UTILIZING PRUNING AND LEAF REMOVAL TO RIPEN GRAPES AND ENCOURAGE COLD TOLERANCE IN NORTH DAKOTA

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Utilizing Pruning and Leaf Removal to Ripen Grapes and Encourage Cold Tolerance in North Dakota

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MASTER OF SCIENCE

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ABSTRACT

Experiments were conducted at North Dakota vineyards in 2011 and 2012. Pruning limited vines to a specific number of primary buds while leaf removal exposed ripening grape clusters to increased sunlight. Variables included length of growth prior to dormant pruning, weight of growth, rate of ripening, total weight of harvested grapes, weight per grape cluster, berry weight, number of clusters per vine, soluble solid concentration (°Brix), titratable acidity (TA), and pH. Data were analyzed as a CRD with a factorial arrangement.

Analysis showed varied significance with pruning and shade leaf removal interacting with specific cultivar traits to influence growth, grape yield, and grape quality. Impact on yield was minimal, treatment impacts on grape quality showed potential for use of shade leaf removal as means of decreasing titratable acidity levels in harvested grapes. Research supports the use of pruning and shade leaf removal treatments to influence grape production.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF APPENDIX TABLES

LIST OF APPENDIX FIGURES

INTRODUCTION

A movement toward locally grown fruits and vegetables is providing an opportunity for growers in northern climates to diversify or increase their already alternative production system. Growers producing grapes, especially for wine production, are just one sector of locally grown produce markets hoping to capitalize on this growing demand. Recent state legislative action such as HB 1077 allowing direct to retail sale of wine, and the proposed grape research funding contained in SB 214 are examples of increased state government support in North Dakota to promote the growth of local grape and wine production. In addition, the expansion of wine production in the state has reiterated the immediate need for higher quality locally produced wine grapes to meet winery demand. Unfortunately there are few grape varieties suited to the extreme conditions (hot-cold; wet-dry) which exist in North Dakota. With the industry looking for immediate solutions to this problem and since process of breeding new varieties is in its early stages, a study on cultural practices is at the forefront of industry development.

Cultural practices focus on manipulating the production level through shoot pruning to encourage fruiting at a sustainable level and shade leaf removal to control the exposure of developing clusters to sunlight. With the implementation of these practices growers will be able to not only affect the amount of fruit on each plant but, more importantly, encourage proper fruit development and vine acclimation for winter survival. The ability to control fruit ripening and cold tolerance can potentially decrease the detrimental effect of northern winters and may make consistent production of high quality fruit achievable. If production can become more consistent and reliable, the grape and wine industry in North Dakota will be better equipped to move from primarily a hobby, to a viable and profitable industry without having to wait for the development of new grape cultivars or incurring the expense of replanting their vineyard.

LITERATURE REVIEW

Origins. The grape is a unique plant that has strong historical ties to not only global agriculture but also the development of human culture. The main cultivars used for grape production were developed from domestication of a member of the Vitaceae family, the *Vitis* genus. Existing almost exclusively in the Northern Hemisphere, the *Vitis* genus consists of approximately 60 interfertile species (This et al., 2006). From these species, *Vitis vinifera* is the only species extensively used in the global wine industry. Currently there are two distinct subspecies of V. *vinifera* that still co-exist in Europe and Eurasia: V. *vinifera* subsp. *vinifera* (or sativa) which is cultivated, and the wild form V. *vinifera* subsp. *silvestris* (or *sylvestris*) (Zohary, 1996). Domestication of the grape appears to be linked to the discovery of wine, but it is unclear which event predated the other (McGovern, 2004). During these early stages of domestication the biology of grape cultivars underwent dramatic changes in an effort to develop traits advantageous for consistent and high quality production. Changes such as greater sugar content for better fermentation (Pouget, 1988), greater yield, and more regular production took place along with a change from the dioecious wild plants to hermaphroditic cultivated plants. Once domestication of grapes had taken place in Eurasia, movement of grape followed the movement and exploration of worlds beyond its origin. Areas such as Egypt, Lower Mesopotamia, and areas around the Mediterranean all began incorporating grape growing and wine making into their culture (McGovern, 2004). Expansion proceeded along main trade routes and through dominant cultural forces such as the Roman Empire, Catholic Church and Christianity, and Islam. Following the Renaissance (16th Century), V. *vinifera* spread as people colonized new regions including the New World, first as seeds then cuttings. The spread of grapevines and the produce also facilitated the spread of grape specific pathogens and pests. By the end of the 19th century disease-causing agents from America reached Europe devastating many cultivated grape species and drastically reducing species diversity. To save the European viticulture industry, North American species tolerant to pests such as phylloxera (*Dactulosphaira vitifo*liae) (Finch, 1985) and diseases such as powdery mildew (*Blumeria graminis* DC) and downy mildews were used as rootstocks and for breeding disease-resistant interspecific hybrids. In 1950 these hybrids represented approximately 50 percent of the vines in French vineyards (This et al., 2006). However, a dramatic change in wine marketing over the last 55 years has made these hybrids scarce (Wolf, 1992). With the introduction of global wine marketing and specific brand recognition, cultivars such as Chardonnay, Cabernet Sauvignon, Syrah (shiraz) and Merlot have become global wine staples decreasing, in many cases, local cultivars also known as landraces (Pouget, 1988). This decrease in diversity among *Vitis vinifera* cultivars has in some ways promoted an increase in diversity and breeding of native North American grape hybrids through the breeding efforts of public and private sectors.

North American Grapes. Grapevines in present North America, which currently exhibit the greatest potential for breeding and expanding the current range of hardy grapes, belong to the *Vitis* subgenus *Euvitis* (Wolf, 1992). While V. *vinifera* dominates the global wine market, North American species of grape have been traditionally bred to provide disease resistant rootstock. The development of rootstocks has also lead to the development of cultivars with increased cold tolerance and adaptations to specific environmental conditions that are present in more extreme temperate climates. The ability of interspecific hybrids to be productive in areas typically unsuitable for the production of V. *vinifera* cultivars has given these hybrids a distinct production niche. Even though the potential production value of vinifera cultivars is higher, markets outside the vinifera hardiness range have found cultivars with adequate cold-hardiness and good production value. Breeding efforts by several universities, for example Cornell University, Purdue University, and the University of Minnesota, are currently leading the way in the development of new grape cultivars, specifically those hardy in northern cool climates. Using grape breeding stock with demonstrated cold-tolerance, or the ability to acclimate to and resist cold-injury, yet provide consistent production of quality fruit will continue to provide opportunities for the development of new cold-hardy hybrid grape cultivars.

To date, development of these new hybrids has expanded the potential growing region for grape to nearly all cold hardiness zones in the US except hardiness zones 3 and 4 (USDA, 1990). Within zones 3 and 4, the number of viable grape varieties is limited to varieties with questionable cold tolerance and/or limited winemaking quality. Therefore, vineyards and wineries in these hardiness zones have been forced to make due with varieties that are relatively high in quality but experience periodic winter die back. The lack of consistent survival and quality production levels are currently the most important issues to address in the northern grape industry.

While genetics determine the ultimate degree of cold-tolerance expression, environment, cultural management, and pest management also affect this trait expression. Currently, grape production in the US is focused on the west and east coasts. Most management practices have been adopted from these regions and are utilized in North Dakota vineyards and vineyards in similar climates. However, environmental differences between regions have limited the success of these practices calling for improved standards not only by growers but also winemakers. The lack of consistency in quantity and quality reinforces the need for new management practices specific to the region of growth and the variety being grown. Research has shown cropping load, soil fertility, and vegetative growth are directly related to harvest quality, rate of maturity, and cold tolerance (Howell, 2001; Jackson and Lombard, 1993). In order to achieve the needed consistency, a balance among all growth and yield factors must be found and maintained throughout long-term vineyard production.

Vine Growth and Maintenance. A sustainable growth-yield relationship has been the focus of grape production since the early years of cultivation. Currently the word "sustainable" has taken on many meanings, for the sake of grape production, sustainable production refers to the collective methodology that produces highest yields of ripe fruit with per unit land area with no reduction in vine vegetative growth and does so over a period of years at costs which return a net profit (Howell, 2001). This definition of sustainability refers to a point in production when the fruit production and vegetative production of a vine are in balance. Both production sustainability and vine balance serve the same purpose in terms of vine health and vineyard success. Grape growth in cool-climates requires specific interactions to be taken into consideration. In any genotype-environment interaction there is an optimum method of culture to consistently achieve highest yearly yields of ripe grapes with acceptable quality. Sustainable production of high fruit quality at maximum yield has the potential to occur only if vine balance is achieved through the application of the growth-yield relationship.

A search for this balance point is not a new concept. The first researcher to provide relevant information on the subject was Louis Ravaz in 1911 (Ravaz, 1911). Ravaz developed what he would entitle the Ravaz Index, suggesting that the ratio of fruit to wood is the key to achieving both high fruit quality and consistent production. His work also showed a significant connection between leaf production and fruit production. Continuing Ravaz's work in the early 1920s, Partridge (1925) introduced a hypothesis in which he reasoned vines produce two forms of yield in a growing season: vegetative and reproductive (Howell et al., 1994). Balance through his research was achieved when yield of ripe fruit was maximized without detrimental impact on vegetative growth. He proposed to use weight of cane pruning produced in year 1 as an indicator of the upper vine limit of a vine's capacity to produce and ripen a crop in year 2. While this approach was a vast improvement over how growers previously sought to achieve vine balance, the system has limitations. First, because grapes are perennial plants, the positive or negative impact of each season's vine management can be seen in grape yield over multiple years (Howell et al., 1994; Howell, 2000). Second, strong annual fluctuations in weather conditions during the growing season can make the development of a proper management protocol extremely difficult. Finally, the lack of adequate growing degree days, strong fluctuations in weather conditions during growing season and an inconsistent growing season length will further serve to complicate annual vine balance (Howell, 2000). These inconsistencies and interactions have made proper pruning techniques of grape vines the primary focus of management practices, and the only effective way of managing both vegetative and reproductive yield.

Trellising. The primary and most recognizable management technique in grape production is trellising. A trellis is a structure used to support the proper growth of a grapevine and facilitate the development of fruit with proper attributes for the desired use (Dami et al., 2005). Proper trellising and training will enable the grape vine to intercept the maximum amount of radiation available. Because of the numerous trellis systems and trellis structures utilized worldwide, it is important to address the specific needs of the cultivar being grown. Three questions allow growers to determine the proper trellis system: 1) Does the variety require winter protection? 2) How does the vine want to grow? 3) Are the vines moderately or extremely vigorous? (Plocher and Parke, 2008). Understanding the vine characteristics enable the producer to establish a vineyard that encourages maximum absorption of radiation while taking into account any special growth or overwintering needs.

Pruning. Pruning is the single most important task in the management of a grape vine (Reynolds and Wolf, 2008). Pruning offers the most effective means of achieving vine balance and the desired level of vine productivity. Pioneer viticulturist Albert Winkler examined grape pruning methods for the University of California-Davis from the 1920s until his death in 1990 and from his scientific viewpoint 14 production principles were synthesized (Bravdo et al, 1984; Reynolds and Wolf, 2008). These were: 1) pruning of any sort at any time decreases the capacity of the vine; 2) production of a crop depresses the capacity of the vine; 3) vigor of individual shoots varies inversely with the number of shoots that develop; 4) capacity of the vine varies directly with the number of shoots that develop; 5) vigor of shoots of a given vine varies inversely with the amount of crop in bears; 6) fruitfulness of the buds varies inversely with the vigor of the shoots; 7) vines can properly nourish and ripen only a certain quantity of fruit and its capacity is limited by previous history and its environment; 8) fruitful buds of a vine occur most abundantly on one-year-old canes that arise from two-year-old wood; 9) more erect shoots or canes grow more vigorously; 10) shoots starting farthest from the trunk are the most vigorous; 11) canes with internodes of medium length usually mature their wood the best and have the most fruitful buds; 12) larger canes or vines are capable of greater production and should carry more buds; 13) well-matured canes have the best-developed buds; and 14) bending or twisting canes or shoots may modify their behavior and regulate growth or fruiting. These 14 principles serve to reinforce the importance of proper pruning for the development of every aspect of a vine, from fruiting to general growth.

Because pruning principles dictate basic vine structure and yield potential and it is a very labor intensive process, a decrease in available labor and increase in labor costs have perpetuated a shift in some areas from manual pruning to mechanical pruning affecting the specific pruning requirements of individual plants. Mechanical pruning has potential to be more economical, but when applied to the cool-climate viticulture of the eastern US and Canada, an increased level of unacceptable fruit occurred (Plocher and Parke, 2008).

The level of indiscriminant pruning that is carried out by mechanical pruning may be effective in climates where there is a very high vegetative growth to fruit yield ratio, but in many cool-climate production zones where fruitful vines only show moderate to low levels of vigor, pruning must be more precise. Using pruning to control crop load and vine growth is a critical part of grape production because increasing crop load on a vine has been shown to reduce vine carbohydrate storage and subsequent cropping (Bravdo et al., 1984; Buttrose, 1966; May et al., 1969). Over-cropping, or producing more fruit than the vine can effectively ripen, immediately decreases the vine's productivity and overall vigor. Following a year of over-cropping, the productivity of the grapevine will decrease because of a lack of total root as a result of carbohydrate partitioning the previous year (Buttrose, 1966). By understanding how the partitioning of carbohydrates is carried out within a vine, one can determine which vine structures receive energy even when the plant is stressed. When vines are stressed it has been shown that the carbohydrate demands of trunks are met first followed by shoots, fruit and finally roots. The effects of the distribution of carbohydrates, which are necessary for all functions of vine growth and reproduction, can be seen in grape production most readily in fruit ripening or the soluble solids concentration (SSC) measured in °Brix. Multiple studies have been carried out in an effort to determine the effect of crop level on specific grape cultivars (Miller et al., 1993;

Sims et al., 1990). It has been shown that more heavily cropped vines often have a lower SSC level at harvest. Pruning vines in a manner that keeps them in balance has a significant impact on the plant's ability to ripen fruit, while plants that are over-cropped show an inability to fully ripen fruit when grown under the same conditions. Also, over-cropped vines are unable to develop the carbohydrate reserves needed for overwintering and early spring growth, which subsequently leads to decline and eventual removal from the vineyard. Influencing crop load has been the primary focus of studies attempting to correlate grape quality and grape quantity in relation to vine size or calculated vigor (Partridge, 1925). Using the principles of balance pruning, researchers have attempted to develop cultivar specific pruning treatments leaving only the number of nodes and buds a vine can support. This approach ideally maintains maximum yields from year to year but requires very intensive labor inputs.

