2014

The effects of canopy management practices on fruit quality of northern-hardy interspecific hybrids of Vitis spp.

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The effects of canopy management practices on fruit quality of northern-hardy interspecific hybrids of *Vitis* spp.

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Horticulture

Program of Study Committee:
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Iowa State University

Ames, Iowa

2014

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. Gail R. Nonnecke, and my committee members, Dr. Rajeev Arora, Dr. Paul Domoto, and Dr. Lester Wilson, for their guidance and support throughout the course of my study and this research.

In addition, I would also like to thank my friends, colleagues, and the Department of Horticulture's faculty, staff, and students and Global Resource Systems major for making my time at Iowa State University a wonderful experience. I offer my appreciation to Mr. and Mrs. John and Diane Larson, of Snus Hill Winery in Madrid, Iowa and Mr. and Mrs. Stan and Joanie Olsen, of Penoach Winery in Adel, Iowa for their willingness to participate and aid in the implementation of these experiments in their commercial vineyards. I would like to also recognize the hard work and dedication of my undergraduate research assistants throughout this project: Lexie Boyens, Sam Ennett, James Nesbit, Danika Schaff, Malcolm Smith, Hannah Wallace, and Colin Weaver.

Special thanks go to the Northern Grapes Project, funded by the USDA's Specialty Crops Research Initiative Program of the National Institute for Food and Agriculture, Project #2011-51181-30850 for providing funding to complete the project. I also thank the Midwest Grape and Wine industry Institute for their generous assistance in fruit quality analyses.

Finally, thanks to my friends and family for their encouragement and to Ms. Lauren Parker Davis for her hours of patience, respect and love.

ABSTRACT

The recent release of interspecific hybrid grape cultivars that are hardy for the northern climates of the United States has led to a rapid expansion of the grape and wine industry in the Upper Midwest, as well as other cold-climate regions. These cultivars often exhibit high vegetative vigor and possess fruit quality concerns when their grapes are to be used in wine production. Adaptation in the viticultural practices used to produce the grapes may help to improve fruit quality for winemaking, which could promote increased sales and profitability of the grape and wine industry in the Upper Midwest.

This study examines the effectiveness of three canopy management practices to improve irradiance within the fruiting zone of the grapevine canopies of Frontenac, La Crescent, and Marquette grapevines, and their impact on fruit quality for winemaking. The labor required completing the management practices, irradiance, harvest variables, and fruit quality were measured.

All canopy management practices required additional labor and provided increased irradiance into the fruiting zone. However, the increased irradiance did not correspond to improved fruit quality. These effects varied across the different cultivars, and no overall relationship between increased labor and increased irradiance or between increased irradiance and improved fruit quality was established across the cultivars. While Frontenac vines required an average of 5.6 additional minutes of labor per vine for any canopy management practice, the practices increased irradiance by about 10.1%. La Crescent vines required an average of 4.4 additional minutes of labor per vine for any canopy management practice and the practices increased irradiance by 16.5% on average. Marquette vines required an average of 7.7

additional minutes of labor per vine for any of the canopy management practices, which led to a 19.5% averaged increase in solar irradiance. The effects of the increased irradiance on fruit quality showed minor potential for improvement in quality by lowering malic acid content with shoot thinning in La Crescent.

CHAPTER 1. GENERAL INTRODUCTION

Thesis Organization

This thesis is organized into three chapters and written in the format of the American Journal of Enology and Viticulture. Chapter one includes a general introduction, which includes a literature review and an introduction to the research. Chapter two includes a manuscript, and chapter three provides general conclusions.

Introduction

Iowa Grape and Wine Industry. Wagner (1965) provides a brief history of the American grape and wine industry in his book, A Wine-Grower's Guide. *Vitis vinifera* L., the species that encompasses all classic grapes of the Old World, originated in the Middle East, in the Caucasus Mountains region. From here it spread to many parts of the world including Asia, Europe, Africa, and South America. When settlers first arrived in North America, they were enthusiastic about the prospects of growing grapes and making wine because America had a rich diversity of native grape species that grew in almost every region of the country. However, the settlers found that the wine created from these native grapes was different from the wine from *V. vinifera* grapes, and they decided to import *V. vinifera* from Europe. Unfortunately, *V. vinifera* vines were not adapted to many of the climatic regions of eastern North America due to low temperature injury and the prevalence of indigenous diseases in humid summers to which the *V. vinifera* vines had no tolerance or resistance.

While settlers east of the Rocky Mountains were struggling to find ways in which they could establish *V. vinifera* vineyards, mission friars from Mexico were successful in planting *V.*

vinifera ‘Mission’ grapes in what became the State of California. With the collapse of the mission system in the 1830s, the private wine grape and industry grew rapidly in California, and a larger selection of *V. vinifera* varieties began to flourish in California’s climate. Between 1800 and 1840, vintners in the eastern United States began growing seedlings of native *V. labrusca* varieties, such as Catawba, Isabela, Elvira, and Delaware. The first classical breeding of these grapes was conducted in 1843 as an improvement on the Catawba grape, creating Diana. The winemakers in eastern United States and Canada did not find the wine to be of a quality similar to that produced from the *V. vinifera* grapes.

While natural selections and hybridization of American species were being accomplished in eastern United States, Europeans were dealing with infestations of grape Phylloxera (*Daktulosphaira vitifoliae* Fitch). The insect, which is native to North America, was imported to Europe on grapevine tissue and decimated the European *V. vinifera* grapevines, which had no tolerance or resistance to the insect pest. It was soon noted that while the pest was prevalent in America, the native grapes were not impacted, and therefore must have resistance to Phylloxera.

The French grape growers began to experiment with hybridization of the American varieties to provide Phylloxera resistance with the European *V. vinifera* varieties to provide high quality wine grapes (Wagner 1965). This research led to the establishment of the French hybrids, which were grown in Europe as well as many parts of North America today. In fact, the introduction of the French hybrid grapes led to the expansion of the wine industries in Maryland, New York, Ohio and Pennsylvania in the 1970’s. Eventually, the French grape growers imported several American species to use as Phylloxera-resistant rootstocks, in order to incorporate resistance to root damage from Phylloxera while maintaining varietal traits, and the European *V. vinifera* industry was re-established.

It was not until the late 1970s that grape growers in the Upper Midwest were able to see successful production of wine grapes, because most French hybrids lacked sufficient low temperature tolerance. In 1978 Elmer Swenson, in cooperation with the University of Minnesota, released the first cold-hardy grape cultivars that could be used as fresh table grapes or for wine, including Swenson Red and Edelweiss. The University of Minnesota plant breeders continued to develop cold-hardy cultivars, with peak release of cultivars occurring from the mid-1990s through the mid-2000s, and continuing today (Martell 2014).

The recent releases of cold-hardy hybrid grapevines have allowed for the rapid expansion of the grape and wine industry in the Upper Midwest, including Iowa, over the past decade. The State of Iowa had 30 acres in wine grape production in the year 2000, and in 2014 has over 1200 acres; these grapevines are planted at 316 vineyard locations and supply grapes for 97 wineries in 88 of Iowa's 99 counties (IWGA 2014). Iowa wineries produced 491,609 gallons of wine in 2013 (Tordsen 2014). A recent study of the Iowa 2011 grape and wine industry (Tuck and Gartner 2014) showed that the grape and wine industry created a combined $65.2 million in direct, indirect, and induced economic impact. Of this $65.2 million, $56.2 million was derived from the sale, and other economic activity, of cold-hardy grape cultivars specifically. Seventy-seven percent of the wine grapes grown and 88% of the grapes used in wine production in the State of Iowa are from cold-hardy cultivars (Tuck and Gartner 2014). The successful production and marketing of the cold-hardy wine grape cultivars are critical for the sustainability of the grape and wine industry in Iowa.

Iowans consume 1.46 gallons of wine per capita per year or 53% of the national average consumption of 2.73 gallons per capita per year (IWGA 2014). Repeat sales and market expansion will be important factors influencing the future of Iowa's grape and wine industry.

The improvement of Iowa's wine quality may be an effective way to improve customer retention and increased marketability of Iowa's wines from cold-hardy grapes. Three of Iowa's most widely grown, cold-hardy cultivars include Frontenac, La Crescent, and Marquette. Frontenac and Marquette comprise 23% and 33% of Iowa's red cold-hardy grapevines, respectively, and La Crescent comprises 20% of the total white cold-hardy grape production in the state (Tuck and Gartner 2014). Improving the quality of the grapes, and subsequently wines, produced by these cultivars may have positive implications for the future of Iowa's grape and wine industry.

***Vitis* species and cold-hardy cultivars.** Smiley et al. (2008) highlight three primary environmental limitations facing Iowa grape growers. The first is that of cold-tolerance. The low winter temperatures of the Upper Midwest are detrimental to a grapevine's growth and development and may even lead to total vine death. The cold-tolerance of any given cultivar is affected by its genetic parentage, its overall health, the relative cropload of the vine, the level of pest and disease control exhibited in the past growing season, and the vine's location within a vineyard. The second challenge is that of late frost events in the spring. Many cultivars of wine grapes will have shoot emergence early in the spring, and if a late frost event occurs, the vines' primary buds in its compound buds are killed (Winkler et al. 1974). If the primary bud is killed, secondary, or even tertiary, shoots may have the ability to produce fruit, but typically are not fully productive. The final challenge presented by Smiley et al. (2008) is the length of the growing season in Iowa. Iowa has a relatively cool climate and in normal years, a long-enough growing season to allow for optimal ripening may not occur. Past research noted that in cooler climates the best wines are produced during the hottest seasons, and that the opposite is true of warmer climates (Winkler et al. 1974). The relative heat accumulation over the growing season is one of the most important factors influencing the quality of cold-hardy wine grapes (Kliewer et al. 1967, Smart and Robinson 1991, Spayd et al. 2002, Winkler et al. 1974).

Other climatic factors, including exposure to sunlight, can have substantial impacts on both the yield and quality of a wine from any given cultivar (Lakso and Kliewer 1978, Ruffner et al. 1976, Smart and Robinson 1991, Winkler et al. 1974). Although some general trends in the effects of climatic conditions on fruit quality have been noted, differences among cultivars within the same species occur (Bisson 2001, Kliewer 1965, Kliewer at al. 1967). The variation in the climatic effects on fruit quality creates a need to understand widely grown cultivars within specific geographic regions. Since the cold-hardy cultivars grown in Iowa exhibit growth habits and fruit quality characteristics different from those of traditional *V. vinifera* parentage (Smiley et al. 2008, Tuck and Gartner 2014), establishing appropriate viticultural practices for new cultivars will be an important and challenging part of expanding a high-quality wine industry.

