Grapevine Phenology and Climate Change: Relationships and Trends in the Veneto Region of Italy for 1964–2009

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Abstract: A long-term (1964–2009), multiple Vitis vinifera L. cultivar data set has provided a comprehensive assessment of cultivar similarities/differences in phenological timing and growth phases and relationships with climate and change in the Veneto region of Italy. The budbreak to harvest period for the cultivars studied covered mid-April to late September, averaging 156 days but varying 55 days across cultivars. The main phenological events and intervals between events exhibited a 25 to 45 day variation between the earliest and latest years, with the bloom to veraison growth interval showing the lowest vintage-to-vintage variation. From 1964–2009, trends of 13 to 19 days earlier were found for bloom, veraison, and harvest dates, while budbreak exhibited high interannual variation and no trend. There were similar characteristics and trends for the main phenological events for early, middle, and late maturing cultivars, although early maturing cultivars changed at a higher rate. Changes in climate in the region led to significant breakpoints in the phenology time series, averaging 1990–1991 across all cultivars, with early and middle cultivars shifting sooner than late cultivars. Growing season average temperatures warmed 2.3°C from 1964–2009, while annual and seasonal precipitation amounts did not change significantly. From 1964–2009, the growing period climate differences were 2.0°C between the years with the shortest and the longest budbreak to harvest intervals. The combined trends in phenology and climate resulted in an average shift of eight days per 1.0°C of warming. The extremely warm summer of 2003 (compressed growth intervals) and warm spring of 2007 (shifts in phenological timing) provide analog conditions to those projected for later this century.

Key words: phenology, growing season, climate, grapevines, wine, Italy

Phenology is the study of the relationships between climate and the timing of periodic natural phenomena such as bird migration, insect growth stages, and plant flowering. Knowledge of a plant’s phenological characteristics is important for Vitis vinifera L. grapevines, where the optimum development of quality fruit for wine production is tied to phenological occurrence and timing (Jones and Davis 2000, Keller 2010). In addition, because grapevine phenology is strongly tied to climate, and has been observed in many regions over many years, its study has received considerable attention as a tool to understand how climate variability and change impacts viticulture and wine production (Chuine et al. 2004, Spanik et al. 2004, Jones et al. 2005a, Webb et al. 2008).

Numerous studies have provided evidence for systematic changes in climate (Kutiel and Maheras 1998, Klein Tank and Können 2003, Braganza et al. 2004), showing increasing temperature trends of 0.6 to 0.7°C since the start of the 20th century (IPCC 2007). Furthermore, according to the global climate record, the past few decades have been some of the warmest on record (Salinger 2005) and the rate of increase in the last 25 years has been over three times the century-scale trend (IPCC 2007). The observed temperature changes have also occurred in both higher maximum and minimum temperatures and a greater frequency of extremes (Klein Tank and Können 2003, Kostopoulou and Jones 2005). Climate scenarios also project that globally averaged surface temperatures will increase by 1.4 to 5.8°C by 2100 (IPCC 2007).

While changes in average temperatures are important for agriculture in general, increasing temperatures have been accompanied by alterations of other climatic parameters such as precipitation, evapotranspiration, and the diurnal temperature range (DTR) (Weber 1994, Dessens and Bücher 1995). In addition, recent studies have shown significant changes in extreme events, such as heat waves, drought, and a higher percentage of the annual precipitation from heavier, more frequent events (Easterling et al. 2000, Klein Tank and Können 2003, Bartolini et al. 2008).

For the Mediterranean basin and Italy specifically, studies have indicated a similar general increase in temperature as compared to other global or hemispheric studies (Brunetti et al. 2000a, 2000b). In Italy, agrometeorological extreme risk indices had not changed tremendously from 1878–2000, with some benefit seen in a reduction of crop damage risk from frost (Moonen et al. 2002). More recently, a study of Mediterranean basin climate extremes during 1958–2000 found
evidence of significant warming trends in both minimum and maximum summer extremes over the region and a decline in the frequency of cold nights (Kostopoulou and Jones 2005). As a result, the DTR in Italy has shown a tendency toward decreasing trends in the north and increasing trends in the south (Brunetti 2000b). For precipitation there is some evidence of a reduction in overall amounts in Italy (Brunetti et al. 2002), while for extremes there have been positive trends in heavy precipitation events and significant increases in the number of consecutive dry days over the Mediterranean basin (Kostopoulou and Jones 2005).

