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ORIGINAL ARTICLE

Recent climate change in the Prince Edward County winegrowing region, Ontario, Canada: implications for adaptation in a fledgling wine industry

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Abstract There is mounting evidence that climate change is already having an impact on the wine industry, with effects being region specific. In order to understand the capacity of regional wine sectors to adapt to changing climate, it is useful to document the conditions that are important to producers and to identify adaptation and management strategies that are employed in the industry. This paper analyzes climatic conditions and adaptation strategies in the wine region of Prince Edward County Ontario, Canada. Wine producers identified the climate variables most important to their operations and described strategies they use to manage climate-related conditions. The identified variables were analyzed for trends over the study period 1987–2011, and interview data were analyzed in order to categorize adaptive strategies. Results indicate that the wine sector is very sensitive to climate, and the region is already experiencing the effects of climate change, especially with regard to increasing growing season mean minimum daily temperatures, increasing total summer rainfall, and later onset of fall frosts. Adaptive strategies employed by producers are largely learned though collaborative efforts and trial and error. The adaptations are mostly tactical and reactive in the short term, but with continued climate change, these strategies may develop into strategic, anticipatory measures. Climate change has the potential to present both challenges and opportunities to Prince Edward County wine producers, and adaptations will continue to require strong networking and collaborative efforts.

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Introduction

It is well documented that climate change will have significant implications for the agriculture sector (IPCC 2007). One sub-sector of Canadian agriculture that may be particularly affected by changing climatic conditions is the wine industry, which has one of the highest growth rates among Canadian industry groups (Hope-Ross 2006). Future climate change is expected to be manifest in increases in mean temperature, altered precipitation patterns, greater frequency of extremes, and increased climatic variability; these changes have the potential to affect both viticulture (the cultivation of grapevines) and the production of quality wine. At a continental scale, commercial wine production is limited to temperate regions between 30° and 50° in the northern hemisphere. Regions where high-quality wines are produced are constrained to even narrower climatic niches and are thus at risk from both short-term variations in climate and long-term climate change (de Blij 1983; Gladstones 1991; Jones 2006). Grapevines themselves are highly climate-sensitive, long-lived perennials that can be in production for 30 years or more (Slinglerland and Fisher 2007).

With respect to the implications of climate change for viticulture, potential challenges include a reduction in the optimum harvest window for high-quality wines, earlier dates of phenological events, shifts in suitable locations for some varieties, and greater management of water resources (Jones 2007). Climate change is likely to be region specific in terms of its effect on wine quality (Jones et al. 2005; Webb et al. 2008) and has the potential to create both risks and opportunities for regional wine industries. For example, climate change in cool climate regions could lead to more consistent vintage quality and possible ripening of warmer climate varieties, while regions with warmer growing seasons may become too warm for the varieties currently grown there. Furthermore, hot regions may become too hot to produce high-quality wines of any type (Jones et al. 2005).

There is mounting evidence that climate change is already having an impact on viticulture and wine making. A study of the Napa and Sonoma wine regions of California found that higher yields and quality over the last 50 years were influenced by a reduction in frost occurrence, advanced initiation of growth in the spring, and longer growing seasons (Nemani et al. 2001). Jones et al. (2005) examined climate trends in 27 of the world's highest quality wine regions: Results indicated that as growing seasons warmed during the 1950–1999 period, wine quality (as measured by vintage ratings) increased and vintage-to-vintage variability decreased. In a study of Bordeaux phenology over a 45-year period, Jones and Davis (2000) found that harvest was 13 days earlier in 1997 than in 1952. These findings are corroborated by work in Alsace, where it has been found that the period between budburst and harvest has become shorter, with budburst occurring earlier, and that ripening is occurring under increasingly warm conditions (Duchêne and Schneider 2005). In an analysis of recent climate change in the cool climate winegrowing regions of Quebec, Jones (2012) showed that increasing average minimum temperatures and growing season lengths were newly enabling the cultivation of high-quality European *Vitis vinifera* wine grapes—previously, these regions were limited to growing fast-ripening native and hybrid grapes with high tolerance for cold.

Many authors have concluded that the challenges and opportunities presented by climate change will necessitate adaptation by wine growers and wine producers (e.g., Duchêne and Schneider 2005; White et al. 2006; Webb et al. 2008; Moriondo et al. 2011). Adaptation to climate change can be understood as adjustment in ecological, social, and economic systems in response to actual or expected climatic stimuli and their effects and impacts (Smit et al. 2000). As vineyards usually have a life of at least 20 years, planning for and adapting to climate change impacts with regard to phenological matching of climates need to start at time of planting (Webb and Barlow 2003). In agribusiness, decisions are always made in the face of uncertainty (i.e., markets, seasonal weather, extreme weather events, institutional policy), and the potential to adapt to future climate change will partly be influenced by the ability of a producer to adapt to current uncertainties (Crane et al. 2011). Therefore, in order to understand and develop future adaptation options, there is a need to document actual adaptation behavior (Adger et al. 2007; Moser and Luers 2008; Nicholas and Durham 2012).

Despite the considerable body of studies addressing grape and wine sensitivity to climate change, there have been few field-based studies of farm-level adaptation responses in the wine sector (Belliveau et al. 2006; Battaglini et al. 2009; Nicholas and Durham 2012). The aim of this study is to identify the climate-related conditions to which the wine industry in Prince Edward County, Ontario, is sensitive, to document changes in these conditions, and to characterize the adaptation responses employed by producers. The potential for adaptation in the face of future climate change is then considered on the basis of the findings.

Climatic variables relevant to winegrowing

Climate and weather affect grape growth and wine production in many ways. Through analyzing growing season average temperatures, Jones et al. (2005) divided the world's quality winegrowing regions into four "climate maturity" groupings: cool (13–15 °C), intermediate (15–17 °C), warm (17–19 °C), and hot (19–20 °C). These growing season temperatures influence the grape varieties that may successfully be grown in a particular region. During the spring, vegetative growth of the vines is initiated by prolonged temperatures above 10 °C (Winkler et al. 1974). Growing degree days (GDDs), or biologically effective degree days, are calculated for wine grapes using a daily mean temperature above a base of 10 °C. In warm climate growing regions, such as Northern California and Chianti (Italy), the number of GDDs normally ranges between approximately 900 and 1,700. In cool climate regions, such as Champagne (France) and southern Ontario, GDDs are in the 1,300–1,400 range (Shaw 2005).