Three of the primary wine grape cultivars grown in Iowa include Frontenac, La Crescent, and Marquette. Frontenac is a cross between the French hybrid cultivar Landot 4511 and the University of Minnesota *V. riparia* selection #89; the cross was made in 1978 and cultivar released in 1996 (UMN 2012). The cultivar is moderately susceptible to black rot (*Guignardia bidwellii* Ellis [Viala and Ravaz]), Botrytis bunch rot (*Botrytis cinerea* Pers.), and powdery mildew (*Unicinula necator* Schw. [Burr.]). Frontenac is slightly susceptible to downy mildew (*Plasmopara viticola* Burk. and Curt. [Berl. and Toni]) and Phomopsis cane and leaf spot (*Phomopsis viticola* Sacc.). It is susceptible to foliar Phylloxera but resistant to root damage by Phylloxera. The cultivar is productive, cold-hardy to -29°C without exhibiting serious injury, and shows moderately high vegetative vigor (UMN 2012). Frontenac exhibits a mid-season harvest around 20 Sep. in central Minnesota. Yields are high at 6.1-kg/vine on average. Slightly higher sugar content has been noted, averaging 24.8 Brix (UMN 2012), but ranging from 24.0 Brix up to 30.0 Brix (Mansfield 2012a). High levels of titritable acidity have been noted, ranging from 15.1-g/L (UMN 2012) up to 15.4-g/L (Mansfield 2012a). The average pH of Frontenac grapes at maturity is 2.9 (Mansfield 2012a). Vos (2014) found malic acid content (9.6-g/L) to be higher than tartaric acid content (8.1-g/L) at harvest.

La Crescent is an interspecific hybrid containing 45% *V. vinifera*, 28% *V. riparia*, and less than 10% each of *V. rupestris*, *V. labrusca*, and *V. aestivalis*. It was crossed in 1988 and selected for release in 2002 (UMN 2012). La Crescent is moderately resistant to black rot and powdery mildew, but susceptible to foliar Phylloxera and downy mildew. The vine is very cold-hardy, surviving temperatures down to -38°C without exhibiting serious injury, has moderately high vegetative vigor, and is reported to produce an excellent quality white wine (UMN 2012). La Crescent grapes ripen mid-season, around 30 Sep. in Central Minnesota. The yield is considered moderate at 4.58-kg/vine. High sugar and acid levels have been noted to average 25.1 Brix and 11.9-g/L respectively, and the pH averaged 3.05 (Mansfield 2012b). Vos (2014) noted a malic acid content of 9.0-g/L and a tartaric acid content of 4.4-g/L.

Marquette is another interspecific hybrid, which includes parentage of *V. riparia*, *V. vinifera*, and other *Vitis* species. It was crossed in 1989 (UMN 2012) and released in 2006 (Mansfield 2012c). Marquette exhibits very high levels of cold-hardiness, surviving temperatures as low as -38°C without exhibiting serious injury, and was stated to be best utilized for a medium-bodied red table wine. The cultivar exhibits low susceptibility to black rot, Botrytis bunch rot, powdery mildew, and downy mildew. It is moderately susceptible to foliar Phylloxera (UMN 2012). The vine exhibits moderate vigor, and while it is susceptible to spring frost damage, it is relatively productive from its secondary buds' shoots (Mansfield 2012c). The grapes ripen early to mid-season, around 19 Sep. in central Minnesota, and produce moderate yields at 4.78-kg/vine (UMN 2012). The grapes have high sugar and acid contents at 25.9 Brix and 12.0-g/L respectively, and a pH of 3.0 (UMN 2012). Malic acid has been reported at 7.0-g/L and tartaric acid at 6.5-g/L (Vos 2014).

Climatic Effects on Fruit Quality. Improvement of fruit quality of the interspecific hybrids Frontenac, La Crescent, and Marquette needs to be addressed for optimal wine production in Iowa. For making table wines, the range for sugar content should fall between 19.5 Brix to 23.0 Brix for white grapes and between 20.5 Brix to 23.5 Brix for red grapes (Amerine et al. 1972). The titritable acidity needs to be between 7.0 and 10.0-g/L for white wine grape juice (Byers et al. 2003, Dami et al. 2005). The titritable acidity of red wine grape juice should fall between 6.0-g/L and 8.0-g/L at harvest (Dami et al. 2005, Winkler et al. 1974). The pH should be between 3.1 and 3.2 for white grapes and between 3.4 and 3.5 for red grapes (Amerine et al.1972, Dami et al. 2005). Wine grapes are typically harvested when tartaric acid content is 5.0-g/L and malic acid content is between 2.0 and 3.0-g/L for either white or red grapes (Bisson 2001).

Other quality indices suggest that there is an optimal balance between sugar and acidity. According to Bisson (2001), Brix multiplied by the square of pH should be between 220 and 260. For example, if Brix of a grape is 22.0 and the pH is 3.2 this would lead to a balance index of 225.3, which falls within the appropriate range. However, if the grape has a sugar content of 24.0 Brix and a pH of 3.6 the balance index would be 311.0, which falls outside the appropriate range. Coombe et al. (1980) found Brix $\times$ pH^2 to be a better quality predictor at harvest for dry table wines than the traditional Brix : TA ratio. Including pH in the measurement better allows for the possibility of grapes that are high-potassium, high-pH, and high-acidity. Brix × pH^2 also provides a wider and more integral range for comparison that does the Brix : TA ratio (Boulton et al. 1996).

In an investigation of *V. riparia* cultivars, Kliewer (1967) found sugar contents ranging from 20.1 to 31.5 Brix, titritable acidity ranging from 5.8 to 16.2-g/L, and a pH range from 3.54 to 3.87. During this study, Kliewer also found that *V. riparia* generally contain more malic acid (3.8 to 16.9-g/L) than tartaric acid (4.9 to 8.2-g/L), which is atypical for *V. vinifera* grapes.

Cooler weather leads to a decreased rate of ripening, which is historically correlated with lower sugar contents (Hellman 2003), higher titritable acidity (Buttrose et al. 1971, Hellman 2003, Kanellis and Roubelakis-Angelakis 1993, Kliewer and Lider 1970, Robinson et al. 1959, Winkler et al. 1974), and a lower pH (Winkler et al. 1974). However, others have not agreed with this ripening pattern (Winkler et al. 1974). Temperature affects the rates of leaf photosynthesis (Winkler et al. 1974) and grape berry respiration (Kanellis and Roubelakis-Angelakis 1993, Winkler et al. 1974), which greatly affects the composition of the berries at harvest, especially malic acid content.

Photosynthesis and respiration greatly affect the composition of the berries in different ways throughout the growing season. Photosynthesis in the leaves utilizes water from the soil and CO_2 from the atmosphere to create carbohydrates, which are transported to other tissues within the vine, including berries. Some of these carbohydrates are used directly as a source of food for respiration (Winkler et al. 1974). While many of these acids translocate from the leaves into the fruit, there is limited photosynthesis that takes place within the fruit itself, and past studies have shown that the photosynthesis that takes place within the grape berry plays a relatively minor role (Hale 1962). After the leaves reach 30% of their full size they transform from being net utilizers of photosynthates to being net producers of photosynthates (Smart and Robinson 1991, Winkler et al. 1974).

Grape berries go through four stages of development, which correspond to different rates of accumulation and degradation of berry components. During the green stage the berries exhibit a rapid increase in size, retain constant sugar levels, and retain consistently high levels of acidity as malic and tartaric acids increase to their maximum levels (Bisson 2001, Kliewer 1965, Watson 2003, Winkler et al. 1974). The second stage is the ripening stage, which begins at veraison. This stage includes the development of color and the softening of the berries (Winkler et al. 1974). This is the period at which the grapes change from being acid-accumulating organs to sugar-accumulating ones (Bisson 2001, Coombe 1992, Ruffner and Hawker 1977, Sweetman et al. 2009, Watson 2003, Winkler et al. 1974). The third and fourth stages of grape development are the ripe stage and the overripe stage. These stages see an arrest in sugar accumulation while acid levels continue to decrease (Kliewer 1965, Winkler et al. 1974).

Tartaric acid and malic acid are the two principle organic acids in grapes, comprising roughly 90% of the total acids (Coombe 1992, Winkler et al. 1974). Tartaric acid is a secondary product of carbohydrate metabolism and malic acid is an intermediate in the tricarboxylic cycle of grape metabolism (Winkler et al. 1974). While the rate of tartaric acid synthesis remains relatively constant as the leaves age, the rate of malic acid synthesis increases with leaf age. Eventually the synthesis of tartaric acid becomes relatively negligible (Kliewer and Nasser 1966). Tartaric acid may be used during ripening to synthesize glucose and fructose, but it is only utilized in very minor amounts (Winkler et al. 1974). Tartaric acid remains relatively constant in the grape berry throughout the ripening process, and as it is a stronger acid (pKa = 2.98) than malic acid (pKa =3.40), it contributes to a lower pH than malic acid in the ripe grape

(Kliewer et al. 1967). Tartaric acid is not metabolized by cellular respiration, and therefore is largely unaffected by climatic factors, such as increased temperature from sunlight exposure (Kliewer 1965, Peynaud and Maurié 1958, Sweetman et al. 2009, Winkler at al. 1974).

Malic acid rapidly degrades during the ripening process by several mechanisms. The principle mechanism by which malic acid is lost during ripening is that of cellular respiration, as it is used as a source of carbon in the reaction (Bisson 2001, Famiani et al. 2000, Kliewer 1965, Peynaud and Maurié 1958, Ruffner 1982, Ruffner and Hawker 1977, Ruffner and Kliewer 1975, Watson 2003, Winkler et al. 1974). A lower rate of malic acid translocated from leaves to fruit post-veraison also leads to the relative degradation of malic acid content in the berries during ripening (Blanke and Lenz 1989, Hardy 1968, Peynaud and Maurié 1958, Winkler et al. 1974). Other causes behind the degradation of malic acid during the ripening process include movement of potassium from the roots into the fruit, which causes salt formation of many acids, but primarily this causes salt formation of the malic acid. Potassium accumulation in the berries occurs most rapidly from the time of veraison to harvest (Morrison and Noble 1990). When these acids are no longer free because they have been bound by potassium into salts, they do not affect fruit quality for winemaking in the same way as free acids (Kliewer 1971, Kliewer et al. 1967, Saito and Kasai 1968). The reduced ability of berries to synthesize organic acids with maturity (Hardy 1968), the transformation of organic acids to sugars and dilution due to the increased volume of the fruit (Winkler et al. 1974) also serve to lower the malic acid concentration during ripening. The transformation of malic acid into a potassium salt is reflected in the rise in pH and the decrease in titritable acidity as the grapes ripen (Kliewer et al. 1967, Winkler et al. 1974).

Malic acid content is decreased via cellular respiration and is correlated with increased temperatures (Hardy 1968, Jackson and Lombard 1993, Kliewer 1971, Kliewer et al. 1967, Spayd et al. 2002, Winkler et al. 1974). For every 10°C increase in temperature of the berries, the respiration rate doubles, which corresponds to a greater reduction of malic acid content (Smart and Robinson 1991). However, some studies have shown that no correlation exists between temperature and malic acid concentration in *V. vinifera* (Crippen and Morrison 1986, Morrison and Noble 1990, Peynaud and Maurié 1958).

Past studies have also shown a positive correlation between high temperatures and yield due to increased rates of photosynthesis, up to 30°C (Smart and Robinson 1991, Winkler et al. 1974). In some situations of temperatures above 30°C, reduced yields due to water stress and shriveling of the berries can occur (Smart and Robinson 1991, Winkler et al. 1974).