Research examining the relationships between climate and grapevine phenology has shown moderate to strong correlations (Calò et al. 1994, Jones and Davis 2000). Budbreak timing and its consistency has been tied to adequate winter chilling requirement followed by warm springs (Moncur et al. 1989, Keller 2010). Bloom events appear to be most strongly correlated with maximum temperature levels in the preceding month (Calò et al. 1994), while average temperatures or heat accumulation indices are more important for veraison and harvest (Jones et al. 2005a). Grapevine phenological timing in Europe has shown strong relationships with the observed warming, with trends ranging 6 to 25 days earlier over numerous cultivars and locations (Jones et al. 2005a). Changes have been greatest for bloom and, consequently, veraison and harvest dates, which typically show a stronger, integrated effect of a warmer growing season than do early growth events. In Alsace, France, research has found strong ties between climate and earlier phenology, with the period between budbreak and harvest becoming both earlier and shorter (15 to 23 days) and resulting in changes in fruit composition and increases in potential alcohol (Duchêne and Schneider 2005). Averaged over all locations and cultivars, grapevine phenology has shown an average 5 to 10 day response per 1°C of warming over the past 30 to 50 years (Jones et al. 2005a, Ramos et al. 2008). Given that wine-region-specific research has shown growing season average temperature warming of 1.3°C from 1950–1999 and projections of 2.0°C by 2050 (Jones et al. 2005b), further changes in grapevine phenology are likely. These impacts have been modelled in Australia, with the prediction that budbreak will be 6 to 11 days earlier by 2050, harvest dates will be up to 45 days earlier, and the growing season compressed to the point that ripening will occur in a hotter period of the season (Webb et al. 2008).

Given the strong influence of climate on grapevine growth behavior, and the potential for continued changes in climate over the next century (IPCC 2007), the main goals of the present study were to evaluate climate and phenological characteristics, variability, and structural changes in the Veneto region of Italy, based on a long-term data set on grapevine phenology (18 cultivars and 46 years) and climate in the region. The length of the time studied and number of cultivars observed allowed us to better capture the underlying responses of numerous different grapevine cultivars to climate and better understand how future climates might influence vine growth in the region and throughout the world.

Data and Methods

The phenology data used in this research are from a comprehensive, long-term collection of the Research Center for Viticulture (CRA-VIT) in Conegliano, Veneto region, Italy (Supplemental Figure 1). The collection is from a 5 ha single vineyard with over 1000 cultivars of both Italian and globally recognized types. Eight plants per cultivar were planted to 3 m x 1.5 m spacing on a Sylvoz trellis system. The collection was initially planted in the 1950s, with cultivars added year by year, and from 1986–1987 the collection was completely replanted in a block next to the original vineyard (same soils). After four years the yearly phenological observations came from the new collection. To ensure reliability between the initial planting and the new planting, the new block was planted with vine material from the old collection, ensuring similar genetic responses, and was planted to the same rootstock (SO4), at the same vine density, and with the same trellis system as the initial plantings. An analysis of overlapping phenological observations from the old and new blocks showed no significant differences between the two.

The phenology observations were recorded by viticultural technicians with CRA-VIT according to the Baggiolini phenological scale for budbreak (stage D), bloom (stage I), and veraison (no stage letter designation) (Baggiolini 1952). Harvest dates were determined by visual monitoring of the fruit development and health, but giving priority to the berry sugar content (Brix), and recorded when the sugar content remained the same after two consecutive measurements. The four main phenological events were also used to derive the intervals between each event (e.g., budbreak to bloom, veraison to harvest), resulting in 10 phenological parameters (Table 1, Table 2). The observations used in this research were from 18 cultivars that represented early, middle, and late maturing cultivars (Table 1). The data cover the 1964–2009 period with complete observations except for Chardonnay, which was missing 1964–1968 for budbreak, bloom, and veraison and 1980–1983 for harvest date.

