in each plot. A 2.54 cm x 2.54 cm x 1.27 cm tee was attached to the mainline at the end of each treatment row in the first two blocks. The three mainlines were reduced to 1.91 cm at the end of block 2 to maintain adequate pressure. A 1.27 cm diameter piece of PVC pipe ran to the vine row, then one 90° turned it vertical and another fitted with a barbed nipple connected it to the drip tubing. In the third and fourth blocks a 1.91 cm x 1.91 cm x 1.27 cm tee was used. The existing drip tubing was used within the treatment plots. Additionally, a blank section of tubing (Netafim, Fresno, CA) was used to connect the existing mainline to the existing drip lines that extended past our plots. At the end of
mainlines 1.91 cm tees were attached. Vertical from the tee was an air check valve and a 1.91 cm ball valve was attached to the horizontal connection to act as a drain valve.

**Shaded area.** The procedure for constructing a Paso panel and measuring shaded area was described in Chapter 3 (pg. 70-72). The shaded area was used to calculate the crop coefficient ($K_c$) as described in Chapter 3 (pg. 71). The $K_c$ value was then used to calculate the $ET_c$, which was used to determine the quantity of irrigation to apply. The accumulated $ET_c$ for the irrigation period started with previous irrigation date and ended the day before the current irrigation minus any precipitation events. The treatment reductions were then applied to the corresponding $ET_c$ values to determine the final amount of water to apply. Daily reference evapotranspiration ($ET_o$) values were obtained from the Washington State University weather station network (Ag Weather Net) Snipes weather station (46° 17’ 56.4”, -119° 54’ 59.22”), which is located less than 5 km from the field plots.

**Neutron Probe.** Instillation of the neutron probe access tubes, calibration of the neutron probe, and the procedure used for soil moisture measurements were the same as outlined in Chapter 3 (pg. 72-74). Additionally, a series of neutron probe measurements were taken over a 24 hour period after an irrigation event in 2012 and 2013. The procedure used in 2012, was the same as the ‘Cabernet Sauvignon’ (pg. 74). However, the dry-down measurements in 2013 changed slightly from what was performed in the ‘Cabernet Sauvignon’ vineyard. A pre-irrigation and a 24 hour post treatment measurement were added, but measurements were only taken during the drying period and an intensive period was not measured (Table 4.2).

The total soil depth measured (140 cm) was divided into two zones: the rootzone ($\leq 60$ cm) and below the root zone ($> 60$cm) based on research conducted by Pradubsuk (2008). The total water content in the root zone and below the root zone was determined using the same
procedure as in Chapter 3 (pg. 74). These values were graphed to determine trends in total water content.

**Shoot length.** Total shoot length was measured weekly using the same procedure utilized in the ‘Cabernet Sauvignon’ vineyard (pg. 75). Total shoot length was transformed into growth rates by estimating a line, based on the plotted points between 250 and 667 GDD (10°C), using the Linest function in Excel (Microsoft Inc., Redmond, WA). The main effects (year and treatment) and interactive effect (year*treatment) were investigated using SAS 9.4, Proc GLM (version 6.2.9200; SAS Institute Inc., Cary, NC). Also, the data was sorted by year and analyzed again in order to eliminate the effect of year to year variation. The Duncan-Waller means separation test was run to determine the degree of separation between the treatment means.

**Yield.** Fruit was harvested using the same procedure as explained in Chapter 3 (pg. 75, 76). The grapes were harvested on October 10, 2011, October 3, 2012, September 26, 2013, and September 23, 2014.

**Grape Quality.** Samples of harvested fruit (1 gallon Ziploc full) were taken for berry analysis. This fruit was blended using a Waring model 31BL91 commercial lab blender (Waring Commercial, Torrington, CT) and 200 ml of pulp was frozen in a Kenmore heavy duty upright freezer model # 253 (Sears, Roebuck and Co., Hoffman Estates, IL) at –10°C until the time of analysis. Total soluble solids (°Brix) was determined using a digital refractometer model 300016 (Kernco Instruments Co., El Paso, TX). TA and pH were determined using a DMS Titrino Metrohm auto tritrator (Brinkmann Instruments, Inc., Riverview, FL) and total color and phenolics were analyzed with a Shimadzu UV-1800 spectrophotometer (Shimadzu Corporation, Nakagyo-ku, Kyoto) using standard methods (Iland, 2004).
**Pruning Weight.** Pruning weight was collected after the 2013, and 2014 field seasons. They were not collected during the first two field seasons (2011, 2012) as the grower pruned late in the fall before pruning weight could be sampled. Pruning weight was measured on a per vine basis. Vines 2 to 8 from the 10 sample vines were pruned to simulate minimal pruning by mechanical operations; at 30 cm below the trellis wire. The shoots removed were collected into a 5 gallon bucket and weighted using a digital fish scale (Berkley, Spirit Lake, IA). A subsample of ~ 20 one foot cuttings were taken from each treatment row. These cuttings were then weighed using an APX-1502 Model balance (Denver Instrument, Bohemia, NY), dried in an oven (manufacturer unknown) at 42°C for a minimum of 24 hours, and then reweighed to determine water content.