Light transmittance influences growth and development of grapevines and their fruit. The effect from decreased light transmittance on yield due to dense leaf and shoot canopies and shaded fruiting zones affects the flower primordia development of the following year's crop. Leaf axil buds contain the primordia for the following year's crop within a compound bud. The development of these primordia is influenced heavily by light transmittance, as shaded canopies have been shown to lower the development of these primordia, thereby reducing the following year's yields (Hellman 2003, Perez and Kliewer 1990, Sanchez and Dokoozlian 2005, Smart et al. 1982, Smart and Robinson 1991, Winkler et al. 1974). Improved sunlight transmittance to as many leaves as possible will provide for the most efficient use of photosynthetic processes, maximize flower primordia development and increase yields (Crippen and Morrison 1986, Hunter et al. 1995, Smart and Robinson 1991).

Photosynthesis is maximized at roughly one-third of ambient sunlight, or 700 $\mu Em^{-2}s^{-1}$. This is a measure of the Photosynthetically Active Radiation (PAR) within the fruiting zone, and PAR is used to describe the light environment within a fruiting canopy. Beyond the point of one-third of ambient sunlight, the leaves are saturated with photosynthetic potential, and increasing the light exposure will have little to no effect on photosynthesis (Smart and Robinson 1991, Winkler et al. 1974). Other sources indicate that photosynthesis will increase with up to two-thirds ambient light, or 1333 $\mu Em^{-2}s^{-1}$ (Hellman 2003). At levels below 1.5% of ambient light, or 30 $\mu Em^{-2}s^{-1}$, photosynthesis cannot occur (Smart and Robinson 1991). Grape leaves only allow 6% of ambient PAR to transmit through the leaf tissue; therefore overly dense canopies can be heavily shaded to the point of photosynthesis not occurring on heavily shaded leaves. Smart and Robinson (1991) noted sunlight levels well below 1% of ambient light at only 10 $\mu Em^{-2}s^{-1}$. Optimal light levels vary between different species and cultivars within the *Vitis* species (Winkler et al. 1974).

Sunlight transmittance can also affect yield and grape quality by affecting the temperature in the microclimate (Crippen and Morrison 1986, Winkler et al. 1974). Leaves are typically 3 to 11°C warmer than the surrounding air depending on sunlight transmittance as well as wind speed and relative humidity (Winkler et al. 1974). Berries that are exposed to bright sunlight on calm days can be warmed up to 15°C above air temperature (Smart and Robinson 1991).

The role of sunlight exposure in influencing the composition of grapes has been widely studied, and although many sources agree that increased sunlight exposure is generally beneficial for the quality of grapes grown in cold climates, there is disagreement in past literature. Studies have shown that increased solar transmittance increases the amount of total soluble solids (Brix) in the berries at harvest (Kliewer et al. 1967, Kliewer and Lider 1970, Price et al. 1995, Reynolds et al. 1986, Smart and Robinson 1991, Williams et al. 1994). However, others have shown that this correlation is not always present (Cortell and Kenedy 2006, DiProfio et al. 2011, Downey et al. 2004, Hunter et al. 1995, Ristic et al. 2007, Wessner and Kurtural 2013). The lowering of total acidity primarily through the respiration of malic acid during the ripening stage of berry development has been noted by many to be directly associated with increased solar irradiance (Coniberti et al. 2012, DiProfio et al. 2011, Jackson and Lombard 1993, Kliewer and Shultz 1964, Kliewer et al. 1967, Kliewer and Lider 1970, Morrison and Noble 1990, Pereira et al. 2006, Price et al. 1995, Reynolds et al. 1986, Ruffner 1982, Smart and Robinson 1991, Williams et al. 1994). However, the lowering of total acidity has not been correlated with solar irradiance in all studies (Cortell and Kenedy 2006, Downey et al. 2004, Hunter et al. 1995, Melino et al. 2011, Morrison and Noble 1990, Ristic et al. 2007, Wessner and Kurtural 2013, Williams et al. 1994). Studies also have noted a higher pH in grapes grown under shade conditions (Coniberti et al. 2012, Dokoozlian and Kliewer 1995, Morrison and Noble 1990, Ristic et al. 2007, Smart and Robinson 1991). However, others have shown that pH is either lowered by shading, or altogether unaffected (DiProfio et al. 2011, Kliewer et al. 1967, Reynolds et al. 1986, Wessner and Kurtural 2013).

Canopy Management. The three canopy management practices of shoot positioning, shoot thinning and lateral shoot thinning all have the same goal of increasing light transmittance into the fruiting zone to improve the canopy microclimate for optimal yield and grape quality. Shoot positioning has been show to improve the PAR flux density to basal leaves of Concord grapes when paired with splitting the canopy into a Geneva Double Curtain training system (Smart et al.

1982). Other studies have shown shoot positioning to lower shading potential and subsequently lower pH, however this lowered shading potential did not affect the yield (Morris et al. 2004). Research literature lacks information on the effects of shoot positioning on sugar and acid contents of the berries.

Shoot thinning has been shown to decrease cropload ratio and yield, as well as canopy density (Morris et al. 2004, Sun et al. 2011, 2012), creating a more favorable microclimate in terms of irradiance (Reynolds et al. 2005, Sun et al. 2011, 2012). It also was found that shoot thinning increased pH and lowered titritable acidity of grapes (Reynolds et al. 2005, Sun et al. 2012), but had no effect on sugar content (Sun et al. 2012). However, other studies have shown that shoot thinning increased sugar content in grape berries while having inconsistent effects on titritable acidity (Reynolds et al. 2005, Sun et al. 2011). Reynolds et al. (2005) also showed that shoot thinning raised pH levels of grapes. Another study by Reynolds et al. (2004) showed variable effects on grape sugar content, pH, and titritable acidity due to shoot thinning, with the effects being dependent on cultivar.

While many studies have examined the effects of shoot tipping on lateral shoot development (Carmo Vasconcelos and Castagnoli 2000, Di Profio et al. 2011, Wolf et al. 1986), there is a lack of knowledge in current literature as to how the removal of lateral shoots affects canopy microclimates, yields and berry quality components.

In summary, the practices of shoot positioning, shoot thinning, and lateral shoot thinning had inconsistent abilities to affect canopy architecture, yield, and berry composition. The subsequent effects of canopy management practices on a grapevine's architecture and associated microclimate indices have variable effects on yield and berry composition across species and cultivars within the *Vitis* species. Understanding the effects of these practices on individual cultivars is needed for specific growing regions.

It is our hypothesis that the canopy management practices of shoot positioning, shoot thinning, and lateral shoot thinning will serve to open the canopy structure and allow for greater irradiance into the fruiting zone. We further postulate that this increase in irradiance will correspond to improved fruit quality of Frontenac, La Crescent, and Marquette grapes grown in Iowa. This study examines the effects of shoot positioning, shoot thinning, and lateral shoot thinning on grapevine yield, Brix pH titritable acidity, and tartaric and malic acid contents of Frontenac, La Crescent, and Marquette grapes at harvest in Iowa.

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CHAPTER 2. THE EFFECTS OF CANOPY MANAGEMENT PRACTICES ON FRUIT QUALITY OF NORTHERN-HARDY INTERSPECIFIC HYBRIDS OF *VITIS* SPP.

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This project is part of the Northern Grapes Project, funded by the USDA's Specialty Crops Research Initiative Program of the National Institute for Food and Agriculture, Project #2011-51181-30850.

The effectiveness of canopy management practices to improve the fruit quality of northern-hardy wine grape cultivars for winemaking through increased irradiance was examined. While these practices and their effects on fruit quality have been widely examined in *Vitis vinifera*, they have not yet been thoroughly studied for their application on northern-hardy interspecific *Vitis* spp. This study investigates the effects on required labor, irradiance into the canopy, yield, and fruit quality of three canopy management practices, shoot positioning, shoot thinning, and lateral shoot thinning, for three cultivars of northern-hardy grapes, Frontenac, La Crescent, and Marquette. While each of the practices increased labor and irradiance, shoot thinning was the only practice that had any positive affect on fruit quality, and occurred only for La Crescent. By lowering the malic acid content, shoot thinning improved the quality level of the La Crescent grapes, but none of the grapes reached optimal fruit quality under any of the treatments. Enological practices may need to be developed to improve the customer acceptance of wine from these cultivars.

Abstract

The ability of three different canopy management practices, shoot positioning, shoot thinning, and lateral shoot thinning, to improve the quality of Frontenac, La Crescent, and Marquette grapes for winemaking was investigated. These northern-hardy interspecific hybrids containing *Vitis riparia* parentage exhibit high vigor and possess fruit quality concerns when their grapes are to be used to make wine. Opening the canopy to increase irradiance may improve yields and fruit quality by promoting light interception for photosynthesis and increasing the temperature of the fruit, thereby affecting respiration and decreasing malic acid content in the berries. In 2012 and 2013 all combinations of shoot positioning, shoot thinning, and lateral shoot thinning were performed on La Crescent vines in Madrid, Iowa, and on Frontenac and Marquette vines in Adel, Iowa. The labor required completing the management practices and the effects on irradiance in the canopy, yield variables, and fruit quality variables were measured. All canopy management practices required higher levels of labor and they increased light penetration into the fruiting zone, but the increase in irradiance had little effect on the quality of the grapes. These effects varied across the different cultivars, and no general relationship between increased labor and increased irradiance, or between increased irradiance and improved fruit quality, occurred across the cultivars. While Frontenac vines required an average of 5.6 additional minutes of labor per vine for a canopy management practice, the practice increased irradiance by 10.1% on average. La Crescent vines required an average of 4.4 additional minutes of labor per vine for any canopy management practice and the practice increased irradiance by 16.5% on average. Marquette vines required an average of 7.7 additional minutes of labor per vine for a canopy management practice, which led to a 19.5% averaged

increase in solar irradiance. Shoot thinning lowered malic acid content in La Crescent, but not to an optimal level.

Key words: *Vitis riparia*, shoot thinning, shoot positioning, lateral shoot removal, irradiance, Frontenac, La Crescent, Marquette

Introduction

The recent and rapid expansion of the grape and wine industry in the Upper Midwest, including the states of Illinois, Iowa, Michigan, Minnesota, North Dakota, South Dakota, and Wisconsin, and other cold-climate regions was made possible by the development and release of interspecific *Vitis* spp. hybrids during the 1990s. In 2000, there were 30 acres of vineyards in the State of Iowa, and in 2014 the state contained over 1200 acres of land in commercial grapevine production, 316 vineyard enterprises, and 97 wineries (IWGA 2014). The statewide grape and wine industry created a combined $65.2 million in economic impact for Iowa in 2011 (Tuck and Gartner 2014). While the industry is rapidly growing within the state, improvement of the quality of wine produced from interspecific northern-hardy cultivars will be necessary for the long-term sustainability of a successful grape and wine industry.

Three primary challenges facing grape growers in the cold-climate regions include low winter temperatures, late spring frost events, and a relatively short growing season (Smiley et al. 2008). Frontenac, La Crescent, and Marquette are interspecific hybrid cultivars containing *V. riparia* parentage and developed by the University of Minnesota plant breeders to be tolerant of the low winter temperature in the Upper Midwest. These cultivars are winter-hardy to temperatures as low as -29°C for Frontenac, and -38°C for La Crescent and Marquette (UMN 2012). The ability to tolerate late spring frost events varies among cultivars and is dependent on several factors involving the stage of growth and development of the plant at the time of the frost event and effect of winter temperatures on secondary bud vitality and overall vine health. The relatively brief growing season in the Upper Midwest can affect the quality of the wine if grape maturation does not occur.