The climate data were from a site next to CRA-VIT cultivar collection in Conegliano, Veneto region, Italy (60 m asl, 45.85°N, 12.26°E). The station recorded observations of maximum, minimum, and average temperatures and precipitation at daily timescales, giving complete daily data from 1964–2009. The daily data were summarized for the growing season for winegrapes (Apr–Oct) based on the fact that simple growing season averages explain much of the phenological development of grapevines, production, and quality (Jones et al. 2005a). Furthermore, two commonly used heat accumulation indices were computed from the daily data: standard growing degree-days (GDD) as classified into the Winkler index (WI; Amerine and Winkler 1944) and the Huglin index (HI; Huglin 1978). GDD was calculated based upon the standard simple degree-day formulation using average temperatures above a 10°C base for the months of April through October. The HI represents a similar degree-day formulation as the WI with an adjustment that gives more weight to maximum temperatures and is multiplied by a coefficient of correction (k) that takes into account the average daylight period
Table 1. Budbreak, bloom, veraison, and harvest statistics for 18 V. vinifera cultivars, overall average and averages for early, middle, and late cultivars, 1964–2009, Conegliano, Italy.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Mean</th>
<th>SD</th>
<th>Min Range</th>
<th>Max</th>
<th>Mean</th>
<th>SD</th>
<th>Min Range</th>
<th>Max</th>
<th>Mean</th>
<th>SD</th>
<th>Min Range</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miller Thurgau (E)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>Pinot Grigio (E)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Chardonnay (E)</td>
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<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
<td>3.2</td>
<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
<td>3.2</td>
<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
</tr>
<tr>
<td>Franciacorta (E)</td>
<td>3.2</td>
<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
<td>3.2</td>
<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
<td>3.2</td>
<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
</tr>
<tr>
<td>Pinot noir (E)</td>
<td>3.2</td>
<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
<td>3.2</td>
<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
<td>3.2</td>
<td>0.8</td>
<td>2.5–3.9</td>
<td>3.8</td>
</tr>
<tr>
<td>Merlot (M)</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Corvinone (M)</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Cabernet Sauvignon (L)</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Corvina (L)</td>
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<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Molinara (L)</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
<td>3.3</td>
<td>1.0</td>
<td>2.5–4.5</td>
<td>4.3</td>
</tr>
</tbody>
</table>

For the latitude studied (Huglin 1978). The HI is commonly summed over the April to September growth period when used in Europe (Jones et al. 2005a), and, while this represents one less month than the normal GDD formulation, both formulations were maintained for the ease of comparison with published data in Europe and elsewhere.

The phenology and climate data were then analyzed separately for their statistical characteristics, interannual variability, and trends. Pearson’s correlation and general stepwise linear regression were used to assess the climate parameter(s) that most influenced the phenological events or intervals. Given that large-scale atmospheric teleconnections had been used to describe interannual variability in climate and viticulture parameters in Bordeaux (Jones and Davis 2000), and Europe in general (Hurrell et al. 2003), we also examined the extent that the North Atlantic Oscillation (NAO) had on the local climate variations and the phenology of the grapevines in the region. In addition, given that many time series of data can have at least one breakpoint where the linear regression coefficient can shift over a range of years from one stable relationship to another (Chu 1996), the R-package “strucchange” version 1.3-7 (Zeileis 2009) was used to analyze the phenological data series for significant breakpoints (a confidence range of 90% for the change point).

Furthermore, to examine the nature and relationships for extreme years, the analysis compared the 2003 and 2007 vintage weather and phenological timing with the remaining years. Both of these vintages were two or more standard deviations outside the period normals due to extreme heat and dry conditions, providing a glimpse of potential grapevine responses from warmer conditions in the future.

Results

General climate characteristics. From 1964–2009 the annual average temperature was 13.1°C, with summer months where the maximum average temperatures were near 29°C and winter months with average minimum temperatures near or slightly below 0°C (Supplemental Figure 1). The growing season (Apr–Oct) average temperature (GST) was 18.5°C, placing it as a warm-climate maturity group as defined elsewhere (Jones et al. 2005b). In terms of heat accumulation, the growing degree-days for 1964 to 2009 averaged 1813, a region III on the Winkler index (Amerine and Winkler 1944). The Huglin index for the same time period averaged 2457, which fell in the warm class (Huglin 1978). Annual precipitation was 1216 mm, with growing season precipitation representing 65% of the annual amount and precipitation
during September through November showed the highest monthly coefficient of variation.

**Phenological characteristics.** The phenological characteristics for the 18 cultivars in the collection for 1964–2009 revealed an overall average budbreak date of 17 Apr (Table 1). Over the time period, the overall budbreak average ranged over 28 days, occurring as early as 3 Apr 1972 and as late as 30 Apr 1987. Between early, middle, and late maturing cultivars, there was a 5-day variation in average budbreak. The earliest cultivar for budbreak was Prosecco, with an average of 11 Apr, while the latest cultivars on average were Garganega and Trebbiano Toscano on 25 Apr. In terms of year-to-year variability in budbreak, Cabernet Sauvignon had the lowest variability, while Marzemino and Albana had the highest. Albana also had the widest range over the time period, with 39 days between earliest and latest budbreak (Table 1).