While the need for adequate vegetative growth has been recognized as it relates to sufficient carbohydrate production and in turn, full fruit ripening (Plocher and Parke, 2008). The impact of over-cropping and the stress it causes a plant with regard to vine health, is observed in cool-climates, when vines overwinter and more specifically by winter dieback. Because carbohydrates are necessary for shoot lignification and energy storage during the winter months, insufficient storage amounts will detrimentally affect grapevine growth and overall health (Dami et al., 2005).

Focusing on consistently and correctly pruning vines at the beginning of the season will enable minimal maintenance throughout the growing season. Utilizing pruning methods that are not only variety specific but also plant specific will allow growers to better anticipate and control reproductive yield and achieve a sustainable balance within their vineyard. This balance point is especially important for small scale growers, which make up the majority of North Dakota's growing grape and wine industry.

Leaf Removal. In addition to pruning, studies have shown the utilization of shade leaf removal as an effective means of reducing fruit rot in rot-prone cultivars (Zoecklein et al., 1992). Shade leaf removal has also been shown to accelerate the soluble solid and flavonoid accumulation in grape berries (Downey et al., 2004). In this application, shade leaf removal is utilized as a means of microclimate control. Decreasing the leaf density of grapevine canopy will have several effects on the growth of the grapevine and the maturation of fruit. The removal of leaves that shade clusters from critical heat units late in the season has the potential to effectively increase the rate of fruit ripening through increased soluble solid accumulation. Increased fruit ripening will shorten the time to harvest and allow increased time for post-harvest carbohydrate accumulation within the vine (Miller et al., 1993). Exposing fruit to increased solar radiation to effectively increase the rate at which grape berries ripen also has the potential to increase grape quality at harvest in northern production regions.

Unfortunately, excessive reduction of leaf area whether through shoot pruning or shade leaf removal has also been shown to have a detrimental effect on all aspects of grapevine development. Studies have shown the impact of diminished leaf area and its effect on the growth of the plant. When leaf area is reduced, carbohydrates assimilated by leaves are sent to specific plant structures such as the trunk, shoots, berries, and roots (Buttrose, 1966). In this list of structures, the trunk is the first to receive necessary nutrients followed by shoots, berries, and finally roots. Study information not only shows the importance of adequate leaf area but also helps broaden knowledge on the effect of canopy management on total vine health. While root development is not a primary focus of most management plans, when developing a management plan for cool-climates it is extremely important to encourage the accumulation of carbohydrate reserves in roots to help facilitate overwintering. In cool-climate conditions a grape's ability to overwinter is critical for consistent year to year production.

Harvest and Marketing. The proper harvest time for grapes is dependent on cultivar, growing season, and the intended use of the fruit. While proper harvest methods can not compensate for poor growing conditions or improper cultural management, a poorly timed harvest can greatly diminish the quality of a crop (Plocher and Parke, 2008). As was previously mentioned, the rate at which fruit of grape mature, as well the time in which they ripen is controlled by several factors, some of which can be manipulated by the grower. The earliest stage of grape maturation can be seen mid-growing season when pigments begin to develop in the skin of the berries, or veraison. Once fruit has reached veraison, sugars will rapidly begin to increase, acid will decrease and the fruit will no longer increase in size. To monitor the progression of grape ripening it is imperative to do regular sampling three to four weeks prior to the anticipated harvest date. Regular sampling and testing must be consistent each time in order to effectively evaluate fruit ripening. Since fruit ripening progresses from the cluster base to the cluster tip, samples must include berries from all parts of the cluster. With information on sugars and acid collected at each sampling, a harvest date can be determined by calculating the sugar/acid ratio. When the ratio has reached a point desired by processors, harvesting of that cultivar should begin. Guidelines for fruit harvest parameters vary according to wine and juice style, and because each cultivar has specific traits it is important to be familiar with the specific characteristics of those traits.

The use of pruning and shade leaf removal methods will be the focus of this project. Determining the effects of retaining a specific number of nodes per vine and removing a percentage of leaves in the fruit zone on vine growth, fruit yield and composition, and overwintering will give much needed direction to growers and wine makers.

MATERIALS AND METHODS

Field Experiments. Experiments were conducted to evaluate which pruning method and/or shade leaf removal method would be most effective for maintaining consistent grape yield and quality. Pruning methods included maintaining 20, 30 or 40 primary buds per vine. Leaving these bud amounts most accurately simulated the pruning range recommended by research and industry experts for our specific climate and growing conditions. In combination with the pruning treatments, two shade leaf removal treatments were used to increase the exposure of ripening fruit to sunlight and create a microclimate more conducive for the ripening of fruit.

Shade leaf removal treatments were implemented at a 0 (control), 50 or 100 % increase in relative exposure to sunlight. In the 50 % exposure treatments one of two leaves next to the fruit cluster were removed approximately three weeks post bloom, when berry size ranged from 0.5 to 0.75 cm, to expose fruit to more direct morning sunlight from the east. Similarly, in the 100 % increase in exposure to sunlight, both leaves next to each cluster were removed. During shade leaf removal only those leaves that directly shaded clusters were removed. Shade leaf removal was also limited to leaves no farther than five nodes from the base of the shoot in order to maintain the proper number of leaves for carbohydrate production.

Checks were used in this experiment for comparison to the pruning and shade leaf removal methods, the 30 bud pruning treatment not only served as a treatment but also the industry recommendation and therefore the standard. Pruning treatments that did not receive a shade leaf removal treatment provided a comparison for shade leaf removal treatments.

General Procedures. Experiments were initially conducted at four locations in 2011: 1) Twisted Sisters Vineyard near Clifford; 2) Red Trail Vineyard near Buffalo; 3) Dakota Breeze Vineyard near Wahpeton; and 4) Prairiewood Vineyard near Lisbon. Experiments were repeated at all locations in 2012 except Prairiewood Vineyard which was dropped from the study. All locations were established vineyards with all grape vines at full production capacity for no less than two years. Vines at all locations were pruned while dormant in both 2011 and 2012 with specific pruning dates varying due to seasonal temperature differences between years.

At each location, vines were arranged in a north to south orientation with 2.44 m spacing between plants, 2.44 m between rows, and 122 m long rows containing 50 vines. Grape cultivars used in this research were limited to those that had sufficient growth for treatment replication and consisted of the main red and white wine grape cultivars used for production in ND. Two cultivars Marquette and Frontenac Gris, both University of Minnesota introductions, are vines that have been planted extensively in North Dakota and other northern climates in the last 5-10 years (Hatterman-Valenti, personal communication). Because of their extensive planting, and high production potential, they were chosen for this study.

Plot locations were not irrigated and only minor fertilization (<5.5 kg N ha^{-1}) took place at the Buffalo location in the spring of 2012. Early-season dormant pruning took place before bud break and after the threat of a late-season killing frost had decreased. Pruning of dormant canes was completed after a measurement of the longest one year-old cane in each direction from the trunk was taken. After pruning to the correct number of retained primary buds, the weight of pruned wood for each plant was recorded using a digital scale (A&D SK-1000, A&D Engineering, Inc., San Jose, CA).

Following bud break and shoot elongation of 5 to 10 cm, a second green pruning was conducted to remove latent breaking buds, unnecessary shoots from secondary and tertiary buds, and other growth not congruent with treatment parameters. This standard of pruning was continued throughout the season to remove any growth that would arise from buds not within the treatment parameters.

All locations had grass grown between vine rows. In the vine line weed control varied between locations with the Buffalo and Blanchard vineyards utilizing herbicides such as glufosinate-ammonium (Rely®, Bayer CropScience, Research Triangle Park, NC) and flumioxazin (Chateau®, Valent U.S.A. Corporation, Walnut Creek, CA) periodically throughout the summer in combination with cultural weed control such as hand removal. Weed control at the Wahpeton vineyard was carried out primarily by hand in the early spring using a “small” rotary tillage implement. While weed control is important within the vineyard setting, the threshold level of weed competition as it relates to detrimental effects on grape production has yet to be studied. Therefore, moderate weed control was maintained throughout the year as was proper sucker management and vine training.

Rate of ripening was observed visually during the growing season from veraison until approximately three weeks prior to anticipated harvest. At this point eight berry samples were taken from each vine weekly and analyzed for pH (Mettler Toledo S20 pH meter, Mettler-Toledo Inc., Columbus, OH) and for SSC in °Brix (Extech Portable Refractometer Extech Instruments, Nashua, NH). All sample berries were obtained from the middle of its respective cluster in order to maintain consistency when sampling and to avoid variable ripeness that can exist between the upper and lower berries of the same cluster.

Grape yields were obtained by harvesting each grape vine individually. During harvest, the number of grape clusters per vine was counted, and the weight of all grapes from each plant was recorded in the field. A random two-cluster sample was collected from each plant following yield weights for further analysis.

The experimental design at each location was completely random block with four replications. Environments were considered random effects, while pruning level, shade leaf removal percentage, and cultivar were considered fixed effects. Data were subjected to ANOVA and analyzed by SAS Proc Mixed (Statistical Analysis Systems, SAS version 9.3, Statistical Analysis Systems Institute, Cary, NC). Treatment means were separated where appropriate using Duncan's Means Separation test at 0.05 and 0.01 levels of significance.

Clifford. The soil was a Gardena silt loam classified as a Coarse-silty, mixed, superactive, frigid Pachic Hapludoll, and Doran clay loam classified as a Fine, smectitic, frigid Aquertic Argiudoll. Prior to vineyard establishment the primary crop grown was an alfalfa (*Medicago satvia*)/smooth brome (*Bromus inermis*) grass mix used for forage production. There had been no documented application of fertilizers in any amount during forage or grape production on this site. Grape cultivars used at this location were Frontenac Gris and Marquette. Frontenac Gris vines had been planted in 2006 one year earlier than Marquette vines. All vines were maintained in a trellis system that represented the basic principles of a Vertical Shoot Positioning (VSP) system with supporting tuck wires. Unfortunately, there were inconsistencies in maintenance that needed to be addressed during initial pruning.

Initial dormant cane pruning treatments were conducted and cane length measurements and pruning weights were recorded accordingly (Table 1). Because of inconsistent vine management conducted during previous years, extensive vine manipulation was required to ensure consistency and proper trellising, which included removal of multiple trunks, unusable canes, and suckering shoots were carried out. As a result of the extensive work in 2011, dormant cane data collection and pruning in 2012 required less labor input. Green shoot pruning was carried out to maintain proper bud number. Pruning of unnecessary shoots, sucker pruning, and routine maintenance were continued throughout the season as needed.

Table 1. Grape pruning and maintenance dates at the Clifford vineyard.

	2011		2012	
	Frontenac Gris	Marquette	Frontenac Gris	Marquette
Dormant Pruning	20 April	21-25 April	3 May	4-5 May
Green Shoot Pruning	27 April	27 April	10 May	10 May
Shade Leaf Removal	22 July	22 July	10 July	10 July
Pre-Harvest Sampling	9 September	9 September	23 August	23 August
Harvest	30 September	30 September	6 October	6 October

Following fruit set and initial development, shade leaf removal treatments were conducted. Maintenance practices were continued both years throughout the growing season. Pre-harvest samples, consisting of 16 berries, were taken from each experimental unit (two vines) at weekly intervals until harvest. All samples were analyzed for pH and SSC in the lab within two days after collection. Observations were recorded and test results were communicated to the vineyard manager.

Time of harvest was dictated by environmental conditions; a killing frost which signaled the end of the growing season, and economic considerations, such as a buyer's request. Time of harvest in 2012 was dictated primarily by grape ripeness, acceptable pH and soluble solid concentration, and economic considerations. Randomly selected samples were collected at harvest and further analyzed for pH, °Brix, titratable acidity (TA), and berry weight through recommended laboratory procedures.

Buffalo. The soils were Hamerly loam classified as a Fine-loamy, mixed, superactive, frigid Aeric Calciaquoll, Barnes loam classified as a Fine-loamy, mixed, superactive, frigid Calcic Hapludoll, and Vallers loam classified as a Fine-loamy, mixed, superactive, frigid Typic Calciaquoll. The land had previously been in a soybean (*Glycine max*), corn (*Zea mays*), and wheat (*Triticum*) crop rotation. No fertilization of the site occurred from vineyard establishment until spring 2012 when 28 kg N ha^{-1} was hand applied in the vine line. Sufficient numbers of established Marquette and Frontenac Gris were present for implementation of all treatments. Grapevines had been planted five years prior to initial pruning in 2011 and were well established with moderate to low levels of production varying greatly from year to year. Trellising followed the guidelines of an established VSP system with no need for tuck wires because of the low vigor of the site.

Initial dormant cane pruning of vines occurred after cane length measurements and pruning weights were recorded (Table 2). Suckers and shoots not following the VSP system were removed to promote proper vine growth and development and to maintain consistency across experimental units. Bud numbers per vine were subsequently adjusted according to treatment specifications. Following initial pruning, green shoot pruning was carried out after shoot elongation had reached 5-10 cm in size and continued as needed throughout the season to maintain the treatment specifications. Pruning in 2012 was delayed approximately two weeks in order to discourage bud break and decrease the possible damage that a late season frost would have on swelling buds and elongating shoots. Once again, pruning the second year (2012) was carried out in much less time than pruning the first year due to increased consistency of management techniques. However, as a result of extensive winter dieback in both cultivars at this location, no green shoot pruning was needed in 2012. Sucker pruning and removal of late breaking buds was carried out throughout the 2011 growing season on both Marquette and Frontenac Gris cultivars. In 2012 sucker pruning was only necessary on the Frontenac Gris cultivars. As a result of complete dieback on most Marquette vines, all data collection was discontinued allowing for vine regrowth from the base of the vine.