Heat accumulation over the growing season is an important factor influencing the quality of cold-hardy wine grapes (Kliewer et al. 1967, Smart and Robinson 1991, Spayd et al. 2002, Winkler et al. 1974). Cooler weather leads to a decreased rate of ripening of grapes, which historically corresponds to lower sugar content (Hellman 2003), higher titritable acidity (Buttrose et al. 1971, Hellman 2003, Kanellis and Roubelakis-Angelakis 1993, Kliewer and Lider 1970, Robinson et al. 1959, Winkler et al. 1974), and a lower pH (Winkler et al. 1974). However, the results of low sugar and high acid of grapes ripening during cooler weather has been disputed by other studies (Amerine 1956, Peynaud and Maurié 1953, 1956). Temperature affects the rates of leaf photosynthesis (Winkler et al. 1974) and grape berry respiration (Kanellis and Roubelakis-Angelakis 1993, Kliewer 1971, Winkler et al. 1974), which greatly affect the composition of the berries at harvest. Increased rates of respiration lower the amount of malic acid present in the berries, as malic acid is an intermediate in the tricarboxylic acid cycle (Winkler et al. 1974).

The role of sunlight exposure in influencing the composition of grapes has been widely studied, and although many sources agree that increased sunlight exposure is generally beneficial for the quality of grapes grown in cold climates, there is disagreement in literature. Studies have shown that increased irradiance increases the amount of total soluble solids (Brix) in the berries at harvest (Kliewer et al. 1967, Kliewer and Lider 1970, Price et al. 1995, Reynolds et al. 1986, Smart and Robinson 1991, Williams et al. 1994). However, others have shown that this relationship is not always present (Cortell and Kenedy 2006, DiProfio et al. 2011, Downey et al. 2004, Hunter et al. 1995, Ristic et al. 2007, Wessner and Kurtural 2013).

The lowering of total acidity, primarily through the respiration of malic acid during the ripening stages of berry development, has been noted to be directly associated with increased solar irradiance due to an increase in berry temperature (Coniberti et al. 2012, DiProfio et al. 2011, Kliewer et al. 1967, Smart and Robinson 1991). The lowering of total acidity has not been correlated with increased solar irradiance in all studies (Cortell and Kenedy 2006, Melino et al. 2011, Ristic et al. 2007, Wessner and Kurtural 2013), especially with *V. vinifera* cultivars, which may be due to the higher proportion of tartaric acid compared to malic acid in *V. vinifera*.

Some previous studies also noted a higher pH in grapes grown under shade conditions (Coniberti et al. 2012, Dokoozlian and Kliewer 1995, Morrison and Noble 1990, Ristic et al. 2007, Smart and Robinson 1991). But, other studies have shown that pH is either lowered by shading or altogether unaffected by decreased irradiance (DiProfio et al. 2011, Kliewer et al. 1967, Reynolds et al. 1986, Wessner and Kurtural 2013). Determining general rules for how canopy management, or any other practice, will affect fruit quality has proven difficult. The impacts of climate, vineyard location, management practices, pest pressures, individual vine age, and many other factors vary widely across cultivars and are often very difficult to replicate in research (Jackson and Lombard 1993).

Improvement of fruit quality of the interspecific hybrids Frontenac, La Crescent, and Marquette needs to be addressed for optimal wine production in Iowa. Table 1 shows the recommended ranges of grape juice parameters for optimal wine quality. For making table wines, the range for sugar content should fall between 19.5 Brix to 23.0 Brix for white grapes and between 20.5 Brix to 23.5 Brix for red grapes (Amerine et al. 1972). The titritable acidity needs to be between 7.0 and 10.0 g/L for white wine grape juice (Byers et al. 2003, Dami et al. 2005). The titritable acidity of red wine grape juice specifically should fall between 6.0 g/L and 8.0 g/L at harvest (Winkler et al. 1974). The pH should be between 3.1 and 3.2 for white grapes and between 3.4 and 3.5 for red grapes (Amerine et al. 1972, Dami et al. 2005). Wine grapes are typically harvested when tartaric acid content is 5.0-g/L and malic acid content is between 2.0 and 3.0-g/L (Bisson 2001). Coombe et al. (1980) found Brix × pH^2 to be a better quality predictor at harvest for dry table wines. Including pH in the measurement better allows for the possibility of grapes that are high-potassium, high-pH and high-acid than would a simple Brix : TA ratio. Brix × pH^2 also provides a wider and more integral optimal range for comparison than the Brix : TA ratio (Boulton et al. 1996).

Frontenac, a red wine grape, averages 24.8 Brix, a titritable acidity of 15.1 to 15.4-g/L, and an average pH of 2.9 at maturity (Mansfield 2012a). A study on the stage of maturation, cropload ratio, and shoot density of northern-hardy cultivars in Iowa by Vos (2014) found that Frontenac averages 21.4 Brix, increasing with stage of maturation, titritable acidity averages 10.4-g/L and decreases with maturation, and pH averages 3.39, increasing with maturation. La Crescent, a white wine grape, averages 25.1 Brix, a titritable acidy of 11.9-g/L, and an average pH of 3.05 at maturity (Mansfield 2012b). Vos (2014) found La Crescent to have an average sugar content of 21.8 Brix, increasing with maturity, a titritable acidity of 8.9-g/L, decreasing with maturity, and an average pH of 3.36, increasing with maturity. Marquette, a red wine grape, averages 25.9 Brix, a titritable acidity of 12.0-g/L, and an average pH of 3.0 at maturity (Mansfield 2012c). Vos (2014) found that Marquette averages 22.7 Brix, increasing with maturity, a titritable acidity of 8.2-g/L, decreasing with maturity, and an average pH of 3.39, increasing with maturity and shoot density.

In a general study of *V. riparia* cultivars Kliewer (1967) found that these grapes contained more malic acid (3.8 to 16.9-g/L) than tartaric acid (4.9 to 8.2-g/L), which is different than what has been noted in *V. vinifera*. Vos (2014) completed the first analysis of malic and tartaric acid concentrations in Frontenac, La Crescent, and Marquette grapes. In Frontenac he found malic acid contents of 9.6-g/L, tartaric acid contents of 8.1-g/L, and a tartaric : malic acid ratio of 0.87. In La Crescent he found malic acid contents of 9.0-g/L, tartaric acid contents of 4.4-g/L, and a tartaric : malic acid ratio of 0.50. In Marquette he found malic acid contents of 7.0-g/L, decreasing with maturation and increasing with shoot density, tartaric acid contents of 6.5-g/L, decreasing with maturation, and a tartaric : malic acid ratio of 0.98, decreasing with maturation and shoot density.

The practices of shoot positioning, shoot thinning, and lateral shoot thinning have inconsistent results on their abilities to affect irradiance in the canopy, yield, and berry composition. The subsequent effects of canopy management practices on the irradiance in the fruiting zone of a grapevine and associated microclimate indices have variable effects on yield and berry composition across species and cultivars within the *Vitis* species. Understanding the effects of these practices on individual cultivars is needed for specific growing regions.

We hypothesize that the canopy management practices of shoot positioning, shoot thinning, and lateral shoot thinning will serve to open the canopy structure and allow for greater solar irradiance into the fruiting zone. We further postulate that this increase in solar irradiance will correspond to improved fruit quality of Frontenac, La Crescent, and Marquette grapes grown in Iowa. This study examines the effects of shoot positioning, shoot thinning, and lateral shoot thinning on grapevine yield and fruit quality for winemaking of Frontenac, La Crescent, and Marquette grapes grown in Iowa.

Materials and Methods

Experimental sites and climate conditions. The experiment was conducted over two consecutive growing seasons from 2012 to 2013 at Snus Hill Winery, in Madrid, Iowa (lat. 41°52N; long. 93°44W) with ten-year-old, own-rooted La Crescent grapevines, and at Penoach Winery, in Adel, Iowa (lat. 41°65N; long. 94°03W) with six-year-old, own-rooted Frontenac and five-year-old, own-rooted Marquette grapevines. The Snus Hill vineyard site had Clarion loam soils with between 5 and 14 percent slope, and the Penoach Winery vineyard site had Clarion loam soils with between 2 and 9 percent slopes (websoilsurvey.sc.egov.usda.gov). Clarion loams are characterized as fine-loamy, mixed, superactive, mesic Typic Hapludolls with moderately good drainage and a high available water holding capacity (USDA 1984).

Very low rainfall amounts in the late summer and fall of 2011 created widespread and severe drought in Iowa during the 2012-growing season (Figures 1A, 1B). During 2012, temperatures averaged 11.1°C during the daytime and 2.2°C during the nighttime above normal, while precipitation totaled 668.3-mm and was 227.6-mm below normal (Hillacker 2014). It was the third warmest and the nineteenth driest year in Iowa's 141-year recorded history (Hillacker 2014). The exceptionally warm winter from 2011 to 2012 resulted in the vines breaking dormancy by late March. A frost event in April 2012 damaged the majority of the primary buds from these vines with early-season growth, and the resulting growth for the season came from secondary buds. The Marquette vines did not produce vigorous secondary growth, and the vines were deemed unusable for the study during the 2012 season. The weakened state of the secondary bud shoots from the Frontenac and La Crescent vines was further exacerbated by the 2012 drought.

During 2013, temperatures averaged 8.1°C during the daytime and 0.9°C during the nighttime below normal while precipitation totaled 899.4-mm and was 35.6-mm above normal (Hillacker 2014). 2013 was the twenty-fifth coolest and the thirty-seventh wettest year in Iowa's recorded history (Hillacker 2014). The variability in climactic conditions among the years represents the largest recorded year-to-year temperature change in Iowa (Hillacker 2014). Figure 1 illustrates the variation in temperature and precipitation, which severely affects grape quality and yield.

All vines were trained to a high wire cordon (HWC) training system and had vine and row spacing of 2.4-m and 3.0-m, respectively. All cordons were positioned 2.4-m above the soil. The Frontenac and Marquette vines were positioned to a north-south row orientation, and the La Crescent vines were positioned to an east-west row orientation in order to contour a north-facing slope onto which they were planted. All vines were pruned using the balanced pruning system of 25 buds plus 10 buds for every pound of pruning weight for Frontenac and La Crescent, and 30 buds plus 10 buds for every pound of pruning weight for Marquette (White 2014).

Experimental design. A randomized complete-block design with four replications of eight treatments was used; each treatment was repeated on three vines totaling 96 vines per cultivar or 288 vines for all three cultivars. The same treatment vines were used in the second year. Treatments included all combinations (±) of pre-bloom non-count shoot thinning (ST), post-bloom shoot positioning (SP), and post-bloom lateral shoot thinning (LT). The eight treatments included C, SP, ST, LT, SP+ST, SP+LT, ST+LT, and SP+ST+LT.