**Statistics.** SAS 9.4 software (version 6.2.9200; SAS Institute Inc., Cary, NC) was used for data analysis. The results were subjected to a general linear model (Proc GLM) analysis of variance (ANOVA).

**Results and Discussion**

**Weather.** The temperature varied dramatically from year to year during the trial. Each season during the trial period increased in accumulated GDD (Table 3.1, Fig. 3.3). However, the total ET₀ for the growing season remained relatively constant around 963 mm (Table 3.1). Precipitation during the growing season was low and tended to be concentrated at the beginning and end of the growing season (Fig. 3.4).

**Paso panel.** Paso panel measurements were a relative indication of total canopy size. The larger the Kₑ value the greater the canopy size. The shaded area measurements provided a unique look into canopy variability. Low values indicated a very dense/large canopy, while high numbers indicated a small or underdeveloped canopy. The Paso panel measurements for shaded
readings ranged from 0.02 to 0.95 indicating that the ‘Concord’ canopy was highly variable (data not shown).

There were several factors that resulted in the variability of the ‘Concord’ canopy. The vineyard was 21 years old and there were several areas where vines had been replaced for various reasons (tractor damage, vine death, etc.). This lead to smaller or underdeveloped canopies in newer vines possibly due to a difficulty in establishing new plants in an existing vineyard due to ‘Concord’ replant disorder (Proano Garcia, 2014). Additionally, the existing vines on either side of the replaced vine tended to be larger and occupied a longer section of trellis wire. These conditions contributed to high variability within a single row. Additionally, there was variability between different rows within the vineyard. The height of the single trellis wire was approximately 1.8 m, but in some areas the wire was closer to 1.2 m. Differences in height limited the total measurable size of the canopy as the Paso panel only measured the shaded area of the canopy above the solar panel. However, the variability in the canopy was minimized by taking a large number of readings per row to ensure a representative mean value.

Although there was a high degree of variability in the shaded area readings, the sample size was large enough (36 readings per treatment) to minimize the effects of the variable canopy on the $K_c$. The maximum $K_c$ values were highest in 2011. The very low treatment had a $K_c$ of 0.78, while the high, moderate, and low treatments were 0.76, 0.76, and 0.77 respectively. These results were not completely representative of the treatments applied because it was the first field season in a perennial crop. Additionally, the canopy was fully established prior to the imposition of water deficits. In 2012, the highest $K_c$ value was from the high (0.67) and the moderate and low treatments were closely grouped (0.64, 0.66), but the very low treatment was 0.59. This trend continued through the next two seasons. The very low treatment always had the lowest
maximum $K_c$ value, at 0.58 and 0.59 for 2013 and 2014, while the other treatments averaged 0.65 (Fig. 4.2).

The vines reached their maximum $K_c$ values by day of year (DOY) 190 in all treatment years, with the exception of 2011. After DOY 190 the values began to decline slightly. The high, moderate, and low treatments were very closely grouped, indicating very similar canopy size between the treatments; however, the very low treatment always had lower values than the rest of the treatments (Fig. 4.2). This could indicate a critical point of water stress at which canopy size was significantly reduced.

Additionally, any management practices that manipulate the canopy can increase or decrease the $K_c$. For example Williams and Ayars (2005) found that when they raised the canopy curtain of *Vitis vinifera* L. cv. Thompson Seedless, the $K_c$ value increased from a value of 0.9 to 1.3 due to the increase in exposed canopy. The $K_c$ values dropped again once the curtains were lowered (0.95) and decreased further once the vines were hedged (0.8). Although this was typically not a concern in ‘Concord’ grapes as minimal canopy management was practiced, it is important to be aware of, as removal of low hanging shoots/leaves by either mechanical or chemical treatments to prepare for harvest will affect the $K_c$.