Table 2. Grape pruning and maintenance dates at the Buffalo vineyard.

	2011		2012	
	Frontenac Gris	Marquette	Frontenac Gris	Marquette
Dormant Pruning	28 April	27 April	5 May	18 May
Green Shoot Pruning	6 May	6 May	N/A	N/A
Shade Leaf Removal	4 August	4 August	15 July	N/A
Pre-Harvest Sampling	28 August	28 August	24 August	N/A
Harvest	9 September	9 September	N/A	N/A

Maintenance practices were continued both years throughout the growing season on grapevines included in the study. Approximately four weeks after veraison and three weeks prior to the proposed harvest, pre-harvest sampling began. Samples of 16 berries were taken from each experimental unit (two vines) at weekly intervals until harvest. All samples were analyzed in the lab within two days after collection for pH and SSC. All data collected was recorded and information was communicated to the vineyard manager. Random samples were collected at harvest and further analyzed for pH, SSC, TA, and berry weight through recommended laboratory procedures.

Wahpeton. The soil was an Aberdeen silty clay loam classified as a Fine, smectitic, frigid Glossic Natrudoll. Prior to vineyard establishment the primary crop grown was an alfalfa/smooth brome grass mix used for forage production. There had been no documented fertilizer applications in any amount during grape production at this site. Frontenac Gris was the only grape cultivar present in sufficient numbers at this location to carry out all treatments and replications. All vines were maintained in a trellis system representing the basic principles of a VSP system with tuck wires to help guide growth upward.

Initial dormant cane pruning treatments were conducted 28 April 2011 (Table 3). Measurements of the previous year's longest growth and pruning weights were collected accordingly. Because of inconsistencies that existed in vine management conducted during previous years, extensive vine manipulation was required to ensure consistency and proper trellising and included removal of multiple trunks, unusable canes, and suckering shoots was carried out. As a result of the extensive work carried out in 2011 dormant cane data collection and pruning in 2012 required significantly less labor input. Green shoot pruning along with pruning of unnecessary shoots, sucker pruning, and routine maintenance were conducted throughout the growing season as needed.

Table 3. Grape pruning and maintenance dates at the Wahpeton vineyard.

	2011	2012
	Frontenac Gris	Frontenac Gris
Dormant Pruning	28 April	4 May
Green Shoot Pruning	8 May	11 May
Shade Leaf Removal	27 July	12 July
Pre-Harvest Sampling	28 August	14 August
Harvest	28 September	28 August

Following fruit set and initial development, shade leaf removal treatments were conducted. Similar to previous locations, described shade leaf removal was carried out several times because of seasonal variations. Maintenance practices were continued both years throughout the growing season. Pre-harvest samples containing 16 berries were taken from each experimental unit (two vines) at weekly intervals until harvest. All samples were analyzed within two days of collection for pH and SSC. Data collected was recorded and information was communicated to the vineyard manager. Randomly selected samples were collected at harvest and further analyzed for pH, SSC, TA, and berry weight through additional laboratory procedures.

Lisbon. The soils were a complex consisting of Hamerly, Tonka soil classified as a Fine, smectitic, frigid Argiaquic Argialbolli, and Parnell soil classified as a Fine, smectitic, frigid Vertic Argiaquoll. Prior to vineyard establishment the primary use of the land was for the production of alfalfa/brome grass mix for forage production. No fertilizer applications had been documented since the establishment of the vineyard in 2007. Grape cultivars being present in sufficient numbers at this location were Frontenac Gris and Marquette. Vineyard managers stated all vines were initially set up to be maintained in a VSP system but had become excessively overgrown. Many pruning inconsistencies needed to be addressed during initial dormant cane pruning, because vines were extensively overgrown as a result of the complete absence of vine management the previous two years (as stated by vineyard manager). Pruning and vine manipulation to re-implement the VSP system were conducted on only the Marquette vines. Prior to pruning of Frontenac Gris vines, vineyard managers withdrew the cultivar from the study.

Minimal green pruning was needed in 2011 and fruit set was extremely poor. Sucker pruning was carried out throughout the season in an attempt to maintain the vines. Unfortunately, because communication difficulties and the unforeseen early harvest of treatment vines, harvest sampling and harvest were not carried out and the vineyard was dropped from the study.

Fruit Analysis. Fruit quality analysis on all berry samples took place within two days of sample collection. Berries for pre-harvest analysis were collected from the center of random clusters in each experimental unit. Once collected, pre-harvest berries were stored at 7°C until analysis. A garlic press was used for juice extraction. Two to three droplets of juice were placed on the glass plate of a refractometer (Extech Portable Refractometer Extech Instruments, Nashua, NH) to determine SSC with the remaining juice being used to measure pH (Mettler Toledo S20 pH meter, Mettler-Toledo Inc., Columbus, OH). Post-harvest berry samples were collected from clusters retained at harvest. Collected clusters were stored at 7°C until berries were hand de-stemmed for analysis. Fruit samples consisted of 50 randomly selected berries. Samples were juiced in their entirety to determine SCC and pH as previously described. In addition TA was determined on a 2 mL sample using a mini-titrator (Hannah Instruments HI 84102 Mini-titrator Hannah Instruments, Smithfield, RI).

RESULTS AND DISCUSSION

Phenology. Climatic collected from NDAWN showed late winter and early spring environmental conditions (February – May) differed in 2011 and 2012 (Table 4). Cold winter conditions combined with wet and cold spring conditions in 2011 delayed bud swell and emergence from winter dormancy. Conversely, above average winter and spring temperatures in 2012 encouraged early bud break and more accumulated GDD (Table 5).

Table 4. Average late winter and early growing season monthly air temperatures (°C) for 2011 and 2012 at field locations collected from nearest NDAWN weather station (in parenthesis).

	Clifford (Galesburg)			Wahpeton			Buffalo (Prosper)		
Month	2011	2012	30 yr avg	2011	2012	30 yr avg	2011	2012	30 yr avg
	°C								
February	-12	-7	-11	-13	-6	-9	-13	-6	-10
March	-8	3	-4	-6	5	-2	-8	4	-3
April	5	8	6	6	9	7	5	9	6
May	11	15	13	12	16	15	12	15	13
June	18	20	18	19	20	20	18	21	19
July	23	23	21	23	24	22	23	25	21
August	21	20	20	20	19	18	21	20	19
September	15	14	15	15	15	16	15	15	15

Table 5. Growing degree day data from 2011 and 2012 collected from NDAWN weather station (in parenthesis) nearest field locations and the comparison to the 5-year average.

	Clifford (Galesburg)		Wahpeton		Buffalo (Prosper)	
	2011	2012	2011	2012	2011	2012
Growing Degree Days (50)	2365	2704	2443	2910	2471	2869
Departure from 5-yr average	+19	+383	+99	+401	+71	+485

Therefore, delayed dormant cane pruning was used to discourage bud swell and bud break in 2012. Unfortunately, delayed pruning could not prevent early emergence from dormancy by distal buds, and above average spring temperatures resulted in an accelerated rate of growth and development in 2012 when phenology dates were compared to 2011 regardless of differences in rainfall over the same time period (Table 6).

Table 6. Monthly rainfall totals from 2011 and 2012 measured for Clifford, Wahpeton, and Buffalo locations collected from nearest NDAWN weather station (in parenthesis).

	Clifford (Galesburg)		Wahpeton		Buffalo (Prosper)	
Month	2011	2012	2011	2012	2011	2012
	---cm---					
April	3.5	3.6	3.6	8.1	4.5	4.6
May	10.1	2.6	6.9	3.7	8.1	4.6
June	10.2	1.6	8.7	7.5	13.2	6.7
July	10.2	0.7	14.6	4.6	15.1	1.6
August	8.9	1.1	12.2	5.8	8.9	2.3
September	1.3	0.3.	1.3	0.9	0.6	1.5
Total	44.2	9.9	47.3	30.6	50.4	21.3

Cane dieback estimates taken prior to spring pruning reinforced suspected late winter/early spring temperature stress differences during 2010-2011 and 2011-2012. Visual estimates showed 65 to 80% bud and cane dieback in the spring of 2011 while the same plants only had 10 to 20% dieback in the spring of 2012. Shade leaf removal treatments did not significantly influence growth of one year old canes regardless of the cultivar. However, factorial analysis indicated a significant pruning level by cultivar interaction (see appendix, Table 1A). Pruning has a well-documented connection to overall vine health particularly in respect to carbohydrate partitioning, vine balance, and the vine's ability to overwinter successfully and produce fruit the following growing season (Bravdo et al., 1984; Buttrose, 1966; May et al., 1969).

Both cultivars pruned to retain only 30 buds per vine had shorter canes compared to those pruned to retain 20 or 40 buds per cane (Table 7). The longest one year old canes occurred on vines which were pruned to retain the highest number of retained buds. Marquette vines pruned to retain 20 buds per vine had significantly shorter one year old canes when compared to vines pruned to retain 40 buds per vine, but longer one year old canes when compared to vines pruned to retain 30 buds. The longest one year old Frontenac Gris canes were approximately 20% shorter when averaged over pruning levels and compared to the longest one year old Marquette canes. The reason for the differences between lengths of the longest one year old cane is not clear because of the long term impact of pruning on vine balance and carbohydrate reserves. However, vines pruned to 30 buds per vine may exhibit the correct ratio of vegetative to reproductive growth (Partridge, 1925), while vines pruned to 40 and 20 buds per vine are possibly showing increased vigor to compensate for unbalanced growth resulting in unmet carbohydrate needs (Buttrose 1966; Plocher and Parke, 2008).

Table 7. Effect of pruning on length of longest one year old cane averaged over shade leaf removal treatments and both 2011 and 2012.

Buds Retained	Frontenac Gris		Marquette		Mean
	--------------------------------------cm-----------------------------------				
20	209	a[z]	241	b[z]	226
30	183	b	227	c	206
40	205	a	283	a	244
Mean	199		251		225

[z]Treatment means followed by the same letter(s) in the same column are not significantly different according to Duncan's mean separation at *$P \leq 0.05$*

Analysis indicated significant year by cultivar and cultivar by pruning level interactions. Year by cultivar significance was directly linked to significant differences between the amount of growth removed from vines in 2011 and the amount of growth removed in 2012. Increased training and pruning resulted in an increase in vine vigor causing significantly higher vegetative yield in 2012. Frontenac Gris showed more than a 75% increase in pruning weight from 2011 to 2012. Similarly, Marquette showed a 72% increase in pruning weight over the same period. Also, significant differences were seen when shade leaf removal treatments were compared within each cultivar. Frontenac Gris vines, which received the highest percentage of shade leaf removal, had the lowest weight of pruning while Marquette vines, with the lowest percentage of shade leaf removal, had the highest weight of pruning (Table 8). Because pruning weights were taken on dormant canes void of any leaf material, the effect of shade leaf removal on pruning weight is once again likely linked to specific plant carbohydrate accumulation within those one year old canes (Buttrose, 1966).

Table 8. Effect of shade leaf removal on weight of dormant cane pruning averaged over pruning treatment and years 2011 and 2012.

Shade Leaf Removal Percentage	Frontenac Gris		Marquette		Mean
	----------------------------------		g		----------------------------------
0	365	a^z	1031	a^z	698
50	414	a	883	b	649
100	247	b	925	b	586
Mean	342		947		645

^{z}Treatment means followed by the same letter(s) in the same column are not significantly different according to Duncan's mean separation at $P \leq 0.05$

Yield Components. Grape vine yield was measured by the total weight of grapes harvest at the conclusion of one growing season. A significant interaction between cultivar, bud retention, and shade leaf removal percentages was found for grape yield (see appendix, Table 3A). Since a three-way interaction is difficult to interpret, the significant shade leaf removal level by cultivar interaction and significant pruning level influence on yield will be discussed. Shade leaf removal significantly affected Frontenac Gris vines when the highest percentage of leaves was removed. This high level of leaf removal resulted in the lowest total mass of harvested grapes (Table 9).

Table 9. Effect of shade leaf removal on total mass of harvested grapes averaged over pruning treatments and years 2011 and 2012.

Shade Leaf Removal Percentage	Frontenac Gris		Marquette		Mean
	------------------------------------		kg-------------------------------		
0	2.7	a^z	2.7	a^z	2.7
50	2.9	a	2.9	a	2.9
100	2.1	b	2.8	a	2.4
Mean	2.5		2.8		2.7

[z] Treatment means followed by the same letter(s) in the same column are not significantly different according to Duncan's mean separation at $P \leq 0.05$

Significant differences in harvest yield may have been related to specific pruning levels. Grape vines with 20 retained buds produced the least amount of fruit with an average of 1.9 kg/vine, vines with 30 retained buds producing an average of 2.6 kg/vine, and vines with 40 retained buds produced the most fruit with an average of 3.5 kg/vine (Table 10). Results suggested that increased production was possible through the retention of more buds and that vine vigor, when compared to growth of the longest canes or pruning weights, was not affected by the increase in retained buds. In addition, shade leaf removal only slightly influenced yield in Frontenac Gris and had no influence on Marquette yield, suggesting that the removal of photosynthetic material did not greatly alter carbohydrate partitioning even though fruit are third in priority for carbohydrate reserves behind the trunk and canes (Buttrose, 1966). These results reinforce the importance of proper bud retention in grape production (Howell et al., 2001).

Table 10. Total mass of harvested grapes separated by number of retained primary buds averaged over shade leaf removal treatment, years 2011 and 2012, and cultivar.