Shoot tips were hedged at 30-cm above the soil on all vines at post-veraison in both growing seasons. Shoot thinning consisted of a one-time, pre-bloom removal of all secondary shoots occurring at double-buds and basal shoots. If a shoot was needed to fill a gap in the canopy, non-count basal shoots were retained. Shoot positioning consisted of a onetime post-bloom, but pre-veraison, positioning of the shoots to promote downward growth on the appropriate side of the cordon for each shoot. Lateral shoot thinning consisted of removing all lateral shoots from within 15.2-cm of the fruiting zone and was performed once immediately following veraison (Table 2). Lateral shoot thinning dates were 20 Jul 2012 and 8 Aug 2013 for Frontenac, 16 Jul 2012 and 6 Aug 2013 for La Crescent, and 2 Aug 2013 for Marquette. In 2012, lateral shoot thinning was performed only once on the Frontenac and La Crescent vines, and in 2013, it was completed twice for each cultivar. The same level of lateral shoot thinning was performed again two weeks later in 2013: 22 Aug 2013 for Frontenac, 20 Aug 2013 for La Crescent, and 16 Aug 2013 for Marquette. The second round of lateral shoot thinning in 2013 was required in order to maintain the open canopy intended by the practice.

Labor requirements. Two workers working on a single vine canopy, together on opposite sides of the trellis determined the time required to complete canopy management and harvest practices. Each worker recorded the minutes and seconds required to complete the viticultural practices using Sportline Giant Sport Timers (EB Sport Group, Yonkers, NY), and their time was added together for each vine. No time was recorded for shoot-tip hedging. One individual, harvesting a single vine on his or her own, recorded labor required for harvesting the vine.

Light Measurements. In accordance with Bavougian et al. (2013), Chorti et al. (2010) and Sandler et al. (2009), Photosynthetically Active Radiation (PAR) was measured with a LI-191 line-quantum sensor and recorded with a LI-1400 data logger (LI-COR Biosciences, Lincoln, NE), both above the canopy and within the fruiting zone (20.3-cm under the 2.4-m high cordons) of treatment plants. PAR readings were taken between veraison and harvest, when the canopy structure remained relatively stable and shoots were no longer elongating. Three measurements were taken within the fruiting zone of each sample vine and averaged to determine the PAR and relative irradiance of the fruiting zone. Between each sample vine, an ambient PAR reading taken above the canopy was recorded and all of these ambient readings were averaged over the entire plot to determine the ambient PAR. PAR was measured on the south side of the canopy for the La Crescent vines, and on the east side of the canopy for the Frontenac and Marquette vines within one hour of solar noon. Irradiance within the fruiting zone was calculated by dividing the PAR readings from within the canopy by the ambient PAR readings above the canopy to determine the percentage of irradiance transmitted through the canopy to the fruiting zone.

Harvest Indices and Berry Composition. The date of harvest each year was determined by the vineyard owners, and based on field sample measurements of Brix, pH, and availability of harvest laborers. A 300-berry sample was collected from each treatment from the three vines of each replication within five days before harvest. The berries were immediately frozen to -32°C after harvest and thawed at a later date for analysis. Thawed berry samples were weighed; berries counted, and then hand-squeezed through cheesecloth to produce juice samples using the LEMRA Squeezo® strainer (Best Products, Inc., Jeffersonville, VT). The Brix was measured twice with a digital hand-held refractometer (PAL-1; ATAGO, Tokyo) and averaged. The pH was measured twice with a pH/mV/°C/°F meter (pH 1100 Series; OAKTON, Vernon Hill, IL) and averaged. The titritable acidity (TA) was measured twice by titration with sodium hydroxide

(0.1*N* NaOH) to 8.2 pH, using the same pH/mV/°C/°F meter (pH 1100 Series; OAKTON, Vernon Hill, IL) and averaged. Using high-performance liquid chromatography (HPLC), malic acid content and tartaric acid content were determined according to Walker at al. (2003) by the Iowa State University, Midwest Grape and Wine Industry Institute. After spring pruning was completed in 2014, the Ravaz index, a measure of a vine's relative fruitfulness, was calculated by dividing the yield from 2013 by the weight of the pruned canes from 2014.

Statistical Analysis. Statistical analysis of the data was performed utilizing the SAS 9.2 statistical package (SAS Institute Inc., Cary, NC). The Glimmix procedure was used to perform an analysis of variance on the data. Differences between least square means of treatments was determined using lsmeans statements as well as defining custom orthogonal contrasts between lsmeans of treatments involving all combinations (±) of SP, ST, and LT versus the lsmeans of the control treatment for all variables. Significance of these differences was determined based on Tukey's adjustment for multiple comparisons.

Results

Growing Season Variability. The 2012 and 2013 growing seasons exhibited a greater variation in mean temperature than any two consecutive years in Iowa's recorded history (Hillacker 2014). Figure 1A shows the mean high and low temperatures and monthly precipitation from 2012 and 2013 as they compare to the average mean temperatures and precipitation patterns in central Iowa. 2012 had a rapid warming during March, April, May, and June, which was followed by a decrease in temperatures after the onset of veraison. The 2013 growing season had a general warming throughout the entirety of the season, including during the ripening phase, up until the month of September. Figure 1B shows the drought conditions that occurred throughout 2012, and the high precipitation conditions of early 2013 followed by the drought conditions that existed during the veraison stage of the berries.

Table 2 shows the multiple-week differences in the veraison and harvest dates for each cultivar between 2012 and 2013. These dates coincided with relatively similar accumulated growing degree-days between 2012 and 2013, although the growing degree-days varied primarily among the different cultivars and not seasons (Table 3).

Due to the interaction of treatment and growing season effects on the labor requirements, irradiance, yield, and cluster number (Table 4), these variables were separated by season for analysis. Season-treatment interactions were not found in the fruit quality indices, except for pH of La Crescent, and these variables were not analyzed by season (Table 5). Comparison statements combined the relative effects of a canopy management practice, utilized individually or in combination with other practices, and compared it against the control treatment of not using any canopy management practice (Tables 6, 7, 8, 9, 10, 11, 12, 13).

Frontenac. All canopy management treatments, shoot thinning, shoot positioning, and lateral shoot thinning, added between 4.02 and 4.79 minutes of labor per vine in 2012 and between 5.64 and 8.70 minutes of labor per vine in 2013 compared to the control treatment (Tables 6,7). Of the individual canopy management practices, lateral shoot thinning required the least amount of additional labor in 2012, but was similar to shoot positioning and shoot thinning. In 2013 lateral shoot thinning showed the highest labor requirement. Comparison statements showed that in both seasons lateral shoot thinning had the greatest effect on increasing solar irradiance compared to the control treatment (Tables 6, 7). During both seasons all canopy management practices increased solar irradiance by at least 7.98% compared to the control. Canopy management practices had no effect on yield or cluster number in 2012. In 2013 shoot thinning lowered yield by an average of 1.24-kg/vine, compared to the control (Table 7). Shoot positioning, shoot thinning, and lateral shoot thinning lowered the number of clusters/vine in 2013, as well as the Ravaz index compared to the control. Shoot thinning had the greatest effect on lowering the Ravaz index in 2013, as it did on the yield. Few effects from the canopy management practices on the fruit quality of Frontenac occurred (Table 8). All three practices lowered the berry weight compared to the control, but the differences were small (0.04 to 0.05 g/berry) (Table 8).

La Crescent. The effects of the canopy management practices on labor requirements and solar irradiance in La Crescent were similar to Frontenac. Lateral shoot thinning required the least amount of labor in 2012 and the highest amount in 2013, and in both seasons it had the greatest impact on increasing sunlight penetration compared to the control (Tables 9, 10). Shoot positioning, shoot thinning, and lateral shoot thinning increased both labor requirements, between 2.06 and 7.16 minutes per vine compared to the control treatment, and increased irradiance in both seasons by no less than 12.69% compared to the control (Tables 9, 10). Opposite of Frontenac, lateral shoot thinning decreased La Crescent yield in 2012, by 0.81-kg/vine compared to the control (Tables 9, 10). Cluster number and Ravaz index were unaffected by any of the canopy management practices in 2012 (Table 9). All three practices lowered yields between 1.33 and 2.36-kg/vine in 2013, and both shoot thinning and lateral shoot thinning were detrimental towards the Ravaz index compared to the control (Table 10).

The pH of the grapes was the only quality variable affected by an interaction of season and treatment, and it was therefore analyzed separately for the two seasons (Table 11). All canopy management practices increased the pH of the grapes compared to the control in 2013 (Table 11). Grapes receiving shoot thinning treatments had a lower malic acid concentration, by 0.82-g/L compared to the control, which in turn, increased the ratio of tartaric to malic acid, as measured across both seasons (Table 11).

Marquette. Due to a late spring frost in 2012, the primary growth of the Marquette vines was destroyed, and the vines' buds did not have sufficient secondary bud growth. In 2013, Marquette showed increased labor requirements between 6.18 and 9.70 minutes per vine and increased irradiance of at least 16.54% due to all canopy management practices compared to the control (Table 12). Most of the increased labor as well as the increased irradiance were due to lateral shoot thinning (Table 12). Yield, cluster number, Ravaz index, and fruit quality variables were unaffected by the practices compared to the control (Tables 12, 13).

Discussion

Improving the quality of grapes for wine made from northern-hardy grapes is an important aspect in securing the sustainability of Iowa's recently developed grape and wine industry. These northern-hardy cultivars comprise the majority of the grapes used in the industry in the Upper Midwest (Tuck and Gartner 2014), because other hybrids are not sufficiently cold-hardy to survive the Upper Midwest winters (Wagner 1965). Frontenac, La Crescent and Marquette, are interspecific hybrids with *V. riparia* parentage and they are economically important for the state of Iowa (IWGA 2014, Smiley et al. 2008, Tuck and Gartner 2014). Past studies involving interspecific hybrids with *V. riparia* parentage have demonstrated that these cultivars typically have high sugar and acid content, exhibit a rapid rise in pH during maturation, and possess a different balance of malic and tartaric acids than the recommended ranges for winemaking (Kliewer 1967). In order to improve the quality of the wine, viticultural practices that lower the total acidity of the grapes without raising the sugar levels or the pH significantly need to be developed. Improving irradiance in the fruiting zone has improved the quality of fruit in past research, and this study examined the effects of canopy management to improve irradiance on fruit quality of Frontenac, La Crescent and Marquette vines in central Iowa.

Temperature plays a significant role in affecting the yield and composition of the berries at harvest (Hellman 2003, Winkler et al. 1974). However, during our studies ambient temperatures recorded at local weather stations, in Ames, Iowa (lat. 41°99N; long. 93°62W), were close to normal during the ripening stage of berries, corresponding to the post-veraison period (Iowa Environmental Mesonet 2014, U.S. Climate Data 2014). The canopy management practices had little effect on the fruit quality of any of the three cultivars and results differ from Smart et al. (1982) in which shoot positioning was found to lower pH. The cultivars within our studies had pH, titritable acidity, tartaric and malic acid content, tartaric : malic ratio, and sugar : pH balance values at harvest in the unacceptable range even with the dramatic canopy management practices performed (Amerine et al. 1972, Bisson 2001, Byers et al. 2003, Dami et al. 2005). Studies by Reynolds et al. (2005) and Sun et al. (2012) found shoot thinning to increase pH and lower total acidity, but had no effect on sugar content. Our study, which found that shoot thinning had almost no effect on fruit quality disagreed with most past studies (Reynolds et al. 2005, Smart and Robinson 1991, Sun et al. 2012), in that canopy management practices had no or little effect on fruit quality. Determining general rules for how canopy management, or any other practice, will affect fruit quality has proven difficult. The impacts of climate, vineyard location, management practices, pest pressures, individual vine age, and many other factors vary widely across cultivars and are often very difficult to replicate in research (Jackson and Lombard 1993). The canopy management practices that increased irradiance may not have increased berry temperature and subsequent berry respiration sufficiently to reduce malic acid since it remained high under all treatments in all cultivars.