Bloom averaged 8 June for all cultivars from 1964–2009, with an overall average range of 37 days between the earliest (17 May 2007) and latest (23 June 1965 and 1980) years (Table 1). Early maturing cultivars tended to bloom 4 to 5 days earlier than middle or late maturing cultivars on average. The earliest flowering cultivar on average was Chardonnay (3 June), and the latest on average was Albana (13 June). Corvinone had the least year-to-year variation, and Pinot noir had the highest year-to-year variation and greatest range (42 days) between its earliest and latest bloom years (Table 1).

The average date for veraison was 13 Aug over all cultivars and years in the record (Table 1). Average veraison dates showed a 39-day variation between the earliest and latest years, with the earliest occurring on 24 July 2007 and the latest 1 Sept 1980 and 1983. Differences between early, middle, and late maturing cultivars were more pronounced with veraison than with budbreak or bloom. Early maturing cultivars averaged 9 and 14 days earlier veraison events compared to middle and late cultivars, respectively. The earliest veraison on average was for Müller Thurgau (30 July) and the latest was for Molinara (24 Aug), resulting in a range of over three weeks between the two cultivars (Table 1). Müller Thurgau and Corvinone had the lowest year-to-year variation in veraison of ±7.6 days and Corvina and Molinara varied by ±10.8 days from 1964–2009. Albana had the widest range (52 days) between the earliest and latest years for veraison.

The average date for harvest was 22 Sept (Table 1). The earliest average harvest dates were 30 Aug 2007 and 5 Sept 2003; however, during these years harvest dates did occur as early as the mid-August for some cultivars. The latest average harvest dates occurred on 13 Oct 1974 and 1980, resulting in a range of 43 days between the earliest and latest years. Harvest dates for early maturing cultivars occurred on average 12 days ahead of middle maturing cultivars and 20 days before late maturing cultivars. The earliest average harvest dates were for Müller Thurgau (6 Sept), and the latest average harvest dates were for Molinara (3 Oct). Pinot noir had the highest year-to-year variability, Corvinone had the lowest, and Marzemino had the widest range between earliest and latest years (66 days).

Average intervals between the main phenological events are an important measure of vine and berry development timing due to climate. The 18 cultivars in Veneto from 1964–2009 revealed an average budbreak to bloom interval of 52 days (Supplemental Table 1). The time period range was 35 days, with the shortest average interval between budbreak and bloom 36 days in 1986 (with an April/May average temperature of 16.0°C) and the longest 71 days in 1984 (with an April/May average temperature of 13.4°C). Trebbiano Toscano, Cabernet Sauvignon, and Garganega had the shortest interval (48 days) and Trebbiano Toscano also the lowest variability from year-to-year (SD ±8.2 days), and Prosecco and Marzemino had the longest interval of 56. Albana had both the highest variability (SD ±11.7 days) and the greatest range (59 days) of the collection.

The budbreak to veraison interval was 118 days on average (Supplemental Table 1), with a range of 34 days from the shortest average interval of 104 days in 2000 to 138 days in 1984. Müller Thurgau had both the shortest average budbreak to veraison interval (108 days) and the lowest year-to-year variability (SD ±9.0 days). Albana had the highest variability in the interval (SD ±12.5 days) and the greatest range between its earliest and latest occurrence (57 days) and Molinara and Corvina had the longest average interval (127 days).

The period from bloom to veraison averaged 66 days (Supplemental Table 1), with a range of 36 days from the earliest to latest average years. The shortest interval on average occurred in 1966 and 1970 (51 days) and the longest interval occurred in 1983 (87 days). The bloom to veraison period had the lowest standard deviation (SD ±6.8 days) of any of the event intervals, indicating that it was the most consistent growth period. By cultivar, Chardonnay had the lowest year-to-year variability and Pinot noir had the highest. In addition, a 20-day range was found between the shortest (Müller Thurgau, 56 days) and the longest (Molinara, 76 days) average interval.

The bloom to harvest interval for the 18 cultivars averaged 106 days during 1964–2009 with the shortest interval in 1995 (86 days) and the longest in 1986 (130 days) (Supplemental Table 1). Müller Thurgau had the shortest average interval at

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**Table 2** Linear trend characteristics ($R^2$, $p$ value, slope or annual trend, and total trend over the 46 years) for each of the overall average phenological growth events and intervals between growth events (averaged over all 18 cultivars) for 1964–2009. Conegliano, Italy. (ns indicates that that trend for that variable is not significant.)