Throughout the growth of the berries, extremes of both heat and cold can be detrimental to the vines. While a few days of temperatures greater than 30 °C can be beneficial to ripening potential, prolonged periods can induce heat stress in the vine, premature véraison (ripening), berry abscission, enzyme inactivation, and decreased flavor development in the fruit (Mullins et al. 1992). Injury caused by low temperatures is one of the major production problems in cool climate viticulture (Heinricks 2001). Winter injury can affect all species of vines, but there is a direct relationship between the quality of a grape and its susceptibility to damage from cold. The high-quality European *vinifera* are the least hardy of cultivars; depending on the variety, the minimum winter temperature that grapevines can withstand ranges from −5 to −20 °C and is chiefly controlled by micro-variations in location and topography (Winkler et al. 1974). Frost timing in the spring and fall is often used to define the length of the growing season (the frost-free period), which has been found to average approximately 160–200 days in most viticulture regions. From a plant standpoint, the length of the frost-free season is important to the onset of budburst, flowering, and the time of harvest (Jones 2005).

History and climate of the Prince Edward County Winegrowing region

Prince Edward County (PEC) is an island community located in Southern Ontario's "golden triangle" between Toronto, Montreal, and Ottawa (Fig. 1). PEC encompasses a land area of 1,050 km^2 and is bounded by the Bay of Quinte to the north and Lake Ontario to the east, south, and west.

Grape growing in PEC dates back to the 1800s, but the first *V. vinifera* grapes were planted in the early 1980s. At that time, several grape varieties and rootstocks were being experimented with. In 1991, one of the grape growing pioneers in PEC suggested that the region's Lake Ontario-moderated climate and limestone soils had the potential to produce quality grapes and wines comparable to those from Burgundy, widely recognized as one of the world's high-quality wine regions (Heinricks 2001). The first commercial vineyard in Prince Edward County was planted in

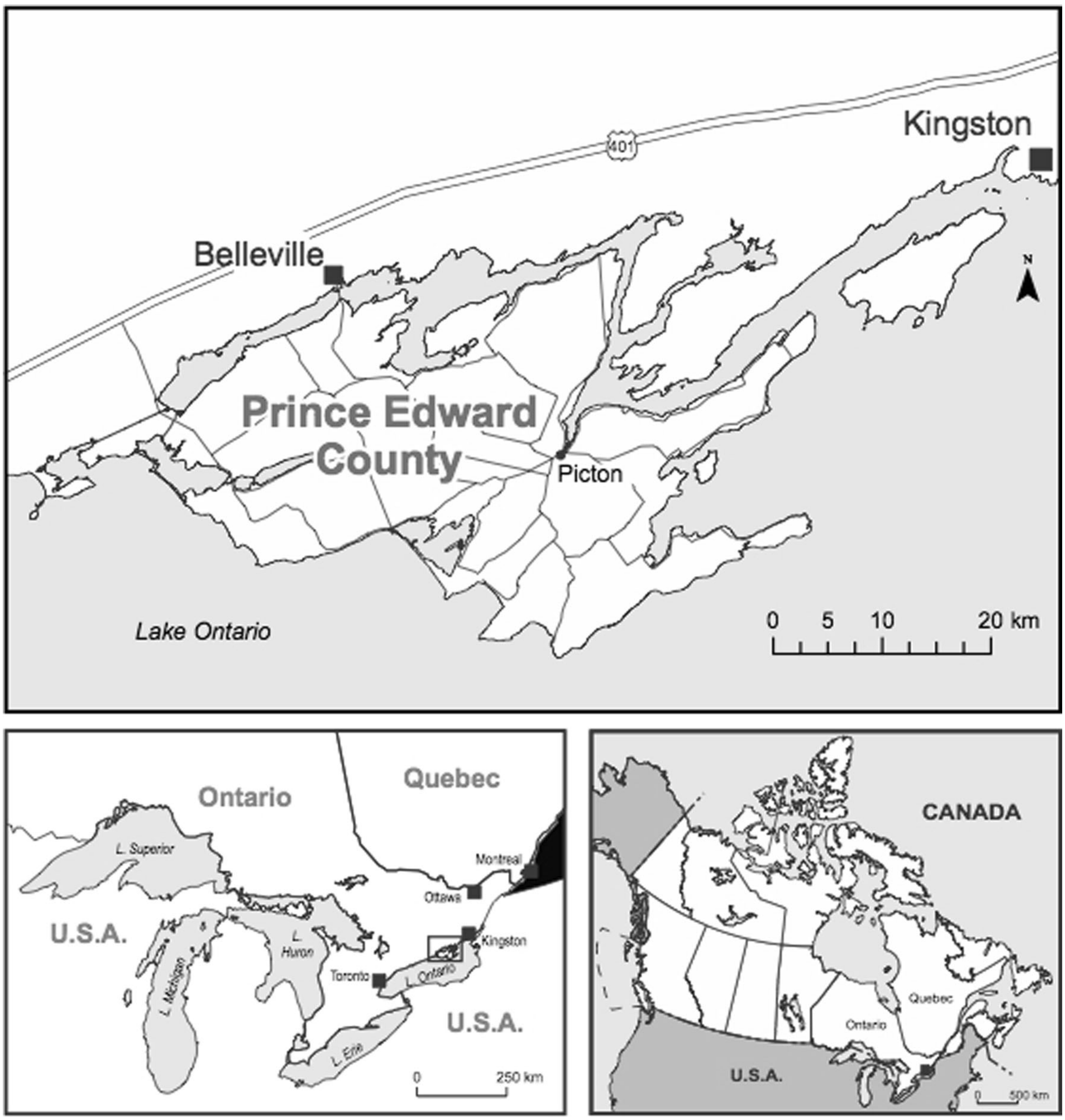

Fig. 1 Location of Prince Edward County winegrowing region

1993, and the first vintage wine from these grapes was produced in 2001. The regional wine sector has expanded from having one vineyard and 20 acres of land devoted to producing grapes in 2001 to having thirteen vineyards encompassing over 750 acres in 2012. PEC was named a Designated Viticultural Area (DVA) in 2007, making it Canada's newest and Ontario's fourth official wine region. As of 2012, the PEC wine region is home to thirty commercial wineries. In relation to major wine regions, PEC is tiny: For comparison, the Napa Valley American Viticultural Area (AVA) has 43,000 acres of planted vineyards and is home to over 300 wineries.