The only positive affect on fruit quality was found for La Crescent with shoot thinning compared to the control, creating a lowered malic acid content and an increased tartaric : malic ratio. While the lowering of malic acid content is a desirable effect of canopy management, these minimal results do not support utilizing shoot thinning to improve fruit quality for winemaking with an increase labor of 3.62 minutes per vine unless a higher price for quality offsets the additional labor costs.

Variation in cultivar response to the canopy management practices for labor, irradiance, yield, cluster number, and Ravaz index did not provide general conclusions. All canopy management treatments required additional labor to complete the tasks, but lateral shoot thinning was the most efficient use of labor for Frontenac and La Crescent in 2012 and increased irradiance into the fruiting zone. Past research concluded that shaded canopies exhibit poor development of bud primordial, thereby reducing the following year's yield (Hellman 2003, Perez and Kliewer 1990, Sanchez and Dokoozlian 2005, Shaulis et al.1966, Smart et al. 1982, Smart and Robinson 1991, Winkler et al. 1974), but in our study canopy management treatments increased irradiance without an increase in yield compared to the control. Vines grown on a high wire cordon training system receive sufficient sunlight interception of the shoots, so yield increase may not be dependent on canopy management practices.

Limitations facing this experiment included that the 2012 and 2013 growing seasons showed the widest variability in temperature of two sequential growing seasons in Iowa's recorded history (Hillacker 2014). The relative effects of the macroclimate temperature may have overshadowed the effects on microclimate temperature of the canopy management treatments. The extreme overall temperature differences between 2012 and 2013 may have had too great an influence on the berry development and composition for the effects of increased irradiance on fruit quality to be notable. Research projects in commercial vineyards mean that harvest dates and management practices were dictated by the availability of work crews and not by the physiological state of the vines. Therefore, grapes may have been harvested at sub-optimal times, and the treatments may have been more effective had the grapes been harvested at the optimal level of ripeness.

Conclusion

Further studies on the effects of canopy management practices to improve fruit quality by increasing irradiance for northern-hardy grape cultivars needs to be completed to develop a standard set of recommended viticultural practices for these cultivars that optimizes fruit quality for winemaking. Increasing the geographical and temporal range of the study and conducting it in additional growing seasons will aid in reducing the influence of uncontrollable outside variables, such as the temperature divergence between 2012 and 2013 in the pre-veraison time period.

Canopy management practices increased irradiance into the fruiting zone of the northern-hardy cultivar canopies, but it did not have a subsequent benefit towards improving the fruit quality of these grapes for winemaking in the years of our study. Further study should determine canopy management strategies that have a positive influence on the quality of northern-hardy grapes. Delaying harvest, as recently studied by Vos (2014), may be an effective way of lowering titritable acidity and malic acid content while maintaining tartaric acid content and improving the tartaric : malic acid ratio for these cultivars closer to acceptable ranges but not optimized (Amerine et al. 1972, Bisson 2001, Byers et al. 2003, Dami et al. 2005). Finding an optimal shoot density for northern-hardy cultivars also may be a method of lowering malic acid content at harvest without affecting yield, as recently studied in Marquette by Vos (2014).

Further studies should examine the individual influence of shoot positioning, shoot thinning, and lateral shoot thinning on labor requirements for spring pruning and harvest for these cultivars. Studies should also investigate the influence of springtime pruning severity on fruit quality, required labor, yield, cluster number, and Ravaz index of these cultivars.

At this point, no viticultural methods have been developed that can bring titritable acidity, tartaric and malic acid contents, or the tartaric : malic ratio of northern-hardy grape cultivars into acceptable ranges for winemaking. Currently, enological practices may need to be emphasized as the preferred method of controlling the fruit quality variables associated with northern-hardy grape cultivars.

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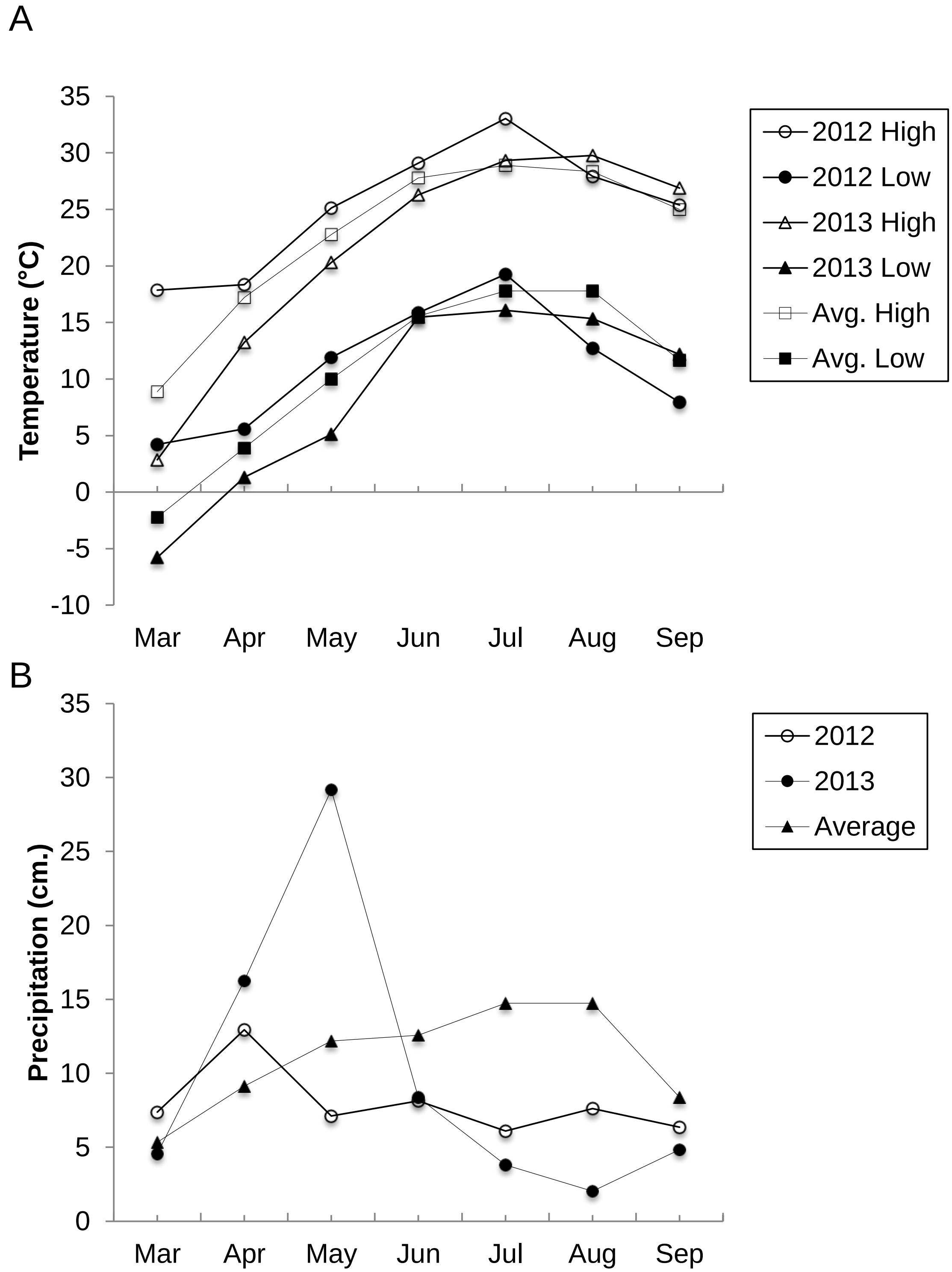

Figure 1. Average monthly (A) low and high temperatures of 2012 and 2013 growing seasons in Central Iowa. Average monthly (B) precipitation amounts of 2012 and 2013 growing seasons in Central Iowa. Data obtained from the Iowa Environmental Mesonet website (2014), Ames, Iowa (lat. 41°99N; long. 93°62W), and from U.S. Climate data website (2014).

Table 1 Recommended fruit quality ranges at harvest for subsequent optimal wine production[a].

	Brix	pH	TA (g/L)	Tartaric acid (g/L)	Malic acid (g/L)	Tartaric: malic[b]	Sugar : pH balance[c]
Wine type							
Red	20.5 - 23.5	3.4 – 3.5	6.0 – 8.0	5.0	2.0 – 3.0	1.7 – 2.5	220 – 260
White	19.5 – 23.0	3.1 – 3.2	7.0 – 10.0	5.0	2.0 – 3.0	1.7 – 2.5	220 – 260

[a]Optimal fruit quality ranges as established by Amerine (1972), Bisson (2001), Byers et al. (2003), Dami et al. (2005) and Dharmadhikari and Wilker (2001).
[b]Ratio of tartaric acid (g/L) to malic acid (g/L).
[c]Total soluble solids (Brix) multiplied by the square of pH.

Table 2 Dates of veraison and harvest for Frontenac, La Crescent, and Marquette grapes for 2012 and 2013.

	Veraison		Harvest	
	2012	**2013**	**2012**	**2013**
Cultivar[a]				
Frontenac	20 Jul	8 Aug	17 Aug	7 Sep
La Crescent	16 Jul	6 Aug	4 Aug	31 Aug
Marquette[b]	-	2 Aug	-	7 Sep

[a]Frontenac vineyard in Adel, Iowa; La Crescent vineyard in Madrid, Iowa; Marquette vineyard in Adel, Iowa.

[b]Marquette not available for experiments in 2012 due to spring frost shoot damage.

Table 3 Accumulated growing degree days (GDD) for Frontenac, La Crescent, and Marquette grapes for 2012 and 2013.

	Total GDD[a]		**Veraison to Harvest GDD**[b]	
	2012	**2013**	**2012**	**2013**
Cultivar[c]				
Frontenac	2800	2600	640	660
La Crescent	2600	2400	520	540
Marquette[d]	-	2600		790

[a]Growing degree days calculated from 1 Jan 2012, 2013 to harvest date at a base of 10°C.
[b]Growing degree days calculated from date of full veraison to harvest date at base of 10°C.
[c]Frontenac vineyard in Adel, Iowa; La Crescent vineyard in Madrid, Iowa; Marquette vineyard in Adel, Iowa.
[d]Marquette not available for experiments in 2012 due to spring frost shoot damage.
Data obtained from Iowa Environmental Mesonet website (2014).

Table 4 Probability of null hypothesis from analysis of variance of canopy management treatments and growing season for Frontenac, La Crescent, and Marquette grapes for the 2012 and 2013 growing seasons.

	Labor[a] (min./vine)	**Solar Irradiance[b] (% of ambient)**	**Yield (kg)**	**Cluster (No./vine)**
Cultivar[c]				
Frontenac				
Treatment x Season[d]	**<0.001**	**<0.001**	0.53	0.16
La Crescent				
Treatment x Season[d]	1.00	**<0.001**	**<0.001**	**<0.001**
Marquette[e]				
Treatment x Season[d]	-	-	-	-

[a]Required labor to conduct canopy management practices and harvest measured in minutes per vine.
[b]Sunlight penetration into the fruiting zone measured as a percent of ambient sunlight measured above the canopy in $\mu Em^{-2}s^{-1}$.
[c]Frontenac vineyard in Adel, Iowa; La Crescent vineyard in Madrid, Iowa; Marquette vineyard in Adel, Iowa.
[d]P value of interaction effect between treatment and season as determined by Tukey's adjustment for multiple comparisons.
[e]Marquette not available for experiments in 2012 due to spring frost shoot damage.