Furthermore, because grapevine shoot growth is very sensitive to water stress, it is recommended to only use the $K_c$ values measured from fully watered vines (Battany, 2006). Measurements taken from a water stressed grapevine will not reflect full ET as ET is reduced under water stress conditions, due to limited shoot growth. This could result in a determination that the grapevine $ET_c$ was lower than it actually was and any reduction for RDI would be more severe than originally estimated. However, there was no evidence of such a negative feedback in the data from this study. This was probably because the stress period was very limited, lasting
between 80 and 92 days. \( K_c \) measurements remained lower for the most severe treatment (4) but there was no dramatic decreases in \( K_c \) as the treatment period progressed (Fig. 4.2). The most likely explanation for the large drop in \( K_c \) in the very low treatment was that the growth potential for the following season was limited due to the limited irrigation. The smaller canopy size probably resulted in a lower number of healthy compound buds in the spring, as the shoot growth rate was not significantly different between the treatments. A smaller number of shoots would result in a smaller \( K_c \) value.

The total accumulated \( E_{T_0} \) for the treatment period and the rate at which it accumulated, 6 mm/day, remained constant throughout all four seasons (Fig. 4.3). However, the timing of the treatment period shifted in terms of day of year because of the disparity in accumulation of GDD (10 °C) prior to the treatment period. In 2011, the treatment period began on day 171 at 283 GDD (1 April). The treatment period began earlier in 2012, on day 155 at 279 GDD. The final two seasons began even earlier on day 142 and 147 at 248 and 262 GDD respectively. This indicates that despite variation in the day of year the beginning of the treatment period (bloom) corresponded to the accumulation, at minimum, approximately 250 GDD.

The accumulated \( E_{T_c} \) for the treatment period in 2011 was 325 mm for the high, low, and very low treatments and 324 mm for the moderate treatment. As the trial progressed there was more separation between the very low treatment and the other treatments (Table 4.3). The difference between the high and very low treatment was 44 mm, 28 mm, and 26 mm, in 2012, 2013, and 2014. This difference corresponded with the Paso panel measurement indicating that the canopy of the very low treatment was smaller than that of the other treatments. Changes in the \( E_{T_c} \) between the treatments was solely the result of changes in the \( K_c \) value, as the \( E_{T_0} \) did not change with regard to treatments.
**Soil Water Content.** In 2011 the soil water content in the root zone fluctuated greatly from the initial soil water content in the spring (Fig. 4.4). Generally, there was a decrease in soil water content across the treatment period for the moderate to very low treatments. This trend continued past the end of the treatment period and resulted in a loss of between 25 and 35% of the initial soil water content for the season. However, the high treatment ended the season with a soil water content 25% higher than the initial measurement. At the beginning of the treatment period in 2011 all the treatments were grouped together and they stayed grouped for approximately one third of the trial period. At DOY 207, the high and moderate treatments increased in soil water content and continued to match each other until DOY 220, when the moderate treatment decreased in soil water content to the level of the low and very low treatments. The high treatment remained separated from the rest of the treatments through the end of the season.

When examining the soil water content below the root zone in 2011 there were trends similar to what was observed in the root zone (Fig. 4.4). All the treatments, except for the high treatment, decreased in soil water content by 35 to 40% over the season. The high treatment increased soil water content by approximately 15%. The fluctuations in soil water content were not as large below the root zone. At the beginning of the treatment period the high and very low treatments had higher soil water content than the moderate and low treatments. This continued until DOY 207 when all the treatments converged and were not statistically different for two additional measurements (DOY 213 and 220). A difference did develop again on DOY 228 when the high treatment increased in soil water content. That increase was maintained throughout the remainder of the season, while the other treatments continued to decrease.
The subsequent years of the trial exhibited the same general trends as 2011 (Figs. 4.5 – 4.7). There was a decrease in soil water content in both the root zone and below the root zone throughout the trial period and the rest of the season, except for 2013 when there was a small increase at the final measurement over the initial measurement (Fig. 4.6). The high treatment tended to have a slightly higher soil water content, but was not significantly different, than the other treatments. Again, fluctuations in soil water content were more intense in the root zone than below the root zone. It took longer to develop the same percentage loss in soil water content below the root zone than in the root zone. For example, on DOY 195 in 2012 treatment 3 SWC in the root zone had decreased by approximately 35%, while it had only decreased by just under 20% below the root zone (Fig. 4.5).