Buds Retained	Mass
	-----------------kg-----------------
20	1.9 c[z]
30	2.6 b
40	3.5 a
Mean	2.7

[z] Treatment means followed by the same letter(s) are not significantly different according to Duncan's mean separation at $P \leq 0.05$

In combination with total yield, the cluster weight and number of clusters per vine at harvest were also used to determine vine and vineyard productivity. A significant interaction between pruning treatments, shade leaf removal treatments, and cultivar was found for cluster weight (Table 5A). For Frontenac Gris, vines with 30 buds retained and 50%shade leaf removal had larger clusters than vines with 20 buds retained and no shade leaf removal. For Marquette, vines with 20 buds retained and 100% shade leaf removal had larger clusters than all other treatments except vines with 30 buds retained and no shade leaf removal. While significant differences were found, no correlation between pruning treatments, shade leaf removal treatments, and cultivar was found for cluster weight.

The only significant two-way interaction was between cultivar and shade leaf removal level. Frontenac Gris vines with 50% shade leaf removal had heavier average clusters when compared to vines with 100% shade leaf removal (Table 11). On the other hand, Marquette vines with 100% shade leaf removal had heavier average clusters when compared to vines receiving 50% shade leaf removal. Both Marquette and Frontenac Gris cluster mass averages were far below the recognized averages of 89 and 131 g/cluster.

Table 11. Effect of shade leaf removal on cluster mass at harvest averaged over pruning treatments and years 2011 and 2012.

Shade Leaf Removal Percentage	Frontenac Gris		Marquette		Mean
	-----------------------------------g-----------------------------------				
0	44.9	ab[z]	44.3	ab[z]	44.7
50	46.9	a	39.3	b	39.3
100	37.9	b	49.5	a	49.5
Mean	43.3		44.4		44.5

[z] Treatment means followed by the same letter(s) in the same column are not significantly different according to Duncan's mean separation at $P \leq 0.05$

The average number of clusters per vine was directly related to the number of buds retained. Even though average cluster number differences are explained simply by difference in bud numbers, average cluster weight was not related to bud retention numbers suggesting vines may have been able to support additional clusters if additional buds had been retained.

Shade leaf removal treatments did not significantly influence berry weight regardless of the cultivar. Analysis indicated a significant pruning level by cultivar interaction (see appendix, Table 6A). Vines with the highest number of retained buds (40) had heavier berries compared to vines that had only 20 or 30 retained buds (Table 12). This interaction was due to a difference in magnitude with the number of buds retained significantly affecting average berry weight. Berry masses for Marquette and Frontenac Gris were near the recognized average of 1.1 g/berry. Results suggested average berry weight was directly related to the number of retained buds. Observed results were counter intuitive to previous research on carbohydrate reserves and pruning methods when yield limits have been reached (Buttrose, 1966; Partridge, 1925).

Table 12. Effect of number of buds retained on berry mass at harvest averaged over shade leaf removal treatments and years 2011 and 2012.

Buds Retained	Frontenac Gris		Marquette		Mean
	--------------------		g		--------------------
20	0.97	b[z]	1.00	b[z]	0.97
30	0.97	b	1.02	b	0.99
40	0.99	a	1.04	a	1.02
Mean	0.96		1.02		0.99

[z] Treatment means followed by the same letter(s) in the same column are not significantly different according to Duncan's mean separation at $P \leq 0.05$

Quality. The progressive ripening of grapes was measured to help illustrate the effect of pruning and shade leaf removal on the post-veraison ripening of grapes. Figures are separated by cultivar, year, and ripeness characteristics (°Brix or pH). Fruit ripening figures aid in describing the ripening process to grape producers and those less familiar with how time affects pH and SSC. Using line graphs allows for the visual comparison of valuable information allowing grape quality to be more effectively related to time after veraison (see appendix Figures 1A-16A). Analysis of SSC measured in ^{o}Brix showed a significant interaction between year and cultivar (see appendix, Table 8A). Marquette grapes harvested in 2012 had significantly higher SSC compared to grapes harvested from the same vines in 2011 (Table 13). However, Frontenac Gris, had similar levels of SSC each year. SSC differences observed between 2011 and 2012 for Marquette grape data can be directly correlated to the length of time allowed for fruit ripening. Marquette is a late maturing cultivar and because the previously mentioned seasonal temperatures differences, an extended length of ripening occurred in the fall of 2012 and these grapes assimilated more soluble solids. SSC levels in Marquette were near the recognized average harvest level of 25.7 ^{o}Brix when averaged across years, Frontenac Gris were not near the recognized average of 26 ^{o}Brix at harvest when averaged across year.

Table 13. Effect of year on soluble solid concentration in grapes at harvest averaged over shade leaf removal treatments and pruning treatments.

Year	Frontenac Gris		Marquette		Mean
	°Brix				
2011	21.40	a[z]	22.95	a[z]	22.18
2012	20.89	a	27.07	b	23.99
Mean	21.15		25.15		23.08

[z] Treatment means followed by the same letter(s) in the same column are not significantly different according to Duncan's mean separation at $P \leq 0.05$

Continued analysis of fruit quality revealed no significant differences in pH levels in pruning treatments or shade leaf removal treatments regardless of cultivar. Because grape pH is a measure of free hydrogen ions that decrease during ripening, a lack of significance shows there was little to no effect by treatments or by seasonal variation. While not significant Frontenac Gris pH values were very near the recognized average harvest pH of 3.0, Marquette values on the other hand were much higher than the recognized average of 2.9. Significant differences were found between cultivars for juice pH (see appendix, Table 7A). The lower pH values with Frontenac Gris were associated with the wine making characteristics of the each grape cultivar instead of environmental conditions (Table 14).

Table 14. Effect of variety on pH of grapes at harvest average over shade leaf removal treatments and pruning treatments.

Year	Frontenac Gris		Marquette		Mean
	pH				
2011	3.01	b[z]	3.09	a	3.05
2012	2.87	b	3.56	a	3.22
Mean	2.94		3.33		3.13

[z] Means followed by the same letter(s) are not significantly different according to Duncan's mean separation at $P \leq 0.05$

Titratable acidity was also measured as an indicator of grape ripeness at harvest. Pruning treatments did not show significant differences in TA. However, further analysis indicated a significant interaction between shade leaf removal treatments and cultivars (see appendix, Table 9A). Marquette grapes from the 100% shade leaf removal treatment had lower TA levels than and those receiving 50% and 0% shade leaf removal (Table 15). Juice from vines which received the highest shade leaf removal level, (100% around clusters), a TA 6.40 g/L followed by the 50% shade leaf removal treatment with 7.82 g/L, and 8.19 g/L when no leaves were removed.

Table 15. Effect of shade leaf removal on titratable acidity at harvest averaged over pruning treatments and years 2011 and 2012.

Shade Leaf Removal Percentage	Frontenac Gris		Marquette		Mean
	----------------------------------		g/L	----------------------------------	
0	8.17	a[z]	8.19	a[z]	8.18
50	8.02	a	7.82	a	7.92
100	8.40	a	6.40	b	7.41
Mean	8.21		7.47		7.84

[z] Treatment means followed by the same letter(s) in the same column are not significantly different according to Duncan's mean separation at *$P \leq 0.05$*

Unfortunately, shade leaf removal did not influence TA levels in Frontenac Gris suggesting that this response was cultivar dependent. Both Marquette and Frontenac Gris had TA levels much lower than the recognized averages of 12.3 and 14 g/L respectively. Also when years were separated and analyzed the prevalence of trends decreased showing results are highly dependent on specific annual fluctuations in growing conditions with shade leaf removal and cultivar only playing a specific role in TA levels (Table 16).

Lower TA levels when leaves are removed near the fruit clusters have been reported in previous research with V. *vinifera* cultivars (Bavaresco et al., 2008; Tardaguila et al., 2010). However, the significance found with Marquette at the highest level of shade leaf removal suggests that one can manipulate TA levels by increasing sunlight exposure with some hybrid cultivars. Because the lowest TA level occurred with the highest shade leaf removal treatment, one should also evaluate if additional shade leaf removal would reduce the TA level with Marquette. Also, because other fruit quality characteristics were not influenced, one should be able to reduce TA levels without detrimentally affecting other quality characteristics essential for wine production.

Table 16. Effect of shade leaf removal on titratable acidity at harvest averaged over pruning treatments

Shade Leaf Removal Percentage	Frontenac Gris		Mean	Marquette		Mean
	2011	2012		2011	2012	
	----------------------------------	g/L	-------------------------------			
0	7.2 a^z	9.1 a^z	8.1	10.6 b^z	5.7 a^z	8.1
50	6.5 a	9.4 a	8.0	10.0 b	5.6 a	7.8
100	7.6 a	9.1 a	8.4	7.5 a	5.2 a	6.4
Mean	7.1	9.2	8.2	9.4	5.5	7.4

^{z}Treatment means followed by the same letter(s) in the same column are not significantly different according to Duncan's mean separation at $P \leq 0.05$

SUMMARY

Field experiments were conducted to evaluate the overall effectiveness of using pruning to control the number of retained buds and shade leaf removal to increase light penetration to ripening grape clusters. The effect of each treatment on the growth of the vines and the development of fruit would determine whether or not the specific training method has potential to positively influence grape production in North Dakota.

In the study, three pruning treatments were applied in which vines retained 20, 30, and 40 primary buds. In addition, three levels of shade leaf removal, 0, 50, and 100% were evaluated. Pruning treatments had a distinct effect on the growth of vines. Grape vines pruned to only 30 primary buds per vine showing the least amount of growth when longest one year old canes were compared. Average length for vines which retained 20 buds and 40 buds were significantly greater in both cultivars. Shade leaf removal treatments affected the overall weight of vine growth with the two cultivars, but the results were mixed. There was a year by cultivar interaction which was attributed to the significantly higher pruning weights in 2012. Also, Frontenac Gris vines with the lowest levels of shade leaf removal (0 and 50%) exhibited significantly greater weights, while in Marquette, only vines which received the lowest treatment (0%) had significantly higher pruning weights.

Shade leaf removal also had a significant effect on the weight of harvested grapes with Frontenac Gris vines receiving the highest shade leaf removal treatment (100%) having the lowest weight of harvest grapes observed. Results verified the importance of number of primary buds in relation to total harvest weight with vines retaining 40 buds yielding the highest and vines retaining 20 buds yielding the lowest.

There was a significant three way interaction between pruning treatments, shade leaf removal treatments, and cultivar when cluster weights were compared. While significant differences did exist, they could not be correlated to any specific treatment or treatment combination to form a trend. Shade leaf removal also affected the average cluster weight with Frontenac Gris and Marquette, but differing results allowed no clear conclusion to be drawn. Number of retained buds had a significant effect on grape yield, with an increased number of retained buds having a positive effect on the average berry weight at harvest. Both Frontenac Gris and Marquette vines showed an increase in berry weight as the numbers of retained buds per vine were increased. This result was counter intuitive to the normal reaction of vines to increased fruit load.

When °Brix were analyzed there was a significant year by cultivar interaction. This interaction showed that Marquette grapes accumulated significantly higher levels of soluble solids in 2012 than in 2011. Even though Frontenac Gris did not exhibit the same response, higher SSC in 2012 were attributed to a longer growing season. Further analysis of grape quality showed significant differences in pH but only between cultivars because of obvious differences in phenology. More interesting significant differences were found when titratable acidity was measured. A significant interaction between titratable acidity, shade leaf removal, and cultivar was found. While the significant difference only existed between the 50 and 100% shade leaf removal treatments in Marquette, the 0% treatment followed the trend. This trend showed grapes that received more sunlight due to increased shade leaf removal had lower levels of titratable acids. Low titratable acidity is a desirable characteristic in wine grapes.

The results of this experiment warrant further research into the development of a cultural grape vine maintenance program for wine grapes grown in North Dakota. This research poses new questions about the positive and negative effects of pruning and shade leaf removal on grape production, vine balance, vine hardiness, and specific wine grape quality attributes. These results support the use of proper pruning to regulate vine growth and establish vine balance as well as shade leaf removal to encourage increased sunlight penetration through the grape canopy, specifically when growing Marquette grape vines. However, because of seasonal variation and the influences of specific weather events on grape vines, correct application of pruning and shade leaf removal must be carefully timed.

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APPENDIX

Table A1. ANOVA for length of longest one year old cane.

Source of Variation	df	MS	F	
year	1	38977.00	2.79	
PT[z]	2	13738.00	65.32	*
year x PT	2	6145.56	5.37	
LR[y]	2	3840.09	1.55	
year x LR	2	1692.05	0.54	
PT x LR	4	3942.13	0.22	
year x PT x LR	4	2317.65	0.24	
cultivar	1	61336.00	1.58	
year x cultivar	1	21603.00	1.52	
PT x cultivar	2	6389.27	20.61	**
year x PT x cultivar	2	2174.15	0.22	
LR x cultivar	2	13292.00	2.32	
year x LR x cultivar	2	2895.63	0.72	
PT x LR x cultivar	4	10731.00	0.11	
year x PT x LR x cultivar	4	2836.18	0.44	
rep(year)	6	9840.28	-	
Error	135	5905.13	-	

*, **, *** significant at $P \leq$ 0.05, 0.01, or 0.001 respectively.

[z] PT pruning treatment retaining 20, 30, or 40 primary buds

[y] LR shade leaf removal treatments 0, 50, and 100%

Table A2. ANOVA for dormant cane pruning weight of all vines.