Table 5 Probability of null hypothesis from analysis of variance on fruit quality of canopy management treatments and growing season measured on Frontenac, La Crescent, and Marquette grapes for the 2012 and 2013 growing seasons.

	Weight (g/berry)	Brix	pH	TA (g/L)	Tartaric acid (g/L)	Malic acid (g/L)	Tartaric: malic[a]	Sugar: pH[b]
Cultivar[c]								
Frontenac								
Treatment x Season[d]	0.38	0.43	0.70	0.38	0.57	0.42	0.28	0.30
La Crescent								
Treatment x Season[d]	0.52	0.47	**0.04**	0.57	0.20	0.48	0.19	0.15
Marquette[e]								
Treatment x Season[d]	-	-	-	-	-	-	-	-

[a]Ratio of tartaric acid (g/L) to malic acid (g/L).
[b]Total soluble solids (Brix) multiplied by the square of pH.
[c]Frontenac vineyard in Adel, Iowa; La Crescent vineyard in Madrid, Iowa; Marquette vineyard in Adel, Iowa.
[d]P value of interaction effect between treatment and season as determined by Tukey's adjustment for multiple comparisons.
[e]Marquette not available for experiments in 2012 due to spring frost shoot damage.

Table 6 Effect of canopy management practices on labor, solar irradiance, and harvest variables of Frontenac grapes at harvest on 17 Aug 2012, Adel, IA.

	Labor[a] (min./vine)	Solar Irradiance[b] (% of ambient)	Yield (kg)	Cluster (No./vine)	Ravaz Index[c]
Treatment					
Control (C)	5.04 b[d]	11.18 b	3.56	56.33	-
Shoot positioning (SP)	8.11 ab	14.63 b	4.42	62.00	-
Shoot thinning (ST)	7.81 b	11.91 b	3.15	53.75	-
Lateral thinning (LT)	6.53 b	18.33 ab	3.60	61.17	-
SP+ST	10.41 ab	18.58 ab	3.39	55.00	-
SP+LT	8.63 ab	22.78 ab	3.43	56.92	-
ST+LT	10.75 a	21.42 ab	4.15	65.75	-
SP+ST+LT	10.34 ab	24.75 a	3.39	50.42	-
Orthogonal Comparisons[e]					
SP vs. Contol	4.33	9.01	NS	NS	-
ST vs. Control	4.79	7.98	NS	NS	-
LT vs. Control	4.02	10.64	NS	NS	-

[a]Required labor to conduct canopy management practices and harvest measured in minutes per vine.
[b]Sunlight penetration into the fruiting zone measured as a percent of ambient sunlight measured above the canopy in $\mu Em^{-2}s^{-1}$.
[c]Measure of vine vigor and relative fruitfulness as season one yield (kg) over season two spring pruning weight (kg).
[d]Means separated by a letter are significantly different at $Pr \leq 0.05$ using Tukey's adjustment for multiple comparisons.
[e]Comparison value is difference of all treatment combination means compared to the control; NS = not significant.

Table 7 Effect of canopy management practices on labor, solar irradiance, and harvest variables of Frontenac grapes at harvest on 7 Sep 2013, Adel, IA.

	Labor[a] (min./vine)	Solar Irradiance[b] (% of ambient)	Yield (kg)	Cluster (No./vine)	Ravaz Index[c]
Treatment					
Control (C)	6.39 c[d]	15.33 b	4.30 ab	81.92 ab	16.91 a
Shoot positioning (SP)	8.60 bc	21.00 b	3.94 ab	74.00 ab	8.48 b
Shoot thinning (ST)	7.67 bc	13.42 b	2.88 b	59.00 b	6.31 b
Lateral thinning (LT)	15.15 a	21.42 b	4.35 a	85.25 a	8.87 b
SP+ST	10.48 b	21.58 b	3.20 ab	57.42 b	7.49 b
SP+LT	15.22 a	30.50 ab	4.19 ab	78.33 ab	10.29 ab
ST+LT	14.64 a	24.17 ab	2.80 b	53.75 b	6.68 b
SP+ST+LT	15.35 a	35.50 a	3.20 ab	56.00 b	10.07 ab
Orthogonal Comparisons[e]					
SP vs. Contol	6.02	11.81	NS	-15.48	-7.83
ST vs. Control	5.64	8.33	-1.24	-25.38	-9.27
LT vs. Control	8.70	12.56	NS	-13.58	-7.93

[a]Required labor to conduct canopy management practices and harvest measured in minutes per vine.
[b]Sunlight penetration into the fruiting zone measured as a percent of ambient sunlight measured above the canopy in $\mu Em^{-2}s^{-1}$.
[c]Measure of vine vigor and relative fruitfulness as season one yield (kg) over season two spring pruning weight (kg).
[d]Means separated by a letter are significantly different at Pr ≤ 0.05 using Tukey's adjustment for multiple comparisons.
[e]Comparison value is difference of all treatment combination means compared to the control; NS = not significant.

Table 8 Effect of canopy management practices on fruit quality indices of Frontenac grapes at harvest on 17 Aug 2012 and 7 Sep 2013, Adel, IA.

	Weight (g/berry)	Brix	pH	TA (g/L)	Tartaric acid (g/L)	Malic acid (g/L)	Tartaric: malic[a]	Sugar: pH[b]
Treatment								
Control (C)	0.94	24.84	3.57	9.08	2.49	5.02	0.52 ab[c]	317.01
Shoot positioning (SP)	0.93	23.25	3.63	8.71	1.91	5.06	0.41 b	305.25
Shoot thinning (ST)	0.90	25.43	3.63	8.86	2.71	5.01	0.60 ab	333.87
Lateral thinning (LT)	0.93	24.06	3.62	9.05	2.57	5.16	0.51 ab	314.60
SP+ST	0.87	25.04	3.64	9.12	2.39	4.29	0.60 ab	331.85
SP+LT	0.88	24.44	3.65	8.95	2.19	5.07	0.50 ab	326.66
ST+LT	0.89	24.87	3.62	9.13	2.44	4.97	0.49 ab	326.80
SP+ST+LT	0.90	23.46	3.55	8.89	2.25	4.13	0.66 a	294.98
Orthogonal Comparisons[d]								
SP vs. Contol	-0.04	NS	NS	NS	NS	NS	NS	NS
ST vs. Control	-0.05	NS	NS	NS	NS	NS	NS	NS
LT vs. Control	-0.04	NS	NS	NS	NS	NS	NS	NS

[a]Ratio of tartaric acid (g/L) to malic acid (g/L).
[b]Total soluble solids (Brix) multiplied by the square of pH.
[c]Means separated by a letter are significantly different at Pr ≤ 0.05 using Tukey's adjustment for multiple comparisons.
[d]Comparison value is difference of all treatment combination means compared to the control; NS = not significant.

Table 9 Effect of canopy management practices on labor, solar irradiance, and harvest variables of La Crescent grapes at harvest on 4 Aug 2012, Madrid, IA.

	Labor[a] (min./vine)	**Solar Irradiance[b] (% of ambient)**	**Yield (kg)**	**Cluster (No./vine)**	**Ravaz Index[c]**
Treatment					
Control (C)	4.22 c[d]	7.92 b	2.90	41.00	-
Shoot positioning (SP)	7.32 ab	11.00 b	2.86	42.00	-
Shoot thinning (ST)	6.05 bc	18.83 b	2.19	36.50	-
Lateral thinning (LT)	4.08 c	36.67 a	1.93	32.00	-
SP+ST	9.50 a	14.83 b	2.90	44.83	-
SP+LT	7.03 b	25.50 ab	2.62	46.75	-
ST+LT	6.11 bc	30.50 ab	2.18	38.08	-
SP+ST+LT	7.91 ab	28.08 ab	1.61	31.00	-
Orthogonal Comparisons[e]					
SP vs. Contol	3.72	12.69	NS	NS	-
ST vs. Control	3.18	15.15	NS	NS	-
LT vs. Control	2.06	23.02	-0.81	NS	-

[a]Required labor to conduct canopy management practices and harvest measured in minutes per vine.
[b]Sunlight penetration into the fruiting zone measured as a percent of ambient sunlight measured above the canopy in $\mu Em^{-2}s^{-1}$.
[c]Measure of vine vigor and relative fruitfulness as season one yield (kg) over season two spring pruning weight (kg).
[d]Means separated by a letter are significantly different at Pr ≤ 0.05 using Tukey's adjustment for multiple comparisons.
[e]Comparison value is difference of all treatment combination means compared to the control; NS = not significant.

Table 10 Effect of canopy management practices on labor, solar irradiance, and harvest variables of La Crescent grapes at harvest on 31 Aug 2013, Madrid, IA.

	Labor[a] (min./vine)	Solar Irradiance[b] (% of ambient)	Yield (kg)	Cluster (No./vine)	Ravaz Index[c]
Treatment					
Control (C)	8.65 bc[d]	5.08 c	5.12 ab	72.67 ab	10.10 ab
Shoot positioning (SP)	12.73 b	14.75 bc	5.45 a	105.75 a	12.70 a
Shoot thinning (ST)	8.50 c	15.92 b	3.32 b	48.42 b	7.87 ab
Lateral thinning (LT)	15.17 ab	16.33 b	3.55 ab	54.83 ab	5.81 ab
SP+ST	11.65 bc	17.50 ab	3.55 ab	56.75 ab	6.39 ab
SP+LT	17.38 a	27.08 a	3.78 ab	59.50 ab	11.83 ab
ST+LT	12.86 b	19.33 ab	1.80 b	28.00 b	3.35 b
SP+ST+LT	17.83 a	26.33 ab	2.40 b	37.25 b	5.17 b
Orthogonal Comparisons[e]					
SP vs. Contol	6.25	16.33	-1.33	NS	NS
ST vs. Control	4.06	14.69	-2.36	-30.06	-4.41
LT vs. Control	7.16	17.19	-2.24	NS	-3.56

[a]Required labor to conduct canopy management practices and harvest measured in minutes per vine.
[b]Sunlight penetration into the fruiting zone measured as a percent of ambient sunlight measured above the canopy in $\mu Em^{-2}s^{-1}$.
[c]Measure of vine vigor and relative fruitfulness as season one yield (kg) over season two spring pruning weight (kg).
[d]Means separated by a letter are significantly different at Pr ≤ 0.05 using Tukey's adjustment for multiple comparisons.
[e]Comparison value is difference of all treatment combination means compared to the control; NS = not significant.

Table 11 Effect of canopy management practices on fruit quality indices of La Crescent grapes at harvest on 4 Aug 2012 and 31 Aug 2013, Madrid, IA.