The general trend for soil water content in and below the root zone was a gradual decrease over the season. This was a result of increasing ETc and decreasing water applications (RDI). Plants under RDI (low and very low treatments) relied on stored soil water, resulting in a loss of stored soil water. The degree of water loss did not necessarily correlate with the degree of deficit. For example, in 2012 through 2014, the moderate and low treatments often lost a greater amount of soil water than the very low treatment (Figs. 4.5 – 4.7) even though when less water was applied vines were more likely to rely on stored water versus supplemental irrigation.

**Shoot Length.** There was a significant difference ($\alpha = 0.05$) by year ($P <0.0001$), but no difference by treatment or the interactive effect of Year*Treatment of shoot growth rate. After further analysis to eliminate the influence of the year, there was no significant differences between treatments in any year, except for 2011. There was a significant difference in the growth rate between treatments ($P = 0.0184$). The means for the high through the very low treatments in 2011 were 0.87ab, 0.65b, 0.72b, and 1.13a respectively. Using the Duncan-Waller means
separation it was determined that the very low treatment was significantly different from the moderate and low treatments, but not significantly different from the high treatment. Additionally, the moderate and low treatments were not significantly different from each other or the high treatment.

The reduced water application treatments (moderate, low and very low) did not have an effect on shoot growth rate. There were no significant differences in shoot growth rate based on treatment throughout the entire trial, except for 2011. This was likely because the majority of shoot growth had occurred prior to or during the beginning of the treatment period before significant soil water deficits had developed (Fig. 4.8). The difference that occurred in 2011 was likely caused by differences in soil moisture prior to the treatment period as the very low treatment had the highest growth rate and the longest total shoot lengths (Fig. 4.8). Even though shoot length is one of the first indicators of water stress the total shoot length was not affected as deficit treatments were not applied until after bloom.

**Yield.** The yield in 2011 was variable. The very low treatment had the highest yield at 22.57 Mg/ha followed by the low at 21.28 Mg/ha, the moderate at 20.71 Mg/ha, and the high at 15.4 Mg/ha (Fig. 4.9). In 2012, all yields decreased, but the moderate to very low treatments dropped dramatically (Fig. 4.10). The moderate, low, and very low treatments yielded 12.50, 14.61, and 7.53 Mg/ha in 2012, while the high treatment yielded 19.24 Mg/ha. Yields increased in 2013 to 28.02, 28.25, 22.42, and 18.26 Mg/ha. In 2014, yields decreased for the high and moderate treatments, 23.44 and 22.10 Mg/ha, while the low and very low treatments remained consistent at 22.07 and 18.74 Mg/ha (Fig. 4.9).

The biggest source of variability in yield was between years differences \( P = 0.0002 \). Therefore, yields were sorted by year and tested again to determine if the treatments had any
significant impact on yield. There were no significant differences in yield by treatment during the trial period, except for 2012. In 2012 there was a significant difference between the high treatment (19.24 Mg/ha) and the very low treatment (7.53 Mg/ha) (Fig. 4.9). Although the differences in yield were generally not statistically significant, they were likely biologically and/or economically significant. Because the price for ‘Concord’ grape is based primarily on tonnage, any decrease in yield, even slight, has the possibility of dramatically affecting the grower’s economic viability especially when the price per ton drops to current levels of $110 per ton (J. Davenport, personal communication).

The percent change in yield as compared to the control was calculated and in 2011 the moderate, low, and very low treatments had an increase in yield of approximately 40% as compared to the control. However, the yield for this year was more influenced by the previous season (2010) than the treatment applied in 2011 because grapes are a perennial crop whose crop potential for the following season is determined in the current year (Williams, 2000; Wample and Smithyman, 2002). The yields in 2012 were a better reflection of the effects of the applied treatments. The moderate, low and very low treatments all decreased in yield by 35%, 24% and 61% respectively as compared to the control. Over the next two seasons the severity of decrease lessened and recovered to match the yield of the high treatment (Fig. 4.10).

The severe decrease in yield from 2011 to 2012 was a good indication of what growers could expect in water short years when they cannot apply the amount of water that they would normally. However, as the treatments were repeated over several years the percent change stabilized. Within a year, the decrease in yield suffered by the moderate treatment recovered, and matched the yield of the control (Fig. 4.10). After two years both the moderate and low
treatments recovered from the initial decrease in yield, and the very low treatment, while it did not fully recover, only had a 20% decrease compared to the initial 60% decrease (Fig. 4.10).