Source of Variation	df	MS	F	
year	1	14817175	1264.03	
PT^{z}	2	199995	1.20	
year x PT	2	113413	0.11	
LR^{y}	2	59982	2.82	
year x LR	2	144616	5.22	
PT x LR	4	88661	0.47	
year x PT x LR	4	115834	1.44	
cultivar	1	7967565	0.27	**
year x cultivar	1	5680178	101.85	**
PT x cultivar	2	162324	0.02	
year x PT x cultivar	2	415013	2.80	
LR x cultivar	2	108327	3.38	
year x LR x cultivar	2	198405	3.15	
PT x LR x cultivar	4	107559	0.87	
year x PT x LR x cultivar	4	111517	2.06	
rep(year)	8	110164	-	
Error	135	1422361	-	

*, **, *** significant at $P \leq$ 0.05, 0.01, or 0.001 respectively.

[z] PT pruning treatment retaining 20, 30, or 40 primary buds

[y] LR shade leaf removal treatments 0, 50, and 100%

Table A3. ANOVA for total weight of harvested grapes.

Source of Variation	df	MS	F	
year	1	161246483	0.95	
PT[z]	2	24420651	55.78	*
year x PT	2	315229	0.37	
LR[y]	2	2844936	6.62	
year x LR	2	348194	1.49	
PT x LR	4	222846	1.2	
year x PT x LR	4	635194	1.75	
cultivar	1	2823822	0.09	
year x cultivar	1	19019443	0.32	
PT x cultivar	2	597021	0.07	
year x PT x cultivar	2	9892.25	1.25	
LR x cultivar	2	139407	4.41	*
year x LR x cultivar	2	305863	2.16	
PT x LR x cultivar	4	239675	3.07	*
year x PT x LR x cultivar	4	307244	0.74	
rep(year)	6	490457		
Error	137	1953563		

*, **, *** significant at $P \leq 0.05$, 0.01, or 0.001 respectively.

[z] PT pruning treatment retaining 20, 30, or 40 primary buds

[y] LR shade leaf removal treatments 0, 50, and 100%

Table A4. ANOVA for total number of clusters on all vines at harvest.

Source of Variation	df	MS	F
year	1	58202	4.12
PT[z]	2	10704	12.69
year x PT	2	675.14	5.87
LR[y]	2	914.45	3.84
year x LR	2	122.09	1.44
PT x LR	4	132.22	2.91
year x PT x LR	4	142.41	4.03
cultivar	1	3521.85	3.66
year x cultivar	1	105.01	0.18
PT x cultivar	2	369.91	0.09
year x PT x cultivar	2	96.25	3.01
LR x cultivar	2	546.20	0.07
year x LR x cultivar	2	104.64	0.54
PT x LR x cultivar	4	159.37	1.81
year x PT x LR x cultivar	4	107.96	0.89
rep(year)	6	114.09	-
Error	135	312.21	-

*, **, *** significant at $P \leq 0.05$, 0.01, or 0.001 respectively.

[z] PT pruning treatment retaining 20, 30, or 40 primary buds

[y] LR shade leaf removal treatments 0, 50, and 100%

Table A5. ANOVA for cluster weight of all grapes harvested.

Source of Variation	df	MS	F	
year	1	5900.06	0.28	
PT[z]	2	47.17	0.11	
year x PT	2	1843.72	4.6	
LR[y]	2	41.47	0.18	
year x LR	2	628.32	1.81	
PT x LR	4	318.23	4.11	
year x PT x LR	4	512.03	2.02	
cultivar	1	607.41	0.11	
year x cultivar	1	1879.08	0.7	
PT x cultivar	2	35.12	0.75	
year x PT x cultivar	2	698.39	0.47	
LR x cultivar	2	318.24	7.57	***
year x LR x cultivar	2	329.43	1.85	
PT x LR x cultivar	4	271.22	2.71	*
year x PT x LR x cultivar	4	482.51	3.12	*
rep(year)	6	971.51	-	
Error	137	470.58	-	

*, **, *** significant at *P*≤ 0.05, 0.01, or 0.001 respectively.

[z] PT pruning treatment retaining 20, 30, or 40 primary buds

[y] LR shade leaf removal treatments 0, 50, and 100%

Table A6. ANOVA for berry weight of all grapes at harvest.

Source of Variation	df	MS	F	
year	1	0.067	0.1	
PT[z]	2	0.016	16.46	*
year x PT	2	0.023	0.63	
LR[y]	2	0.023	0.34	
year x LR	2	0.014	0.84	
PT x LR	4	0.013	0.23	
year x PT x LR	4	0.009	0.23	
cultivar	1	0.189	0.71	
year x cultivar	1	0.139	1.51	
PT x cultivar	2	0.013	10.60	**
year x PT x cultivar	2	0.012	1.22	
LR x cultivar	2	0.027	0.69	
year x LR x cultivar	2	0.025	0.87	
PT x LR x cultivar	4	0.020	0.45	
year x PT x LR x cultivar	4	0.010	0.33	
rep(year)	6	0.037	-	
Error	135	0.010	-	

*, **, *** significant at $P \leq$ 0.05, 0.01, or 0.001 respectively.

[z] PT pruning treatment retaining 20, 30, or 40 primary buds

[y] LR shade leaf removal treatments 0, 50, and 100%

Table A7. ANOVA for pH of all grapes at harvest.

Source of Variation	df	MS	F	
year	1	0.321	0.55	
PT[z]	2	0.012	0.13	
year x PT	2	0.003	0.47	
LR[y]	2	0.005	0.29	
year x LR	2	0.014	0.04	
PT x LR	4	0.011	0.12	
year x PT x LR	4	0.004	0.35	
cultivar	1	0.527	4.59	*
year x cultivar	1	0.017	1.96	
PT x cultivar	2	0.014	1.86	
year x PT x cultivar	2	0.003	-	
LR x cultivar	2	0.002	0.51	
year x LR x cultivar	2	0.014	-	
PT x LR x cultivar	4	0.028	0.41	
year x PT x LR x cultivar	3	0.017	-	
rep(year)	6	0.035	-	
Error	134	0.010	-	

*, **, *** significant at $P \leq$ 0.05, 0.01, or 0.001 respectively.

[z] PT pruning treatment retaining 20, 30, or 40 primary buds

[y] LR shade leaf removal treatments 0, 50, and 100%

Table A8. ANOVA for °Brix of all grapes at harvest.

Source of Variation	df	MS	F	
year	1	38977.00	0.00	
PT^z	2	13738.00	1.80	
year x PT	2	6145.56	0.05	
LR^y	2	3840.09	0.12	
year x LR	2	1692.05	0.38	
PT x LR	4	3942.13	2.02	
year x PT x LR	4	2317.65	0.36	
cultivar	1	61336.00	0.96	
year x cultivar	1	21603.00	14.44	***
PT x cultivar	2	6389.27	0.04	
year x PT x cultivar	2	2174.15	5.56	
LR x cultivar	2	13292.00	1.00	
year x LR x cultivar	2	2895.63	0.40	
PT x LR x cultivar	4	10731.00	0.40	
year x PT x LR x cultivar	4	2836.18	2.97	
rep(year)	6	9840.28	-	
Error	135	5905.13	-	

*, **, *** significant at $P \leq 0.05$, 0.01, or 0.001 respectively.

[z] PT pruning treatment retaining 20, 30, or 40 primary buds

[y] LR shade leaf removal treatments 0, 50, and 100%

Table A9. ANOVA for titratable acidity in all grapes at harvest.

Source of Variation	df	MS	F	
year	1	2.43	0.03	
PT^{z}	2	1.41	0.03	
year x PT	2	11.07	0.08	
LR^{y}	2	3.18	2.54	
year x LR	2	2.91	0.1	
PT x LR	4	6.59	0.11	
year x PT x LR	4	11.05	0.48	
cultivar	1	44.45	0.51	
year x cultivar	1	54.30	2.32	
PT x cultivar	2	12.98	0.01	
year x PT x cultivar	2	57.32	0.73	
LR x cultivar	2	30.50	3.61	*
year x LR x cultivar	2	18.20	0.2	
PT x LR x cultivar	4	28.93	0.65	
year x PT x LR x cultivar	4	51.92	0.48	
rep(year)	6	25.86		
Error	134	19.86		

*, **, *** significant at $P \leq 0.05$, 0.01, or 0.001 respectively.

^{z}PT pruning treatment retaining 20, 30, or 40 primary buds

^{y}LR shade leaf removal treatments 0, 50, and 100%

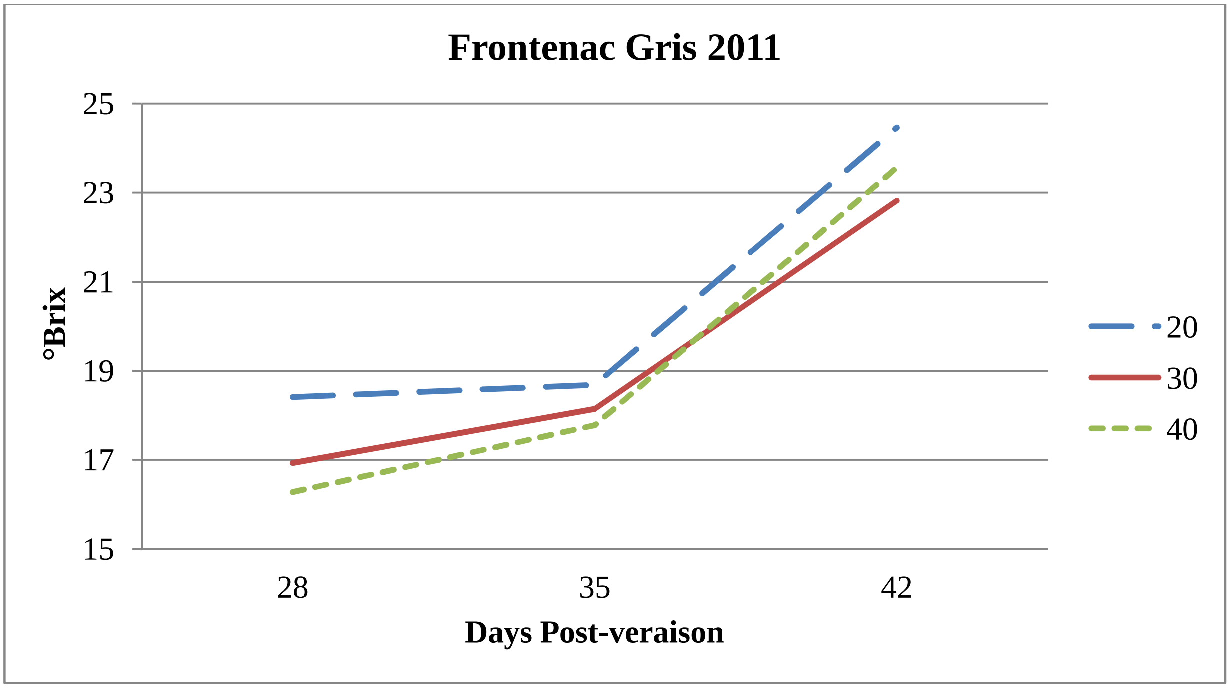

Figure A1. 2011 soluble solids concentration (°Brix) pre harvest in Frontenac Gris separated by the number of buds retained.

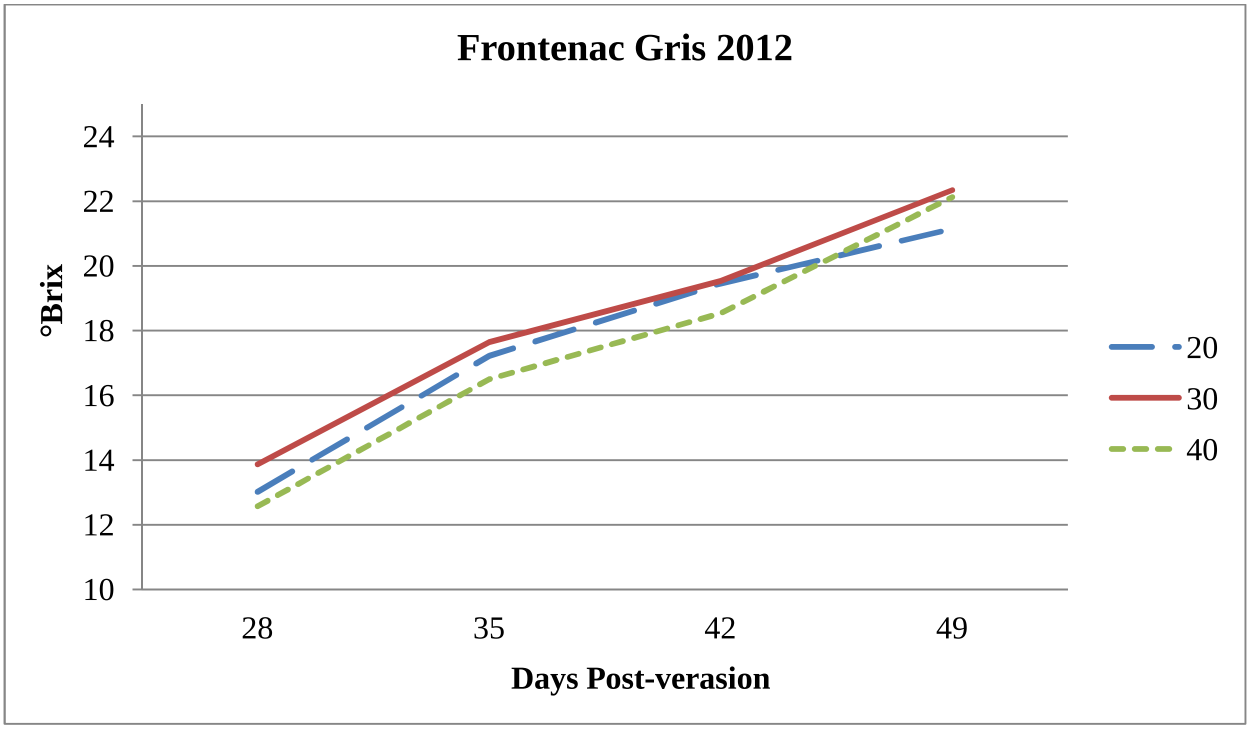

Figure A2. 2012 soluble solids concentration (°Brix) pre harvest in Frontenac Gris separated by the number of buds retained.