Located at a latitude of 44°, PEC is the Ontario's northernmost appellation (Fig. 2) and relies on the moderating effect of Lake Ontario to provide a productive growing season. At this latitude and within this relatively cool climate zone, vineyards must be planted on sites with favorable microclimates. PEC vineyards survive best in areas where they receive the moderating effects of the lake and are planted on a gentle slope (ideally 3°) in a north–south orientation, to encourage good surface air and water drainage and to take best advantage of sunshine (Slinglerland and Fisher 2007). Most of these vineyards are relatively small (2–26 ha). The marginal growing climate of PEC favors ripening of cool climate *vinifera* varieties such as Pinot Gris, Gewurztraminer, Riesling, Pinot Noir, and Chardonnay (Jones 2005). GDDs for PEC sites range from 1,100 to 1,350. PEC experiences an average of 160 frost-free days per year (Heinricks 2001); according to climate normals, the average last spring frost is May 5 and the average first fall frost is October 15. PEC is one of the most drought-prone areas in Ontario, with a very high evaporation rate. This may help control some diseases, but it can also stress vines. However, the usual moisture deficit in July and August comes at a beneficial time for the vine—between fruit set and veraison (ripening)—when controlled water stress has been shown to have the greatest effect in improving wine grape quality (Heinricks 2001).

The greatest environmental challenge to Prince Edward County winegrowers is the harsh winter; damage to *vinifera* can become apparent any time the temperature dips below −15 °C, which is a regular occurrence in PEC. Additionally, in the late winter, as the vine starts to deacclimate, fluctuations in temperature can cause more damage to vines than absolute cold. Late spring and early fall frosts can do extensive damage at the time of budding and harvest, respectively. To adapt to these conditions, growers in Prince Edward County must select cultivars, sites, and cultural techniques that will both maximize profit (i.e., wines produced are those in demand by consumers) and produce a quality product from season to season.

Climate change resulting in milder winters and warmer summers could be beneficial for winegrowers in this region. A longer growing season, for example, would allow

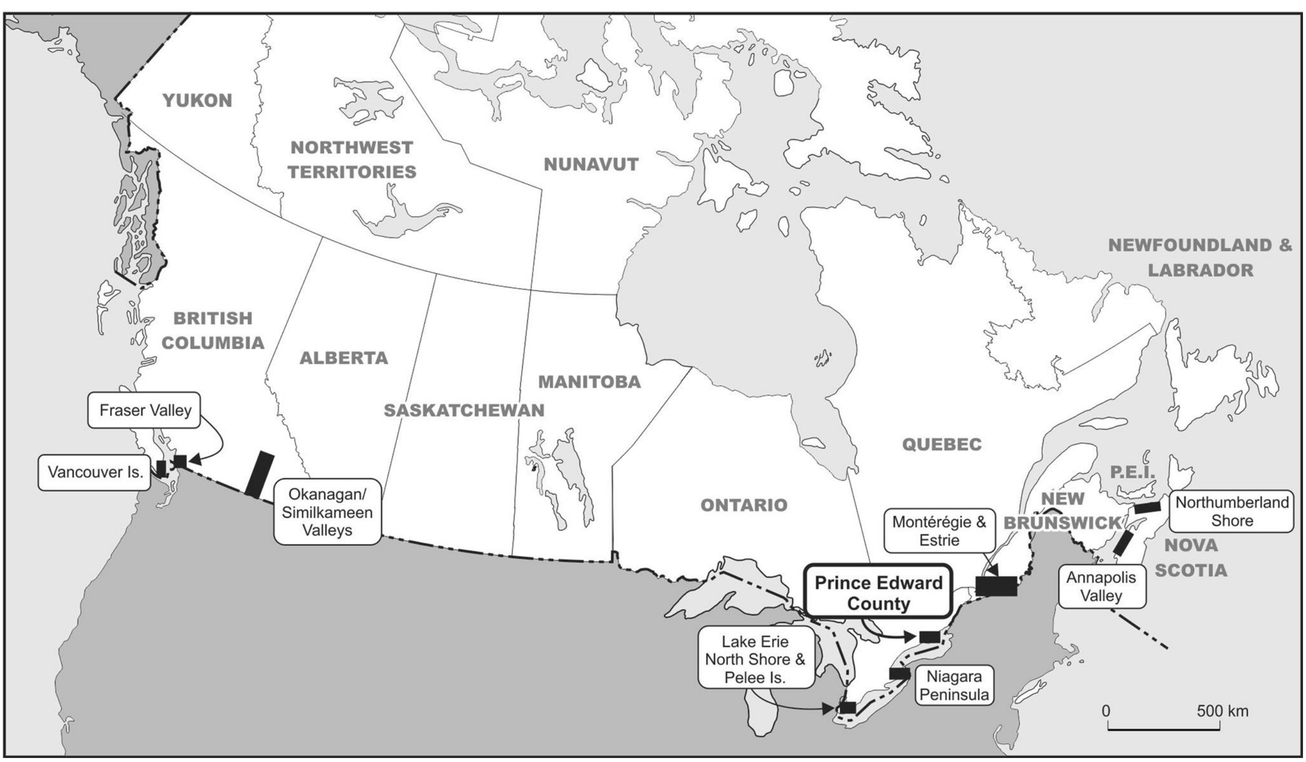

Fig. 2 Winegrowing areas in Canada (adapted from Shaw 2005)

for cultivation of a wider selection of varieties; in addition, a lower risk of cold injury damage in winter could alleviate some of the currently labor-intensive grapevine protection practices. However, a changing climate could also mean more widely fluctuating temperatures in spring and periods of extreme rainfall or drought in summer and fall, which would present major challenges to winegrowing.

The following sections identify climate variables relevant to winegrowing in this region, analyze recent trends in these variables, and characterize adaptive strategies currently used by producers to manage environmental conditions. A distinctive feature of this analysis is that it does not assume the climatic variables that are important to the sector, rather it starts by drawing on the experience of producers to identify those climate-related conditions, which matter to them and their operations. This approach is consistent with developments in climate change vulnerability and adaptation research, which have demonstrated the utility of engaging with stakeholders to ensure that the climate stimuli examined are those that are relevant to the decision-makers involved (Belliveau et al. 2006; Wall and Marzall 2006). Similarly, adaptation strategies are not assumed or hypothesized, but are identified from the decisions described by producers themselves. This approach provides an understanding of the range and characteristics of management strategies employed and establishes a realistic basis for assessing prospects for adaptation under future climate change (Ebi and Semenza 2008; Eakin and Patt 2011).

Methods

Important climate variables and current adaptive strategies used by winegrowers

In order to determine the climate variables important for winegrowing in this region and to identify adaptive strategies employed, interviews were conducted with PEC wine producers over the course of the 2011 growing season. Wine "producers" in PEC are almost all both grape growers and wine makers. Of the 30 producers in PEC, 23 agreed to participate in the study. Semi-structured interviews, completed on-site or by phone, lasted 45 min on average and were recorded with the respondents' consent. Field notes were transcribed immediately following the vineyard/winery visits and were later used to contextualize the transcription of the interview recording.