One possible reason for the recovery of the yields for the moderate, low, and very low treatments was the vines were adapting to the decrease in soil water content by shifting root growth to areas of high soil water content. There has been research indicating grapevines redistribute roots both vertically and horizontally (Celette et al., 2008). In the high treatment, the soil water content was very high throughout the season, while during the treatment period the highest concentration of soil water was directly under the drip emitters. Therefore, instead of being able to utilize the entire root volume that was established under high soil moisture conditions, the vines under moderate, low, and very low treatments only had a fraction of their roots available to take up water. Celette et al. (2008) found that grapevines primarily take up water from directly under the row and at depth when a cover crop was present, because the time-shift between the two crop cycles created a dry zone in the inter-row space prior to grapevine shoot emergence. They found as much as a 50% reduction in root length density in the inter-row beneath the cover crop. However, after the second year of deficit applications the vines had adapted to where water was going to be and possibly increased the amount of feeder roots in that area to compensate for the lack of soil water content in other areas. Soar and Loveys (2007) found when changing from sprinkler to drip irrigation the roots of ‘Cabernet Sauvignon’ and ‘Shiraz’ grapes concentrated under the drip line, but they also found that there was no reduction in root volume in the mid-row, leading them to believe that the roots within the wetting zone were funneling water to the roots in the dry zone.

There was potential for water savings by reducing the quantity of water applied to ‘Concord’ vineyards from bloom to veraison. However, it would require a gradual reduction in
water applications to avoid sharp decreases in yield, like that experienced during 2012. Adopting the moderate treatment would potentially save 25-50% of water currently applied, the low treatment could save 40-65%, and the very low treatment would provide the greatest savings, however the longer recovery period would make it unfeasible.

**Grape Quality.** Soluble solids (°Brix) was the most important quality factor for ‘Concord’ growers and was the parameter used to determine the acceptability of grapes at local processors. The minimum standard for soluble solids was 15 °Brix. The fruit from 2011, 2012, and 2013 met that standard (Table 4.4) with the exception of the low treatment in 2011. There were no statistical differences between soluble solids between treatments in any treatment year. In 2011, the °Brix values for the high, moderate, low, and very low treatments were 16.1, 15.4, 14.8, and 15.3 respectively, while in 2012 the values were 16.1, 17.4, 17.1, and 18.0 °Brix respectively. In 2013, the °Brix values for the high, moderate, low, and very low treatments were 17.0, 18.0, 18.3, and 18.3 respectively. Although there were no statistical differences in the °Brix values, there was a trend of slightly increased °Brix values in the low and very low treatments in 2012 and 2013. However, fruit from the low and very low treatment in 2014 fell below that standard (14.5 and 14.9 °Brix). This was most likely a result of the exceptionally hot season, ‘Concord’ grapes will shut down after at high temperatures. This slows berry development and sugar accumulation. As a result, sugar levels in ‘Concord’ grapes during hot years do not reach as high a level as a warm or average year.

There were no statistical differences between treatments in any of the other parameters measured; pH, titratable acidity (TA), color (A520), and total phenolics (A280), (Table 4.4). The values of the quality parameters were consistent with historical values presented by Johnson and Nagel (1976). The pH of the ‘Concord’ berries averaged 3.45, 3.59, 3.71, and 3.64 across all
treatments for 2011, 2012, 2013, and 2014 respectively. The reported value for ‘Concord’ grape berries was approximately 3.6 by October 3 (Johnson and Nagel, 1976). The difference in 2011 was likely related to the cool season since acid concentrations remain higher in grapes produced under cool conditions (Buttrose et al., 1971). TA was high in 2011 as it was a cooler season and there was overall more acid present in the berries. However, the TA did not follow the trend of decreasing within increasing temperature, but remained relatively constant between 4.5 and 5.5 g tartaric acid/L in 2012, 2013, and 2014. The color (A520) ranged and widely and did not remain consistently low or high based on any single treatment. Johnson and Nagel (1976) reported absorbance of approximately 0.8 in early October, which this trial matched in 2011 and 2013, but was below in 2012 and 2014. The total phenolics remained constrained to a relatively small range in values across all treatments and years, absorbance of 0.20 to 0.25. These values and the lack of statistical significance between treatments indicated that the berry quality was not directly or solely influenced by the treatments.