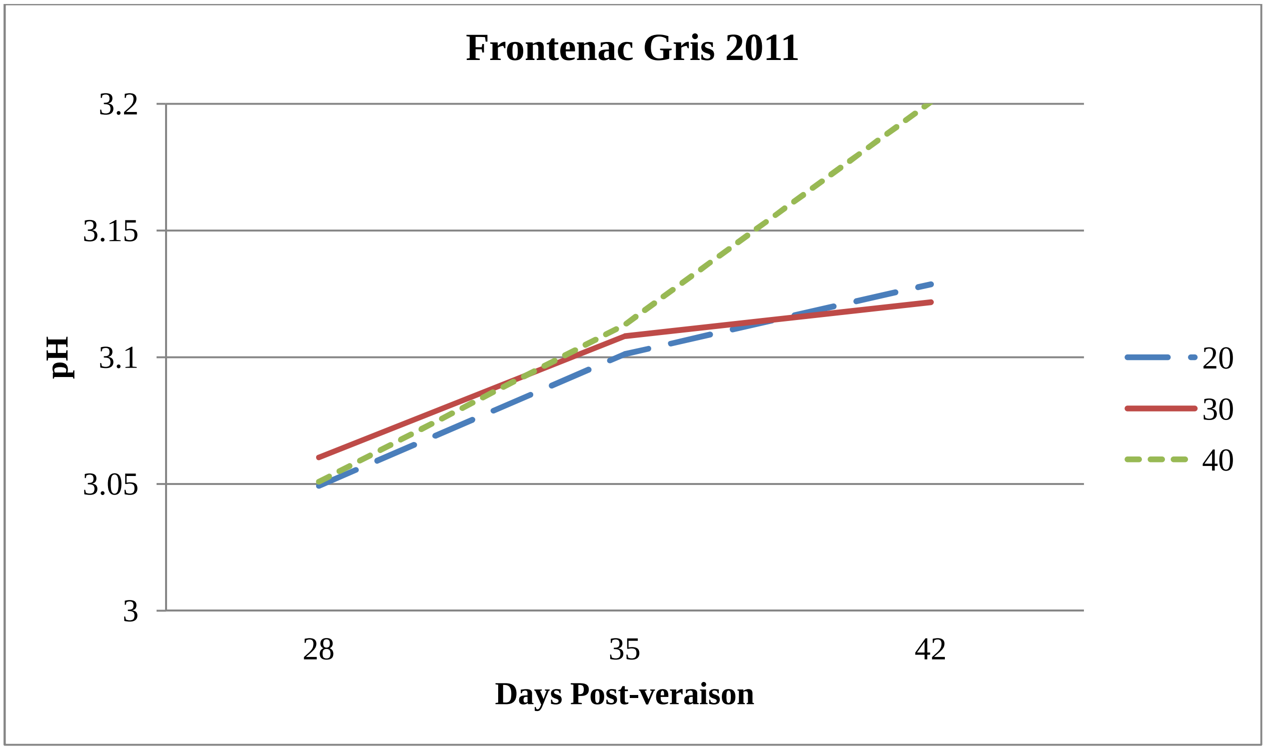

Figure A3. 2011 pH pre-harvest in Frontenac Gris separated by the number of buds retained.

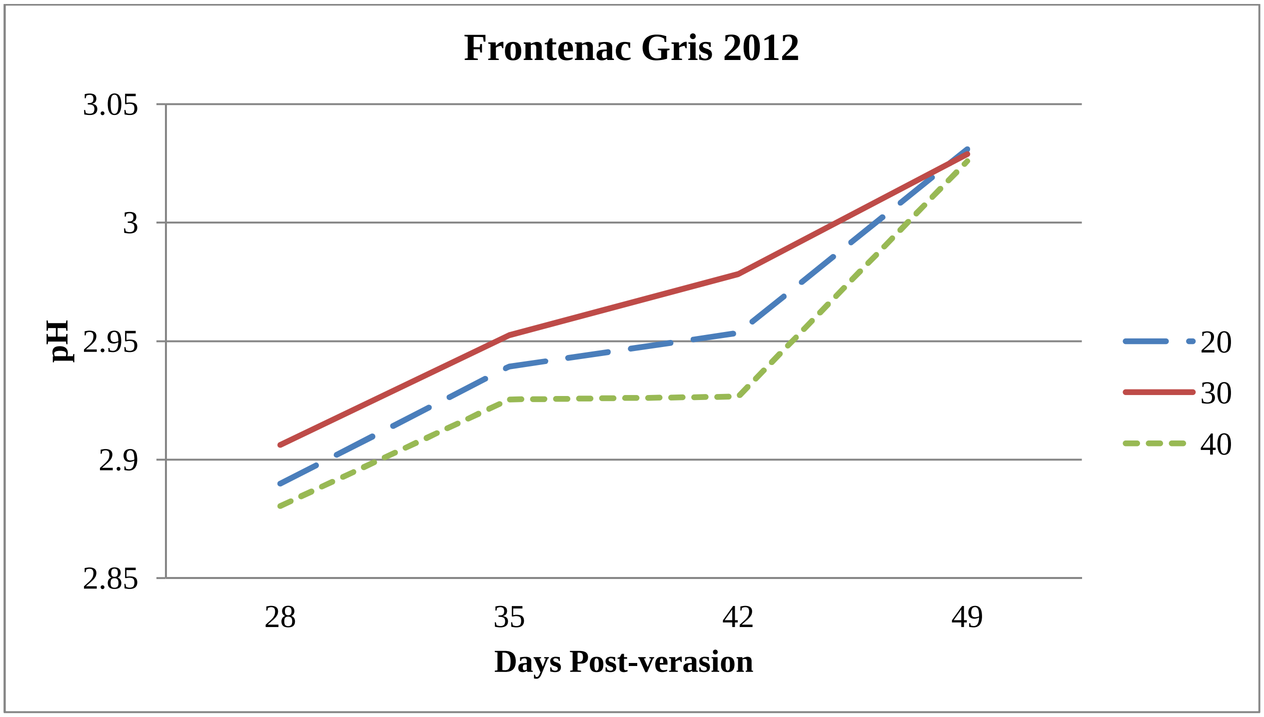

Figure A4. 2012 pH pre-harvest in Frontenac Gris separated by the number of buds retained.

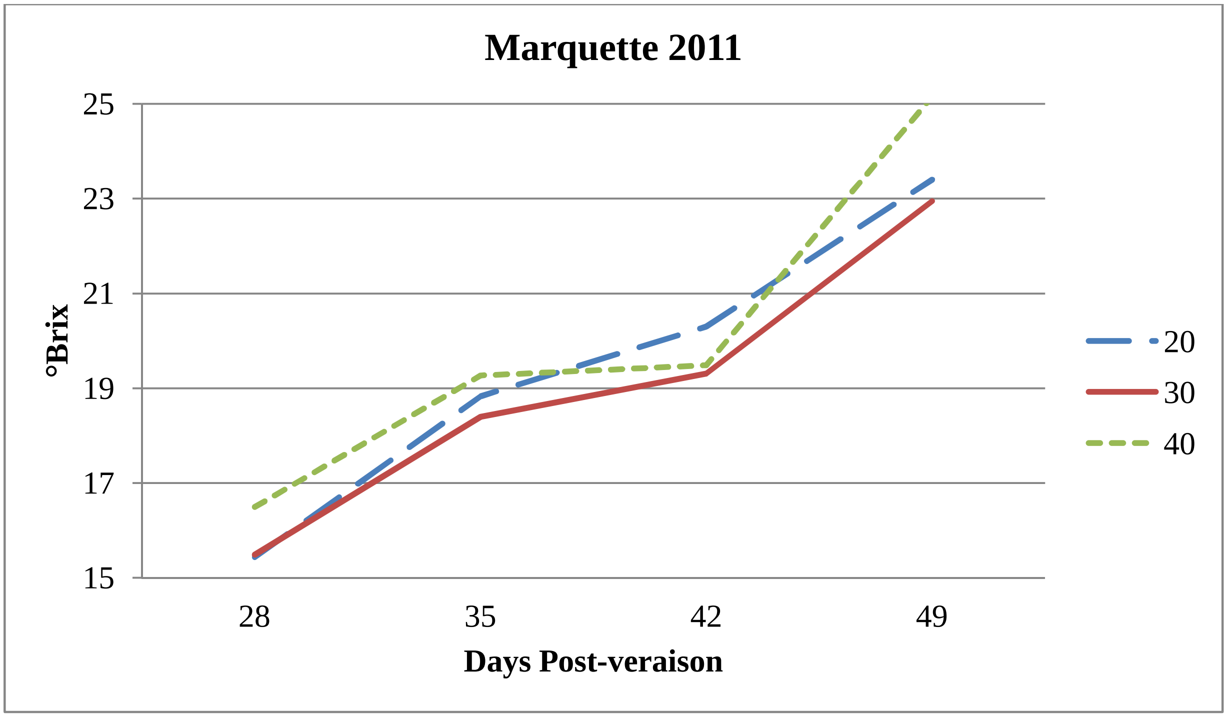

Figure A5. 2011 soluble solids concentration (°Brix) pre-harvest in Marquette separated by the number of buds retained.

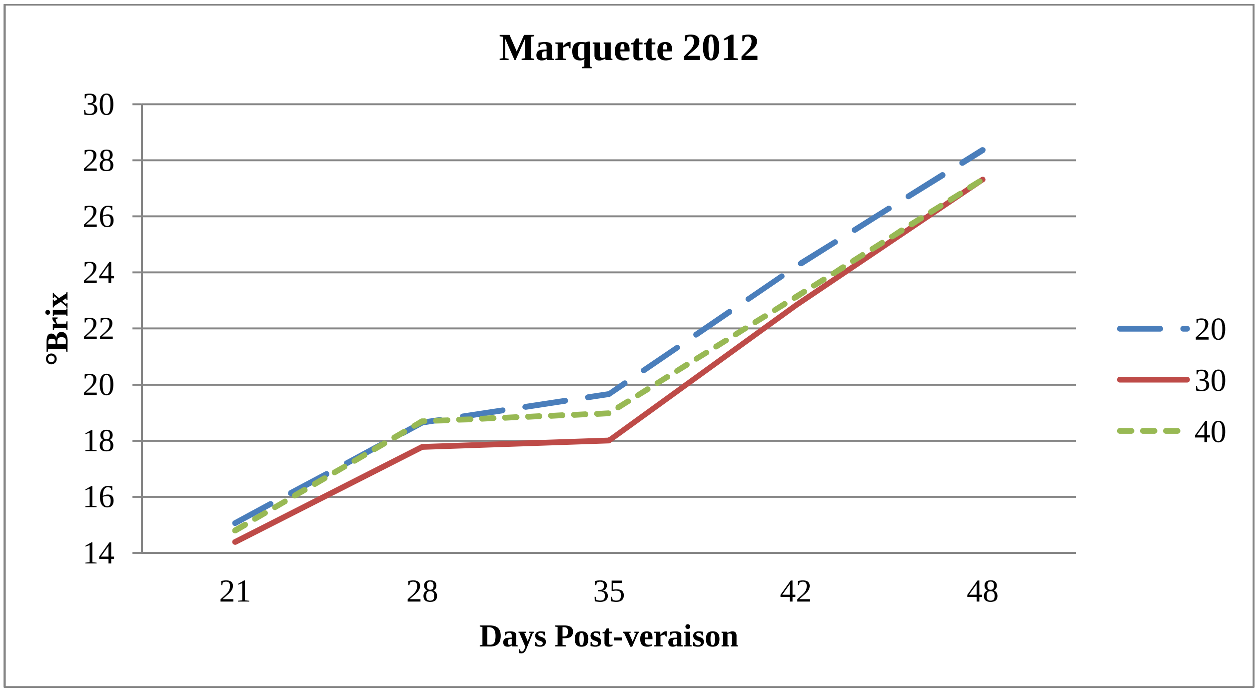

Figure A6. 2012 soluble solids concentration (°Brix) pre-harvest in Marquette separated by the number of buds retained.

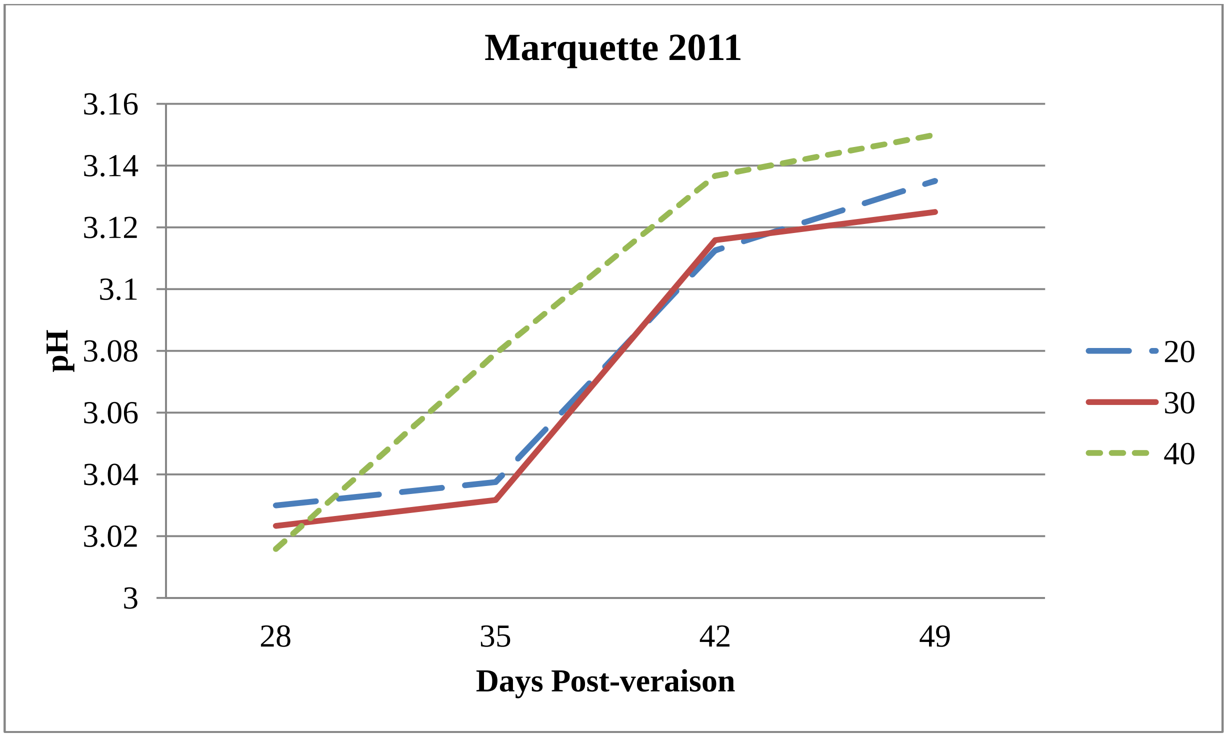

Figure A7. 2011 pH pre-harvest in Marquette separated by the number of buds retained.