Producers were first asked to describe the general characteristics of their vineyard/winery (e.g., acreage planted, varietals, year of establishment, and first vintage). They were then posed open-ended questions that asked them to list and explain the climate parameters most important for the success (or otherwise) of their vineyard and quality of the wine. Respondents were next asked to describe their experiences since beginning their winegrowing operation, including a characterization of past good and bad years and the farm management practices that were used to respond to these conditions.

Table 1 Key climate variables for viticulture in PEC

Climate variable as identified by interview respondents	% of respondents	Variable derived from climatic data for analysis
Extreme cold in winter	100	# days < −20 °C
Minimum temperature during growing season	87	Mean minimum daily temperature (April 1 Oct 31)
Length of growing season	87	Growing degree days (GDDs)
Average temperature of growing season	83	Mean temperature (April 1 Oct 31)
Length of frost-free period	78	# days > 0 °C
Summer rainfall	48	Total rainfall (June 1 August 31)
Timing of spring and fall frosts	43	Dates of last and first frost
Fall rainfall	35	Total rainfall (Sept 1 Oct 31)

Interview transcripts were analyzed using Dedoose (2012), initially coding the data based on the themes of climate and weather variables to which operations were sensitive, and then on adaptation measures employed by producers. Answers to each question were grouped across all respondents and were coded in an iterative process (Nicholas and Durham 2012). Responses regarding the variables important to wine production were grouped into seven categories, each represented by a measurable climate variable. Responses regarding adaptation were grouped to characterize the actions according to type and duration and according to the climate attribute to which the adaptation is related. A selection of verbatim quotes from producers is used to support the analytical results and to provide more insight into the behavior of producers.

Analysis of identified climatic variables

Grapevines have been planted in Prince Edward County for commercial wine production since 1993, and they are now distributed across the county. Microclimatic conditions to which grapes are sensitive can vary significantly over relatively short distances; hence, data from any climate station can provide only a general indication of the climate trends and variability experienced by producers. The Environment Canada station at Mountain View airport

(44.05°N, 77.3°W) is the only station located in the winegrowing region of PEC. It provides a continuous record of climate data only for the period 1987–2011. Many analyses of climate change seek time series data for more than 100 years; longer time series are important to provide enough data points for testing statistical significance of trends. In this study, the interest is in the climatic conditions experienced by people in the wine sector (or considering entering the sector), so the relevant time period is the more recent one. While the period since 1987 serves the purpose of this paper, with only 25 data points (years), statistical significance would be expected only for extremely strong trends.

Based on the interviews, seven key climatic variables affecting wine production in PEC were identified: the growing season mean minimum daily temperature and mean temperature, the number of total annual frost-free days, the total annual number of days with temperatures below −20 °C (days with extreme cold), the mean number of GDDs, and the amount of precipitation in the summer and fall (Table 1).

Daily maximum and minimum temperatures and precipitation totals recorded at the Mountain View station were obtained from the National Climate Data and Information Archive (Environment Canada 2012) and were used to derive the values for the seven key climatic variables. In this study, trends in these variables are examined over the 25-year period from 1987 to 2011. Additional data are provided on the timing of spring and fall frosts over the study period.

Trends in the climatic variables are portrayed and compared using standardized annual percentage departure from the long-term mean (Jones 2012), given by

$$X_y^* = \frac{\bar{X}_y - \bar{X}_t}{\bar{X}_t} \times 100 \quad (1)$$

where $\bar{X}_y$ is the mean of the daily values of a climate variable X in a given year and $\bar{X}_t$ is the mean of the annual values of the climate variable over the time period 1987–2011. A positive value of X_y^* indicates that the value for the climate variable in year y is above the long-term mean; a negative value indicates that the value in year y is below the long-term mean. The standardized values are used in the graphs.

Statistical analyses of climatic trends have been performed using a variety of tests. Climatic time series have an inherent variability and often exhibit non-normal distributions and temporal auto-correlation, thus making linear regression analyses inapplicable. The robust, nonparametric Mann–Kendall test (Hipel and McLeod 1994) has often been used to conduct trend analyses of climatic variables (e.g., McLeod et al. 1990; Burn et al. 2004; Jones 2012). Mann–Kendall is used in this study, employing the raw climatic data, to test for significance in trends. The 95 % probability level is used for significance.

Results

Trends in climatic variables

The key climate variables important to wine producers in Prince Edward County are given in Table 1. Table 2 presents descriptive statistics for each climate variable over the study period and the results from the Mann–Kendall tests for significant trend. Graphical presentations of trends in these variables (standardized) over the period 1987–2011 are given below.

All interview respondents identified extreme cold in the winter as a variable important to their wine growing operations. Prince Edward County regularly experiences intensely cold winter temperatures, which makes wine grape growing a challenge; indeed, the cultivation of grapevines in PEC has been referred to as "extreme viticulture" (Heinricks 2001). Winter temperatures that drop below −20 °C are damaging to vines, often causing bud mortality and potentially cane and trunk injury (Shaw

Table 2 Climate data for Mountain View station, 1987–2011

Climate variable	Mean	SD	Min.	Max.	Annual change	Trend	Probability (%)
Annual days below −20 °C	19.7	9.3	5	43	−0.29	Decreasing	65
Growing season mean min daily temp (°C)	9.94	0.66	8.7	11.2	0.02	Increasing	**95**
Annual GDDs	1,315.9	126	1,056	1,520	3.92	Increasing	53
Growing season mean temp (°C)	15.2	0.74	13.6	16.7	0.02	Increasing	73
Frost-free period (days)	190.5	15	163	222	0.25	Increasing	36
Total summer precipitation (mm)	233.58	68.4	83.8	233.6	3.55	Increasing	**97**
Total fall precipitation (mm)	174.64	58.2	66	365.8	1.41	Increasing	75
Date of last spring frost	April 17	11 (days)	Mar 25	May 13	0.25 (days)	Getting later	63
Date of first fall frost	Oct 21	11 (days)	Oct 7	Nov 11	2 (days)	Getting later	**98**

Probabilities given in bold are significant at the 95 % level

1999). One producer stated that they are "petrified" of the winters in PEC and thus have developed many adaptive strategies to manage the extreme cold (more on this below). Fewer days of extreme cold means lower risk of vine damage and better prospects for growers.

Trends in this variable are shown in Fig. 3, depicting the annual percentage departure from the mean for number of days with temperatures below −20 °C. The data display a decreasing trend for the study period, although this is not statistically significant (Table 2); to be expected given the high interannual variability.