**Pruning Weight.** In 2013, the average pruning weight per vine was 0.28, 0.19, 0.17, and 0.14 kg/vine in the high, moderate, low, and very low treatments respectively. The high treatment was significantly different from the other treatments. However, in 2014, there were no statistical differences by treatment: 0.18, 0.12, 0.12, and 0.12 kg/vine in the high, moderate, low, and very low treatments respectively. High irrigation rate vines were not limited by a soil water deficit, while the moderate, low, and very low experienced a low deficit. However, the shoot growth rates were not significantly different between treatments in either 2013 or 2014. Thus, the mass of the shoots were likely responsible for the difference seen in 2013. It is possible that there was no difference in 2014 due to sustained high temperatures.
Conclusion

Regulated deficit irrigation (RDI) is common in other sectors of grape production, but not prevalent in the production of juice grapes. The reduction in water applied over a given time period has the potential to reduce total water use and potentially improve berry quality as with the wine grape industry. In this experiment the RDI treatments, moderate, low and very low treatments, did not reduce the shoot growth rate as compared to the high treatment, over the treatment period, because the canopy was already well established prior to the imposition of deficit treatments. As a result, there was no reduction in soluble solids, which require a large canopy area to fully ripen the fruit to minimum levels (15° Brix). Further, there was no statistical difference between treatments for pH, TA, color, or total phenolic compounds. However, RDI had a short term effect on yield. The yield was reduced by 20 to 60 % in the second season, but the vines were able to adapt to the reduced water applications and the moderate and low treatments were able to match the yield of the control, high treatment.

Overall, RDI has the potential to reduce the water usage of ‘Concord’ grapes, however, industry might be reluctant to implement such a strategy because of the short term losses in yield. In water short years, this research would allow industry to determine potential crop loss.
Literature Cited


Tables

Table 4.1: Summary of treatment including total water applied between bloom and veraison based on grower supplied information.

<table>
<thead>
<tr>
<th>Water Application</th>
<th>Percentage Reduced from Control</th>
<th>Total Water Applied (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2011</td>
</tr>
<tr>
<td>High</td>
<td>0</td>
<td>na</td>
</tr>
<tr>
<td>Moderate</td>
<td>~ 25%</td>
<td>108.2</td>
</tr>
<tr>
<td>Low</td>
<td>~ 33%</td>
<td>92.2</td>
</tr>
<tr>
<td>Very Low</td>
<td>~ 45%</td>
<td>76.0</td>
</tr>
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Start and End of Treatment Period (DOY)

<table>
<thead>
<tr>
<th></th>
<th>171</th>
<th>251</th>
<th>155</th>
<th>236</th>
<th>142</th>
<th>231</th>
<th>147</th>
<th>239</th>
</tr>
</thead>
</table>

Total Days in Treatment Period

<table>
<thead>
<tr>
<th></th>
<th>80</th>
<th>81</th>
<th>89</th>
<th>92</th>
</tr>
</thead>
</table>

Table 4.2: Timing of dry down measurements in 2012 and 2013.

<table>
<thead>
<tr>
<th>Pre-Irrigation</th>
<th>Dry Down</th>
<th>24 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>na</td>
<td>6:15 7:45</td>
</tr>
<tr>
<td>2013</td>
<td>14:40</td>
<td>6:30 8:00</td>
</tr>
</tbody>
</table>
Table 4.3: Accumulated ETc from bloom to veraison for all four treatment years. The ETc values were expressed in mm.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>325</td>
<td>294</td>
<td>291</td>
<td>338</td>
</tr>
<tr>
<td>Moderate</td>
<td>324</td>
<td>281</td>
<td>295</td>
<td>337</td>
</tr>
<tr>
<td>Low</td>
<td>325</td>
<td>287</td>
<td>291</td>
<td>333</td>
</tr>
<tr>
<td>Very Low</td>
<td>325</td>
<td>250</td>
<td>263</td>
<td>312</td>
</tr>
</tbody>
</table>