<table>
<thead>
<tr>
<th>Variable</th>
<th>$R^2$</th>
<th>$p$ value</th>
<th>Annual trend (days)</th>
<th>Total trend (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budbreak</td>
<td>ns</td>
<td></td>
<td>-0.34</td>
<td>-16</td>
</tr>
<tr>
<td>Bloom</td>
<td>0.36</td>
<td>≤0.001</td>
<td>-0.24</td>
<td>-13</td>
</tr>
<tr>
<td>Veraison</td>
<td>0.21</td>
<td>≤0.001</td>
<td>-0.39</td>
<td>-19</td>
</tr>
<tr>
<td>Harvest</td>
<td>0.37</td>
<td>≤0.001</td>
<td>-0.42</td>
<td>-19</td>
</tr>
<tr>
<td>Budbreak to bloom</td>
<td>0.30</td>
<td>≤0.001</td>
<td>-0.39</td>
<td>-18</td>
</tr>
<tr>
<td>Budbreak to veraison</td>
<td>0.22</td>
<td>≤0.001</td>
<td>-0.33</td>
<td>-15</td>
</tr>
<tr>
<td>Budbreak to harvest</td>
<td>0.14</td>
<td>≤0.001</td>
<td>-0.32</td>
<td>-15</td>
</tr>
<tr>
<td>Bloom to veraison</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bloom to harvest</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Veraison to harvest</td>
<td>0.11</td>
<td>≤0.001</td>
<td>-0.14</td>
<td>-6</td>
</tr>
</tbody>
</table>

94 days while Molinara and Corvina had an average 116-day interval. Similar to the bloom to veraison interval, Chardonnay and Pinot noir exhibited the least and most year-to-year variability for the bloom to harvest interval, respectively. Corvinone had the widest range in this interval, varying by 58 days over the time period.

The ripening stage from veraison to harvest had an average of 39 days during the time period (Supplemental Table 1), with a range of 44 days from the shortest interval of 19 days in 1983 to 63 days in 1986 (similar to the bloom to harvest interval). By cultivar, the veraison to harvest interval varied from the shortest for Chardonnay (34 days) to the longest for Garganega and Cabernet Sauvignon (43 days). Similar to the previous event intervals, Chardonnay had the lowest year-to-year variability in the veraison to harvest interval, while Pinot noir had both the highest variability (SD ±12.1 days) and greatest range for the shortest to longest interval (65 days).

The length of budbreak to harvest for the region averaged 156 days over all cultivars from 1964–2009 (Supplemental Table 1). This interval characterized the time needed for each cultivar to ripen and ranged 55 days from the earliest years with 144 days in 2003 to the latest year with 189 days in 1980. Chardonnay, Pinot Grigio, and Müller Thurgau had the shortest average budbreak to harvest dates of 145 days, while Molinara had the longest average interval of 169 days. Müller Thurgau and Pinot Grigio had the lowest year-to-year variability from budbreak to harvest, while Albana had the highest. Albana and Chardonnay had the greatest range from their shortest to longest intervals.

Temporal correlations between the phenology averaged over all the cultivars showed that budbreak timing is not significantly correlated with the later growth stages. On the other hand, bloom dates were strongly correlated with both veraison ($r = 0.85, p \leq 0.001$) and harvest ($r = 0.74, p \leq 0.001$) dates. Furthermore, the timing of veraison and harvest dates are highly correlated ($r = 0.79, p \leq 0.001$). These correlations indicate that budbreak and bloom timing are largely independent phenological events driven by the more variable weather influences early in the season but that as the vine continues its annual growth cycles, each successive event is significantly correlated to the previous event. The veraison to harvest interval is at times driven by picking decisions, which tend to drive the variability in the length of time needed more so than previous growth intervals.

Relationships between climate and phenology. Climate and the phenology of winegrapes have been shown to be strongly coupled (Calò et al. 1994, Jones and Davis 2000), and the results for this analysis also revealed significant relationships. The average budbreak for the 18 cultivars in the collection showed the most significant response to the average temperature during February and March, where budbreak was on average 2.9 days earlier per 1°C (Figure 1A). Average bloom dates were most significantly related to maximum temperatures during 10 Apr to 10 June, with 4.1 days earlier per 1°C (Figure 1B). Maximum temperatures during 10 June to 20 Aug had the most significant relationship with veraison dates, with 3.2 days earlier per 1°C (Figure 1C). The most significant relationship with harvest dates and climate was with the average growing season temperatures from April through October, where an 8.0 day earlier harvest was achieved with a 1°C warmer vintage (Figure 1D). Measures of heat accumulation, such as growing degree-days and the Huglin index, did not explain more of the variation in the

Grapevine Phenology and Climate Change – 333

main phenological events than did simple measures of average or maximum temperatures (Figure 1).