Producers indicated that both minimum daily temperatures and average temperature during the growing season are important variables to consider when determining which grape varieties to plant. In PEC, the growing season is defined as beginning April 1 and ending October 31. Therefore, the mean minimum daily temperature and mean temperature for the growing season were derived from the climate data for each year of the study period. Trends in these variables (standardized) are shown in Figs. 4 and 5.

The mean minimum daily temperature of the growing season shows a warming trend over the study period

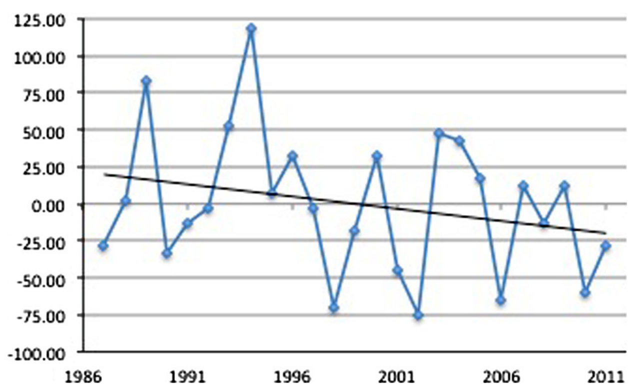

Fig. 3 Days with extreme cold <−20 °C (annual % departure from mean)

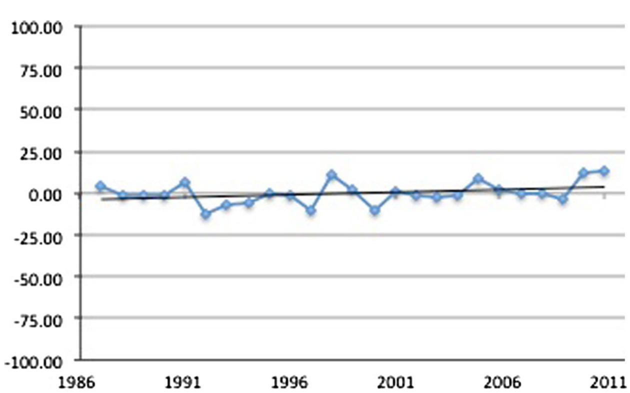

Fig. 4 Growing season minimum daily temperature (annual % departure from the mean)

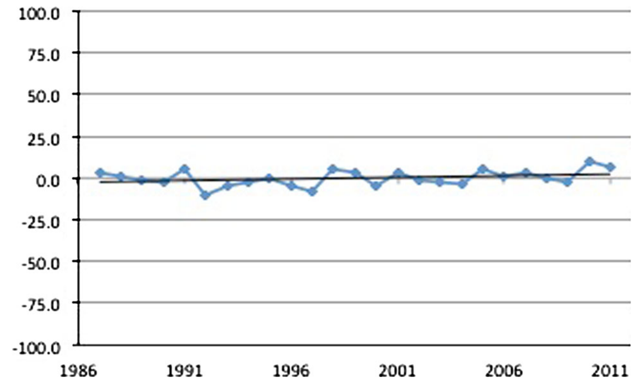

Fig. 5 Growing season mean temperature (annual % departure from the mean)

(Fig. 4), statistically significant at a confidence level of 95 % (Table 2). Mean minimum daily temperatures have warmed by 0.02 °C annually, for a total warming of 0.5 °C over the study period. The growing season mean temperature also warmed between 1987 and 2011 (Fig. 5), although the trend is not statistically significant (Table 2).

Spring and fall frosts are a major problem for wine production in Prince Edward County, as is typical of cool climate regions. The frost-free period for grape production is typically defined as the number of consecutive days when the critical minimum temperature is above −2 °C, starting at the bud burst stage in spring. Fully emerged shoots or actively growing grapevine tissues will rarely withstand temperatures below this level for more than 0.5 h. The frost-free period ends in autumn with the first occurrence of critical minimum temperatures −2 °C, which could result in freeze damage to mature leaves and consequently terminate photosynthetic activity (Shaw 2005). The number of frost-free days any winegrowing region experiences plays a key role in influencing the varieties of grapes that can be grown in that area and the associated risks. The minimum time for any varietal to ripen is 145 days, but a frost-free period of 180 days is preferable, especially for late-season varieties such as Riesling, Cabernet Sauvignon, and Cabernet Franc. Early-season varieties (e.g., Merlot, Pinot Noir, and Chardonnay) could reach full maturity in a season of 160–170 frost-free days (Shaw 2005).

Prince Edward County experienced a mean number of 190 frost-free days (consecutive days with temperatures above −2 °C) over the study period, with a minimum number of 163 days and a maximum of 222 (Table 2). The number of frost-free days increased very slightly from 1987–2011 (Fig. 6), but the trend is not statistically significant.

According to producers, in relation to the total frost-free period, a secondary variable that can affect the successful cultivation of grapevines is the timing of spring and fall

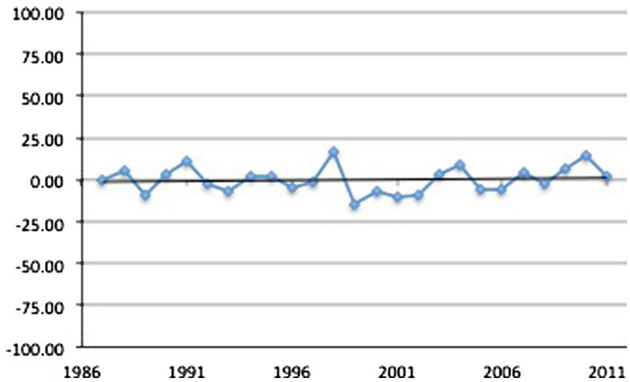

Fig. 6 Frost-free period (annual % departure from the mean)

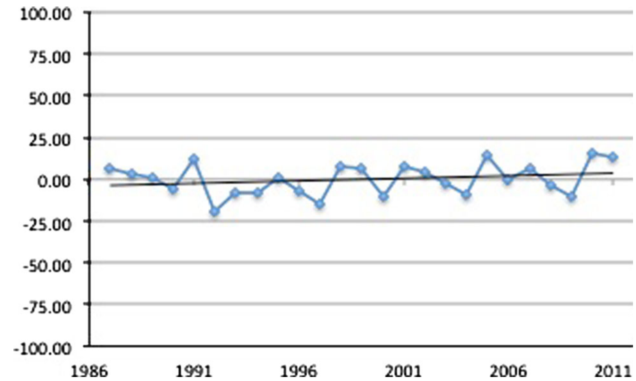

Fig. 7 Growing degree days (GDD) (annual % departure from the mean)

frosts. Late spring frosts, especially in the wake of a thaw that initiates bud burst in early-ripening varieties like Chardonnay, can kill off a large percentage of buds. A fall frost that occurs before the time of harvest has the potential to upset the sugar–acid balance in late-ripening varieties like Cabernet Franc.