Table 4.4: Summary of berry quality results. Parameters include soluble solids (°Brix), pH, titratable acidity (TA) g/L tartaric acid, color (A520), and total phenolics (A280). There were no statistical differences between measured parameters.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Year</th>
<th>°Brix</th>
<th>pH</th>
<th>TA</th>
<th>A520</th>
<th>A280</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>2011</td>
<td>16.1</td>
<td>3.49</td>
<td>7.34</td>
<td>0.099</td>
<td>0.24</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td>15.4</td>
<td>3.43</td>
<td>7.53</td>
<td>0.080</td>
<td>0.21</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td>14.8</td>
<td>3.43</td>
<td>6.81</td>
<td>0.088</td>
<td>0.23</td>
</tr>
<tr>
<td>Very Low</td>
<td>High</td>
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<td>3.45</td>
<td>7.05</td>
<td>0.078</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>16.1</td>
<td>3.61</td>
<td>4.58</td>
<td>0.044</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
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<td>3.58</td>
<td>4.50</td>
<td>0.043</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Low</td>
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<td>3.57</td>
<td>4.34</td>
<td>0.048</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Very Low</td>
<td>18.0</td>
<td>3.59</td>
<td>4.55</td>
<td>0.052</td>
<td>0.22</td>
</tr>
<tr>
<td>High</td>
<td>2013</td>
<td>17.0</td>
<td>3.70</td>
<td>4.47</td>
<td>0.062</td>
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</tr>
<tr>
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<td>3.70</td>
<td>4.34</td>
<td>0.063</td>
<td>0.23</td>
</tr>
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<td>18.3</td>
<td>3.75</td>
<td>3.80</td>
<td>0.070</td>
<td>0.25</td>
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<tr>
<td>Very Low</td>
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<td>18.3</td>
<td>3.68</td>
<td>4.25</td>
<td>0.080</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>15.6</td>
<td>3.70</td>
<td>5.33</td>
<td>0.052</td>
<td>0.24</td>
</tr>
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<td>14.5</td>
<td>3.66</td>
<td>5.20</td>
<td>0.044</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Very Low</td>
<td>14.9</td>
<td>3.60</td>
<td>5.30</td>
<td>0.043</td>
<td>0.23</td>
</tr>
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</table>
Figure 4.1: Layout of irrigation valves. Additional irrigation lines were connected to existing mainlines through the vertical connection on the right. A main shutoff valve was connected and the three treatment valves (Treatments 2, 3, 4) were added at a 45° angle to keep them close to the vine row (prevent damage from equipment). Timer controlled valves (not shown in picture) were used to control the quantity of water applied to each treatment.
Figure 4.2: Crop coefficients during the treatment period for 2011 to 2014.
Figure 4.3: ET$_o$ during the treatment period. This graph shows that the accumulation of ET$_o$ over the treatment period was very similar across the four year trial period at a rate of approximately 6 mm/day, but the differences in temperature prior to the treatment period shifted the timing. The first year, 2011, was a cool year, thus the treatment period began later on day 171. 2012 was an average year with the treatment period starting on day 155, while 2013 and 2014 were very warm starting on day 142 and 147 respectively.
Figure 4.4: Soil water content in the root zone (A) and below the root zone (B) during the 2011 season. The primary y-axis is soil water content in percent (v/v) and the secondary y-axis indicates the percent change from the initial measurement. The treatment period for 2011 begins on day 171 and ends on day 251.
Figure 4.5: Soil water content in the root zone (A) and below the root zone (B) during the 2012 season. The primary y-axis is soil water content in percent (v/v) and the secondary y-axis indicates the percent change from the initial measurement. The treatment period for 2012 begins on day 155 and ends on day 231.
Figure 4.6: Soil water content in the root zone (A) and below the root zone (B) during the 2013 season. The primary y-axis is soil water content in percent (v/v) and the secondary y-axis indicates the percent change from the initial measurement. The treatment period for 2013 begins on day 142 and ends on day 231.
Figure 4.7: Soil water content in the root zone (A) and below the root zone (B) during the 2014 season. The primary y-axis is soil water content in percent (v/v) and the secondary y-axis indicates the percent change from the initial measurement. The treatment period for 2014 begins on day 147 and ends on day 239.
Figure 4.8: Total shoot length over treatment period. Each year is indicated by a different color: 2011 yellow, 2012 green, 2013 red, and 2014 blue. The treatments are indicated by different point icons: treatment 1 circle, treatment 2 triangle, treatment 3 an x, and treatment 4 a plus sign. This graph indicates that the majority of the shoot growth has occurred rapidly at the beginning of the treatment period and begins to diminish by approximately 650 GDD. The slope of each line is the rate of growth.
Figure 4.9: Concord yield. This figure shows the total yield in Mg/ha for each treatment during the study period. Error bars indicate one standard deviation.