**Trends, variability, and breakpoints in phenology.** From 1964–2009, the collection's average phenological events indicated higher interannual variability early in the record and lower interannual variability since approximately 1990 (Figure 2). Furthermore, the year-to-year coefficient of variation for the average budbreak dates was nearly double that observed for the three other events, revealing the higher springtime variability in temperatures and growth (not shown). An examination of the most prominent large-scale atmospheric-forcing mechanism in the region (NAO) found no significant correlations between the dominant period of the NAO winter index (DJFM) or seasonal NAO index values (MAM or JJA) compared with the main phenological events or the intervals between the events.

While there was no long-term trend for budbreak (Figure 2, Table 2), each of the three other main phenological events trended earlier over the time period. The trend in average bloom dates was 16 days earlier from 1964–2009, while the trends in average veraison and harvest dates were 13 and 19 days earlier, respectively. There were similar trends for the main phenological events for early, middle, and late maturing cultivars, although early maturing cultivars changed at a slightly higher rate.

The intervals between the main phenological growth events had higher interannual variation compared to the individual growth events themselves, hinting at a strong vintage weather conditions connection driving plant development rates between events. The bloom to veraison interval had the lowest interannual variation of all the intervals at four days, while the coefficient of variation for budbreak to bloom (19 days) and for veraison to harvest (15 days) was significantly higher than for the other intervals (not shown). The intervals also displayed trends during the time period, with the budbreak to bloom interval changing the most at 18 days shorter from 1964–2009 (Table 2). Other intervals trending shorter were budbreak to veraison (15 days), budbreak to harvest (15 days), and veraison to harvest (6 days). The growth intervals from bloom to veraison and bloom to harvest did not change significantly over the time period. For early maturing cultivars, differences from the average values included a slight lengthening trend in the bloom to veraison period (6 days) and a greater shortening of the budbreak to harvest interval (21 days). For middle maturing cultivars, there was a similar greater shortening of the budbreak to harvest interval (22 days) and the veraison to harvest period did not trend shorter. Trends for late maturing cultivars were similar to early maturing cultivars.

While the general trends described above show changes over the entire time period, it is important to examine if there were significant breakpoints in the time series. For budbreak, no breakpoints were found in the overall average, early, middle, or late maturing cultivars; however, there was a slight change to later budbreak (2 to 3 days) in the middle of the 1970s (Figure 3A, only for the overall average for the cultivars; early, middle, and late cultivar figures not shown). For bloom there was a significant breakpoint in 1991 for average, early, and middle cultivars, with a step change of 10 days earlier (Figure 3B). Early and middle maturing cultivars had a similar breakpoint to the average; however, late maturing cultivars had a significant breakpoint that was six years later in 1997 but with the same 10 day earlier change (not shown). Results were similar for veraison, where the overall average (Figure 3C) and early and middle maturing cultivars had significant breakpoints in 1991–1992 with a 10 to 11 day earlier step change, and the breakpoint for the late maturing cultivar was in 1996 and was 12 days earlier (not shown). For harvest, each of the four groupings of cultivars had similar results, with significant breakpoints from 1990–1992 with step changes from 12 to 15 days earlier (Figure 3D). Overall, the breakpoint analysis showed that was a significant advance in the vine phenology, which occurred over a 10-year period during the late 1980s through the late 1990s, in accordance with the temperature increases (Figure 4).

**Variability and trends in climate.** From 1964 to 2009, there were moderate interannual variability and interdecadal fluctuations in temperature (Figure 4). There were trends for average, average maximum, and average minimum temperatures for both the entire annual period and the growing season (Apr–Oct) (Table 3). Maximum temperatures increased the most, warming 2.5°C over the entire year and 2.4°C during the growing season. Minimum temperatures increased by 2.0°C over the entire year and 2.3°C during the growing season, while average temperatures increased 1.6°C and 2.3 °C for annual and growing season periods, respectively. However, annual and growing season (Apr–Oct) average maximum temperatures declined from 1964 to the mid-1980s and then increased markedly through to 2009, while minimum temperatures declined slightly in the past decade (Figure 4).

Given the differences in the underlying time series for maximum and minimum temperatures, there was a gradual decline in the diurnal temperature range (DTR) from 1964 to 1999 followed by a noted increase in DTR through 2009 (Figure 5). As is common in midlatitude regions, precipitation
in the Veneto region showed much greater interannual variability and interdecadal fluctuations than temperature (Figure 6), and no trends were found for annual or growing season precipitation (Table 3). Annual precipitation averaged 1238 mm with a 216 mm standard deviation and ranged from a low of 777 mm in 2003 to a high of 1552 mm in 1979. Overall annual precipitation showed high interannual variation, but exhibited a moderate decline through 2009 (Figure 6). Similar to phenology, we examined the climate time series for relationships with the NAO and found that the winter and seasonal NAO index values had significant, albeit minor, relationships with growing season temperatures but not precipitation (not shown). The overall effect is that when the NAO is in its positive phase, the growing season is slightly warmer than normal.