The PEC winegrowing region has experienced last spring frost as early as March 25 and as late as May 13 (Table 2). The timing of the last spring frost shows a weakly positive trend. The date of first fall frost shows a strong and significant trend toward getting later in the season, at a rate of 2 days per year over the study period. The first fall frost has occurred as early as October 7 and as late as November 11.

Eighty-seven percent of interview respondents indicated that the length of the growing season influences which varieties they are able to plant. In viticulture, the length of the growing season is most often represented by the proxy variable of the sum of total heat units during the growing season, expressed as growing degree days (GDDs). GDDs for *V. vinifera* are calculated using a mean daily temperature above a base of 10 °C, below which photosynthesis and vine growth are minimal (Winkler et al. 1974). GDDs are thus calculated by subtracting 10 from the mean daily temperature. If the resultant value is less than zero, it is set to zero; therefore, GDDs are always zero or greater. Annual GDDs are then calculated as a cumulative total throughout the growing season (from April 1–October 31):

$$\mathrm{GDD} = \sum_{\mathrm{Oct31}}^{\mathrm{April1}} \left(\frac{T_{\max} + T_{\min}}{2} \right) - 10 \qquad (2)$$

The annual number of GDDs in PEC ranged from a minimum of 1,056 to a maximum of 1,520 over the study period (Table 2). The graph (Fig. 7) indicates that this variable (standardized) has increased between 1987–2011, although the trend is not statistically significant (Table 2).

Producers also indicated that rainfall during the summer and fall are important variables for viticulture. Overall dry summers are ideal, and fall rains can be problematic if occurring at the time of harvest. Total precipitation was calculated for the summer period (defined here as June 1–Aug 31) and the fall period (Sept 1–Oct 31). Trends in these variables (standardized) over the study period are given in the graphs (Figs. 8, 9). Mean precipitation in the summer shows a statistically significant increasing trend

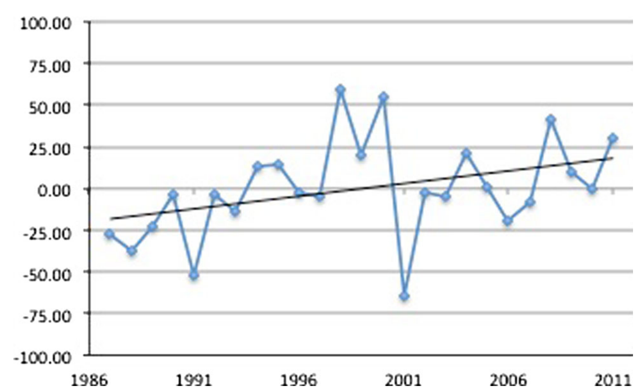

Fig. 8 Total summer precipitation (annual % departure from the mean)

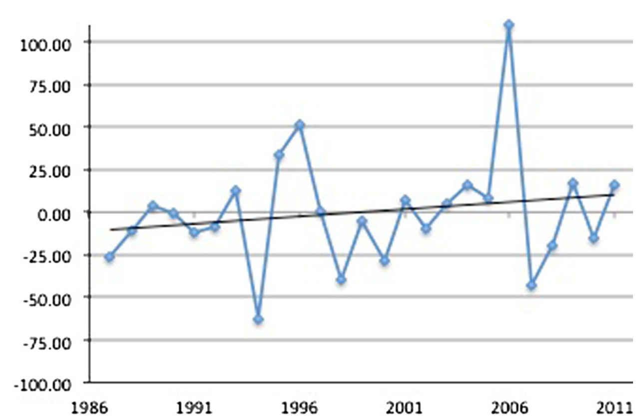

Fig. 9 Total fall precipitation (annual % departure from the mean)

(Table 2); mean rainfall increased at a rate of 3.55 mm per year over the study period. The graph for fall precipitation (Fig. 9) also indicates that this variable increased; however, the trend is not statistically significant.

Producers make decisions in the face of multiple interacting forces including, for example, climate, day-to-day weather, market forces, and federal and provincial wine sector regulations. A full analysis of adaptive behavior in this sector would involve characterizing the ways these interrelated factors (of which climatic forces are a subset) are experienced and managed, but this analysis is beyond the scope of this paper. The purpose here is to highlight responses to changes in climatic variables relevant to the winegrowing sector of Prince Edward County. The following section presents the adaptive strategies that growers and wine makers in PEC are employing to manage both short-term and long-term changes in weather and climate-related variables.

Adaptive strategies

Producers were asked to describe the conditions that led to good or bad years since they began their operation and to explain the strategies they used to manage risks or take advantage of opportunities. Adaptive strategies can be characterized on many dimensions, including the agents involved; the intent, timing and duration of the adaptation employed; and the form and type of the adaptive measure (Smit and Skinner 2002). Adaptations to climate-related events in Prince Edward County are categorized according to timing (anticipatory or reactive) and duration (tactical or strategic) (Table 3).

It is worth noting that producers commonly employed a variety of adaptations in a season and undertook adaptive initiatives as part of their short-term and long-term management, often greatly influenced by non-climate conditions and expectations. Hence, choices relating to varieties and sites were invariably driven by many factors, of which climate may be just one. The adaptations listed in Table 3 are illustrative of the types of actions that producers undertake as part of their ongoing management.

Tactical adaptations are short-term actions undertaken within the growing season to deal with a problem (Smithers and Smit 1997; Risbey et al. 1999). In PEC, these initiatives were most often used to manage seasonal and daily variability in weather. Some tactical adaptations are anticipatory, such as burying vines in the winter season to protect from extreme cold. The burying of vines in PEC is a labor-intensive process that has been perfected over years of trial and error and begins as soon as the grapes are harvested. Initially, growers attempted to cover the vines with straw, but soon realized that after a few extremely cold days, the cold became trapped under the straw.

Table 3 Types of adaptations used to manage climate-related risks and opportunities

Type of adaptation	Climate risk/ opportunity (# of respondents)	Example of adaptation (# of respondents)
Tactical, reactive	Early-spring warming (20)	Early unburying (17)
	Rain during summer and harvest (18)	Fruit thinning (18)
		Leaf removal (18)
	Humid growing season (10)	Spray vineyard with antifungal agent (8)
		Prune canopy to allow air circulation (10)
	Drought (23)	Irrigate vineyard (23)
	Extremely hot summer (16)	Harvest early (16)
Tactical, anticipatory	Extreme winter cold (23)	Buying vines (23)
		Hilling of graft unions (23)
	Frost (17)	Light fires in vineyard (15)
		Turn on wind machines (2)
Strategic, reactive	Extreme winter cold (23)	Modify and create equipment to hill and bury (23)
Strategic, anticipatory	Extreme winter cold (23)	Varietal selection (23)
	Frost (17)	Site selection (15)
		Varietal selection (17)

Eventually a process was developed that involves tying down and then using soil to “hill up” the canes (the fruit-producing part of the grapevine), and then burying the entire vine underground.