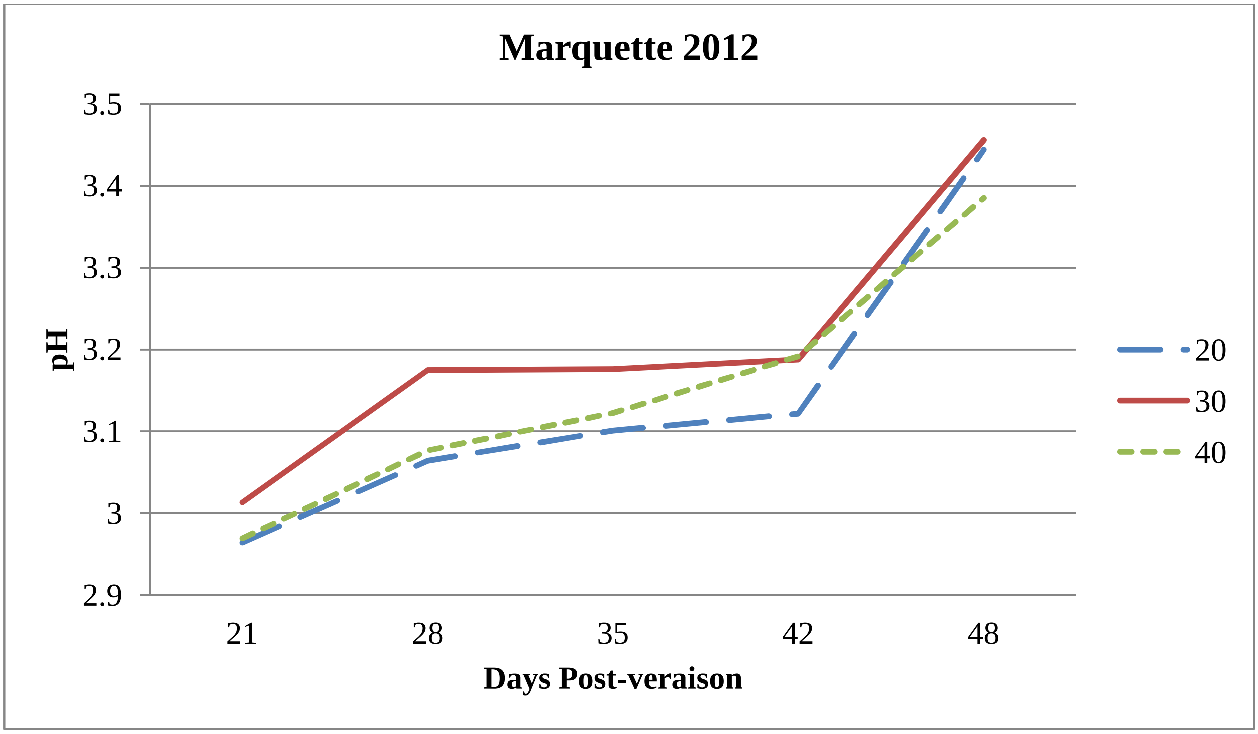

Figure A8. 2012 pH pre-harvest in Marquette separated by the number of buds retained.

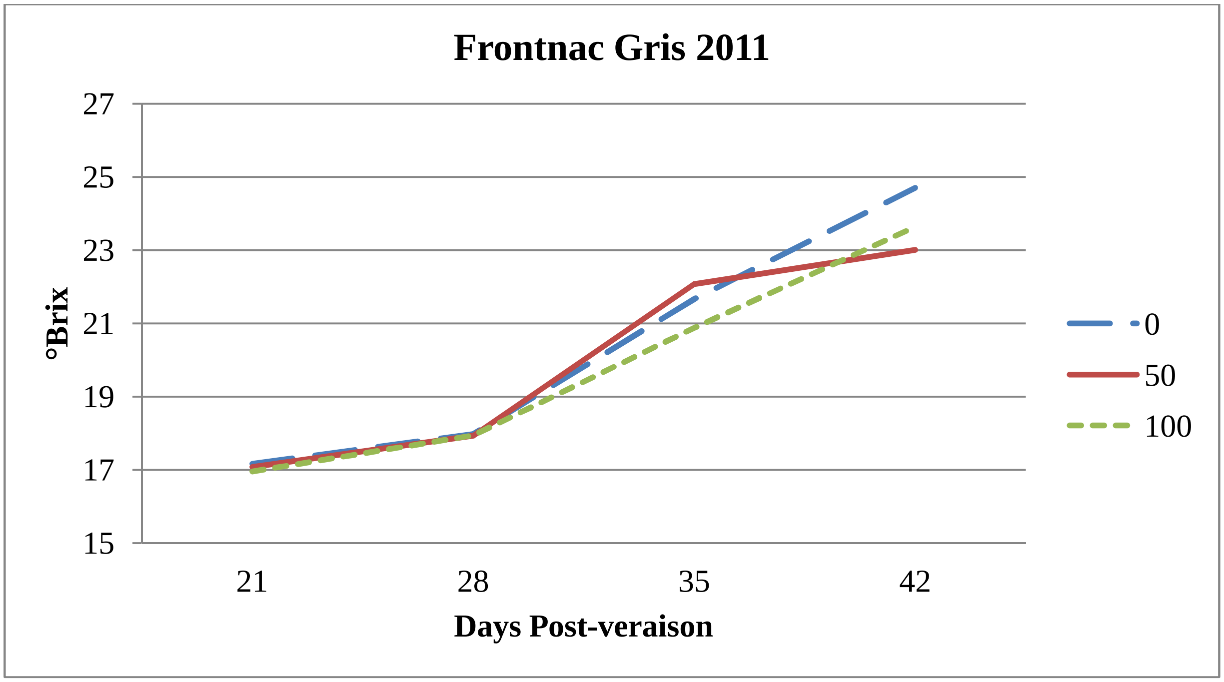

Figure A9. 2011 soluble solids accumulation (°Brix) pre-harvest in Frontenac Gris separated by percent leaf removal treatment.

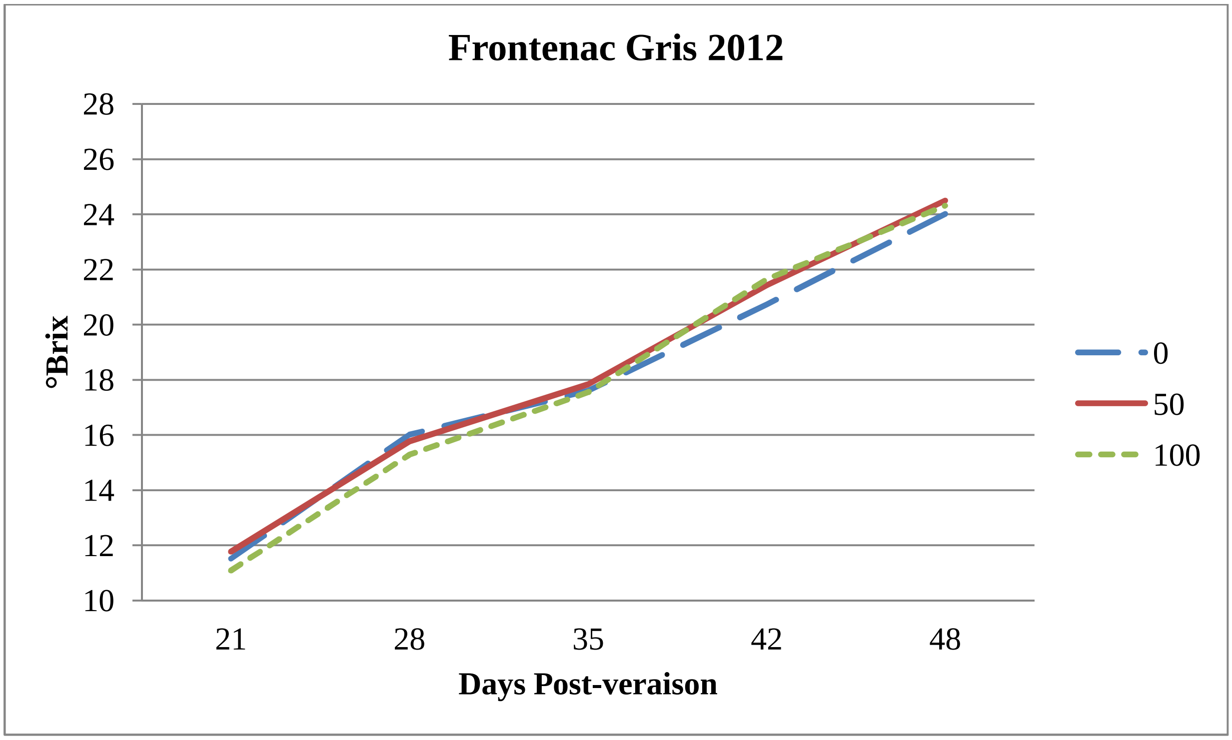

Figure A10. 2012 soluble solids concentration (°Brix) pre-harvest in Frontenac Gris separated by percent leaf removal treatment.

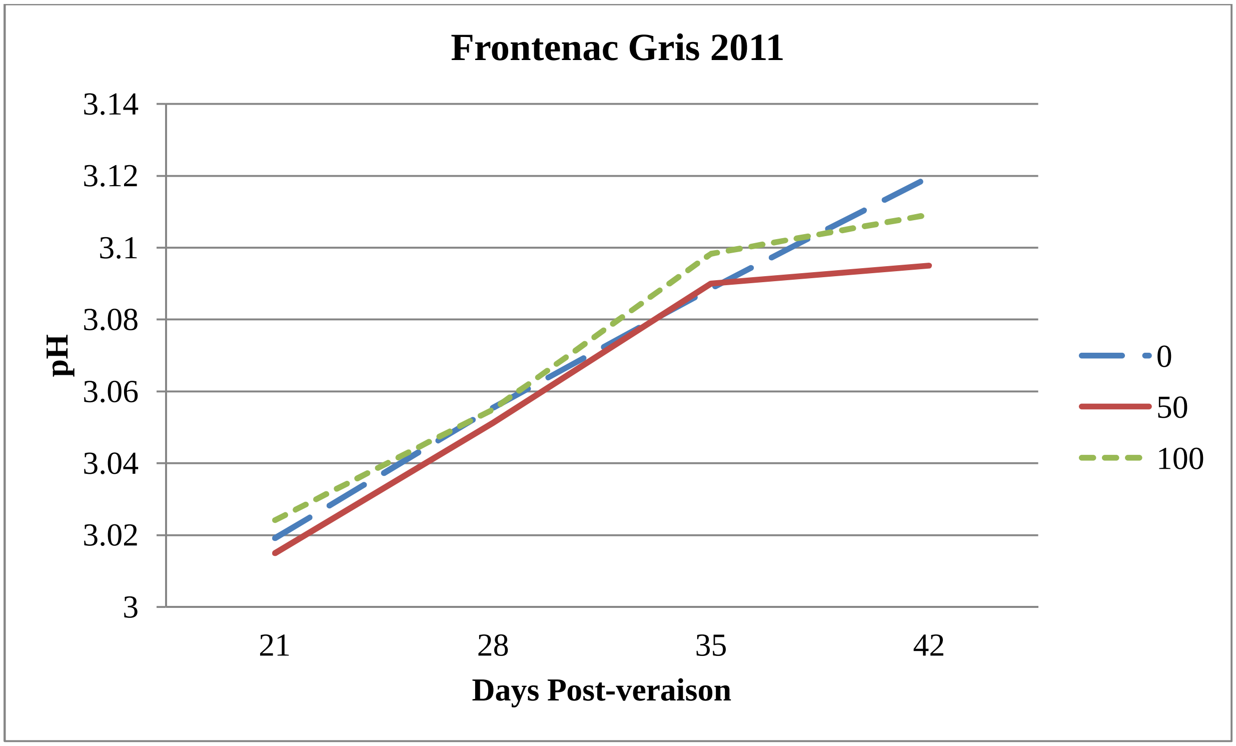

Figure A11. 2011 pH in Frontenac Gris separated by percent shade leaf removal treatment.