	Weight (g/berry)	Brix	pH[a] 2012	pH[a] 2013	TA (g/L)	Tartaric acid (g/L)	Malic acid (g/L)	Tartaric: malic[b]	Sugar: pH[c]
Treatment									
Control	1.11	23.33	3.43	3.32 b[d]	11.55	1.57 ab[d]	6.66	0.23 b	265.20
Shoot positioning (SP)	1.16	22.65	3.41	3.36 ab	11.39	1.40 b	6.39	0.20 b	259.61
Shoot thinning (ST)	1.09	23.33	3.43	3.38 ab	10.87	1.78 ab	5.37	0.33 ab	270.13
Lateral thinning (LT)	1.13	22.00	3.39	3.42 a	11.17	1.71 ab	6.50	0.26 ab	254.23
SP+ST	1.10	23.33	3.44	3.39 ab	11.14	1.48 b	6.10	0.25 ab	270.99
SP+LT	1.11	23.23	3.38	3.39 ab	11.06	1.56 ab	6.54	0.23 b	266.07
ST+LT	1.12	22.34	3.39	3.41 ab	10.86	1.98 a	5.91	0.35 a	258.06
SP+ST+LT	1.07	22.97	3.39	3.43 a	11.21	1.76 ab	5.97	0.29 ab	267.60
Orthogonal Comparisons[e]									
SP vs. Contol	NS	NS	NS	0.07	NS	NS	NS	NS	NS
ST vs. Control	NS	NS	NS	0.09	NS	NS	-0.82	0.07	NS
LT vs. Control	NS	NS	NS	0.09	NS	NS	NS	NS	NS

[a]pH was separated by season because significant interaction occurred between season and treatment at $p < 0.05$ using Tukey's adjustment for multiple comparisons.
[b]Ratio of tartaric acid (g/L) to malic acid (g/L).
[c]Total soluble solids (Brix) multiplied by the square of pH.
[d]Means separated by a letter are significantly different at Pr > F 0.05 using Tukey's adjustment for multiple comparisons.
[e]Comparison value is difference of all treatment combination means compared to the control; NS = not significant.

Table 12 Effect of canopy management practices on labor, solar Irradiance, and harvest variables of Marquette grapes at harvest on 7 Sep 2013, Adel, IA.

	Labor[a] (min./vine)	**Solar Irradiance[b] (% of ambient)**	**Yield (kg)**	**Cluster (No./vine)**	**Ravaz Index[c]**
Treatment					
Control (C)	6.98 c[d]	9.83 c	1.24 ab	39.25 ab	2.22
Shoot positioning (SP)	8.62 c	27.42 b	0.96 ab	29.92 ab	1.94
Shoot thinning (ST)	7.41 c	11.83 c	1.28 ab	42.58 a	2.18
Lateral thinning (LT)	16.67 ab	28.33 b	1.64 a	48.75 a	2.62
SP+ST	12.08 bc	18.00 bc	1.53 ab	42.92 a	2.74
SP+LT	16.91 ab	31.83 b	0.89 ab	28.67 ab	3.95
ST+LT	14.18 b	46.92 a	0.71 b	19.92 b	1.63
SP+ST+LT	18.98 a	28.75 b	0.82 b	28.17 ab	1.60
Orthogonal Comparisons[e]					
SP vs. Contol	7.16	16.67	NS	NS	NS
ST vs. Control	6.18	16.54	NS	NS	NS
LT vs. Control	9.70	24.13	NS	NS	NS

[a]Required labor to conduct canopy management practices and harvest measured in minutes per vine.
[b]Sunlight penetration into the fruiting zone measured as a percent of ambient sunlight measured above the canopy in $\mu Em^{-2}s^{-1}$.
[c]Measure of vine vigor and relative fruitfulness as season one yield (kg) over season two spring pruning weight (kg).
[d]Means separated by a letter are significantly different at Pr ≤ 0.05 using Tukey's adjustment for multiple comparisons.
[e]Comparison value is difference of all treatment combination means compared to the control; NS = not significant.

Table 13 Effect of canopy management practices on fruit quality indices of Marquette grapes at harvest on 7 Sep 2013, Adel, IA.

	Weight (g/berry)	Brix	pH	TA (g/L)	Tartaric acid (g/L)	Malic acid (g/L)	Tartaric: malic[a]	Sugar: pH[b]
Treatment								
Control	0.96	27.39	3.82 ab[c]	8.49	2.86	6.59	0.50	400.85
Shoot positioning (SP)	0.98	26.55	3.71 ab	9.28	2.87	6.30	0.47	366.65
Shoot thinning (ST)	0.93	26.86	3.64 b	9.54	2.81	5.85	0.59	354.50
Lateral thinning (LT)	0.98	24.75	3.87 ab	7.23	2.46	5.41	0.46	373.47
SP+ST	0.92	25.63	3.91 a	7.41	2.62	5.64	0.48	391.59
SP+LT	0.94	25.94	3.77 ab	8.93	2.61	6.15	0.48	369.59
ST+LT	0.92	26.88	3.94 a	7.84	3.30	6.07	0.55	419.74
SP+ST+LT	0.97	24.79	3.72 ab	9.56	2.42	6.78	0.36	343.09
Orthogonal Comparisons[d]								
SP vs. Contol	NS	NS	NS	NS	NS	NS	NS	NS
ST vs. Control	NS	NS	NS	NS	NS	NS	NS	NS
LT vs. Control	NS	NS	NS	NS	NS	NS	NS	NS

[a]Ratio of tartaric acid (g/L) to malic acid (g/L).
[b]Total soluble solids (Brix) multiplied by the square of pH.
[c]Means separated by a letter are significantly different at Pr ≤ 0.05 using Tukey's adjustment for multiple comparisons.
[d]Comparison value is difference of all treatment combination means compared to the control; NS = not significant.

CHAPTER 3. GENERAL CONCLUSIONS

General Discussion

The recent and rapid expansion of the grape and wine industry in the Upper Midwest, as well as other cold-hardy regions, was made possible by the development and release of interspecific hybrid *Vitis* spp. with *V. riparia* parentage. These vines are more tolerant of the cold winter temperatures of the Upper Midwest than *V. vinifera* and French hybrids. The industry developed at a rapid pace in Iowa, and contributes significant economic impact to the state. However, little research has been conducted on the optimal production, processing, and selling of these northern-hardy grapes and their associated wines. In order to establish a sustainable industry in Iowa, research needs to be performed to determine optimal viticultural practices for producing quality grapes of northern-hardy wine grape cultivars.

This study was designed to determine optimal canopy management practices to improve the fruit quality of grapes for winemaking of Frontenac, La Crescent, and Marquette in central Iowa. The work presented in this thesis provides information that addresses the current challenges in grape production in the Upper Midwest and other cold-climate regions and provides a basis from which future research can develop.

Impact of Canopy Management Practices on Fruit Quality

The fruit quality parameters of the northern-hardy interspecific hybrids differ dramatically from those of *V. vinifera* and the French hybrids, as well as across the different northern-hardy cultivars. While many fruit quality variables of the northern-hardy grapes do not match the recommended levels for wine production, established for *V. vinifera* grapes, the most notable difference between the species is the malic acid content. Recommended ranges of malic acid content for winemaking are 2.00 to 3.00-g/L; the northern-hardy cultivars examined in this experiment exhibited malic acid content of no less than 4.00-g/L and up to nearly 7.00-g/L. Current enological methods for lowering malic acid content during winemaking, such as malolactic fermentation, are not capable of handling this level of divergence from the recommended ranges without seriously affecting the flavor of the associated wine.

Fruit quality is directly related to the microclimate of the fruiting zone in which the berries develop. One of the primary goals of canopy management is to improve the microclimate for optimal growth and development of the berries for northern-hardy cultivars. Increasing the rate of respiration in the berries would improve the quality of the grapes by promoting the degradation of malic acid and by retarding the rise of pH in the berries. All combinations of shoot positioning, shoot thinning and lateral shoot thinning were conducted on the vines for two consecutive seasons and compared against a control vine of each cultivar that received no canopy management treatments. The canopy management practices increased solar irradiance into the fruiting zone, but did not result in an improvement of fruit quality across all cultivars and treatments. La Crescent grapes exhibited a small decrease in malic acid content due to shoot thinning, but the effect was not near the level needed for malic acid content to be within the recommended ranges. All canopy management practices increased the pH of the La Crescent grapes, which was an undesirable effect.

Additional labor was required per vine to conduct canopy management practices. The canopy management strategies increased irradiance, however this increase in irradiance did not lead to an associated increase in yield, cluster number or Ravaz index. All canopy management practices lowered yields in at least one season for at least one cultivar compared to the control vines.

The lower yields in 2012 may be expected since the canopy management practices served to reduce photosynthetic material from the vine. Shoot positioning does not necessitate the removal of any tissue, but shoots often are lost accidentally by mechanical damage during this process. Shoot thinning reduces the potential number of clusters by reducing the available shoots and their clusters. Lateral shoot thinning removes leaves and smaller shoots, which serve as both sources and sinks of photosynthetic materials. Thus, the effects on yield depend on growing season and physiological stage of the vine.

The fruit quality variables of northern-hardy interspecific hybrids differ from those of *V. vinifera* and also between cultivars of the northern-hardy grapes. Optimal growing strategies need to be determined for each important cultivar individually. In general, these cultivars have a higher sugar content, acid content and pH than what is recommended for winemaking, and the growing strategies should be tailored to lower acidity and pH without subsequently raising sugar content above acceptable levels. Canopy management practices increase solar irradiance within the fruiting zone, which increases the rate of respiration within the berries and should lower the malic acid content of the grapes. Increasing the irradiance to leaves within the fruiting zone also should serve to raise the sugar content and lower the pH of berries at the time of harvest. This study found no relationship between increased irradiance and improved fruit quality. Canopy management practices require additional labor and decreased yields. Unless future research demonstrates a substantial effect on improving fruit quality through increased irradiance, overall, these practices provide no benefit to grape growers.

Recommendations for Future Research

Further research on the effects of canopy management practices on irradiance and fruit yield and quality should be conducted across a wider temporal and geographical range. Further studies on canopy management should record berry temperature as well as relative humidity within the fruiting zone in order to better understand the microclimatic impacts of canopy management. Methods of reducing labor costs, such as mechanization of canopy management strategies, may make the strategies more realistic for growers if it is discovered that there is a relationship between increased irradiance and improved quality for the northern-hardy cultivars.

Because shoot thinning was the only practice to lower malic acid content in La Crescent, it should be the primary focus of further research. The effectiveness of shoot thinning may have been due to a combination of increased irradiance and cropload control, and this combination of factors should be investigated further. Expanding the time frame of the study to additional growing seasons would give the vines more time to acclimate to their improved canopy architecture, and may prove to increase yields through the promotion of more bud floral primordia within the fruiting zone. Utilizing vines of the same age across cultivars may also provide more general conclusions across the different cultivars.

Because the effects of canopy management on fruit quality were minor, other avenues of improving fruit quality, such as reducing vine shoot density and delaying harvest, as well as variable degrees of dormant pruning severity, should be explored. Further research also should be conducted on the effects of shoot positioning, shoot thinning, and lateral shoot thinning on required labor for specific viticultural tasks such as grape harvest and dormant pruning.

Wine made from grapes produced under different canopy management practices should be used to determine if any differences in fruit quality parameters translate into differences in chemical and sensory characteristics. Additional studies could investigate if consumers accept wines from these cultivars and canopy management strategies.