Another common tactical, anticipatory adaptation involves managing spring and fall frosts, which can be extremely detrimental to grapevines. Wind machines are commonly used in the Niagara Peninsula winegrowing region to manage cold winter temperatures and frosts (Shaw 2005); however, at the time of the interviews, only two producers in PEC had installed wind machines in their vineyards. The more common strategy was to ignite bales of hay in the vineyard whenever the temperature was expected to dip below −2 °C; according to producers, the smoke from the fires creates a temperature inversion that keeps frost of the vines. As with winter burial, this adaptation is highly labor intensive and requires that producers keep a constant watch of nighttime temperatures in the spring and, to a lesser extent, in the fall.

Tactical adaptations can also be made in reaction to short-term variability in weather. Early-spring warming can be either a boon or bust to winegrowing in PEC; if temperatures rise to above 10 °C for several consecutive days, budburst will be initiated in some varieties of wine grape. This creates a quandary for producers, who need to decide whether to unbury their vines early: after buds have emerged, the process of unburying runs the risk of breaking the buds off of the vine; however, if the vines are uncovered and there is a subsequent frost, the vine may also be damaged. Most respondents indicated that they would rather take the risk of the frost (which they can manage) than the risk of leaving the vines underground for too long.

Strategic, long-term adaptations cited were mostly anticipatory management practices, some of which occurred at the time of the vineyard establishment. Producers reduced frost risk through site selection, by avoiding frost pockets in the vineyard, or by planting an early-maturing variety. Similarly, the acknowledgment of extreme winter cold prompted some producers to choose to plant winter-hardy hybrids instead of (or in addition to) *V. vinifera* grapes. The majority of vineyards in PEC are now growing *V. vinifera,* and some are even experimenting with later-ripening varieties such as Cabernet Franc. It should be pointed out that the selection of varieties is not a decision based solely on climate; growers and winemakers need to weigh the risks and benefits of planting a variety that is suited to the climate vs. one that is in demand by consumers. Canadian wine drinkers are increasingly looking for quality wines that are made from the more readily recognized European grapes, and despite the marginal growing conditions, most growers in PEC are committed to producing low quantities of high-quality wine.

Producers also noted that in order to manage vines during the cold winter, it was necessary to modify and create equipment for the hilling and burying process. This can be considered a strategic, reactive adaptation. Most viticulture equipment (plows, etc.) is purchased in the Niagara Peninsula winegrowing region (Fig. 2), where vines are generally planted in lower density arrangements than in PEC and canes are not buried in the winter. Therefore, a local mechanic created equipment specific to the planting structure and winter management needs of PEC. Every producer that was interviewed either owned modified equipment or, in the case of two very small-scale vineyards (1 and 2 hectares, respectively), borrowed the necessary equipment from other producers.

Implications of results and potential for adaptation to future climate change

Analysis of the key climatic variables for winegrowing in Prince Edward County over the study period indicates that climate change is already having an effect on the region. The documentation of current adaptation strategies employed by producers in the context of these changes enables an analysis of the potential for adaptation to future climate change, should the observed trends continue.

A warming trend in the growing season minimum temperature has influenced producers to increasingly cultivate relatively fragile *V. vinifera* grapes. One respondent noted that if growing season temperatures continue to warm, it could have the potential to have both positive and negative impacts on her operation:

> The varietals that we have planted now, the warmer temperatures incrementally wouldn't really affect them badly; it would help them. If anything, we'd just be able to harvest a bit earlier than the rest of the world. I mean you could open it up to more varieties but then again it depends on where you are standing because then you are getting into more costs with ripping out plants and then putting in new ones in and that kind of thing.

This producer had her entire acreage already under vine and therefore would need to incur the cost of replacing vines if she decided to change cultivars under prospects of a warming growing season. However, 16 of the 23 respondents noted that they have additional fields that are currently unplanted (for a total of 43 ha). Therefore, these potential sites and the trend toward a warming growing season could enable the cultivation of later-ripening varieties that are not currently being grown. This effect has already been noted in the cool climate winegrowing regions of Quebec, where a trend toward longer and warmer growing seasons over the last 30 years has allowed growers to begin to switch from winter-hardy hybrids to *V. vinifera* varieties (Jones 2012).

The trend toward fewer extremely cold days in the winter has the potential to benefit winegrowing in PEC. As one PEC grower and winemaker explained,

> I remember not too long ago, maybe 4 decades ago a bit of vinifera were first introduced in Niagara but it was thought to be impossible because the winters would be too cold. Then they were buried, but over the years this has changed so they don't bury canes as we have to in PEC. So I think if global warming continues then we may become more like Niagara in the sense that we don't have to go through this really laborious process of burying our canes and then unearthing in the spring.

Another producer, however, noted that he would rather continue to go through the process of burying the canes than worry about drops in temperature all winter long. Vines become dormant in mid-December when a vine stops growing because of both physiological factors (endo-dormancy) and environmental factors (eco-dormancy) (Heinricks 2001). Vines acclimate to deep cold slowly over the course of several weeks as daily temperatures continue to decrease. Vine cold hardiness is lowest in early and late winter, and peaks at the time of most severe cold (late January–early February) (Plocher and Park 2001). As such, fluctuating temperatures in early and late winter could be extremely damaging because the vine is not at its maximum hardiness during those periods.

Climate change can influence extreme events such as unseasonable frost occurrences (IPCC 2007). If the last spring frosts were to occur later in the season, this could prove to be highly problematic for growers:

> In our case it's the unpredictability of extreme weather…you could have really late onsets of frost like we had last year in May…there was a lot of bud damage from that. Or maybe it will happen in September and kill everyone's crop before it finally hits the sugar level it needs.

While Shaw (2005) found that close to 90 % of the frosts that occur in the late spring or early fall can be prevented by the use of wind machines, this infrastructure is expensive and few producers in Prince Edward County have installed them. Wind machines used in vineyards are tall, fixed-in-place, engine-driven fans that pull warm air down from high above ground during strong temperature inversions, raising air temperatures around the vines. The cost of installing a wind machine is about $36,000 CDN and fuel costs vary from $25–$50/h (Fraser et al. 2009). PEC wine producers have developed an alternative, affordable adaptive strategy of lighting fires in their vineyards, which is mostly successful at keeping frost at bay but extremely labor intensive. As the PEC wine industry expands, it is likely that producers who have the financial resources available will increasingly invest in wind machines for spring frost maintenance. If the statistically significant trend toward a later onset of fall frost continues, however, this has the potential to alleviate the urgency of tying down and burying the canes immediately after the fruit comes off at harvest.