Analysis of the climate data by the two periods defined by the phenological breakpoints, 1964–1990 and 1991–2009, revealed significant differences in temperature. The later period was 1.0 to 1.5°C warmer than the earlier period for
average, maximum, and minimum temperatures, while no differences in precipitation were found. Furthermore, both the range and interannual variability in temperature were higher during 1964–1990 than the later time period (not shown), which matched well with the lower interannual phenological variability since 1990 (noted previously).

**Before and after breakpoint and extreme years.** A comparison of the phenology before and after the breakpoint (1964–1990 and 1991–2009) revealed significant differences in timing and interval lengths (Figure 7). Averaged over all cultivars, budbreak was not significantly different in timing between the two periods, although bloom, veraison, and harvest dates were all significantly earlier. Overall, the length of time from budbreak to harvest length was 13 days longer during the earlier period, driven by mostly longer budbreak to bloom and veraison to harvest intervals (Figure 7A). There were similar results for early, middle, and late ripening cultivars (Figure 7B, C, D).

To examine the grapevine phenology response to extreme climatic years, we compared the temperature and phenology after the breakpoint (1991–2009) with the two warmest vintages during this period (2003 and 2007). The 2003 vintage was extremely warm and dry during the middle of the summer throughout most of Europe (Seguin et al. 2004), while the 2007 vintage was extremely warm during the early spring (April average temperature +4°C over the long-term average), slightly above average the rest of the vintage, and with near-normal precipitation. For the 2003 vintage, budbreak was a few days later than average (Figure 7A), but was followed by warm conditions that hastened bloom, reducing the budbreak to bloom interval 8 to 10 days for early, middle, and late cultivars. Even with the warmest summer on record, the bloom to veraison interval remained near the period average, potentially indicating greater overall growth stability during this stage. However, the veraison to harvest interval during 2003 compressed to 31 days, more than one week shorter than the average during 1991–2009 (Figure 7A). The overall length of the budbreak to harvest period was 127 (early varieties) to 144 days (late varieties) in 2003, 10 to 16 days shorter than the 1991–2009 period average (the warmest and shortest in the record). For 2007, budbreak and bloom occurred nearly two weeks ahead of the 1991–2009 average, with no differences between the early to late ripening cultivars (Figure 7). However, even with the exceptionally early budbreak and bloom in 2007, the remaining growth intervals were almost the same as those during the 1991–2000 period. Both 2003 and 2007 had the shortest budbreak to bloom intervals in the data record (38 to 39 days across all cultivars); however, in 2007 the remaining growth periods were earlier but not shorter.

**Discussion**

This research used a long-term data set of multiple cultivars and site-specific climate data to examine the characteristics, relationships, and trends for grapevine phenology and climate in Conegliano, Italy. The results have shown that climate in the region has clearly changed; temperatures increased appreciably since 1980, the diurnal temperature range decreased because of more rapid changes in minimum temperatures, and precipitation decreased after 1995. Similar results have been seen elsewhere in Europe (Duchêne and Schneider 2005, Jones et al. 2005a, Ramos et al. 2008, Orlandini et al. 2009). Results also showed trends in winegrape phenology, differences between phenological timing of different cultivars, and moderate to strong relationships between phenology and climate. From 1964 to 2009 the 18 cultivars had a range of 14 days for budbreak, while the range between cultivars dropped to 10 days for bloom, but increased to 25 and 27 days for veraison and harvest, respectively. The overall average for bloom, veraison, and harvest had interannual variability of 37, 39, and 43 days between years, respectively, and the budbreak date had 28 days between years. Across all varieties, budbreak and harvest dates had a higher coefficient of variability from year-to-year while bloom dates were the most consistent.

Examining the phenological timing across the growing season, the results showed that there are not always strong relationships between growth events. For example, an early budbreak was not always followed by an early bloom and
an early bloom did not always correspond to an early ripening. The observations of the length of the intervals between stages support this observation and confirm other work (Calò and Costacurta 1974, Moncur et al. 1989). Evidence is from two of the warmest vintages in the region, 2003 and 2007. The 2003 vintage, the hottest on record in much of Europe (Seguin et al. 2004), experienced a normal spring and budbreak, but a very warm summer that resulted in 127, 135, and 144 day growing intervals for early, middle, and late cultivars, respectively (on average 14 days shorter compared with the 1991–2009 period). While the 2007 vintage budbreak began 2 to 3 weeks early with spring temperatures 3.5°C warmer than average, the vintage commenced with a near-normal budbreak to harvest period (only 6 days shorter than the 1991–2009 period).