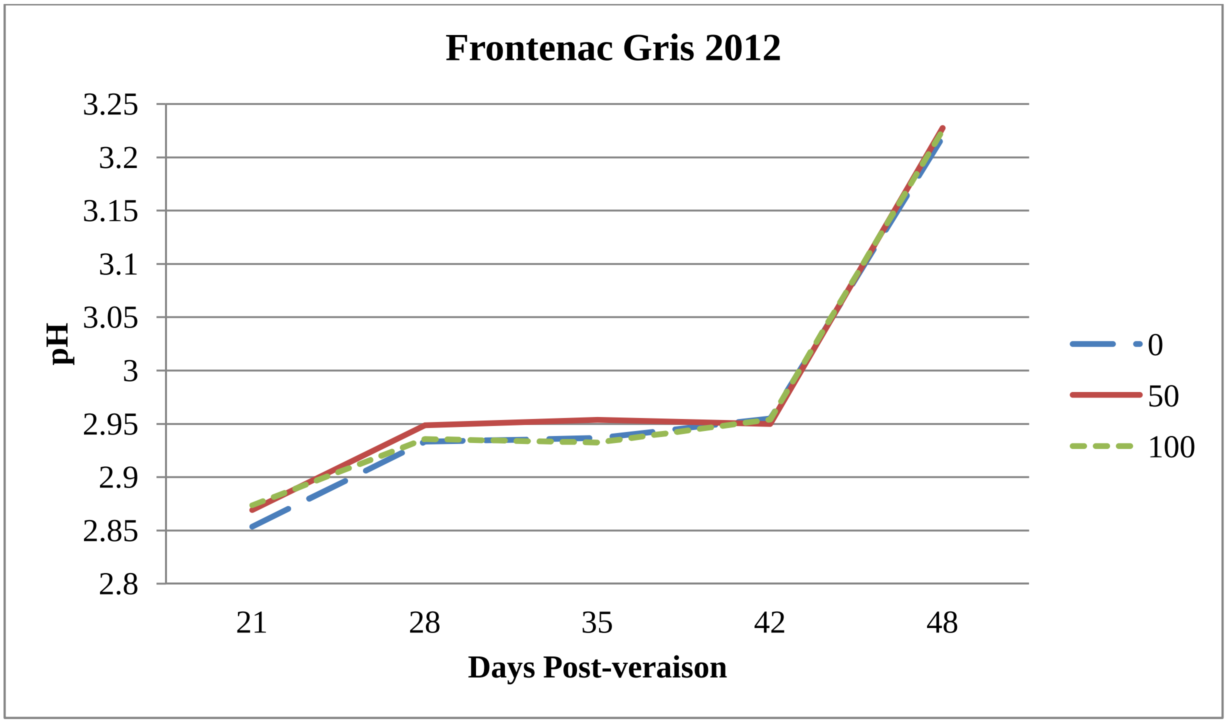

Figure A12. 2012 pH in Frontenac Gris separated by percent shade leaf removal treatment.

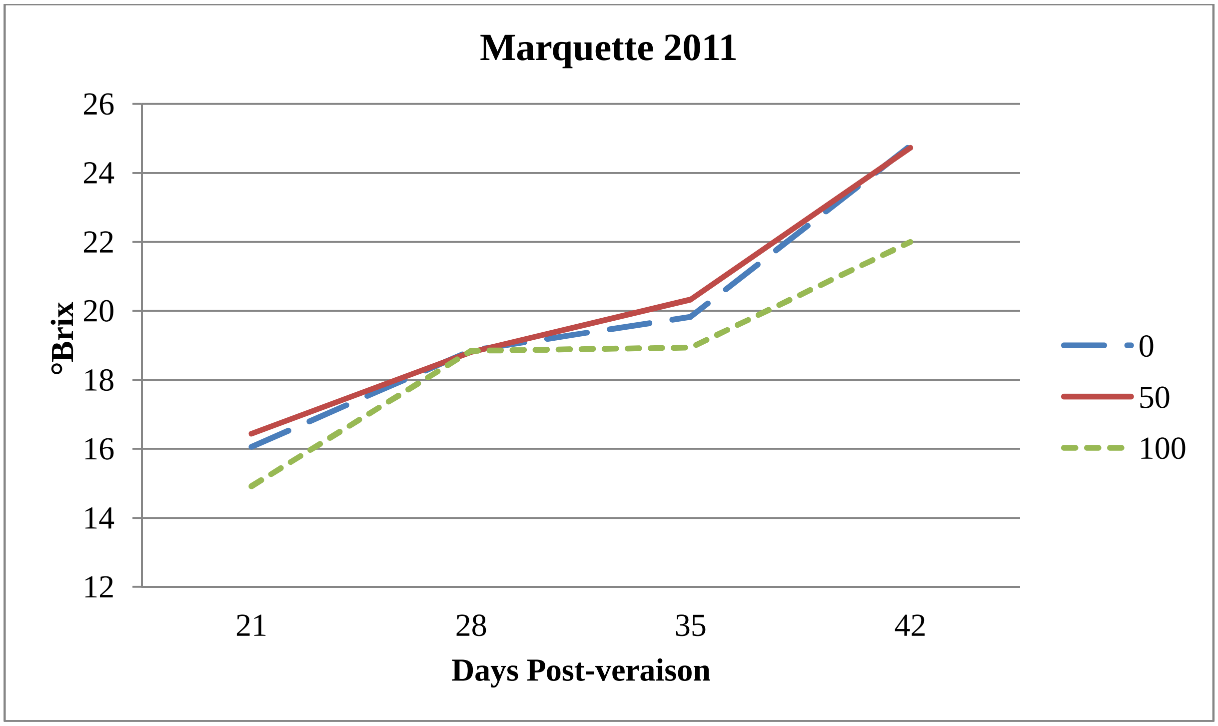

Figure A13. 2011 soluble solids concentration (°Brix) pre-harvest in Marquette separated by shade leaf removal percentage.

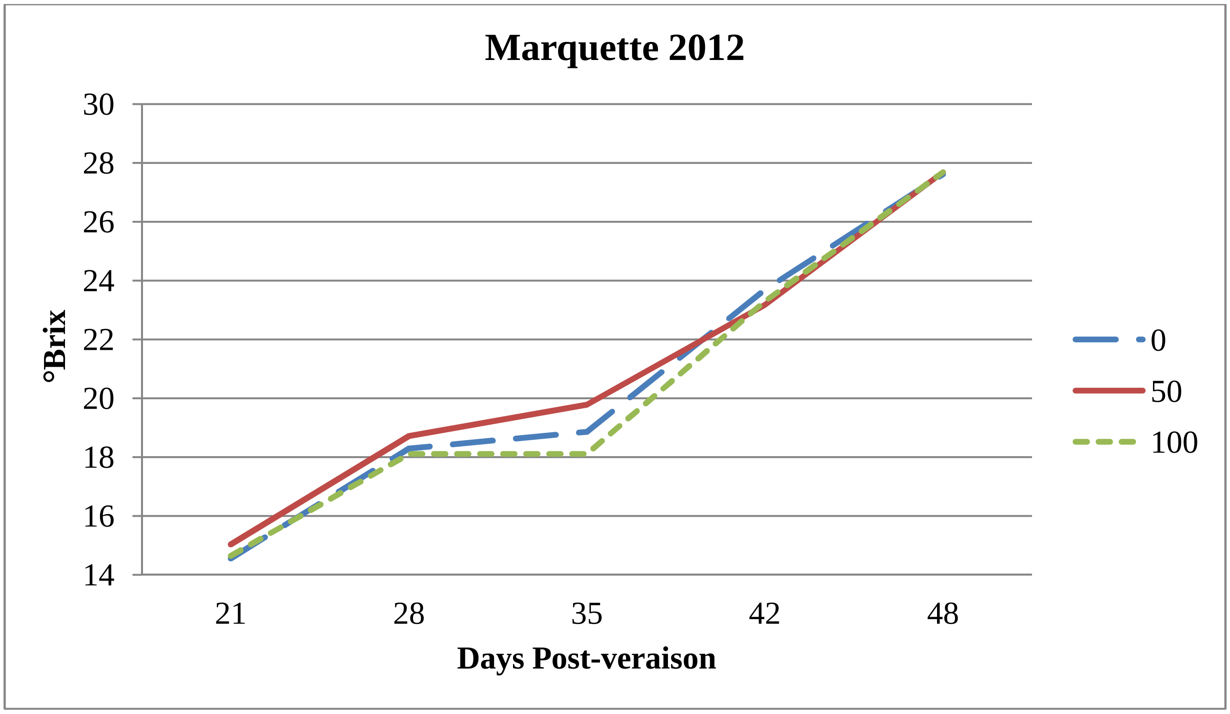

Figure A14. 2012 soluble solids concentration (°Brix) pre-harvest in Marquette separated by shade leaf removal percentage.

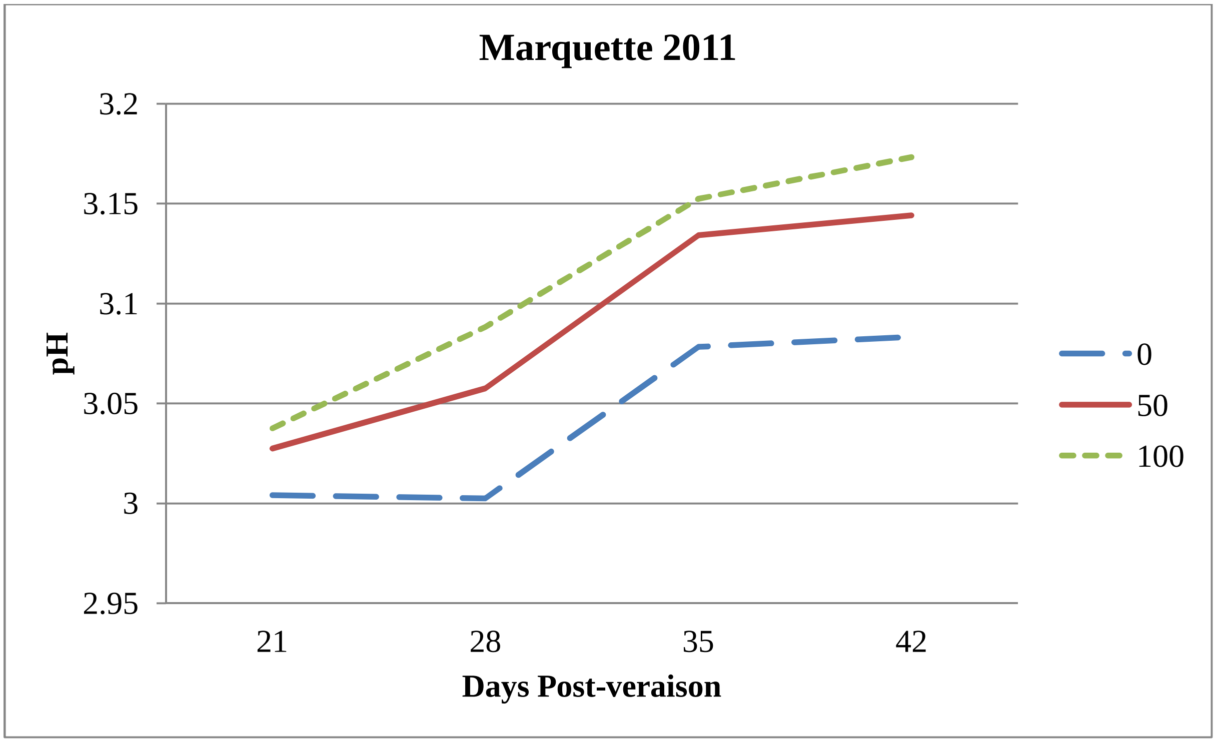

Figure A15. 2011 pH in Marquette separated by shade leaf removal percentage.

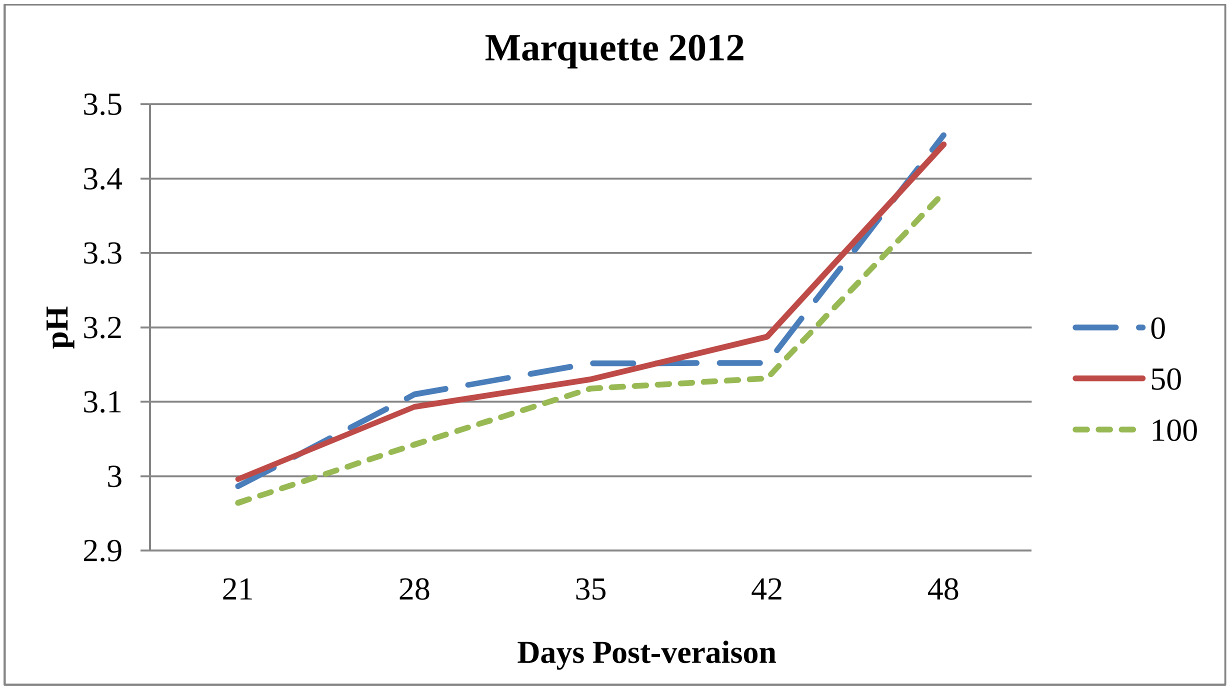

Figure A16. 2012 pH in Marquette separated by shade leaf removal percentage.