Almost half of the producers interviewed (48 %) cited summer rainfall as an important variable in viticulture; they noted that mostly dry summers are ideal for producing quality wines. Heinricks (2001) suggests that a moisture deficit in July and August is beneficial to the vine and can have an effect on improving wine quality. The climate change analysis indicated that summer rainfall showed a statistically significant increasing trend over the study period. This trend can prove challenging for growers, but does not necessarily lead to negative outcomes. Jones et al. (2005) note that climate variability is often what determines vintage-to-vintage differences. One winemaker remarked that in a particularly rainy year (2009), he produced a very light Pinot Noir that was entirely different from the 2008 and 2010 vintages, but still of high quality.

A challenge associated with an increasingly wet summer in concert with a warming growing season is an increase in humidity. Most producers cited the need to adapt to humid conditions by augmenting disease control measures:

> Spraying in the vineyard is one big challenge so a year like this year where we have had a lot of moisture, the humidity's been up and down, it creates a lot of disease pressures: downy mildew, stuff like that. It increases the amount that you have to spray. Years like last year where it was just hot and dry all summer, it reduces your number of sprays.

Downy mildew is a fungal disease that may injure grapes directly by causing deformed shoot, tendril, and cluster growth, or indirectly through premature defoliation resulting in delayed ripening of fruit and increased vine sensitivity to winter injury (Ker et al. 1990). Adaptation strategies by producers in PEC include spraying with fungicide and pruning and training vines in a system that improves air circulation and promotes rapid drying of the foliage. These cultural practices are currently used as reactionary adaptations to humid conditions, but may increasingly be employed as anticipatory adaptations if the trend of warmer and wetter summers continues. The implications of altered moisture regimes are complicated by possible changes in precipitation intensity and frequency and by the role of evapotranspiration (Huntington et al. 2009). Increases in summer rainfall may be offset by longer growing seasons and increased evapotranspiration.

When asked to describe strategies employed to deal with climatic conditions and/or changes, a common theme that emerged was the need for collaboration among wine producers in PEC in order to successfully employ all types of adaptation strategies. Twenty out of the 23 growers interviewed belonged to the Prince Edward County Winegrowers Association (PECWA), which was founded in 2000 with the mission of marketing PEC wines and providing educational support for producers. One producer noted that,

> The good thing about PECWA from the beginning was it was very collaborative and we were all trying to help each other and that is still alive today, although there is increasingly competitive aspect to it. Some of us have not lost that old collaborative stuff but there have been a few who somehow think that they would do better by differentiating themselves from the crowd than being part of the crowd.

While most wineries and vineyards are associated with PECWA, there are several that are not mostly due to political differences of opinion. The majority of respondents, however, indicated that they learned the practice of viticulture and appropriate climate adaptive strategies through being part of formal and informal networks in the regional winegrowing community. Informal networks include, for instance, calling a neighbor to ask what pruning technique they are using or borrowing equipment for hilling and burial of the canes. Formal networks of collaboration include PECWA and a monthly grape study group facilitated by a representative from OMAFRA. All respondents said that they had been to the grape study group at least once since beginning their operation, either in the capacity of sharing knowledge with newer producers or gaining knowledge from more experienced producers.

Adger et al. (2007) state that individual and institutional knowledge and expertise are the foremost resources for adapting to the impacts of climate change. In this sense, the potential for adaptation is developed if people have the time to strengthen networks, knowledge, and resources, and the willingness to find solutions. Faced with an already changing climate as well as the day-to-day uncertainties that all farmers must manage, Prince Edward County wine producers have thus far instituted adaptive strategies through research, trial and error, and collaboration. If the observed trends in climate change continue, ongoing networking and collaborative efforts will be of utmost importance in order to manage risks as well as to take advantage of opportunities. By starting from a baseline of existing adaptive strategies, processes and institutions, the development of new or improved adaptation practices will have the advantage of being well situated within the producers' technical and cultural expertise.

Conclusions

The aim of this study was to identify climate conditions relevant to the wine industry in Prince Edward County, to document trends in those conditions, and to characterize adaptation responses by producers. These results provided the basis for considering the potential for future adaptation. PEC is presently a cool climate winegrowing region that experiences extremely cold winters and mild summers moderated by Lake Ontario. The most common grapes planted are fast-ripening varieties of *V. vinifera*. Producers indicated that the key climate variables for their operation were the growing season mean minimum daily temperature and mean temperature, the number of total annual frost-free days, the total annual number of days with temperatures below −20 °C (days with extreme cold), the mean number of GDDs, and the amount of precipitation in the summer and fall. The analysis of the climate data suggests that some of the climate-related conditions important to producers have changed over the 25-year study period, especially with regard to increasing minimum daily temperatures in the growing season and later onset of fall frost. This is likely to have influenced new winegrowers to plant *V. vinifera* grapes in increasing numbers and varieties. Winters are becoming slightly less harsh, with fewer extremely cold days. Summers are experiencing significantly more rainfall, which can be problematic for wine quality and disease pressures.

Information derived from producers indicates that a variety of adaptation strategies are being employed in response to environmental stresses. The most common responses are either reactive (such responding to early-spring warming by unburying vines earlier than normal), or anticipatory in the short term (such as lighting fires to avoid damage when frost conditions are imminent). Some adaptations, however, are long term, such as planting suitable varieties for the regional climate. Most adaptation strategies have been developed through research into viticulture practices in other cool climate regions, trial and error, and collaboration in both formal and informal networks.

Given the growing number of scientific studies indicating that climate change has already and will continue to impact regional wine industries, it is crucial that growers and winemakers are well prepared to adapt to changing conditions. PEC has a fledgling wine industry that is rapidly expanding and stands to be both challenged and rewarded by climate change. As long-term adaptations are often practiced at the time of vineyard establishment, a warming climate presents an opportunity to producers who have acreage left to plant on their property and could potentially increase the number of varieties grown. Producers with their entire acreage planted with a certain suite of varieties, on the other hand, may find their response options more limited. Increasingly, management strategies that are currently reactionary may develop into strategic, anticipatory adaptation measures, especially if the trend of warmer and wetter summers continues. Both short- and long-term adaptations to climatic change will continue to require strong networking and collaborative efforts in order to build on the existing knowledge and expertise of wine producers.

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