Extreme years also provide further insight into the relationships between vintage weather and grapevine growth. For example, the very short budbreak to harvest periods of 1993, 2003, 2005, and 2007 (155 days or less) were driven by ~2°C higher average temperatures, while the very long budbreak to harvest periods of 1967, 1973, 1980, and 1983 (185 days or more) had ~2°C lower growing season temperatures on average. The interval between budbreak and harvest, averaged across cultivars and vintages, was shortened by 8 days per 1°C warmer growing season. However, budbreak and bloom appeared to be the more climatically sensitive stages. Verasion and harvest dates exhibited lower correlations with climate, but stronger relationships with the timing of prior phenological events (mostly for verasion versus bloom), which is similar to observations in Bordeaux (Jones and Davis 2000). The low correlations between the verasion to harvest events and climate indicate the importance of the influence of grower subjectivity on maturity and picking decisions.

This research found evidence of a changing climate in Conegliano, Italy, with warming rates of 1.6 to 2.5°C in annual and growing season average, maximum, and minimum temperatures from 1964–2009, with maximum temperatures trending at a higher rate than minimum temperatures. These warming rates are similar to those found elsewhere in Alsace (Duchêne and Schneider 2005), Catalonia (Ramos et al. 2008), Tuscany (Orlandini et al. 2009), and for other locations in Europe (Jones et al. 2005a) and worldwide (Jones et al. 2005b). While other research has found significant changes in seasonal precipitation and potential evapotranspiration...
demand (Brunetti et al. 2002, Duchêne and Schneider 2005, Ramos et al. 2008), there was no evidence of changes in rainfall regimes in this study.

The observed warming in the region has influenced grapevine phenology, resulting in earlier bloom, veraison, and harvest dates of 16, 13 and 19 days, respectively, during the 1964–2009 time period. Similar trends in phenology have been found across many cultivars and locations in Europe (Jones et al. 2005a). However, budbreak did not trend earlier, which is likely related to numerous previous vintage, postharvest, and dormant factors such as root starch levels, chilling requirements, and soil temperature and moisture levels (Lombard and Richardson 1979) and higher temperature variability that occurs during the spring. The breakpoint analysis showed significant changes in the late 1980s through the early 1990s for bloom, veraison, and harvest, while budbreak did not exhibit a significant shift. In addition, after 1990–1991 the phenological events exhibited less variability, potentially indicating that the higher temperatures resulted in more consistent growth cycles on average. Furthermore, the early and medium maturing cultivars appeared to react sooner to the climate warming, with breakpoints in 1987 to 1988, compared to late maturing cultivars, with breakpoints in 1996 to 1997 (not shown). Similar results were found for Chardonnay (early) compared with Cabernet Sauvignon (late) in Australia (Webb et al. 2008). Moreover, the earlier veraison and harvest dates combined with a shortened interval between the two result in a ripening phase that is now occurring in a warmer period of the year with potential issues of lowered acidity, higher sugar content, lower anthocyanin levels, and changes in aromatic compound development (Haselgrove et al. 2000, Seguin et al. 2004, Webb et al. 2008, Keller 2010).

Conclusions

Grapevines yield high-quality fruit at economically sustainable production levels when grown in suitable climates. This research examined the growth habits and phenological timing of a range of early, middle, and late maturing cultivars and their relationships to the prevailing climate in the Veneto region of Italy. In addition, this research has detailed the trends in phenology and the influence of a warming climate, which has the potential to significantly affect cultivar suitability and wine production in this region and elsewhere worldwide.

If climates continue to change as projected (1.5 to 2.5°C by 2050), then further changes in vine growth will likely continue. However, as the 2003 and 2007 vintages in the Veneto region have shown in this research, vine growth intervals as short as 127 to 144 days for early and late cultivars, respectively, are extreme and not likely to be any shorter in the near future. This trend will likely mean significant changes in cultivar suitability to the climate in the region and/or further separation among the timing of sugar/acid balance, phenolic maturation, and fruit character. Future research using this large cultivar collection will examine how fruit composition from these cultivars is influenced by phenological timing and climate, providing greater insight into the complex interactions that result in wine.

Literature Cited