Figure 4.10: Percent change in yield by treatment. Treatment 1 was omitted as it was the baseline for comparison.
Chapter 5

SUMMARY AND CONCLUSIONS

The goals of this project were to determine the effects of a range of water deficits on soil water distribution, yield, and quality of ‘Cabernet Sauvignon’ wine grapes (Vitis vinifera L.) and ‘Concord’ juice grapes (Vitis labruscana Bailey). This project was conducted in a commercial vineyard located in the Yakima Valley American Viticulture Area, near Sunnyside, WA. The results of this project will help to better optimize water usage in drought years when water is limited.

Soil water content was intensively sampled at three times during the growing season to characterize the temporal and spatial patterns of soil water distribution during the growing season (April-October), determine differences resulting from deficit irrigation regimes, and ascertain if soil moisture can be replenished to pre-deficit levels prior to the end of irrigation water availability in this growing region (November). In both ‘Cabernet Sauvignon’ and ‘Concord’ vineyards, soil water content was high in the spring due to overwinter refill coupled with early season irrigation applications, leading to uniform spatial distribution of soil water. Deficit irrigation treatments dried the soils to permanent wilting point at veraison, but increased in soil water content to near or above field capacity by the fall. Thus, the soil water content can be replenished in a short period following a period of severe regulated deficit irrigation (RDI).

The soil water content decreased with increasing distance from emitter. This was evident when examining the cross section profile of the vine row. The wetting pattern was very narrow and centered on the drip line. The majority of the available soil water content was within a 100 cm strip centered on the drip emitter. Deficit irrigation in both vineyards severely limited the lateral movement of soil water. However there was uniform distribution below the drip line.
In the ‘Cabernet Sauvignon’ vineyard, the effect of several levels of RDI on yield and quality was investigated. The treatments increased the amount of water applied by 1/3 of current grower applications during the treatment period. The treatment period was determined by vine growth stage. The low deficit increased the amount of water applied all season, while the water applied in the moderate and high deficit treatments were increased prior to bloom and post-veraison and post-veraison respectively.

Shoot growth was measured as an indicator of vine water stress, but there were no significant differences based on treatment, and the growth rate was not limited likely because the deficits were not applied early enough to influence shoot growth. Yields were increased by the application of additional water, but the increased yields did not significantly differ by treatment. The most consistent increase in yield resulted from the increase in water applied post-veraison. The high deficit treatment showed a 1 to 1 ratio of increase in water applied to increase in yield. The low and moderate deficit treatments also resulted in increases, but they were less consistent across the trial period and had a lower increased water to increased yield ratio. There were no statistical differences in standard berry quality parameters (°Brix, pH, TA). Therefore, quality was not solely dependent on level of irrigation and extreme deficits did not necessarily improve berry quality. Moderate deficits result in higher yields with similar, if not equal, berry quality.

In the ‘Concord’ vineyard, three levels of deficit irrigation were compared to current grower practice. The treatment period was limited to between bloom and veraison. The moderate, low, and very low treatments were 35, 45, and 60% reductions from the current (grower practice) levels. Shoot lengths were measured to assess water stress and there was no reduction in growth rate by treatment. Yields were reduced considerably in 2012, but in the following year (2013) the moderate irrigation rate treatment yielded the same as the high
(control) treatment. In 2014, both the moderate and low treatments yielded within 1 Mg/ha of the high treatment, suggesting that the yield loss was a temporary plant response to reduced water supply. This could be a result of root adaptation to changing volumes of soil water availability. ‘Concord’ grape quality parameters did not statistically differ between irrigation treatments.

There was a general trend in 2012 and 2013 of the low and very low treatments having slightly higher °Brix levels, but lower in 2014, although none of the differences were statistically significant. The 2014 decrease in Brix may have been related to high temperatures all season, which can delay ripening in ‘Concord’ vines.

Overall, soil water content fluctuated seasonally, especially under deficit irrigation, where the soil dried to permanent wilting point at veraison. Soil water content was limited to within 50 cm of the drip line, and the soil water content decreased with increasing distance from the emitter. This implies that the majority of the vine root system would be concentrated in a narrow zone where soil water is plant available. In the ‘Cabernet Sauvignon’ the timing of water application was important to maximizing increases in yield. Increasing water application after veraison provided the best return or the most “crop per drop.” While, deficit irrigation in ‘Concord’ grapes will reduce yield initially, recovery is possible even if treatments are sustained over multiple seasons.